PLATOON IDENTIFICATION SYSTEM IN CONNECTED VEHICLE ENVIRONMENT

A Thesis

by

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ABSTRACT

Connected vehicle technology has the potential of drastically improving the safety and mobility of transportation system. Recognizing and identifying the vehicle platoons in a traffic stream has the potential of changing the arterial signal control logic and increasing the bandwidth of the signal coordination system.

This thesis investigated the nature of traffic platoons and developed a platoon identification algorithm under the connected vehicle environment. In this thesis, definition and characteristics of vehicle platoons are investigated through past literature and simulation results. A real-time algorithm to identify vehicle platoons is developed based on the findings. The proposed algorithm is implemented and simulated using PTV VISSIM. Performance measures are identified and proposed based on past studies. Impacts of penetration ratio of connected vehicle on the proposed algorithm is also investigated.

A similar platoon identification algorithm from the past research is also implemented in PTV VISSIM and evaluated. The evaluation result of the existing platoon identification algorithm is compared to that of the proposed algorithm. The proposed approach is found to be more robust and practical in platoon identification.

DEDICATION

This thesis is dedicated to my dearest parents who have been supporting and motivating me to accomplish the education away from my hometown.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Zhang, and my committee members, Dr. Wang, and Dr. Cline, for their guidance and support throughout the course of this research.

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NOMENCLATURE

CV	Connected Vehicle
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
OBU	On Board Unit
RSU	Roadside Unit
SCOOT	Split, Cycle and Offset Optimization Technique
STD	Standard Deviation
AVG	Average
CI	Confidence Interval
HDWY	Headway
CDF	Cumulative Density Function

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CHAPTER I

INTRODUCTION

Congestions has become one of the most serious problems in modern urban areas. Among all kinds of roadways, the congestions on signalized arterials are among the most severe. Arterials deliver traffic from collector roads to freeways or expressways, and between urban centers at the highest level of service possible (*1*). The traffic demand on arterials are often massive, which makes the traffic signal control and coordination on arterials crucial.

Arterial street signal control needs to maintain a higher speed to obtain a high capacity while collecting traffic from secondary streets. The nature of arterial streets determines two of its main characteristics:

1. Closely spaced signalized intersections along the road.
2. High speed and high traffic demand.

Therefore, the goal of arterial signal control is to give priority to progressive traffic flow along the arterial and let most traffic pass the arterial without stopping(*2*). In order to achieve this goal, the signals along the arterial street work as a whole system. This kind of signal control strategy is called coordinated signal control. Arterial street control recognizes that a signal releases platoons that travel to the next signal and try to let all or most of the vehicles in this original platoon pass the arterial without stop(*3*).However, after released from the upstream intersection as a whole platoon, the platoon will disperse into several platoons due to speed difference as it proceeds to the downstream intersection. As the platoon disperses, it takes longer time for the platoon to travel through the next intersection. To compensate for the efficiency of the whole system, the green time of the next intersections often not long enough for the whole dispersed platoon to pass. So when to stop the green time of the downstream intersection and let which ones of the child platoons pass the intersection without stopping becomes a major issue of coordinated control.

The current coordination signal control technologies are based on historical data to find a time window for the platoons to pass through. The time period that can allow vehicles to pass the arterial without stopping is called green band and its width is bandwidth. The more intersections are included in this system, the narrower the bandwidth becomes. Also, it is very hard to maintain progressive traffic flow coordination for both directions of the arterial street. The coordinated signal control system should work a lot better if it can recognize real-time platoons on the arterial street and adjust the signal timing based on those real-time information. This kind of coordinated signal control system can be called as a platoon-based signal control system.

An important component of the future platoon-based coordinated signal control system is real-time platoon identification. With the advanced connected vehicle technology, traffic data can be collected in great abundance in real-time to feed into various traffic control systems.

1.1. Problem Statement

Highway Capacity Manual (HCM) defines platoon as "A group of vehicles or pedestrians travelling together as a group, either voluntarily or involuntarily because of signal control, geometric, or other factors" (*4*). The definition of platoon is simply and vaguely "traveling together". This makes it hard to specify the border between platoon and non-platoon objectively. Different people have different understanding of "traveling together". So the first problem of this thesis is to establish the specific definition of "traveling together" by means of exploring traffic characteristics such as speed, headway and spacing in platoon and non-platoon vehicle groups.

The second problem of this thesis is to investigate how the information from connected vehicle technology can help improving the identification of platoons in traffic flow. To solve this problem, firstly the capability of connected vehicle environment should be specified. Secondly, an algorithm that can process the connected vehicle information into established vehicle platoons should be developed.

Once the algorithm is proposed, it should be evaluated and tested under different traffic conditions and be compared with existing platoon identification systems. Recommendations should be made in terms of the proposed system.

1.2. Research Objectives

The goal of this research is to develop a platoon identification algorithm that can fully use the potential of the promising connected vehicle technology. The objects of this research are:

1. To develop a real-time platoon identification system that can work under full penetration condition of connected vehicle.
2. To investigate the impact of lower penetration ratio on the proposed platoon identification system. Propose an estimation method to compensate lower penetration ratio.
3. To identify possible performance measures of the Platoon Identification System.
4. To capture platoon characteristics of interest and investigate the variation of these characteristics under different traffic conditions.
5. To evaluate and test the system under different traffic conditions and compare with existing platoon identification system based on probe vehicle.
6. Compare the proposed platoon identification algorithm with selected past algorithm.
7. To summarize and make recommendations about the proposed system.

1.3. Research Benefits

This research work is being done to provide a foundation of more efficient and intelligent arterial coordinated signal control system. The research project is to develop a detailed algorithm to identify platoons from arterial traffic flow based on traffic flow characteristics. The results of this research will provide the future platoon-based arterial signal control system the information it needed to alter the signal timing for maximum efficiency and capacity. This research can be the foundation of a next generation arterial signal control system. Which can see the platoon coming and maximize the progressive traffic that can go along the arterial without stopping based on the platoon information provided by the proposed system of this research. In addition, this research can provide more insights of the characteristics of vehicle platoons.

CHAPTER II

BACKGROUND

This chapter provides a detailed review of past studies and practices related to platoons and arterial coordination. The previous research serves as a background and guide to the thesis research. Firstly, literatures about platoon and coordination on arterial is reviewed. Then the connected vehicle technology is also introduced in this chapter. In Section 2.3, existing methods of platoon identification are summarized. Besides, the platoon characteristics of interest and performance measures of the platoon identification systems are reviewed.

2.1. Platoon and Coordination

In urban traffic network, arterial plays a very important role collecting traffic from local collector roads and deliver traffic to city centers or to freeways at the highest level of services possible (*1*). The function and nature of arterial road determines that urban arterial roads usually have a large traffic demand and closely located intersections.

Existing studies have shown that most vehicles released from a signalized intersection upstream maintain a platoon for 1000 ft. (*5*). Another study showed platoons stay together for around 6562 ft. (2000m) (*6*). Once released from upstream signal, most vehicles will remain in a platoon before they reach the downstream signalized intersection. In this situation, it will be disturbing and inefficient to have some of the platooned vehicles held at one signal watching the downstream signal green time wasted. Also, drivers will get frustrated when they are held by the red signal again and again driving down the arterial road.

A common practice to solve this arterial traffic problem is to coordinate signals that are less than a mile apart (*5*). The signals in a coordinated signals are considered working together as a system to allow platoons to pass the arterial without stop. The goal of the coordinated signal system is to make sure the downstream signal turns green when the platoon from upstream reaches the downstream intersection. Each coordinated signal has the same cycle length, or in some rare situation, some intersections have a cycle length that is double or half of the common cycle length of the coordinated signal system.

The approach to achieve the signal coordination goal is signal progression. Signal progression is often based on time-space diagram (Figure1). In a time-space diagram, the vehicles released from upstream signal are assumed to be traveling with a steady speed as long as they do not get stopped by red light. The blue arrows in the diagram represent the trajectory of vehicles released from the upstream intersection in a cycle. Red blocks represent the time that the corresponding intersection is in red time. Figure1 shows that if the offsets are set correctly, the green time of the coordinated system can progress with the vehicle platoon and achieve its goal. Bandwidth is the time window that can allow the vehicle platoon to pass the arterial without stopping.

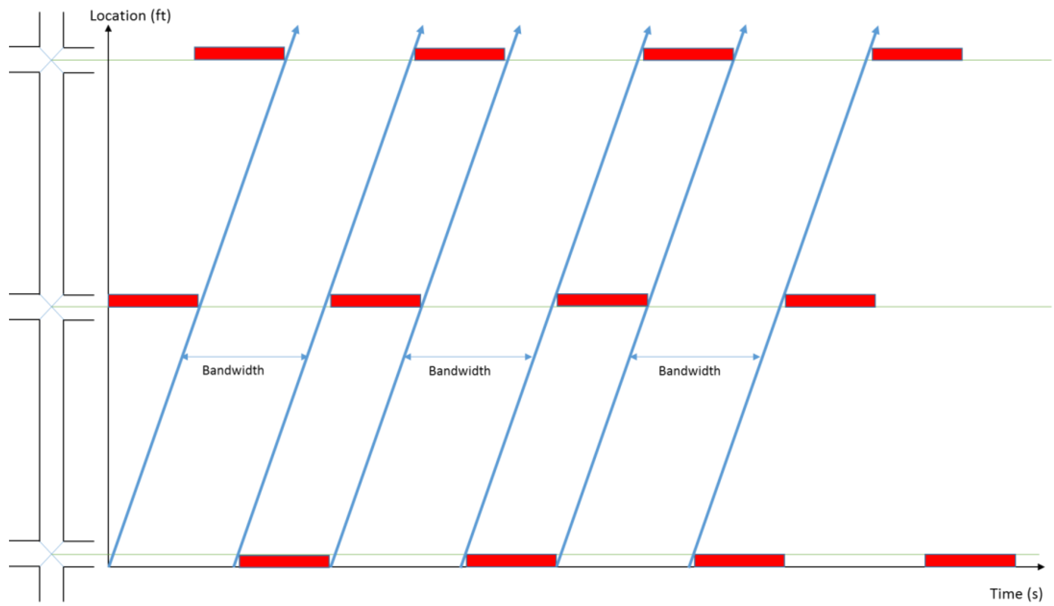

Figure1 Time-Space Diagram

However, signal progression has its problems. Firstly, the signal progression is based on historical traffic data and assumes all platoons under different traffic conditions will all travel at a pre-decided speed. The biggest problem here is that the platoon speed is subjected to various factors and it will not always remain the assumed value. When the platoon travels at a lower speed than the assumed value, green time will be wasted at the downstream intersections. If the platoon travels at a higher speed than the assumed value, the platoon will be forced to stop because the green time progression cannot catch up with its speed. Secondly, signal coordination does not take the existing queue at downstream intersections into consideration, which is not realistic. Current signal coordination system only has limited reaction capability to the real time true traffic condition. Thirdly, one-way signal coordination is easy, but in real world, signal timing has to deal with two directions of platoons. Two-way signal progression often results in compromising the efficiency of one direction, a small bandwidth, or long red time for intersected secondary directions.

Coordination of signals based on historical traffic data may not be the most efficient way to deal with arterial traffic. A desirable approach is to keep isolated control at each signals and provide dynamic coordination when a need arises (*7*). A need of signal progression arises when there is a platoon formed from upstream signal. Platoon identification serves as a tool to find this need. When a platoon is detected, the signal progression should be generated based on the real-time speed and size of the platoon. With the information from state-of-the-art platoon identification and queue detection systems, the efficiency and capacity of arterials can be greatly improved.

A state-of-the-art platoon identification algorithm is the foundation of future arterial traffic control system.

2.2. Connected Vehicle

Connected vehicle includes Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication. Connected Vehicle (CV) technology enables the wireless communication of traffic information between components of transportation system. The GSM Association predicts that by 2020, nearly every vehicle assembled in US will have an embedded cellular-based telematics system (*8*).

Local area connectivity is provided by 5.9GHz Dedicated Short Range Communication (DSRC), which is a radio communication technology similar to Wi-Fi. DSRC can provide connectivity for time-critical application such as V2V collision avoidance applications. Compared to other wireless communication methods, DSRC has several advantages such as designated licensed bandwidth, fast network acquisition, low communication latency and high reliability, interoperability and security (*9*).

Stable connectivity relies on the cooperation of three components:

- On-Board Unit (OBU) is the embedded equipment on connected vehicles to exchange information.
- Road-Side Unit (RSU) is a roadside information broadcaster and receiver. RSU can only communicate with the vehicles within its range.
- Back-office server connects RSEs and monitors the entire traffic network. Relative information can be sent to certain RSEs (*10*).

Communication range and latency are the two most important issues in wireless communication. Currently there are several options to achieve V2V and V2I communication. The most popular one is Dedicated Short-Range Communications (DSRC). Dedicated Short-Range Communications (DSRC) has a communication range of about 3000 ft. (1000m) and it is often used in time sensitive CV applications because of its low communication latency. Other options include cellular communications, Bluetooth communications and satellite communications (*9*).

Applications of Connected Vehicle (CV) technology can be categorized into three classes, they are safety, mobility and environmental applications. Safety applications can reduce the chance of accidents by detecting hazardous situations and give out warnings, advises or even take control of the vehicle when necessary. Dilemma zone protection system is a good example of safety application of Connected Vehicle.

Mobility applications use real-time traffic data to manage traffic dynamically. The topic of this research, real-time platoon identification belongs to this category. Environmental application captures real-time vehicle environmental performance data like fuel consumption and emission measurements and generate speed or routing suggestions or modify signal control strategy to minimize the environmental impact of traffic flow.

Current adaptive control is based on infrastructure detectors. Detectors are installed at fixed locations on the roadway (loop detectors) or hang on the signal poles (video detectors). There is no direct measurement of vehicle state variables such as location, speed, acceleration, current lanes and even turning indicators (*11*). Another limitation of current infrastructure detectors is that they can only detect the traffic condition one time at a fixed point. However, traffic changes as they go. Also, the installation and maintenance cost and demand of current detectors are high. Detector location setting has a great impact on the performance of the whole signal control system.

Connected Vehicles can get most of the vehicle state variables as they go. The complete and real-time traffic data can help signal controllers make better decisions (*11*). Data that can be exchanged via wireless communication technology in connected vehicle system includes each vehicle's latitude, longitude, time, heading angle, speed, lateral acceleration, longitudinal acceleration, yaw rate, vehicle width, vehicle mass, bumper height and the number of occupants in the vehicle (*12*).

Connected vehicles can be used as probe vehicles to monitor real-time traffic condition information such as travel time, speed and delay of each equipped vehicle. The messages that can be sent through wireless communication in connected vehicle environment are described in detail in the SAE J2735 standard entitled “Dedicated Short Range Communications (DSRC) Message Set Dictionary” (*13; 14*). A comparison between traditional advanced detector and connected vehicle environment as traffic control data source is shown in Table 1.

Table 1 Comparison between Advance Loop Detector and Connected Vehicle

Data Source	Pros	Cons
Connected Vehicle	1. Can obtain speed, location and headway information overtime from each vehicle. 2. Can obtain trajectory of each vehicle.	1. During transition phase, penetration ratio of connected vehicle is an issue. Not information from all of the vehicles can be obtained.
Advanced Detector	1. Information of all vehicles can be obtained. No penetration ratio issue.	1. Information of each vehicle can only be obtained once at a fixed location.

2.3. Platoon Identification

There has been a lot of signal control algorithms based on platoon identification like SCOOT, REALBAND (*15*) (*16*).But literatures specifically on platoon identification is very limited. The existing platoon identification algorithms used in each signal control literatures are summarized below in the following aspects: Definition of platoon, data source of past platoon identification and decision threshold selection.

2.3.1. Platoon Definition

A platoon is defined as "A group of vehicles or pedestrians travelling together as a group, either voluntarily or involuntarily because of signal control, geometric, or other factors" in HCM (*4*). This definition is inaccurate and vague for platoon identification. So in each platoon identification algorithm, the definition and criteria of platoon differs in various studies.

The most common platoon definition variable is time headway. Time headway is the time between successive vehicles as they pass by a fixed point on a roadway (*4*). This variable is chosen because the current platoon identification system is based on loop detectors, and time headway is the only variable available from loop detectors representing the closeness of successive vehicles. A large amount of platoon identification system studies define platoon as a vehicle group in which all the vehicles have a headway smaller than a pre-specified threshold (*17-19*). This pre-specified threshold is called critical headway.

Platoon identification can be subjective because of the obscure and non-numerical definition. Some other studies about platoon identification system define platoons based on user preference such as a desired platoon size (*7*). Gaur and Mirchandani define platoon by using vehicle arrival density to measure vehicle closeness.

In general, due to the vagueness of platoon definition, current platoon identification algorithms is subjective and diverse. The key question in platoon identification becomes how to define a platoon numerically. Starting from the original platoon definition in HCM, traveling together is the key word in defining a platoon. Having vehicles traveling together means the vehicles in a platoon stay close to each other over time. Measure of vehicle closeness over time can be the start point of this research.

2.3.2. Data Source

Vehicle data source in most of the literatures are advance detector data (*7; 19; 20*) . High Precision microwave data is used in (*18*), vehicle trajectories can be obtained through microwave sensors. The penetration rate and feasibility of massive deployment of high precision microwave sensors are not mentioned in the paper. Probe data is also used in platoon identification (*17*).

Advance detectors are traditional loop detectors but they are placed at a significant distance upstream of the stop bar (*7*) to provide enough time for platoon detection. The purpose of a platoon identification system is using the platoon information to dictate downstream arterial signal progression. There is no point of platoon identification if most of the vehicles in the platoon has already pass the immediate downstream intersection. Figure1 is an illustration of advance detector setting. Advance detectors can be installed on a single lane or across multiple lanes of the roadway. Most of the detector and critical headway based platoon identification systems only consider single-lane detection, in which vehicles follow each other in sequence as in Figure 3.

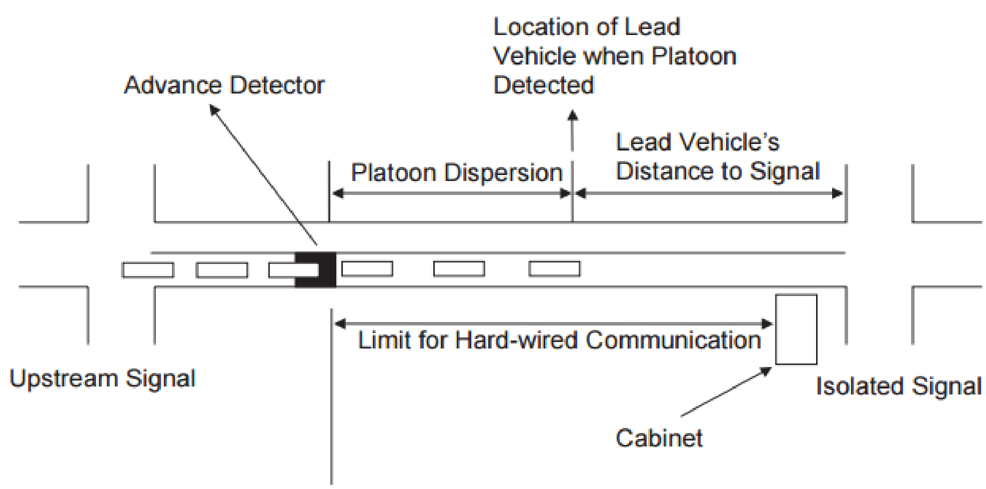

Figure 2 Illustration of Advance Detector (*7*)

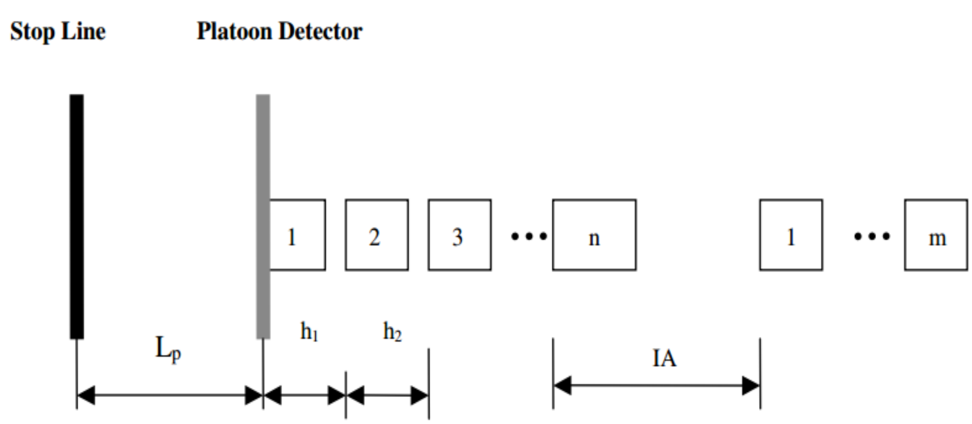

Figure 3 Single-lane Platoon Detection (*19*)

High precision microwave data and probe vehicle data are very much like the data source used in this thesis research. Zhang et al. intended to use high precision microwave sensor data to substitute for Connected Vehicle due to a lack of access to an in-use Connected Vehicle test bed (*18*). They did not explain the functions of high precision microwave sensor data but indicate that the high precision microwave sensor can provide high quality vehicle trajectory data of each detected vehicle. They assume the high precision microwave sensors can detect 100% of the vehicle in the detection area and did not specify the detectable range.

Probe vehicle data is exactly like the Connected Vehicle, they have the same advantages and problems. In most CV-based signal optimization systems, connected vehicles are actually used as probe vehicles. Their common advantage is that they can obtain vehicle trajectory and vehicle speed over time. However, probe vehicles take only a certain percentage of the whole traffic stream and that is why they are called probe. Connected vehicle as a data source has the same problem. Connected Vehicle is a newly emerging technology, the market penetration ratio of CV will not be go to 100% in near future.

2.3.3. Threshold and Decision Process

In this section, the platoon identification algorithm and process in existing literatures are introduced. Studies specifically about platoon identification is very limited, so most of the platoon identification algorithms are from the platoon identification part of platoon-based signal control system studies.

The most common measurement used to make platoon identification decision is critical headway (*17-19*) but cumulative headway (7) and arrival density over time (*20*) are also used in the platoon identification literatures.

For those who use a fixed critical headway as the platoon identification threshold, the major challenge is how to find the critical headway. In the literatures, Zhang et al. (*18*) and Jiang et al. (*19*) used the same approach. They found out when the headway threshold increase, platoon size tends to be larger (Figure 4). They tried different thresholds with collected data and decide the value of critical headway empirically based on platoon size. The setting of a fixed critical headway requires a lot of data collection and model calibration. Also, the platoon size identified using this approach is usually distributed between 0-5 vehicles. Zhang et al. decided the critical headway should be between 2 seconds and 3 seconds (*18*) and Jiang et al. adopted a critical headway of 2.5 seconds(*19*).

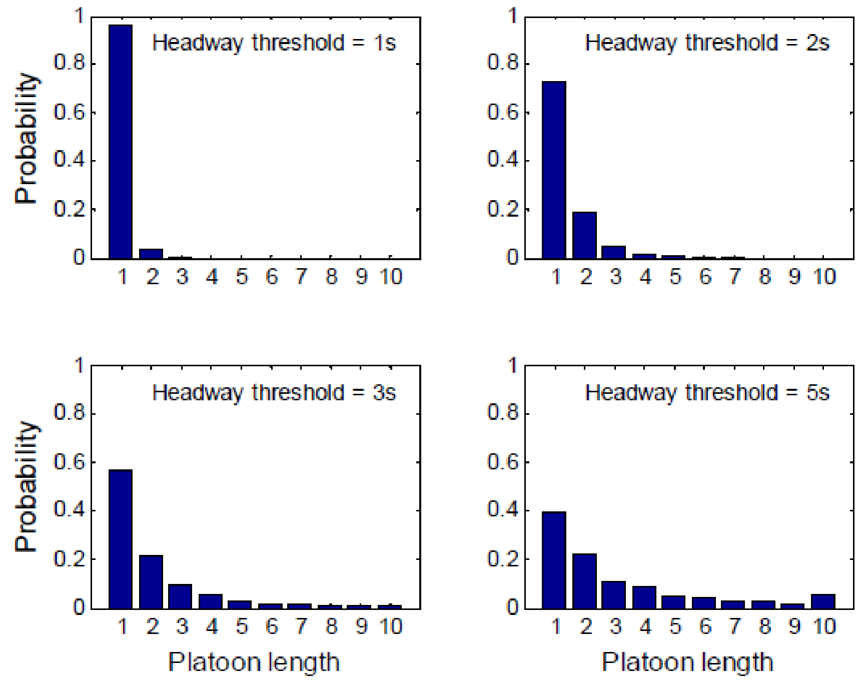

Figure 4 Impact of Critical Headway on Platoon Size (*18*)

With cumulative headway threshold, the size of the platoon is specified by user, and the detector examine the cumulative headway of the last n vehicles passing the detector. The cumulative headway is then compared to a user specified cumulative headway threshold, if not exceeded, the n vehicles will be considered as a platoon (7).

Gaur and Mirchandani (*20*) used vehicle arrival density as the platoon identification measurement. The density is defined as vehicles arrived per second. It is actually the reciprocal of headway. But to examine the density, a time period must be used. So the whole platoon identification system is time based. What is worth to noting is that the platoon identification threshold used in this paper are dynamic rather than fixed. This move provides a better result in platoon size than fixed critical headway configuration. Also, by setting the thresholds dynamic, the system can accommodate different traffic conditions without manually recalibrating or adjusting the system parameters. However, using the density as platoon identification measurement creates some trouble. First, the setting of examining time period is crucial. The paper provides a "platoon refinement phase" to make sure there is no "dead time" in an identified platoon and the platoon starts and ends with a vehicle. Second, the whole system is based on time and the system runs second by second. This setting makes the identified platoon exists on a time axle, making it difficult to obtain platoon characters like platoon speed. Making the identified platoons hard to predict.

He et al. (*17*) approaches the critical headway in a different compared to all the other platoon identification system because it's using probe data which is similar to mobile traffic data. The measurement of platoon identification in this paper is still critical headway, but the headway here is the headway between two consecutive probes. To decide the probe headway threshold, they suppose headways are constant, when penetration rate p=100%, the critical headway is h_1, then they assume there are K vehicles in between two consecutive probe vehicles, so the critical headway between K vehicles is $h_p = Kh_1$. The probability that there are K vehicles between two probe vehicles follows a geometric distribution (K~G (p)), the probability that the next vehicle is a probe vehicle equals the penetration ratio p. Then they concluded that the expectation of K is $E(K) = 1/p$, so the expectation of critical headway between K vehicles should be $E(h_p) = h_1 / p$. The standard deviation of K is $Std\left(h_p\right) = h_1\sqrt{(1-p)} / p$.

The critical headway of consecutive probe vehicles is set to be $E\left(h_p\right)+\lambda Std\left(h_p\right)$. At the result analysis part of the paper, the researchers determined that the minimum penetration rate of probe vehicle for the system to work is 40%.

2.4. Platoon Characteristics

The major purpose of platoon identification is to treat the platoon as a whole entity and provide signal progression for it through the whole arterial. Signal progression adjustment needs information from platoons in this process. So a platoon identification system must output its characteristics variable.

The platoon characteristics of interest include platoon size, arrival time of the leading and tailing vehicle at the downstream intersection (*17*), platoon speed (*7*), platoon average headway, inter-arrival time between different platoons (*18*) and the time it takes for the platoon to pass the downstream intersection.

Traditional platoon identification systems based on one-time detection at the loop detectors assume all the vehicles detected remain the same speed and the platoon characteristics wouldn't change too much after they pass the advance detector and before they reach the stop bar.

However, platoons disperse when they travel down the arterial. Traffic researchers have been trying to model and predict platoon dispersion behavior for decades. There are three major areas in platoon dispersion modeling, the Kinematic Wave Theory, the Diffusion Theory and Recurrence Theory (*21*). The Kinematic Wave Theory did not received application beyond evaluation level because of its computational complexity. Diffusion Theory make some unrealistic assumptions when predicting the arriving profile of vehicles downstream.

Recurrence Theory is the most widely applied platoon dispersion model due to its simplicity in computation and more realistic base assumptions. This model is an empirical model widely used in the TRANSYT series (*21*). The input of TRANSYT platoon dispersion model is the discharge flow rate profile over a time interval at an upstream point. The model outputs the arrival time of the leading vehicles in the platoon to a specified downstream intersection and the flow rate during a period of time (*4*). In general, the flow rate profile downstream is more widespread in time span and has a lower peak (Figure 5).

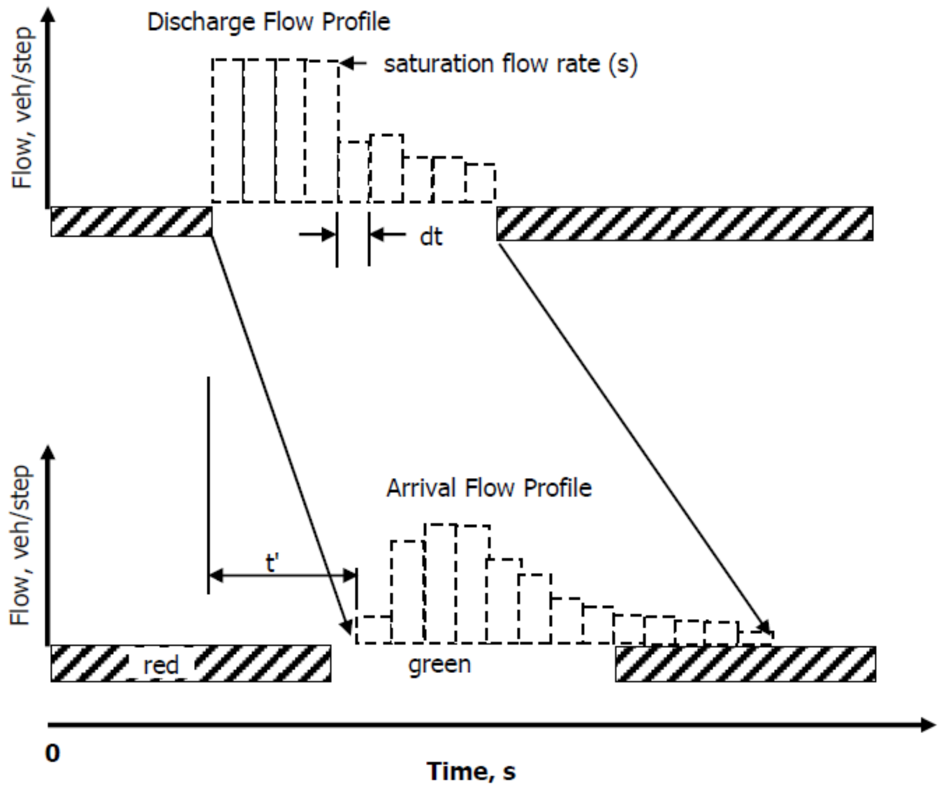

Figure 5 Discharge Profile and Arrival Profile (*4*)

Given such behavior, when the platoon dispersed too much and the time span for the platoon gets too large, the platoon identification system have to find the most compact part of the dispersed platoon. As shown in the arrival profile of Figure 5, the target of platoon identification system is to find the peak intervals of the dispersed platoon profile so the signal progression can serve the most compact platoon.

2.5. Performance Measures

Gaur and Mirchandani summarized the performance requirement for a good platoon identification system (*20*):

1. Robustness: The system can be applied to different traffic networks without major modeling change and with minimal setup requirements.
2. Sensitivity: The system should not be impacted too much by slight perturbations in traffic characteristics.
3. Representativeness: The identified platoon should capture a large percentage of vehicles.
4. Computability: The platoon identification algorithm should not require too much computation time.

Gaur and Mirchandani proposed the following performance measures to evaluate the platoon identification algorithm (*20*):

1. Percentage of vehicles captured in a platoon, the larger the better.
2. Platoon size –desirable the size of recognized platoon increase with traffic density.
3. Number of platoons vs. percentage of inter-platoon time, with a certain number of platoons, the more there is free time, means the platoons are more compact.
4. Model robustness, meaning how the algorithm work under different traffic conditions.
5. Computation time—crucial for real time systems.

He et al. used graphic comparison to show the performance of platoon identification algorithm visually as in Figure 6 (*17*). Their platoon profile is based on the location of the arterial and the snapshot is taken each time step. The solid lines in Figure 6 represents a probe vehicle is present at that position when the snapshot is taken. The dashed lines represent a non-probe vehicle that cannot be seen by the platoon identification system. The green windows mark the identified platoons at the time step. He et al. demonstrated the performance of their platoon identification system under different penetration ratio settings (0.2, 0.4, 0.6 and 0.8). Penetration ratio is the ratio of probe vehicle number over total vehicle number. The higher the penetration ratio is, the more complete information about the traffic stream will be fed into the platoon identification system. Platoon identification algorithm's sensitivity towards penetration ratio is also a very important performance measure.

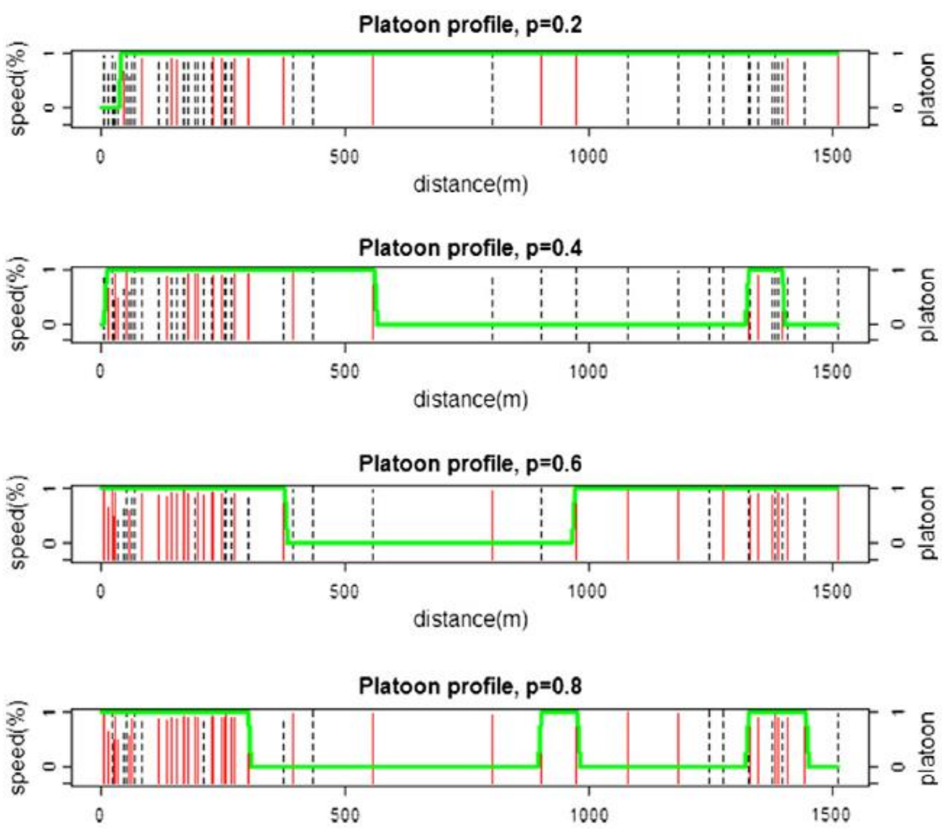

Figure 6 Platoon Identification Visual Performance Measure(*17*)

2.6. Background Summary

This chapter visited the basic idea about platoon identification, including the definition of platoon, basic platoon dispersion behavior and relationship between platoon and signal progression. During the literature review process, the researchers found the definition of platoon is vague and subjective leading to various definitions of platoon in different platoon identification studies. Also, this chapter summarized the data source, identification approach, performance measures and requirements of existing platoon identification systems. The researchers found there is no existing platoon identification algorithm based on connected vehicle technology. The closest research is conducted by He et al. using probe vehicles (17). Their algorithm still uses the idea of critical headway to locate platoons. Their critical headway takes penetration ratio into account but is fixed for each penetration ratio. Gaur and Mirchandani introduced dynamic decision threshold into platoon identification algorithms (20), which is very enlightening for the platoon identification algorithm development in this paper.

CHAPTER III

PLATOON IDENTIFICATION METHODOLOGY

This chapter documents the study and development process of the proposed platoon identification algorithm. This study process sets out from the definition of platoon in HCM, and attempts to translate “traveling together” into a numerically explicable concept. If not specified, all the headways in this chapter means time headway.

In this chapter, microscopic platoon dynamics of single-lane and multi-lane are analyzed in order to find a possible feature in traffic characteristics that correspond to a compact platoon. Various microscopic traffic characteristics are investigated, including vehicle trajectory, platoon and non-platoon vehicle headway distribution, speed profile and distance/time headway profile. Also, a method of combining traffic on multiple lanes into one traffic stream is proposed in this section.

The major approach of investigation is microscopic traffic simulation model. In this thesis research, PTV Vissim 7.0 is used as the primary microscopic traffic simulation model. VISSIM is a time step based, stochastic and microscopic model based on Wiedemann’s traffic flow model to model car-following behavior. The basic units in VISSIM are driver-vehicle units (*22*). Wiedemann’s traffic flow model is a psycho-physical perception model. The basic units in VISSIM are driver-vehicle units. Wiedemann assumes that there are 4 different driving states for a driver (22):

- Free driving: When no preceding vehicle is observed, the driver try to maintain his desired speed. Due to imperfect throttle control, his speed will oscillate around the desired speed.
- Approaching: The process where the driver approaches a preceding slower vehicle. The approaching driver will decelerate until there is no difference in speed when he reaches the desired safety distance.
- Following: The driver follows the preceding vehicle and maintains the safety distance. Due to imperfect throttle control, the following distance oscillates around safety distance.
- Braking: When the distance to the preceding vehicle falls below the desired safety distance, the following driver will apply medium to high deceleration rates to increase the distance.

Drivers switch between driving states when they reach certain perception thresholds. The acceleration of a vehicle is a function of current speed, speed difference, distance to the preceding vehicle and individual driver characteristics. Each driver has his own perception of safety distance, desired speed and speed difference. Each vehicle has its own physical characteristics (*23*).

The determination of time headway is traditionally based on outputs from traditional loop detectors modeled in simulation. A fixed location of observation must exist to record the time between consecutive vehicles. In connected vehicle, the traffic information is obtained from each connected vehicle itself instead of a fix-location external observer, so the definition of time headway need some adjustment to fit the

Connected Vehicle environment. In connected vehicle environment, distance headway can be defined as the real-time distance between each vehicle and its immediate preceding vehicle. However, distance headway can be impacted by speed, when speed is high, distance headway speed tends to be larger. So time headway is a better way to represent closeness between vehicles. In this thesis, time headway in connected vehicle environment for vehicle i, $h_{T,i}$ is defined as

$$h_{T,i} = \frac{h_{D,i}}{v_i} \tag{1}$$

In which,

$h_{D,i}$ =distance headway for vehicle i (m),

v_i =speed of vehicle i (m/s).

Unlike traditional loop detector, each connected vehicle can be detected every time step. A traffic characteristics profile regarding time can be established for each connected vehicle.

3.1. Single Lane Platoon Identification

3.1.1. Single Lane Platoon Nature

3.1.1.1. Aggregated Time Headway Analysis

The researchers started investigating platoon traffic characteristics from single lane situation. Firstly, the characteristics of traffic from upstream signal and free random arrival is compared. Traffic data regarding these two different arrival modes is acquired from a single lane simulation network with the same settings. The vehicle input at the beginning of the link is 1000 vehicles per hour. Characteristics of traffic is recorded on the links with lengths between 400m (1312ft) and 2000m (6562ft). Vehicle speed distribution is set as in Figure 7. In the upstream signal release situation, a signal is set at the location of 350m (1148ft). The signal is timed so that all the released vehicles are discharged from queue and the next cycle green time would not start before the last vehicle of previous cycle pass the location of 2000m (6562ft). Simulation for each scenario runs for 1800 seconds. Assuming 100% market penetration of connected vehicle, distance headway, vehicle position, speed and time headway in connected vehicle environment of each vehicle are recorded every 3 simulation seconds.

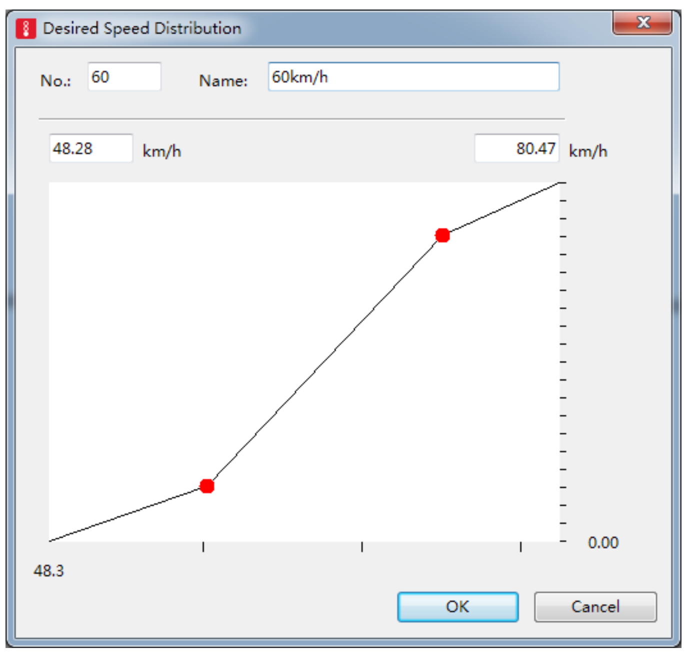

Figure 7 Single Lane Speed Distribution

First, the general time headway distribution of each scenario, signal released and random arrival traffic, is shown in Figure 8 and Figure 9. As can be seen from the histograms, some patterns of both scenarios are similar. Such as the time headway range of both scenarios are the similar, 0s-18.5s for signal release traffic and 0s-19s for random arrival traffic. Time headway modes for both scenarios are 1s to 1.5s.

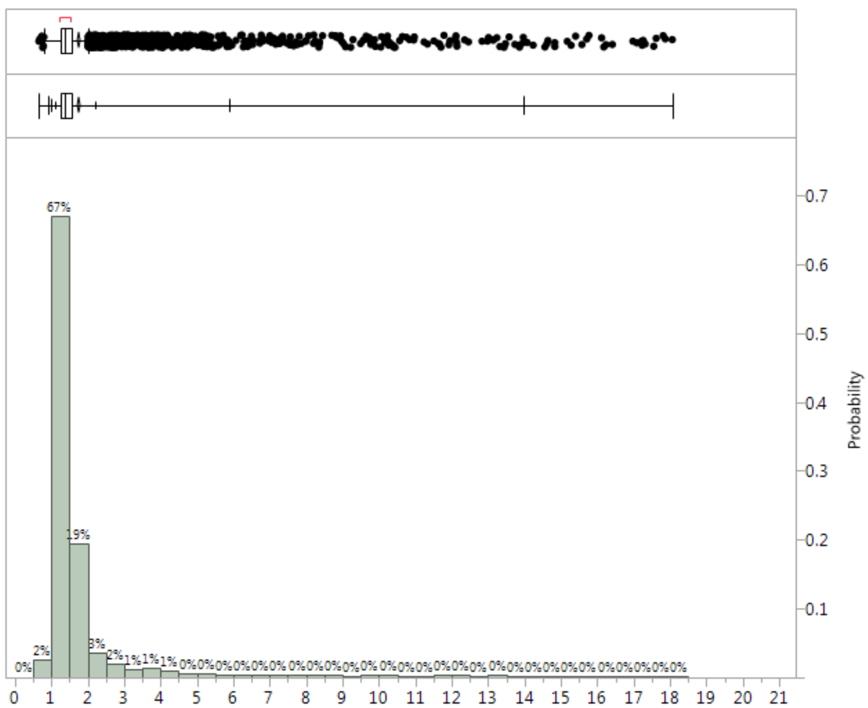

Figure 8 Signal Release Traffic Time Headway Distribution

However, there are some obvious differences in the two scenarios. Firstly, in the outlier box plot, the potential outlier of signal release traffic time headway starts at around 2 seconds and that of random arrival traffic time headway starts at around 3 seconds. Also, larger headways from 4.5 to 12.5 takes more percentage in the random arrival traffic. In addition, more time headway data concentrate in the range of 1s-2s in the signal release traffic scenario.

Difference between the two scenarios can also be seen from the cumulative density function plot (CDF) in Figure 10. Up to 90% of the time headway from signal released traffic concentrates in between 1s-2s and that of random arrival traffic is only around 70%.

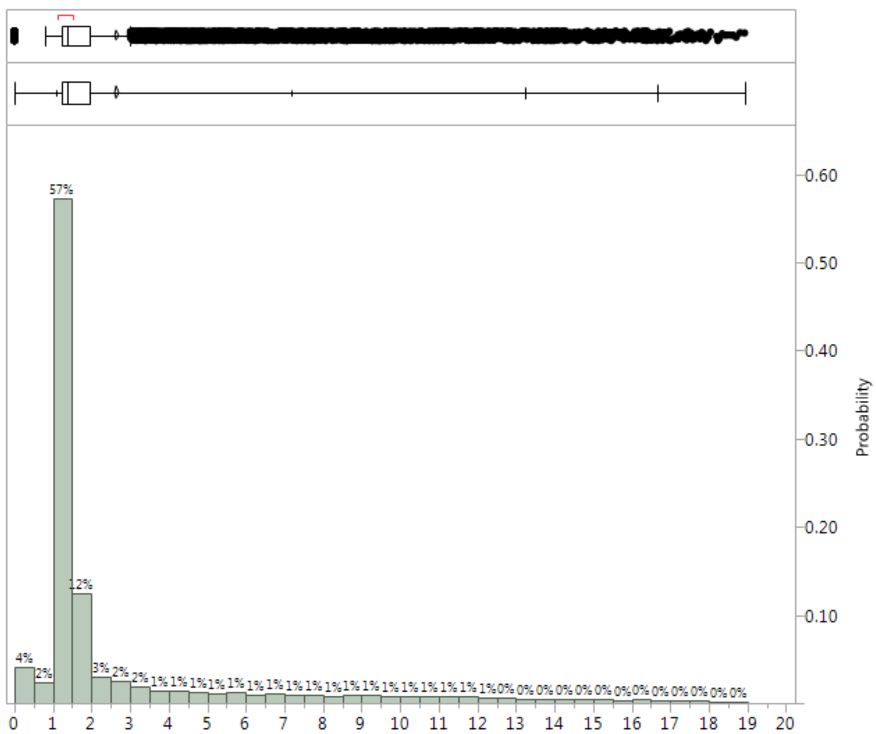

Figure 9 Random Arrival Traffic Time Headway Distribution

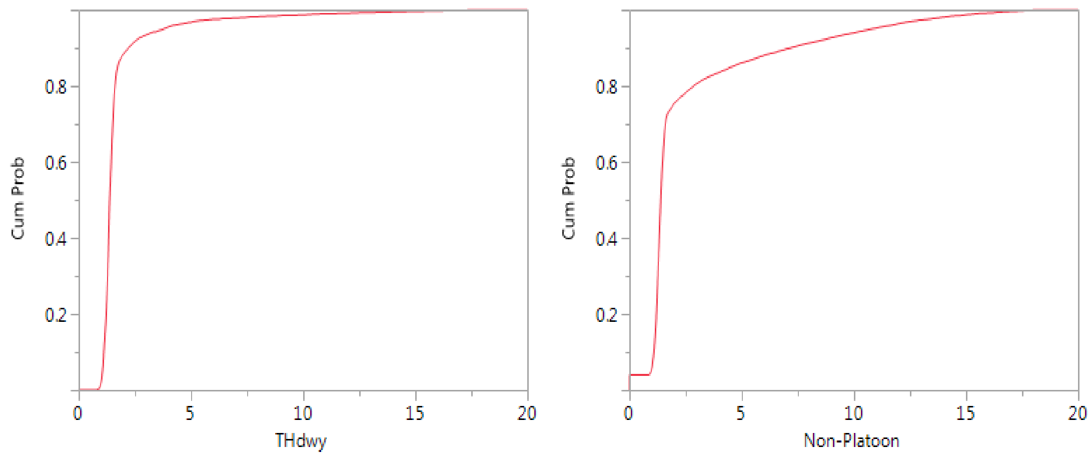

Figure 10 CDF of Signal Release and Random Arrival Time Headway Distribution

Summary statistics and quantile comparison of signal released and random arrival traffic are shown in Table 2 and Table 4. From Table 2, it can be seen that the median of the two scenarios are very close, but other statistics are very different. The mean time headway of random arrival traffic is significant higher than that of signal released traffic. Same with the standard deviation and confidence interval. These statistics difference indicates there are more large time headways in random arrival traffic scenario. In the quantile comparison table (Table 4), the quantile of the two scenarios deviate from 75% quantile and the most significant time headway happens at the 97.5% quantile. This result indicates that the random arrival traffic time headway has a long right tail.

Table 2 Summary Statistics Comparison

Statistics	Signal Released Traffic (s)	Random Arrival Traffic (s)
Mean	1.75	2.65
Standard Dev.	1.64	3.21
Median	1.38	1.39

Table 3 Summary Statistics Comparison (Continued)

Statistics	Signal Released Traffic (s)	Random Arrival Traffic (s)
Upper 95% Mean	1.79	2.70
Lower 95% Mean	1.71	2.6

Table 4 Quantile Comparison

Quantiles (%)	Signal Released Traffic (s)	Random Arrival Traffic (s)
25	1.25	1.22
50	1.38	1.39
75	1.55	1.94
90	2.21	7.17
97.5	5.89	13.23
99.5	13.96	16.68

A typical cycle of vehicle released from upstream signal is extracted from the signal release simulation. Traffic data is acquired every 3 seconds, the average time headway of all vehicles for each time step is calculated and plotted in Figure 11. This diagram demonstrates how average time headway of the whole link change over time and gives an insight of the platoon formation process.

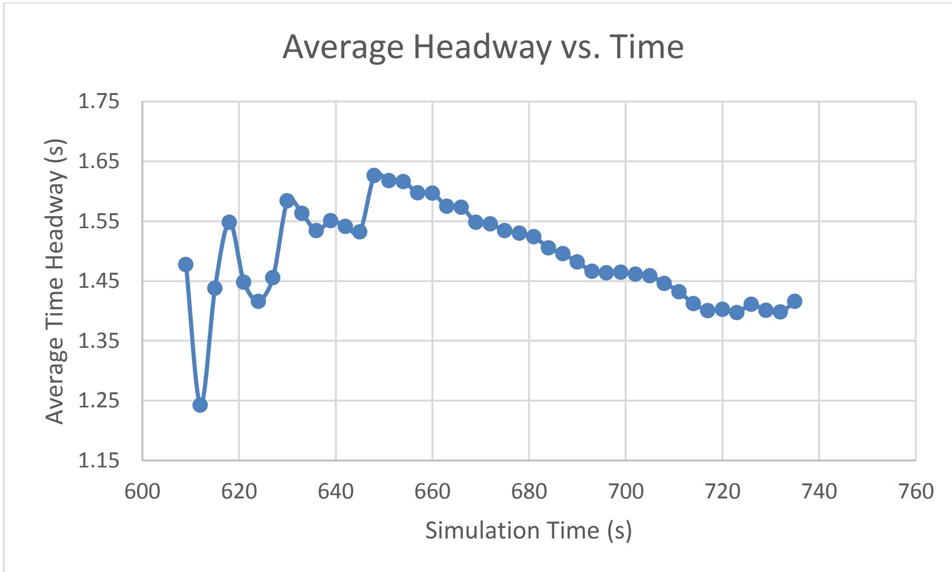

Figure 11 Average Time Headway Profile

In Figure 11, the average time headway fluctuated significantly at first, then it decreased almost linearly and reach a very low value at around 1.45s. The profile of average time headway corresponds to the driver behavior in platoon formation. When the vehicles are first released from upstream signal, the traffic is not stable, the traffic behavior of this period correspond to the fluctuation in Figure 11. Then after all the vehicles in this cycle are released from the signal, the platoon formation process begins. Vehicles with similar desired vehicles cluster into platoons and constantly reduce their time headways. However, given that the experiment network is one lane roadway and no overtake happens, vehicles have to adjust its speed and follow the speed of their preceding vehicles. In this case, any vehicle with a lower desired speed will create a compact platoon after it and become further and further away from its preceding vehicles with a higher speed. After a while the platoons were formed and the spacing between different platoons are too large that the headway value of the first vehicles in each platoon became 0s, the average headway reach the minimum value in the profile.

3.1.1.2. Fixed-Location Time Headway Profile Analysis

The above analysis investigated the nature of vehicle platoons in an aggregated aspect. The findings from the above aggregated platoon headway analysis can help developing the platoon identification algorithm in the following aspects:

- When released from upstream signal, vehicles with similar desired speed will travel together as a platoon and maintain a time headway of 1s to 1.5s.
- Time headway between different platoons can be larger than larger than 2s to 2.5s. The headway values with very low probabilities are considered to be headway between different platoons.
- As the original platoon released from upstream signal travels down the arterial, the original breaks into several child-platoons. The child platoons become more and more compact inside and the spacing between child platoons increases over time.

After investigating the aggregated headway features of platooned vehicles released from upstream signal, the researchers took the next step of exploring the headway and speed profile of individual vehicles over time. First, the researchers comes back to the original definition of time headway and set several fixed locations on the link as “detectors” or “time headway check points”. Since the signal head locates at 350m (1148ft), the “time headway check points” are set to be at 400m, 500m up till 1100m with a 100m interval. When a vehicle pass each “time headway check points”, their real headway will be recorded and stored with the vehicle ID. The researchers randomly chose a typical cycle and plotted out the Headway vs. "time headway check points" location diagram for each vehicle released in this cycle as in Figure 12. Note that the legends in headway profile plots represent vehicle IDs.

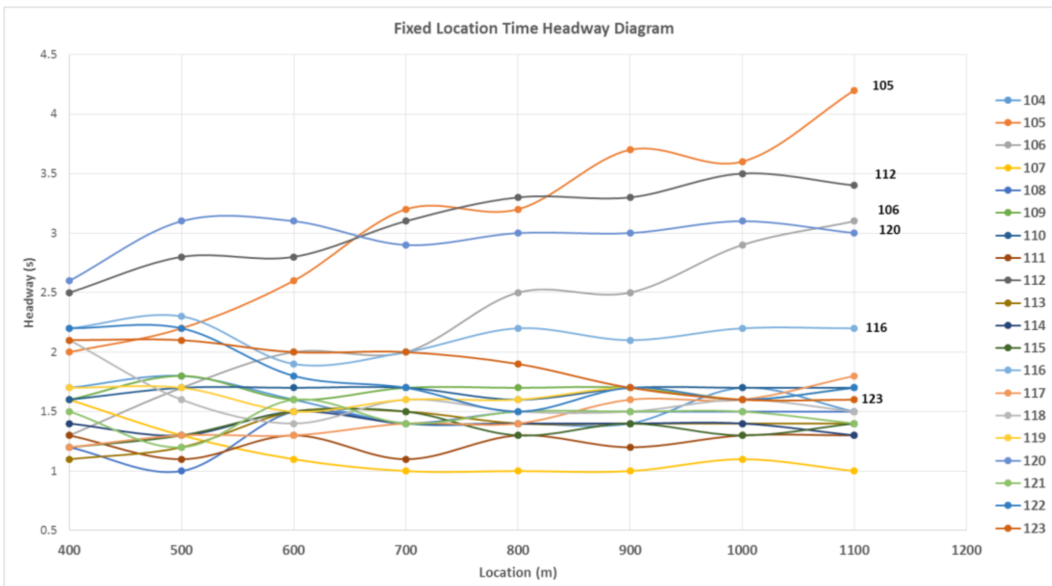

Figure 12 Fixed Location Time Headway Diagram

When there is only one lane in the roadway, the vehicles cannot over take each other, so the vehicle IDs marks their sequence in the roadway. Each line in the above diagram represents the time headway profile of one vehicle. In reality, detectors can only identify time headways but they would not be able to associate time headways with any specific vehicle. Only connected vehicle technology can achieve this. So here the "time headway check points" are to imitate the function of connected vehicle environment and keep to the original definition of time headway.

In Figure 12 there are four types of vehicle headway profiles:

- **Type I**: Flat slope and maintain a low value of headway. Vehicles that follow their preceding vehicles closely in a platoon has a profile like this.
- **Type II**: Flat slope but maintain a higher value of headway than others, Vehicle No. 120 is an example. A headway profile of this type means the vehicle is maintaining a large gap from the preceding vehicle and the gap is stable.
- **Type III**: Has a positive slope, and the headway keeps has an increasing trend. Vehicle No. 105, 106 and 112 belong to this type. This type of vehicle may have a lower desired speed than its preceding vehicle and is getting further and further away from its preceding vehicle.
- **Type IV**: Has a negative slope, headway has a general decreasing trend. This indicates the vehicle is closing to its preceding vehicle.

In the single lane case, vehicle IDs correspond to vehicle sequence. Vehicles with smaller IDs enter the link earlier and their positions are more ahead on the lane. The Type III or Type II vehicles segment the traffic stream in to several compact platoons because they are not really traveling together closely. So if the first vehicle in a platoon is defined as a platoon head, each Type III or Type II vehicle is a platoon head. For example, in Figure 12 the vehicles are separated into 4 platoons based on their time headway, they are [104-105], [106], [107-112], [112-120].

3.1.1.3. Connected Vehicle Time Headway Profile

The results from fixed-location time headway profile showed some preliminary useful patterns to identify potential platoons. However, the biggest advantage of connected vehicle is that it can track equipped vehicles' characteristics every second. So the researchers obtained connected vehicle time headway as in Equation (1) from the same simulation. Similar patterns with more details are discovered as in Figure 13, but the x-axis of the profile is no longer location but simulation time. Both location and simulation time can be the axis of vehicle progression.

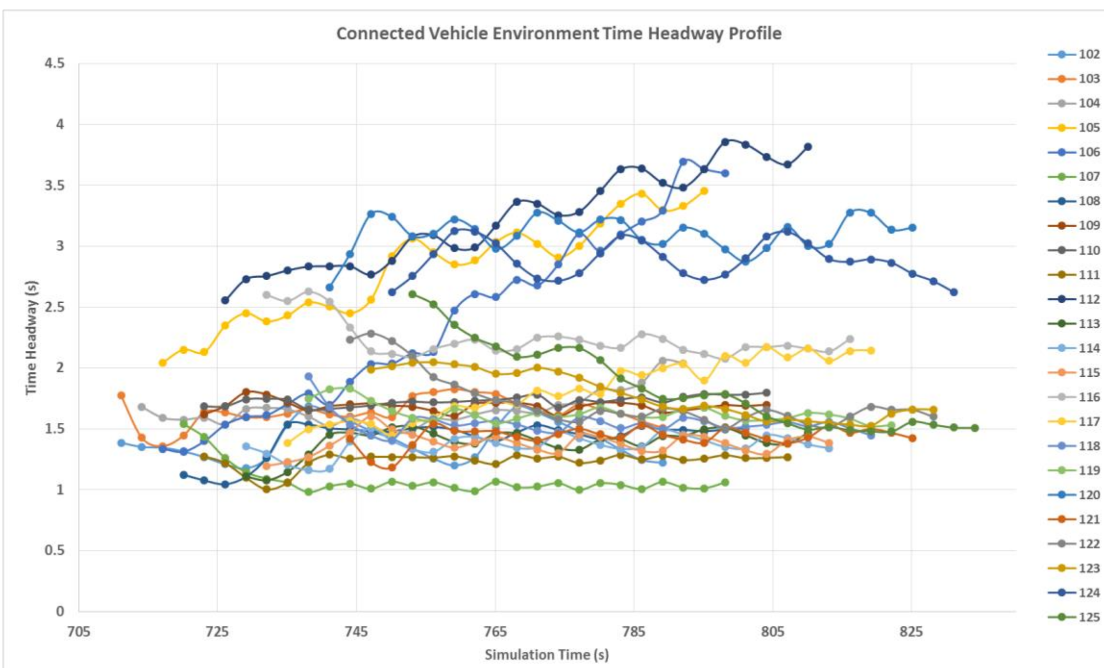

Figure 13 Connected Vehicle Environment Time Headway Profile

3.1.2. Single Lane Platoon Identification Algorithm

With previous analysis results, the key of single lane platoon identification is how to translate the criterial into detailed numerical language and let the computer determine which type a connected vehicle headway profile belongs to. Two questions should be addressed in this process, one is how to decide if a headway profile is flat or increasing, and the other is to determine whether a flat profile maintains a higher value of headway then other profiles.

Type III vehicle headway profile can be characterized by a positive and larger slope. However, the profiles fluctuate when increasing, so linear regression (linear trend line) is introduced to represent the slope of each time headway profile. Each profile consists of several "simulation time-headway" profile. If simulation time is denoted as x and headway is called y, then the slope K of linear regression y=f (x) can be calculated by:

$$K = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - \left(\sum x_i\right)^2} \tag{2}$$

The researchers observed the slope K of typical headway profiles and found out that a flat slope considered in human judgment is smaller than 0.01 and if the headway profile of a vehicle is larger than 0.01, then it appears in the diagram to be a Type III vehicle.

Then the other question is how to find out if a profile maintains a higher value of headway than the others. An easy solution is comparing the average headways in each profile. In each time step, the latest [time, headway] pair of each connected vehicle is obtained and stored for each profile. The historical [time, headway] pairs of each connected vehicle will be used to calculate slope K and each historical headway value will be used to calculate average headway for each connected vehicle. A global average headway database is introduced to implement the average headway comparison. The goal of global average headway database is to calculate the average time headway of all non-Type III connected vehicles. The global average headway database will output two statistics, one is the average headway of non-Type III vehicles and the other is the standard deviation of headways of platooned vehicles. The initial global average headway of platooned vehicles is set to 0s and so is the standard deviation. The global average headway database is updated with latest average headway information of each connected vehicle every time step. Each time step is 3 seconds.

Each connected vehicle headway profile will be examined every time step based on its slope K first, if the profile is considered a Type III vehicle, then its average time headway will not be added to the global average headway database. Otherwise, as long as the headway profile of a connected vehicle is considered flat, its average headway will be added to the global average headway database. Each time step, the global average headway database will output two statistics. Global average headway of non-Type III vehicles will be denoted by H_g and its standard deviation will be called S_g. The upper 95% confidence interval of H_g will be calculated by:

$$U_{95} = H_g + \frac{1.96 \times S_g}{\sqrt{n}} \tag{3}$$

In which, n is the number of average headway values stored in the global average headway database.

The upper 95% confidence interval of H_g is used as a threshold to determine whether a profile maintains a higher value of headway than the others. A non-Type III connected vehicle will be considered maintaining a higher value of headway if its average headway is higher than the global U_{95}.

The whole process of single lane platoon identification algorithm is shown in

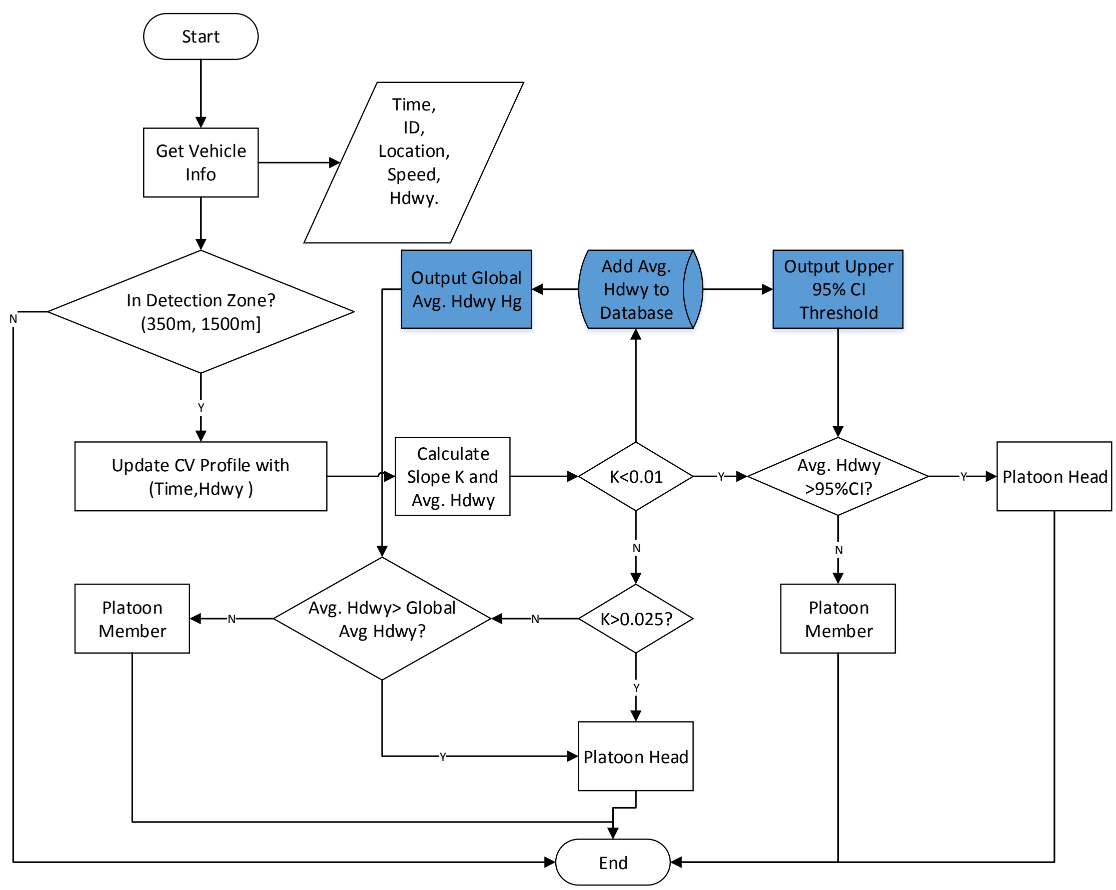

Figure 14 Flow Chart of Single Lane Platoon Identification

The process shown in Figure 14 is executed for each connected vehicle every time step (3 seconds). When the process starts for a connected vehicle, its individual traffic information is obtained via wireless communication. The information include the current time, its ID, its location, its speed and its time headway. Then if the vehicle is in detection zone, which is set to 350m to 1500m in the simulation, the process will carry on, otherwise, the process will end. When the vehicle is in the detection zone, its [time, headway] pair will be added to its headway profile and the profile slope K and average headway will be calculated. Next, the slope K will be examined, if K is smaller than 0.01, then the vehicle's average headway will be added to the global average headway database. In the meantime, the vehicle's average headway will be compared to the upper 95% confidence interval threshold outputted by global average headway database. If the average headway is larger, then it will be considered a Type II vehicle and a platoon head. Otherwise, it is a Type I or Type III vehicle and a platoon member.

If a vehicle headway profile has a larger slope, but start from a very low value of headway. By the end of the detection zone, it still maintains a small headway from its preceding vehicle. Although this vehicle is a Type III vehicle, it can still be considered a platoon member. To prevent this type of vehicle from being identified as a platoon head, the 0.025 mechanism is introduced. When the slope K of a vehicle headway profile is larger than 0.01, it is further examined if K is larger than 0.025. If yes, then the vehicle is considered a platoon head, otherwise, its average headway is compared to the global average headway to check if this vehicle stands out from platoon member profiles. When it is confirmed that the profile does stands out from flat platoon member profiles, it is marked as a platoon head.

3.1.2.1. Verification Method for Single Lane Platoon Identification

After the single lane platoon identification algorithm is addressed, the immediate question is how to verify it. The proposed verification method is based on the assumption that after traveling uncontrolled on a straight link for a long time, vehicles in a platoon will converge and vehicles in different platoons will be further apart. So in the verification process, the researchers use a very large headway value of 5 seconds to determine if a vehicle is a platoon head. The verification process happens when the vehicle reaches the location of 6000m. In the verification process, headway of each vehicle is extracted and compared to the threshold of 5s. If the headway is large than threshold, then the vehicle is a verified platoon head, if not, the vehicle will be a verified platoon member. In the platoon identification output results, 1 will represent platoon head and 0 will represent platoon member. Both the platoon identification results in detection zone and in verification zone will be output. The results from verification zone is considered to be the precise platoon identification.

In the real world application of platoon identification, a vehicle will not travel uncontrolled and uninterrupted for as long as 6000m. So the verification approach is just a way to verify the accuracy of single lane platoon identification algorithm. Two accuracy performance measures are introduced. The first one is miss rate and the other is false alarm rate. Assume the platoon identification results from detection zone is represented by variable D and the platoon verification results from verification location is represented by variable V. Each variable has two possible values, 1 and 0. When D or V equals 1, it means this vehicle is identified to be a platoon head and when D or V equals 0, it means the vehicle is identified to be a platoon member. Under this assumption, miss rate M is defined as:

$$M= \frac{\text{Count (D=0 and V=1)}}{\text{Count (V=1)}} \times 100\% \qquad (4)$$

False alarm rate F is defined as:

$$F= \frac{\text{Count (D=1 and V=0)}}{\text{Count (D=1)}} \times 100\% \qquad (5)$$

After implementing the single lane platoon identification algorithm in the single lane simulation network, the miss rate is 0% and the false alarm rate is 22%. Since single lane platoon identification is not the final applicable platoon identification algorithm this thesis research is going to achieve, the detailed evaluation and simulation analysis will not be carried out. The reasons are explained in the immediate next section.

3.1.2.2. Problems of Single Lane Platoon Identification

Single lane platoon identification is rather easy compared to multiple lane platoon identification. However, most arterials have multiple lanes, so in reality the platoon identification of single lane is not very applicable.

Additionally, connected vehicle has a market penetration ratio issue in reality. A market penetration ratio of 100% or even above 85% will not happen in near future. Currently, connected vehicle is still mainly in research and they are not yet used widely in real traffic. When using connected vehicle technology as the foundation of traffic operation research, the market penetration issue cannot be neglected. When market penetration ratio is lower than 100%, only information from vehicles equipped with connected vehicle technology will be available in the traffic operation system.

A lower market penetration ratio will greatly impact the proposed single lane platoon identification algorithm because the algorithm is based on microscopic individual vehicle headway profile. Missing information will yield a lot of problems. The headway profiles of connected vehicles will either upshift, change its slope or both. The impacts of CV market penetration ratio on vehicle headway profiles depend on the condition regular vehicles missing from the map. If the regular vehicles are called black points of traffic information, then the arrival rate of black points are completely random. Which is making it very difficult to restore the complete picture of traffic stream.

The single lane platoon identification algorithm require too detailed and microscopic information from connected vehicles and it relies too much on the relationship between consecutive vehicles. It is developed under a very ideal and unrealistic assumption. So its scope is only in research. To truly solve the platoon identification problem, a more general and realistic algorithm should be proposed. In this thesis research, the purpose of investigation single lane platoon is to better understand the dynamics of platoons. Additionally, starting with single lane platoon can help the researchers explore the approaches in analyzing platoon behavior.

3.2. Multi-Lane Platoon Identification Methodology

In this section, the characteristics of multi-lane platoon is explored. A method to combine the traffic on different lanes into one traffic stream is proposed and a platoon identification algorithm based on the combined traffic stream is developed. The proposed multi-lane traffic stream identification algorithm's goal is to identify the biggest and most compact platoon in the vehicles released from upstream signal each cycle. After the platoon is identified, each platoon should output its characteristics in order to help traffic signal provide the progression it needs. A summary of platoon characteristics of interest is also provided in this section.

3.2.1. Nature of Multi-lane Platoon

In the study of multi-lane platoon characteristics, a desired speed distribution (Figure 15) with less variety is used to eliminate the long tail in Figure 8. All the analysis in this chapter will be based on this desired speed distribution. A desired speed distribution with more variety is used in section 3.1.1 to create more platoons for upstream released traffic scenario. In this section, the headway distributions of single lane and 3 lane arterial are obtained from the same simulation setting and compared. Figure 16 shows the headway distribution of single lane with less variety in desired speed distribution. As can be seen from the figure, the right side tail is trimmed to 12 seconds but the main part of the distribution does not change too much from Figure 8.

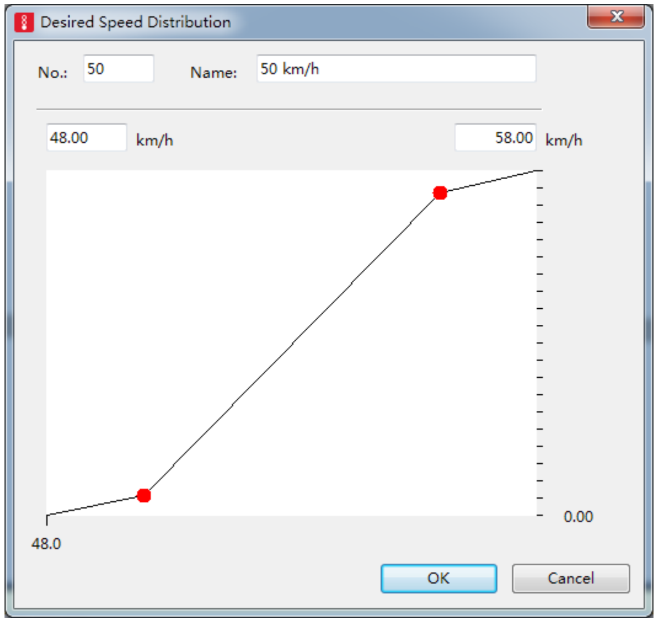

Figure 15 Desired Speed Distribution with Less Variety

If compare the headway distribution of Figure 15 with that of Figure 8, it is obvious that the variety in desired speed distribution will greatly impact the general headway distribution. In Figure 15, large headway values over 12 s no longer exist. Also, more vehicles maintain a headway profile of 1.5s to 2s and 2s to 2.5s. This comparison illustrates that the shape of headway distribution varies greatly as the driver behavior changes so it may not be a very reliable criterion to identify platoon. Additionally, this result indicates that comparisons must be conducted only if the driver behavior is the same in each scenario.

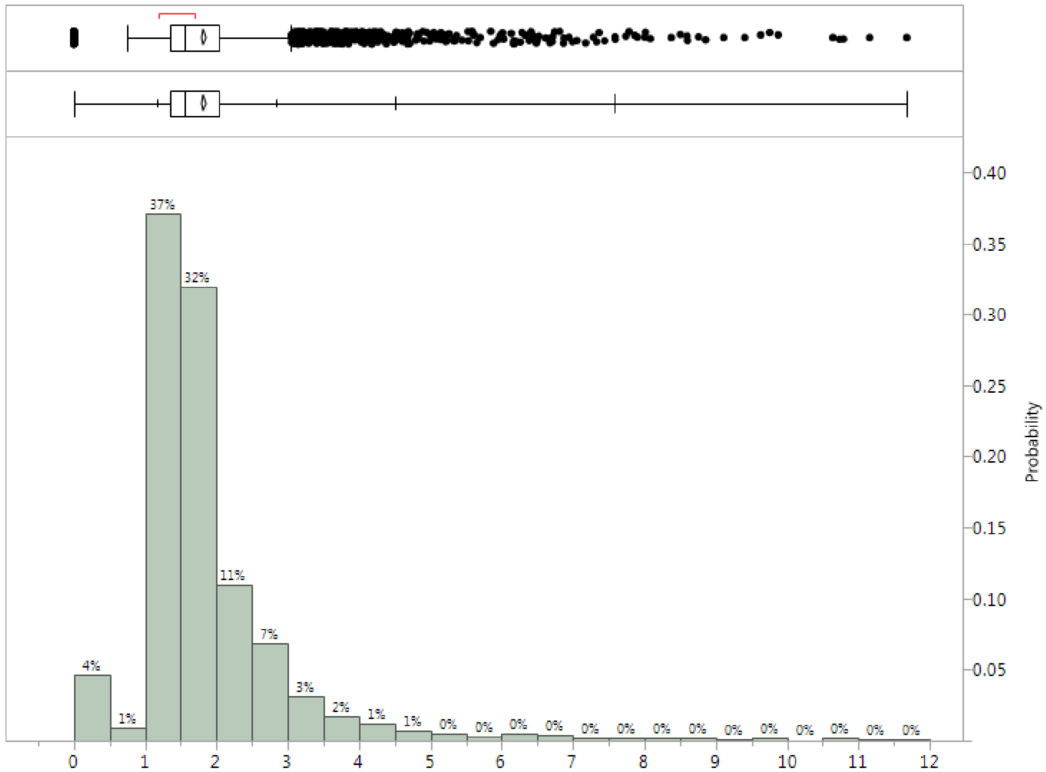

Figure 16 Single Lane Headway Distribution

The multiple lane arterial has three lanes. The distribution shape of single-lane and multi-lane scenarios are similar. However, the headway distribution of multi-lane scenario in more concentrated than the single-lane scenario. The difference can also be visually shown in the outlier box plot.

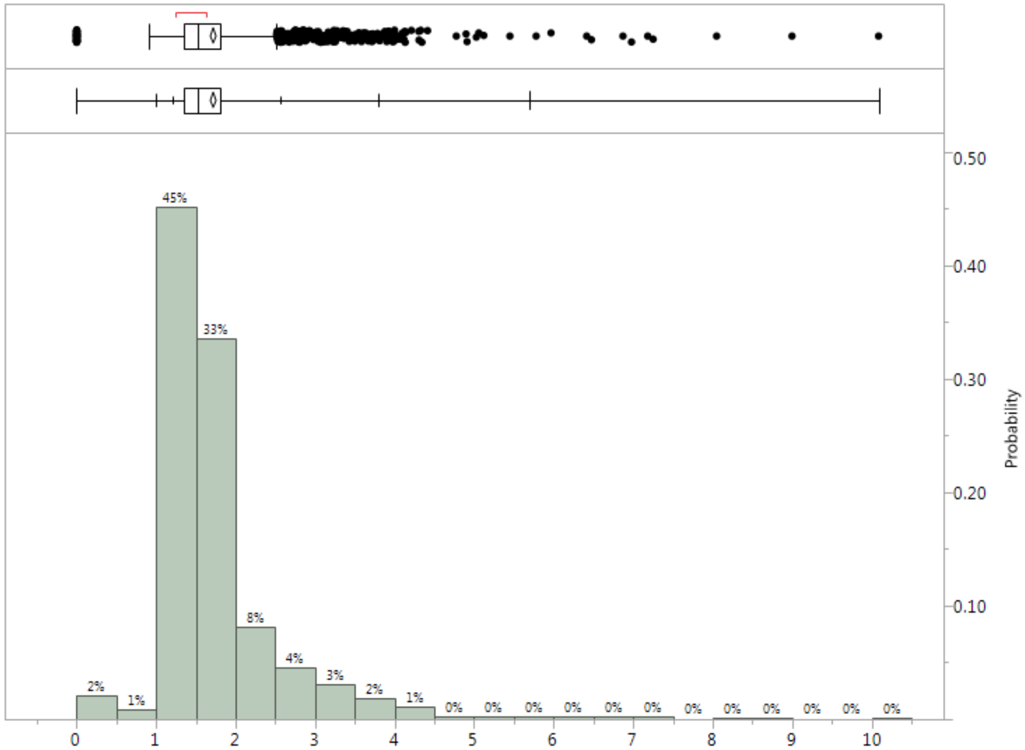

Figure 17 Multiple Lane Headway Distribution

When lane changing and overtaking is applicable, there is less restrictions in vehicle platooning behavior. Vehicles with higher desired speed can overtake a preceding vehicle traveling at a lower speed and join vehicles with similar desired speeds and form a platoon. This overtaking freedom results in less number of platoons, larger platoon size than the single lane scenario.

From the observation of microscopic traffic simulation animation, the vehicles released from upstream signal usually separated into three platoons. Vehicles with a higher desired speed and released earlier form the first platoon, vehicles with common desired speed join the middle platoon and the slower vehicles scatter in the third platoon.

The middle platoon has the largest population. This pattern occurs in most of the cycles in the simulation.

When a green phase is serving the traffic from one approach, it serves all the straight lanes all together. Also, in a multi-lane arterial interaction between lanes always exists. So instead of analyzing traffic dynamics lane by lane in a multi-lane arterial, combining them together makes more sense.

3.2.2. Cross-lane Traffic Stream Combination

When a green phase is serving the traffic from one approach, it serves all the straight lanes all together. Also, in a multi-lane arterial interaction between lanes always exists. Instead of analyzing platoon dynamics lane by lane in a multi-lane arterial, combining them together into one stream makes more sense.

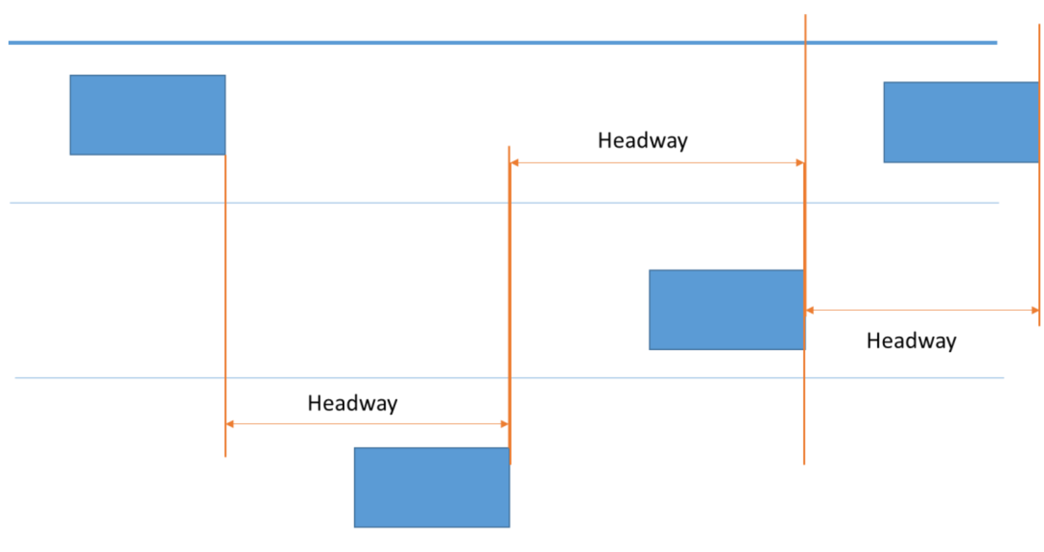

Figure 18 Multi-lane Traffic Combining into One Stream

If the traffic not too congested, most vehicles will not be exactly side by side. If the lanes can be ignored, the headway of each vehicle can be calculated as shown in Figure 18. Headway of each vehicle is no longer between itself and its immediate preceding vehicle in its own lane, but between the ego vehicle and the vehicle ahead of it in another lane. In this way, the traffic in different lanes can be combined into one large traffic stream.

The headway distribution for cross-lane stream is shown in Figure 19 and the corresponding summary statistics are shown in Figure 19 and Table 5.

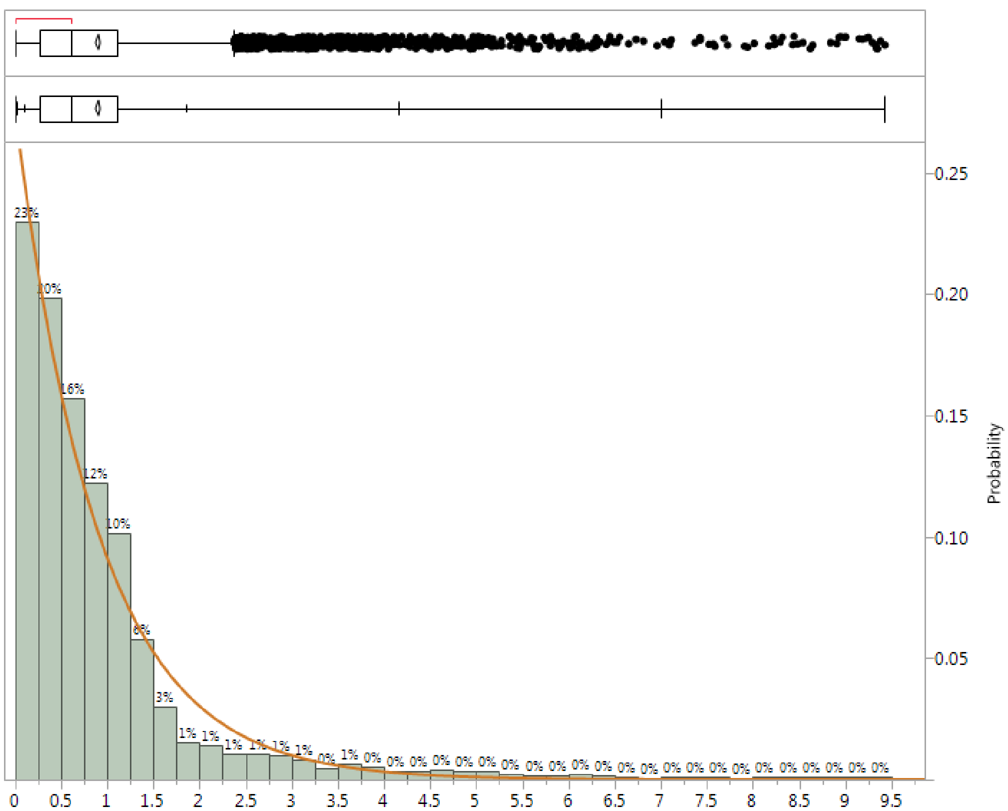

Figure 19 Headway Distribution for Cross-lane Stream

As can be seen in the histogram, the headway distribution of cross-lane stream is drastically different from that of single lane and multilane. Most vehicles has a headway between 0s and 1.25s. All the 0 headway values have been taken out of the distribution. A headway value larger than 2.75s is considered as an outlier. The probability decreases as the headway value increases. The headway distribution of cross-lane stream can be nicely modeled with an exponential distribution.

Table 5 Cross-lane Stream Headway Summary Statistics

Statistics	Cross-lane Stream Headway (s)
Mean	0.906
Std Dev.	1.092
Median	0.611
Mode	0.39
Upper 95% Mean	0.929
Lower 95% Mean	0.883

Similar to the analysis in single lane platoon identification, the headway profile of each vehicle is also plotted out for the vehicles in a cycle randomly chosen from the simulation Figure 20.

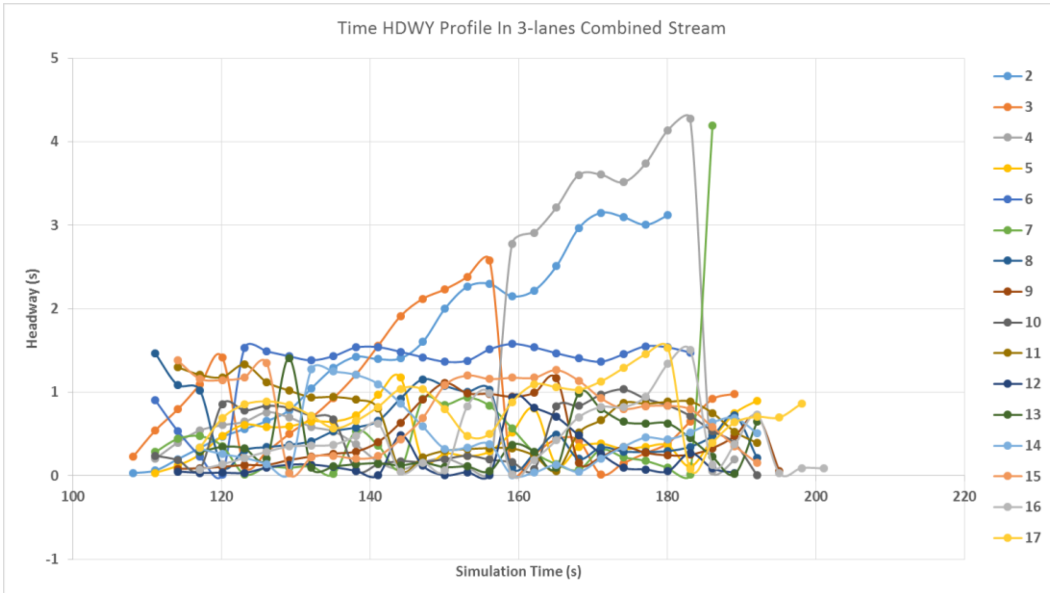

Figure 20 Three-lane Combined Stream Headway Profile

In Figure 20, most headway profiles concentrate in the range of 0s to 1s with large fluctuation. Some profiles have a larger slope or higher headway value, but most of them have drastic sudden drop or jump in the profile. Take vehicle No. 3, 4 and 6 (Figure 21) for example, all three vehicle headway profiles have at least one drastic change in one time step. The sudden drastic change in headway is caused by vehicle overtaking in the traffic stream. A sudden jump in headway profile means the ego vehicle just passed its preceding vehicle in the cross-lane traffic stream. Accordingly, the vehicle that was overtaken have a sudden drop in headway profile. In Figure 21, the overtaking situation happened several times. First vehicle No. 3 is passed by No. 6 at around 120s. Then vehicle No. 3 is again overtaken by vehicle No. 4 at around 159s. At the end of the profile, vehicle No. 4 is passed by another vehicle not shown in Figure 21.

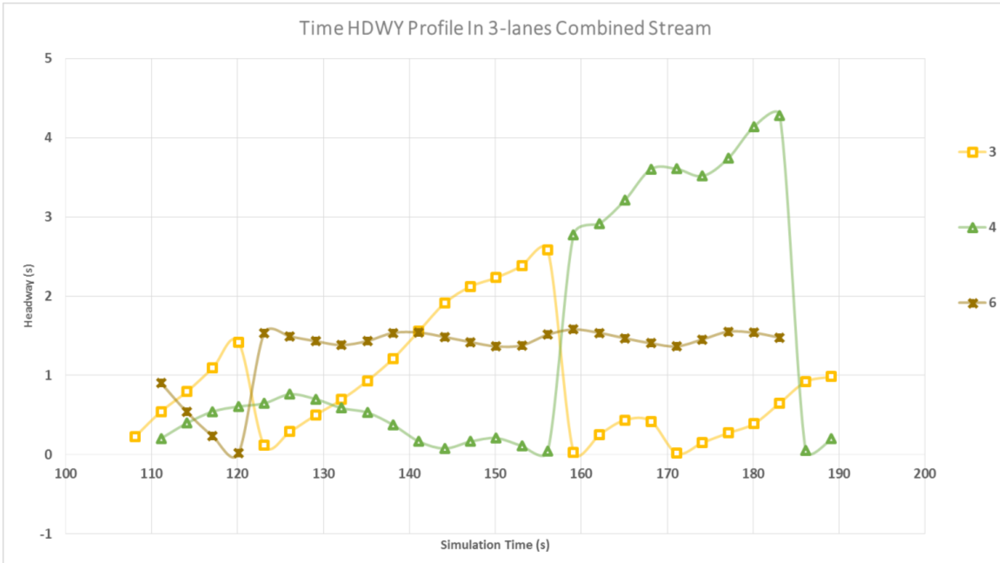

Figure 21 Vehicle No. 3, 4 and 6 Headway Profile

In multi-lane arterials, overtaking happens all the time and vehicle ID no longer represent sequence in traffic stream. These two issues make it more difficult to identify platoons in multi-lane arterials through headway profile diagrams. Moreover, using the headway profile diagram as the foundation of platoon identification algorithm is not very practical when market penetration ratio of connected vehicle is low. To tackle these problems, aggregation to a certain extent should be introduced in the platoon identification algorithm for multi-lane arterial and lower market penetration ratio situations.

3.2.2.1. Group Aggregation

The detection/ study zone of arterial is from 350m to 1500m and its length is 1150m. The researchers divide the arterial detection zone into 23 groups and each group is 50m in length. A brief demonstration of detection zone grouping is shown in Figure 22. Groups are numbered ascendingly according to traffic direction.

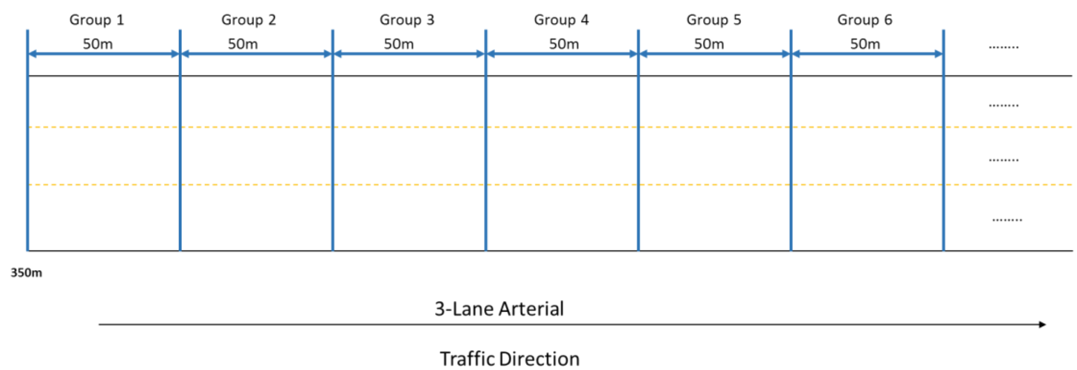

Figure 22 Detection Zone Grouping Illustration

Every connected vehicle will be sorted into groups according to their locations. Vehicle headways in each group are averaged as the aggregated group headway. If there is only one connected vehicle in the group and the vehicle is the lead vehicle of the whole traffic stream, the group headway is set to -1. When there is no connected vehicle detected in the range of a group, the group headway will be set to 10s. The groups are fixed on the arterial detection zone, every group has an average headway in each time step. All the headways of 23 groups in the same time step are collected and plotted in order as in Figure 23 and the legend of the diagram is simulation time. Figure 23 shows the group headway profile of time 150.1s. The x-axis of the plot is group number indicating the location on the arterial detection zone. The larger the group number, the further the group location is to the upstream signal head. So the x-axis of group headway plot can be viewed as the location on the arterial. Y-axis of group headway plot is average headway of the group.

Figure 23 shows that at time 150.1s, the traffic stream released from upstream signal is still entering the detection zone. The leading vehicle of the traffic stream is in Group 14. Group 5 has no vehicle in its range. Group 7 to Group 12 has similar average headways and their headways are the lowest. Group 1 to Group 4 has higher average headway Group 7-Group 12. Group 7 and Group 13 are turning points of the profile because average headways of these two groups has a sudden change. From the analysis of group headway profile of 150.1s, it is obvious that the most compact part of the traffic stream at this moment is between Group 7 and Group 12. Not only because Group7 to Group 12 have the lowest average headways but also because their average headways are similar. Vehicles in the same platoon have similar behaviors and headways.

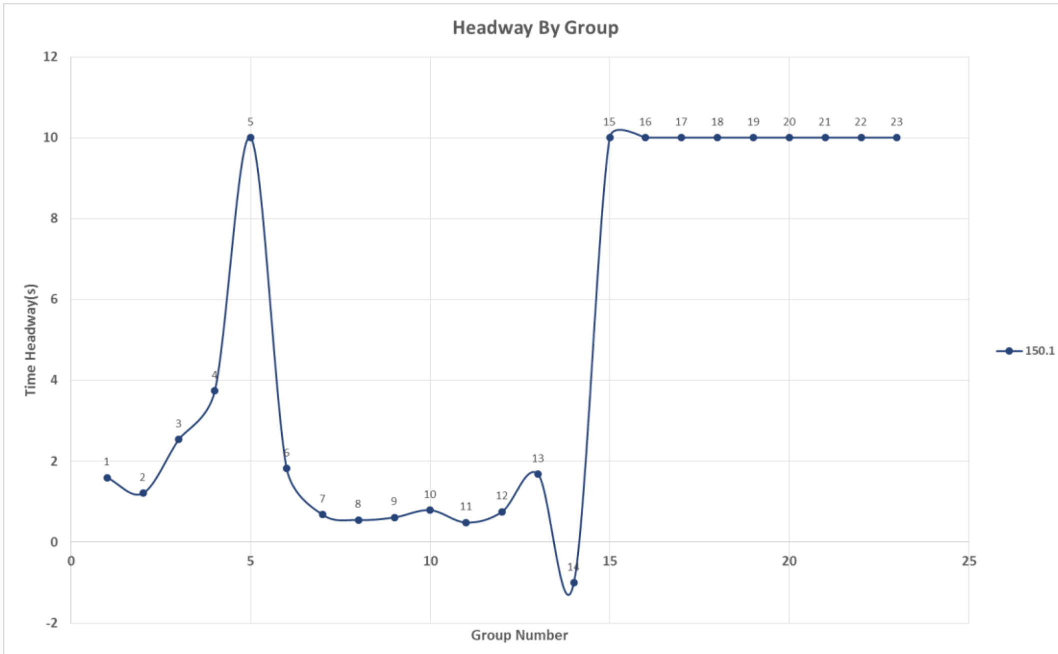

Figure 23 Example Group Headway Plot

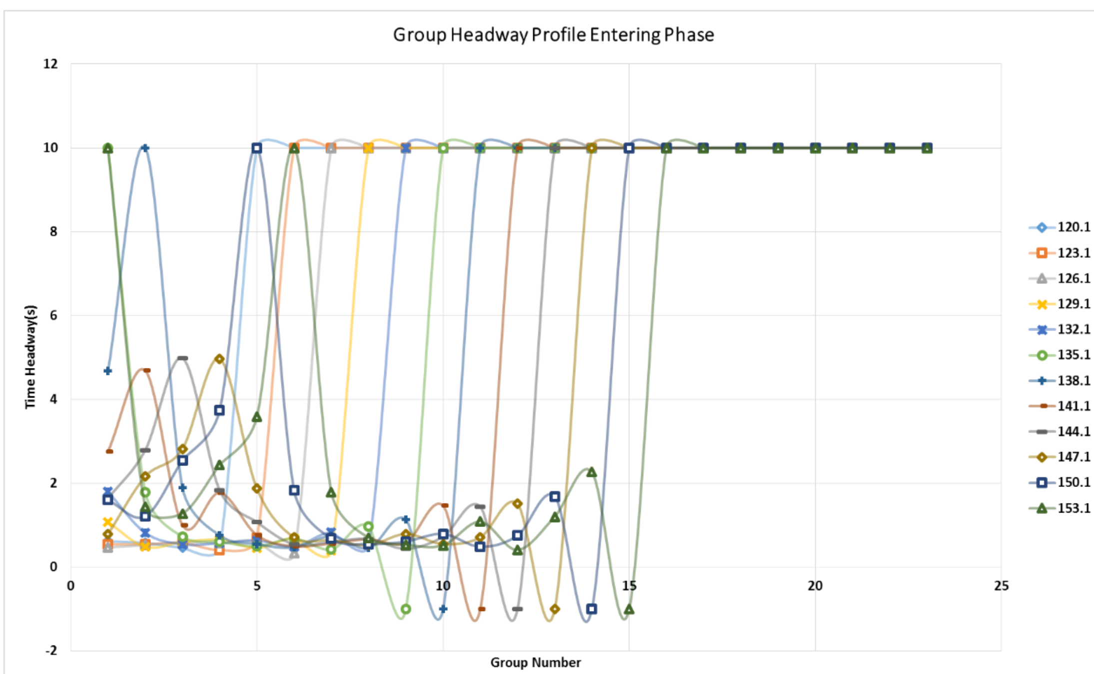

Figure 24 Entering Phase Group Headway Profile

Then the group headway profiles are plot second by second in one diagram. There are three phases regarding second by second group headway diagram:

- Entering Phase (Figure 24): When the upstream signal is still green, vehicles are still entering the detection zone.
- Passing Phase (Figure 25): When the upstream signal turns red. All vehicles have entered the detection zone and the first vehicle in the traffic stream hasn't reach the end of detection zone. The end of a detection zone can be a signalized intersection.
- Exiting Phase (Figure 26): When the vehicles start exiting the detection zone.

Because putting the group headway profiles of all three stages in the same diagram makes the diagram too messy to read, the group headway profiles are plotted separately in three diagrams based on phases.

Figure 24 demonstrates the entering phase group headway profile of a cycle. The feature of this phase is that the first few groups have vehicles in them but most of the last groups in the detection zone are vacant. In addition, there is a lot of fluctuations in the first few groups. When inspecting the group headway profiles by the sequence of time, the progression of traffic stream is clear. The head of the traffic stream moves one group forward every 3 seconds. At the end of the entering phase 153.1s, the start of the traffic stream is at Group 15. This phase is not important for platoon identification algorithm because the platoon is still forming and is very unstable at this phase.

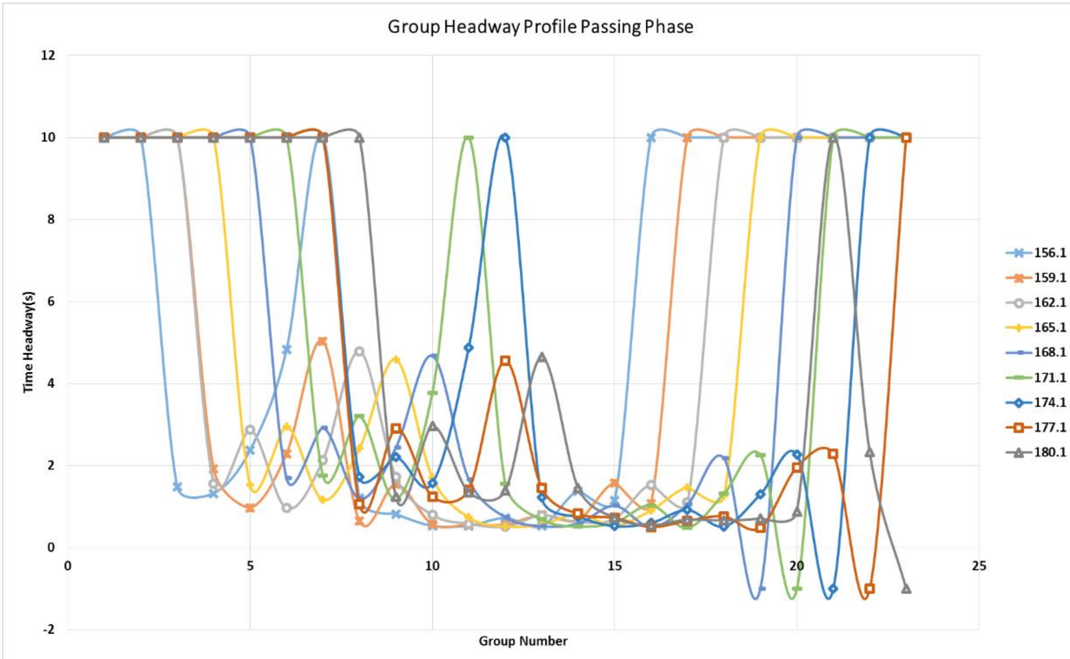

Figure 25 Passing Phase Group Headway Profile

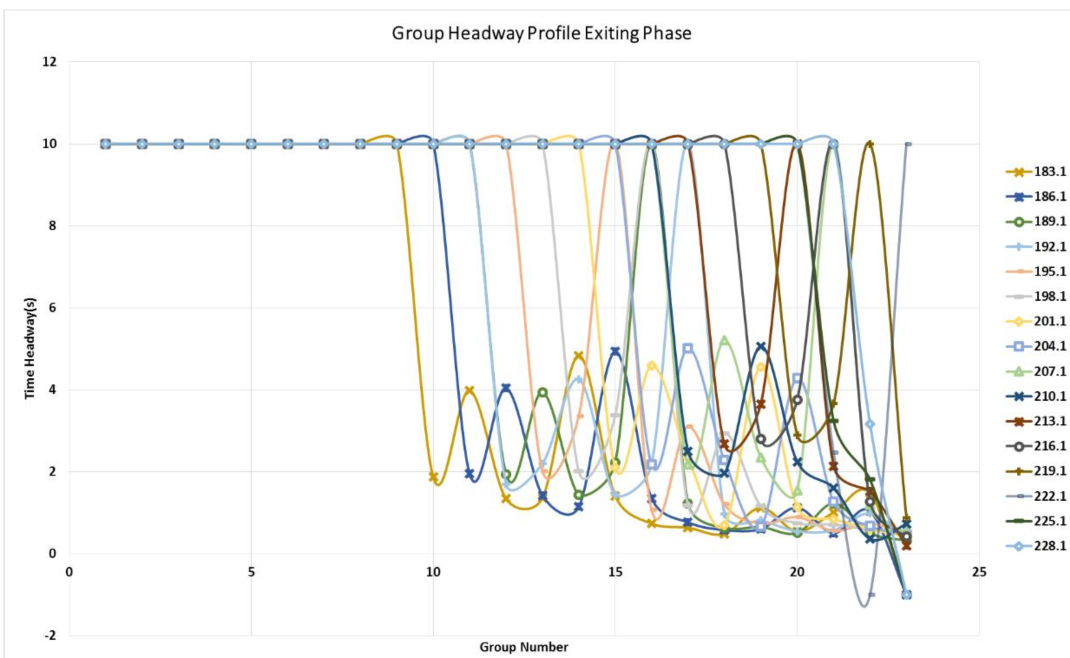

Figure 26 Exiting Phase Group Headway Profile

Figure 25 shows the most crucial phase of platoon identification, passing phase. In this phase, upstream signal has turned red and all the vehicles have entered the detection zone but not yet exiting the detection zone. Platoons are relatively stable in this phase. The feature of group headway profile diagram in this phase is that both the first few and last few groups are vacant. This phase is when the platoon identification should happen.

Figure 26 is the exiting phase of a cycle. In this phase, traffic stream starts to exit the detection zone. First few groups are vacant and last few groups are occupied. Group headway profiles fluctuate heavily in the last few groups. This phase is also not the target phase of platoon identification system. Because usually a detection zone ends at the potential signalized intersection, there is no point in detecting platoons after they leave. The identified platoon information serves as input for the downstream signal at the end of the detection zone. The determination method for the detection zone will be explained in the next section.

To better understand the group headway profile in the passing phase, two typical profile consecutive in time is randomly chosen from the passing phase and shown in Figure 27. These two profiles have all the features of passing phase group headway profile and they are similar to each other because of adjacent time.

Figure 27 Typical Passing Phase Profile

Take the profile at time 168.1s for example, traffic stream is between Group 6 and Group 19. Inside the traffic stream of 168.1s (blue profile), Group 7-10 have more fluctuation and higher headway values. Vehicles in this part of traffic stream are considered to be less compact and unstable. This part can be identified as the tail of a traffic stream. From Group 11, the headway profile decreases drastically and maintain a stable low headway from Group 12 to Group 16 with a small bump at Group 15. Group 12-16 are considered to be a compact and stable part of the traffic stream. Vehicles in Group 12-16 are close to each other and are similar in driving behaviors. They are the most compact platoon in this traffic stream. Vehicles in the same platoon do travel together close to each other and maintain a similar driving behavior according to the definition of vehicle platoon. On the other hand, Group 11 and Group 17-18 are considered to be the transition groups. They connect the scattered part of traffic stream and the compact platoon.

3.2.3. Overview of Platoon Multi-lane Identification Algorithm

3.2.3.1. Basic System Settings

The primary purpose of platoon identification system is to find out the most compact part of a vehicle stream after it is released from upstream signal. The goal of arterial signal control system is to serve as many vehicles in the shortest time as possible. Platoon identification system helps the signal control system to achieve this goal by telling it when to switch to red phase and cut off the platoon. The most efficient cut off time would be right after the most compact platoon pass the intersection because the time efficiency of slower vehicles is not desirable. The saved time can be used to serve other directions instead of wasting on the scattered slower vehicle platoon.

Traffic information is gathered from each connected vehicle every three seconds for the platoon identification system. Three second time step is selected for platoon identification system because traffic platoons take some time to form and change.

Since platoon identification serves as an information input system for signal progression, the detection zone setting is based on signal head setting. Figure 28 is an illustration of how the detection zones of each signalized intersection is set. The horizontal black line represents an arterial and the lines crossed with the arterial correspond to signalized intersections on this arterial. There are in all five adjacent signalized intersections on this arterial, each intersection has its own platoon detection zone marked by different colors. The detection zone is are set to be from the first intersection of the arterial to the ego intersection. In Figure 28, the detection zone of each downstream intersection is marked by a straight arrow in the same color as each ego intersection. For example, the platoon detection zone of intersection #4 is from intersection #1 to intersection #4. The target traffic stream of intersection #4 platoon identification is the vehicles released from intersection #1 and are not stopped by red signals at intersection #2 and #3.

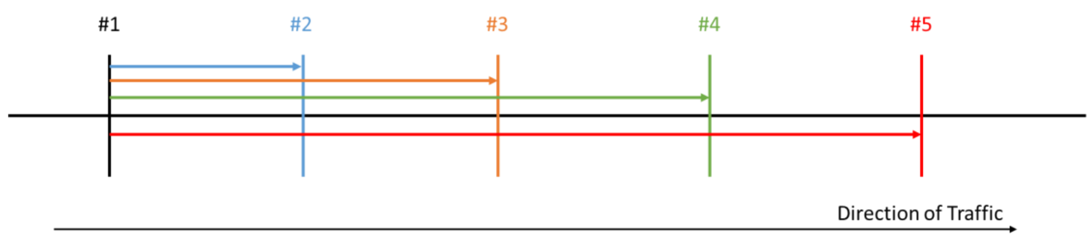

Figure 28 Detection Zone Setting

The platoon identification system only operates in the passing phase as in Figure 25. Two 50m long loop detectors are set at the location of Group 1 and Group 23. The occupancy of the two loop detectors will be checked every time step. When the vehicles are still entering the detection zone, the loop detector at Group 1 location will be occupied. When the vehicles are exiting the detection zone, the loop detector at the location of the last group (Group 23) will be occupied. When either of the loop detectors are occupied, the platoon identification algorithm will not be carried out. The platoon identification algorithm will be executed only when vehicles are neither entering nor exiting the detection zone but traveling inside the detection zone.

This thesis research focuses on the development of platoon identification algorithm itself, so the research scope is simplified from an arterial with multiple to a single 1150m long detection zone. Traffic condition is simplified by assuming there is only one cycle of vehicles traveling through the detection zone at a time. The upstream signal control makes sure that the next cycle will not start until the vehicles released from last cycle have all exited the detection zone. The coordination of arterial signal control system with identified platoon and the situation of multiple cycle platoon identification will be left for future research.

3.2.3.2. Platoon Body and Platoon Extension

The platoon identification system consists of two major components, platoon body identification phase and platoon extension phase. Platoon body is identified from group headway profile as in Figure 27. At 168.1s, Group 12-16 is the most compact platoon body. Because the identified groups with compact platoon are only a range of location on the arterial, it cannot represent the final platoon. The identified group can only be recognized as the main body of the platoon. The process of finding the platoon body from aggregated group headway profile is called platoon body identification phase.

To find the precise platoon, a platoon head ahead of the platoon body and a platoon tail behind the platoon body is necessary. The platoon head and tail have to be specified as two certain vehicles at the very start and end of the identified platoon. The process of finding the head and tail vehicles of the platoon based on the platoon body identified from group headway profile is called platoon sustaining phase in this thesis research.

Platoon body identification phase and platoon sustaining phase will be address in detail in Section 3.2.4 and Section 3.2.5.

3.2.3.3. Connected Vehicle Environment Assumptions

The proposed platoon identification system works in a connected vehicle environment. It is assumed that the connected vehicle wireless Road Side Unit (RSU) can cover the whole arterial. Covering the whole arterial means connected vehicles at anywhere on the arterial can send its vehicle information through wireless communication to the Road Side Unit with little latency.

Traffic information from each connected vehicle will be collected by each roadside unit along the arterial and sent to background server wirelessly for processing and calculation. The calculation results include the start and tail vehicle of the platoon and related platoon characteristics of interest. These calculation results are the outputs of connected vehicle platoon identification system.

Connected vehicle has a market penetration ratio issue. Market penetration ratio marks the percentage of connected vehicle in the whole vehicle population. The distribution of connected vehicle in arrived vehicle is random. In the algorithm development process, the market penetration ratio is first assume to be 100%. In the algorithm, penetration ratio will be taken into consideration as an input parameter. After the algorithm is settled, the impact of market penetration ratio on this platoon will be tested in the evaluation process. The ideal goal is to minimize the proposed algorithm’s sensitivity to penetration ratio change. In this chapter, when explaining the proposed algorithm, 100% penetration ratio is assumed. Which means all the vehicles are connected vehicle and their vehicle information is available.

3.2.4. Platoon Body Identification Phase

The main goal of platoon body identification phase is to find the most compact groups from the group headway profiles in each time step. The key to this problem is how to use a standard algorithm to find the consecutive groups with the lowest headway in a group headway profile (e.g. 168.1s group profile) as is shown in Figure 29. An example of the target consecutive groups to identify is circled in Figure 29.

Figure 29 Platoon Body Identification Phase Illustration

The researchers proposed a standard algorithm to find the target groups in a group headway profile. The standard algorithm is developed based on the common patterns found in the passing phase group headway profiles. The observed common patterns include:

- Each group headway profile represents the snapshot of a time step.
- In the passing phase, each group headway profile has a lowest segment consists of several consecutive groups with similar low headways (Figure 29).
- The above mentioned segment with the lowest group headways usually is the largest stable segment. Other segments with similar headways are mostly disrupted by high time headways.

The proposed platoon body identification algorithm uses intergroup headway difference between adjacent groups to find the low-headway segment in each group headway profile. There are in all 7 steps in the algorithm. Here the algorithm is explained step by step with example of the group profile of time step 177.1s. Group headway profile of time step 177.1s is shown in Figure 30. Average headway of each group is labeled in the diagram. As can be seen from the diagram, there is a segment with the lowest headway value and it takes a big portion of the whole valid profile. Valid profile means the groups that are not vacant and headway value different than 10s.

In this algorithm the platoon body is defined as the longest segment of consecutive groups with similar headway values. This definition makes sense because vehicles in a platoon have similar driving behaviors and the purpose of the platoon identification system is to find the most compact and crowded target platoon.

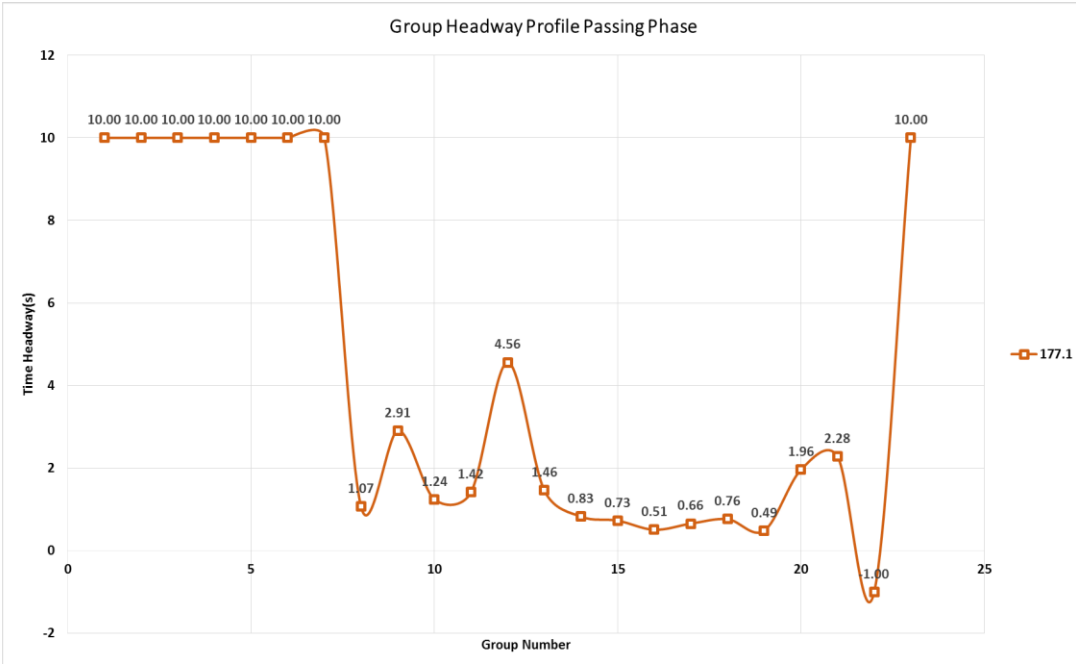

Figure 30 Example Group Headway Profile 177.1s

Steps of the platoon body identification algorithm include:

- **Step 1: Initialization.** Take out the first and last few vacant groups with 10s or -1s headway. Only keep those with real headway values in the middle. After executing this step, the example profile will only be from Group 8 to Group 21.
- **Step 2: Calculate Difference.** Each group is assigned an ID from 1-23 and group ID is noted by i . Then the headway of each group can be represented as H_i . In this step, absolute value of headway difference D_i of each consecutive group is calculated as:

$$D_i = |H_{i+1} - H_i|,\ \text{i=1,2,...22} \tag{6}$$

The headway differences are stored in an array. After the execution of this step, there is a headway difference array shown in Table 6. Only Group 8-20 is included because other groups except Group 21 are vacant and taken out of the picture.

Table 6 Example Absolute Headway Difference Array

ID	8	9	10	11	12	13	14	15	16	17	18	19	20
Di	1.84	1.67	0.17	3.15	3.10	0.63	0.10	0.22	0.15	0.11	0.28	1.47	0.32

- **Step 3: Calculate Headway Difference Threshold:** In this step, the standard deviation σ of headways is calculated. Note that 10s and -1s headways have already been taken out. This step outputs a threshold d_p to determine whether adjacent groups have similar headway values. The threshold is calculated by:

$$d_p = \frac{d_1}{p} + \beta\sigma \qquad (7)$$

Where,

p = market penetration ratio,

d_1 = threshold when market penetration ratio is 100%,

β = system parameter, determine how much the standard deviation σ affects the threshold d_p, set to be 0.1.

The value of d_1 depends on how much difference is considered significant by the user. This threshold changes every time step because it takes the variation of group headways into consideration. This threshold is also designed to be compatible to different penetration ratio. When penetration ratio is not 100%, the threshold is amplified by $\frac{1}{p}$. Additionally, when penetration ratio is lower, the variation in group headways increases, thus again gives the threshold more robustness and tolerance. The standard deviation of example profile is 1.09, and when p=1, the threshold d_p =0.609s.

- **Step 4: Compare and Store.** In this step, adjacent headway difference of each group D_i is compared to the threshold. If $D_i < d_p$ then its group ID will be pushed back to a group ID array. Using the example profile, the output will be [10, 14, 15,16,17,18, 20]. Theses selected group IDs will be the candidate IDs of platoon body.
- **Step 5: Check Continuity.** The candidate ID array will be separated by IDs' continuity. For example, the array outputted from Step 4 will be separated into three candidate platoon bodies: [10], [14, 15, 16, 17, 18] and [20]. Only the candidate with the largest size will be selected as the final platoon body. In this case, the selected platoon body is [14, 15, 16, 17, 18] array.

- **Step 6: Refine Platoon Body.** The group after the last member of the selected platoon body array should be included, making the final platoon body group to be from Group 14 to Group 19.

The outcome matches human judgment well. So with proper user input h_1, p and λ, the algorithm can work well in identifying the previous defined platoon body. Scenarios with lower connected vehicle market penetration ratio is explained later in this chapter.

3.2.5. Platoon Extension Phase

In this phase, the algorithm tries to locate the tail vehicle and head vehicle of platoons based on identified platoon body. Platoon body identification phase works on the aggregated level to see the general picture of target platoon. Platoon extension phase extends and refines the identified platoon body by looking into detailed pictures of the platoon.

Locating the head and tail vehicle of the platoon begins from the front and end of the identified platoon body. In the 177.1s example, the identified platoon body is Group 14 to 19. The start of Group 14 is at 1000m and the end of Group 19 is at 1300m. All the vehicles in between 1000m and 1300m are identified as traveling in the same platoon. Vehicles outside 1000m to 1300m range are examined individually to determine if they belong to the compact platoon.

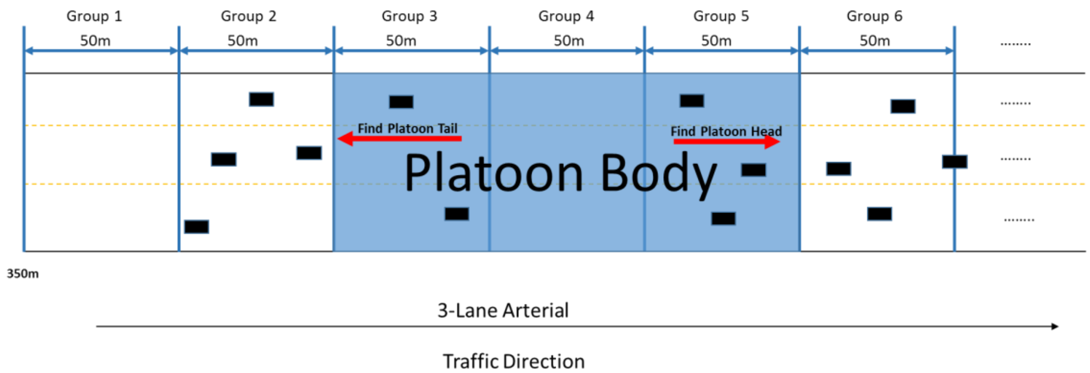

Figure 31 Platoon Extension Illustration

The search starts with the vehicles that are the closest to the borders of second platoon body group and second last platoon body group. The reason for setting the search starting point one group inside platoon body is to remove vehicles with larger headways at both ends of the identified platoon body.

Search of platoon head and tail goes one vehicle further at a time as shown in Figure 31. Headway of each vehicle is compared to an extension critical headway h_c . If a headway is smaller than the critical headway, the vehicle is considered to be included in the compact platoon. The search of platoon head and tail vehicle stop when a headway is larger than the critical headway. For example, in Figure 31, headway of Vehicle #3, h_3 is first examined, if $h_3 < h_c$, then Vehicle #3 is included. Then headway of Vehicle #2, h_2 is compared to h_c , if $h_2 < h_c$, Vehicle #2 is also included in the compact platoon and become the new platoon head. The search stops if, for example, headway of Vehicle #1, $h_1 > h_c$. Then Vehicle #1 is not included in the compact platoon and Vehicle #2 is the final platoon head. The same process is carried out for finding platoon tail but in different direction as shown in Figure 31.

The researchers use the critical headway from the PAMSCOD paper as the threshold for platoon extension (*17*). Assume h_1 is the critical headway when market penetration is 100% and penetration ratio is p. Assume K is the number of vehicles since last connected vehicle, then the critical headway for connected vehicle is $h_p = Kh_1$. Assume K subjects to geometric distribution with parameter p, then expectation of h_p is:

$$E(h_p) = \frac{h_1}{p} \quad (8)$$

Standard deviation of h_p is:

$$Std(h_p) = \frac{h_1\sqrt{1-p}}{p} \quad (9)$$

The critical headway for connected vehicle under penetration ratio p is:

$$H_p = E\left(h_p\right) + \lambda \cdot Std(h_p) = \frac{h_1}{p} + \lambda\frac{h_1\sqrt{1-p}}{p} \quad (10)$$

λ is the number of standard deviations from the expectation, its value is set to 1 in this thesis research. h_1 is a user specified threshold value. h_1 is specified to be 0.75s in this paper according to previous analysis (Figure 19). This critical value changes for every penetration ratio. It is originally developed by He et al. in their probe vehicle based platoon identification. They use this threshold to separate vehicles into platoons. Their approach will be experimented and compared with the proposed platoon identification system later in Chapter IV.

3.3. Lower Market Penetration Scenario

This section demonstrates difference in group headway profiles under different connected vehicle market penetration ratio scenarios. The same 177.1s group headway profile from 30%, 50% and 70% penetration ratio scenarios will be demonstrated and processed using proposed platoon body identification algorithm (Figure 32).

From Figure 32, the impact of incomplete information is very obvious. Using the proposed platoon body identification algorithm, the identified platoon body groups are presented in Table 7. In the table, platoon body identification algorithm does not change too much for 70% and 50% penetration ratio scenarios. However, the platoon body is cut short for 30% penetration ratio scenario.

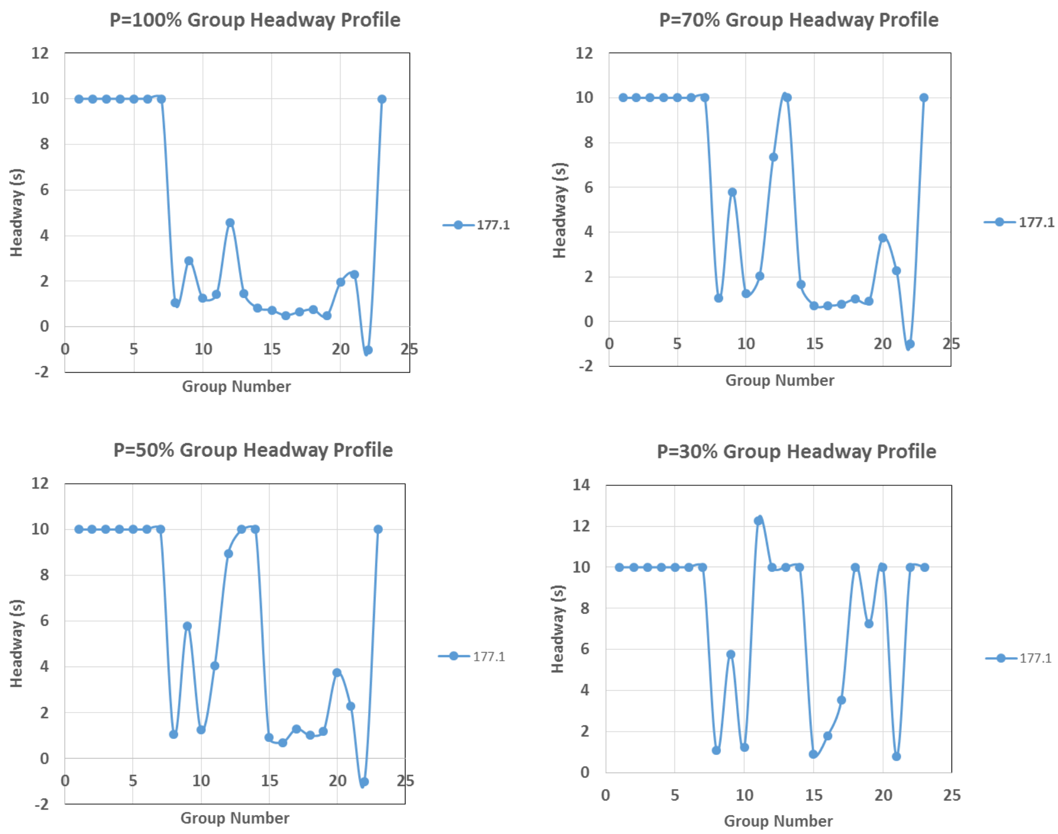

Figure 32 Different Penetration Ratio Profile Comparison

Table 7 Platoon Body Identification vs. Penetration Ratio

Penetration Ratio	Start Group ID	End Group ID
100%	14	19
70%	15	19
50%	15	19
30%	15	17

From the above analysis, it is obvious the proposed platoon body identification system has some robustness against lower penetration ratio scenarios.

3.4. Multi-Lane Platoon Identification Algorithm Summary

This section presents the output platoon characteristics of the identified platoon and summarize the system settings of the proposed system.

3.4.1. Platoon Characteristics of Interest

After the platoon is identified in each time step, information about the platoon should be output from the platoon identification system and sent to downstream signals for signal progression calculation. The platoon characteristics of interest include:

- Number of vehicles in the platoon.
- Average headway of the platoon (s).
- Standard deviation of platoon headway (s).
- Starting and ending location of the platoon (m).
- Platoon Length (m).
- Platoon average speed (km/h).
- Platoon speed standard deviation (km/h).
- Platoon duration, which is platoon length divided by platoon average speed (s).
- Platoon density= platoon size/ platoon duration (vps).

The above platoon characteristics are output from the system every time step (3s). These platoon information can help future arterial signal systems provide smarter progression timing real-time.

3.4.2. Platoon Identification System Setting Summary

User specified and input identification parameters of the proposed system include:

- Time step length, set to 3s in this thesis research.
- Market penetration ratio p.
- Detection zone length.
- Platoon body identification phase 100% threshold d_1 .
- Platoon body identification phase standard deviation impact factor β .
- Platoon extension phase 100% critical headway h_1 .
- Platoon extension phase standard deviation impact factor λ .

CHAPTER IV

SIMULATION RESULTS

This chapter describes the setting of experiments to evaluate the proposed platoon identification system. The first section of this chapter introduces the test bed setting and evaluations. The second part presents the evaluation performance measures and the analysis of evaluation results.

4.1. Experimental Evaluation Setup

This section presents the setup of evaluation test bed for the proposed platoon identification system. Tools used for evaluation and scenarios to be tested are all included in this section.

4.**1.1. Evaluation Network**

The roadway network used to build the evaluation test bed is an imaginary one direction 3-lane straight arterial. The detection zone is set to 1150m. There are loop detectors at the first 50m and the last 50m of the detection zone to determine the travel status of the traffic stream. An upstream signal is located at 350m of the arterial and is timed to make sure the next cycle would not start before the vehicle batch from last cycle leaves the detection zone. The baseline traffic demand is set to 1000 veh/h and the baseline desired speed distribution is set to 50km/h. The range of speed distribution is 48 km/h to 50 km/h. The network is shown in Figure 33.

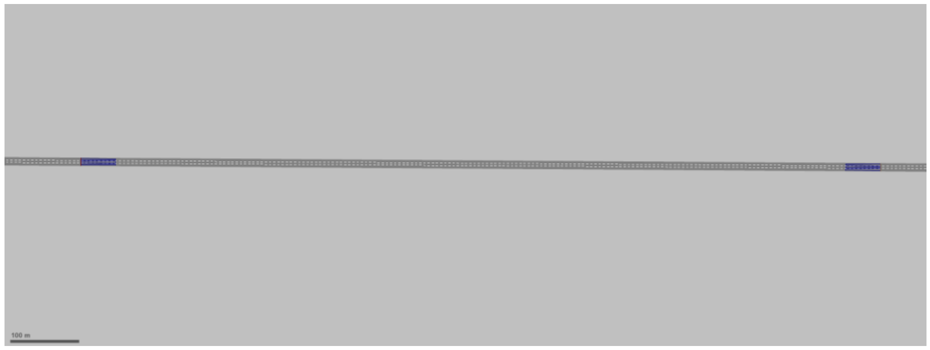

Figure 33 Test Network

4.**1.2. Simulation Environment**

Due to the limited choice of connected vehicle environment testing options and great difficulty in acquiring real time arterial traffic data, the test bed is built using a microscopic traffic simulation package named PTV Vissim 7.0. In the testing process, PTV VISSIM Component Object Model (COM) Application Program Interface (API) is used to implement the proposed algorithm. VISSIM COM API is a program interface that allows users to access and manipulate certain VISSIM simulation object attributes from an outside program.

All the platoon identification algorithms are implemented in a VISSIM COM application program developed using C++ programming language in Window Visual Studio 2013. The program starts a VISSIM simulation when it starts running and controls the simulation run every time step. Simulation object features such as individual vehicle information are passed through COM API to the C++ program to support the platoon identification system.

A more detailed introduction of PTV VISSIM traffic model is provided in Chapter 3.

4.2. System Performance Measures

Gaur and Merchandani provided a very clear and thorough requirement for platoon identification systems in their paper (*20*). They concluded that a platoon identification system should be robust against different traffic conditions, insensitive to traffic perturbations, representative of traffic stream and easy to compute.

Several related performance measures are summarized from past literatures. They are used in this thesis research to evaluate the performance of the proposed platoon identification system. They are classified into three categories:

- **Accuracy:** To demonstrate accuracy, both visual and numerical approaches are used. Visual approaches as in the PAMSCOD paper (*17*) is used to check how well the platoon identification system can match human judgment. Because the definition of platoon is subject, there is not a practical way to test if an identified platoon is precisely right. Numerical approach compares real characteristics of the identified platoon to the platoon characteristics outputted by the proposed system under different penetration ratio scenarios. Performance measures in this category includes system output and real versions of some platoon characteristics, such as platoon size, platoon average headway, platoon starting and ending location, platoon length, average speed, speed standard deviation and so on. The real version of those platoon characteristics are obtained from simulation by accessing all the vehicles in the identified platoon.

- **Representativeness:** The representativeness is represent by the percentage of vehicles captured in the identified platoon. The ideal situation is more vehicle but shorter platoon duration.
- **Sensitivity and Robustness:** These two requirements are evaluated by running the algorithm testing under different traffic conditions and different CV market penetration ratio settings and see how the change in conditions affect its performance. The scenarios are listed in the next section.
- **Computation:** Since the proposed algorithm does not require any complicated computation and the allowable computation time is long for 3s system time step, the researchers do not evaluate this requirement in this thesis research.

4.2.1. Evaluation Scenarios

In the evaluation process, several scenarios with different simulation settings are ran to test the sensitivity and robustness of the proposed system. The evaluation scenarios involve different level of traffic demand, different speed limit and different CV market penetration ratios. The scenario settings are shown in Table 8. Additionally, the baseline scenario is shown bold in the table.

The probe vehicle platoon identification system from He et al. is implemented and used as a comparison of the proposed system. This comparison only uses the baseline scenario settings but with different market penetration ratios.

Table 8 Evaluation Scenario Settings

Variables	Settings
Traffic Demand (vph)	**1000**
	1500
	2000
Speed (km/h)	**50**
	60
	70
Market Penetration Ratio (%)	100
	70
	50
	30

4.3. Experiment Result Analysis

In this section, the evaluation results are presented and analyzed. Firstly, the baseline scenario is tested under different penetration ratio scenarios to evaluate its performance. All the comparisons in this section are controlled comparison, only one variable can be altered in each comparison. Then scenarios with different traffic demand and speed are analyzed in order. When testing the system robustness against speed limit and traffic demand, the penetration ratio is set to be 70%. Other non-investigating variables are set to be the same with baseline scenarios.

4.3.1. Base Line Scenario Simulation Results

First, base line scenario with 1000vph traffic input, 50km/h speed and 100% penetration ratio is ran and tested. Four different time steps are chosen randomly from the simulation, the identification results are shown visually in Figure 34. The identified start and end locations of platoons are marked in vertical black lines. Red dots on the link represent vehicles. As is shown, the algorithm can successfully identify the most compact middle platoon of vehicles in one cycle with 100% penetration ratio.

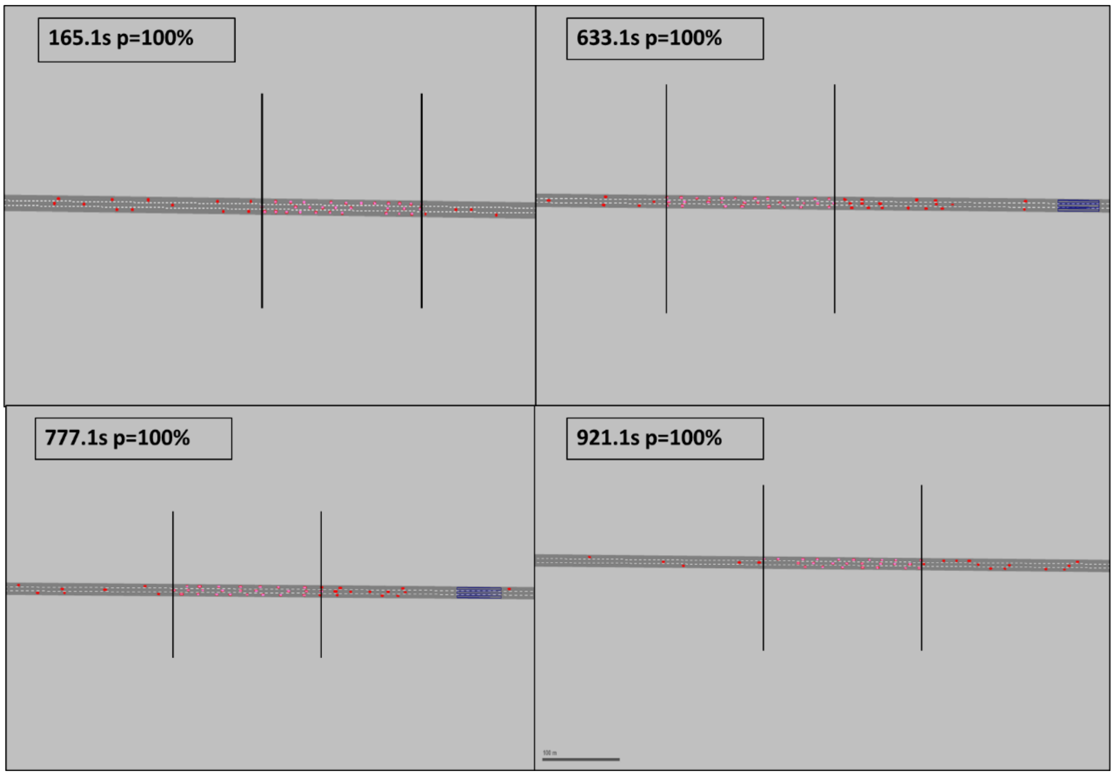

Figure 34 Baseline Identification Result

Then identification results of one time step, 921.1s, under different penetration ratio levels are demonstrated visually in Figure 35, white dots are regular vehicles and red dots represent connected vehicles. Under lower penetration ratio condition, the occurrence of connected vehicles are generated randomly based on penetration ratios.

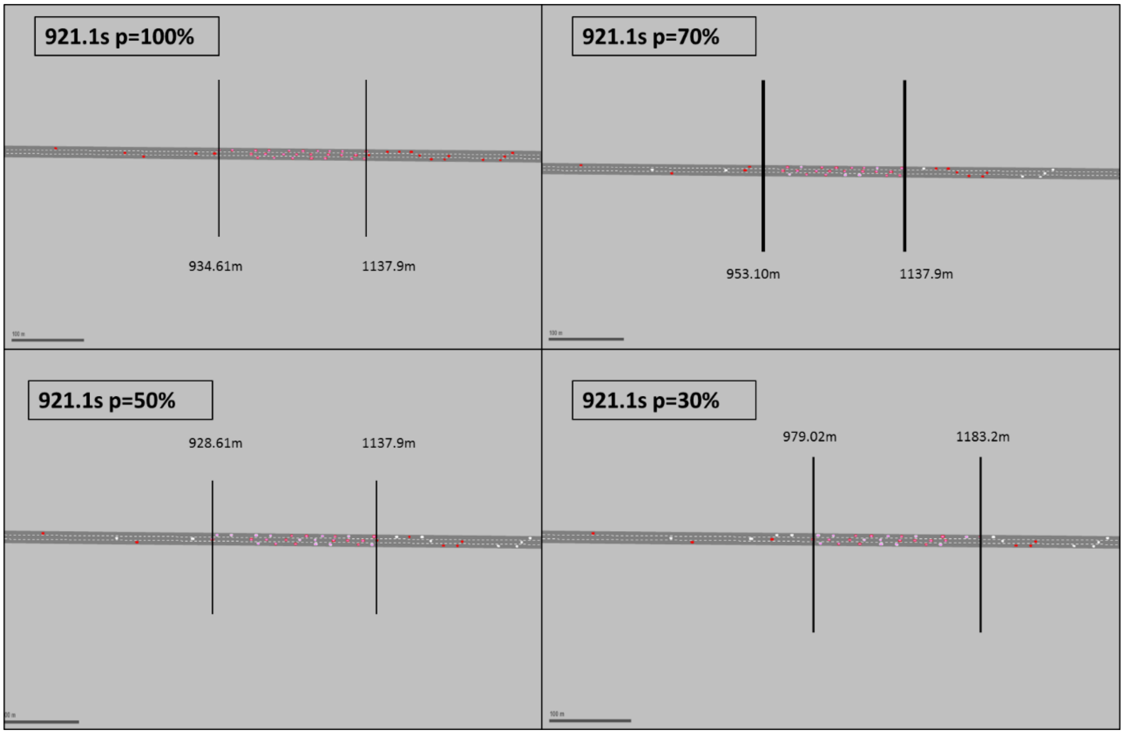

Figure 35 Penetration Ratio Results

Three major performance measures are selected to present and compare evaluation results numerically. They are platoon duration (s), captured percentage (%) and platoon density (vehicle per second). Platoon duration is how much time it takes for the platoon to pass a downstream stop bar. Captured percentage means how much of the vehicles released in this cycle is captured in the identified platoon. Platoon density is platoon size over platoon duration. A large platoon density with proper platoon duration and capture percentage is desired. Platoon duration should be close to typical green phase time for arterial through movements.

Table 9 Proposed Algorithm Robustness against Penetration Ratio

Penetration	Platoon Duration (s)	Capture Percentage	Platoon Density (veh/s)
100%	10.52	52%	2.19
70%	12.67	52%	1.83
50%	15.80	57%	1.47
30%	11.43	44%	1.70

Table 10 Output platoon characteristics

Penetration	CV Size	Captured Size	Total Cycle Veh	Length (m)	Avg. Single-lane Hdwy. (s)
100%	22	22	43	143.38	0.61
70%	19	23	43	172.78	1.80
50%	15	25	43	216.95	2.48
30%	8	20	43	155.99	2.09

The system performance is listed in Table 9 and part of the output platoon characteristics are shown in Table 10. In Table 10, CV size is the number of connected vehicles in the identified platoon and captured size is the real platoon size. Total cycle vehicle is the total number of vehicles released in a cycle. Length is the platoon length. Average single-lane headway is the averaged traditional single lane headway of vehicles in the platoon.

As can be seen in Table 9 and Table 10, penetration ratio does not impact too much on the identification results. 100% penetration scenario has the most desirable results, it has high platoon density and low average single lane headway without sacrificing the capture percentage or platoon duration. As the penetration ratio decreases, the system tends to result in larger and less compact platoons.

4.3.2. System Robustness against Traffic Demand Level

The proposed system is evaluated with three different levels of traffic input. The characteristics and performance measures of the three traffic demand levels are shown in Table 11 and Table 12.

Table 11 Platoon Characteristics vs. Traffic Demand Level

Traffic Demand (vph)	CV Size	Captured Size	Total Cycle Veh	Length (m)	Avg. Single-lane Hdwy (s)
1000	19	23	43	172.78	1.80
1500	31	43	64	324.92	1.70
2000	38	52	76	394.83	1.80

Table 12 Performance Measure vs. Traffic Demand Level

Traffic Demand (vph)	Platoon Duration (s)	Capture Percentage	Platoon Density (veh/s)
1000	12.67	52%	1.83
1500	23.87	66%	1.80
2000	29.06	68%	1.80

As is shown in Table 11 and Table 12, the platoon density is not affected by traffic demand. As traffic demand increases, platoon duration and capture percentage increases but the average single lane headway does not change too much. The increase in platoon size and capture percentage is that when traffic input is higher, vehicles will travel in a more compact way, and more vehicles will be in the compact platoon.

4.3.3. System Robustness against Speed Limit

Three different speed limit scenarios are tested to evaluate the robustness against speed change of the proposed algorithm. The results are shown in Table 13 and Table 14.

Table 13 Platoon Characteristics vs. Speed Limit

Speed Limit (km/h)	CV Size	Captured Size	Total Cycle Veh	Length (m)	Avg. Single-lane Hdwy (s)
50	19	23	43	172.78	1.80
60	17	21	42	175.41	1.72
70	20	26	42	250.50	1.64

Table 14 Performance Measure vs. Speed Limit

Speed Limit (km/h)	Platoon Duration (s)	Capture Percentage	Platoon Density (veh/s)
50	12.67	52%	1.83
60	11.17	48%	2.00
70	13.19	60%	2.00

The results show that the proposed algorithm works better when the speed limit is higher. As speed limit raises, the identified platoon density increases. The system works the best when speed limit is 70km/h, in which the platoon density is the highest, average single lane headway is the lowest and the percent captured is the highest.

4.3.4. Platoon Identification Algorithm Comparison

The proposed platoon identification algorithm for connected vehicle environment is compared with the PAMSCOD platoon identification algorithm (*17*) for probe vehicle. Both platoon identification algorithms are ran with 1000 vph traffic input, 60 km/h speed limit. Average single lane headway, platoon duration, captured percentage and platoon density are compared for the two algorithms. The comparison results are shown in Table 15.

Table 15 Platoon Identification Algorithm Comparison

	Penetration	Avg. Single-lane Hdwy (s)	Platoon Duration (s)	Capture Percentage	Platoon Density (vps)
Proposed	100%	0.61	12.10	55%	2.20
	70%	1.75	11.06	48%	1.99
	50%	1.89	15.33	61%	1.77
	30%	1.69	12.54	49%	1.86
PAMSCOD	Penetration	Avg. Single-lane Hdwy (s)	Platoon Duration (s)	Capture Percentage	Platoon Density (vps)
	100%	0.38	2.32	17%	2.97
	70%	2.13	8.32	42%	1.95
	50%	2.14	9.72	43%	1.67
	30%	1.98	6.97	31%	1.59

Sometimes the platoon identification algorithms will only recognize a one vehicle platoon under lower penetration ratio scenarios. The proposed algorithm can minimize the occurrence of one vehicle platoon. One vehicle platoon happens more under lower penetration ratio scenarios in the PAMSCOD algorithm than the proposed algorithm. Also, in all lower penetration ratio scenarios, the platoon density of proposed algorithm is higher than that of the PAMSCOD algorithm. PAMSCOD algorithm does not work well under 100% penetration ratio. The identified platoons are short and only 17% of the vehicles are captured in the platoon.

CHAPTER V

FINDINGS AND RECOMMENDATIONS

5.*1. Summary*

In this thesis research, a platoon identification algorithm for connected vehicle environment is proposed. In the first stage, aggregated headway characteristics of random arrival and upstream signal released traffic are examined. Difference in the two traffic patterns are summarized. Then individual headway profiles of single lane and multiple lane signal released traffic are investigated. It is found that vehicles with a slower desired speed in a single lane scenario will fall behind from their preceding vehicles and become head of a platoon. As for multiple lane scenario, overtaking makes it hard to track the headway profile of a vehicle. So a cross-lane traffic stream combination method is proposed to combine multiple lane traffic stream into one traffic stream. Vehicle headways are calculated based on the combined traffic stream. Aggregated features of cross-lane traffic stream headway are investigated.

In the second stage, a platoon identification system including platoon body identification and platoon extension phases is developed. Platoon body identification phase divide the detection zone into several groups with same length and find the longest consecutive groups with the lowest and uniform headway values. Platoon extension phase starts from one group inside the identified platoon body and compared individual headways of connected vehicles to a critical headway. The extension phase can refine the platoon by taking out scattered individuals inside the platoon body or adding in compact individuals outside the platoon body.

The problem of connected vehicle penetration ratio is tackled by using dynamic critical headway threshold incorporating penetration ratio as a threshold decision parameter. When penetration ratio is small, the headway characteristics of connected vehicle fluctuates more randomly. Variation in headway characteristics is also taken into consideration when identifying platoon body. These dynamic threshold settings made the identification algorithm more robust against the impact of penetration ratio.

In the third stage, several performance measures and testing scenarios are identified for the evaluation of the proposed system. The proposed system is tested under different penetration ratio and traffic conditions and compared with an existing platoon identification method using the same data source.

5.2. Findings

The proposed algorithm is found to be able to work robustly under different penetration ratio conditions. Additionally, its performance is stable when traffic demand on the arterial increases. More vehicles are captured in the platoon by the proposed algorithm as traffic volume increases. When speed limit of the platoon increases, its performance improves and the identified platoon increases in density. In addition to the proposed platoon identification algorithm, the nature of traffic platoon is carefully examined.

5.3. Future Research

In future research, this platoon identification algorithm can be customized to fit into a platoon based signal control system for arterial. The real value and impact of the proposed algorithm can be evaluated better once it is combined with a proper signal control system.

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