國 立 交 通 大 學
運 輸 與 物 流 管 理 學 系

碩 士 論 文

考量停等車隊型態之混合車流疏解特性分析

Queue discharging characteristics in mixed traffic considering the stopping queue patterns

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中 華 民 國 一 百 零 七 年 一 月

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摘要

在開發中國家常可觀察到汽機車交叉混合的情景，在臺灣，大量的機車導致路況更為壅擠同時增加了運具間互動的複雜性。為了估計號誌化路口的容量，混合車流的疏解分析相當關鍵。疏解時間之估計誤差的降低可以改善疏解率的估計。本研究旨在了解混合車流下的疏解行為並建立混合車流疏解時間模型加以分析。

綜觀過去研究與文獻探討疏解時間與其影響因子的關係，以車輛數、車隊長度、路口和道路幾何型態以及車輛間的相互影響作用為影響疏解時間之重要因素。然而，較少研究指出車隊排列上之失序混雜程度對車隊疏解上的影響；臺灣公路容量手冊在計算飽和流量時認為混合車隊會因停等區的設置而沒有更多延誤產生，與實際混合停等車隊交錯排列之情形相左。本研究因而以停等車隊型態熵 (Queue Pattern Entropy, QPE) 的概念，欲闡述車輛於車流疏解下相對位置之關係，其功能在於同時考量車隊之停等型態以及不同車輛組成下所描述的停等車隊混合程度。

本研究的資料來源是採用無人機進行影片錄製，此方法提供了本研究能一窺混合車流互動的機會。透過收集到的微觀車流軌跡資料發現，車輛之橫向位移程度以及變動的停等車隊疏解順序等特性揭示混合車流不同於一般汽車車流的疏解行為。本研究採用迴歸分析來建立混合車流的疏解模型。並透過線性與非線性的模式結構校估模式對比並無考量車隊停等型態的模式，結果顯示兩模式皆能有效地敘述混合車流的疏解。與過去研究所提出的模式相比，本研究變數使用之考量 QPE 程度的模式可以有效地描述車隊停等型態，並減少疏解時間的估計誤差。

關鍵字：疏解時間預測、車隊停等型態、混合車流、疏解特性

Queue discharging characteristics in mixed traffic considering the stopping queue patterns

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Abstract

The mixed-traffic condition is common in most of the developing countries. In Taiwan, the large ratio of scooters in the mixed traffic increases the complexity of interactions between vehicles. To understand the capacity of signalised intersections, the discharge characteristics under the mixed-traffic condition is critical. The less bias on the estimation of discharge time can improve the estimation of discharge flow rate of intersections. The aim of this study is to understand the discharge behaviour of vehicles under the mixed-flow traffic condition and formulate a model to estimate the discharge time.

Past research discovered the relationship between the discharge time and the affecting factors, such as numbers of the vehicles, length of the queue, geometry design and layout, and the interactions between vehicles. However, there were limited studies that investigated the effect of order and arrangement of vehicles in a queue to the discharge process. In Taiwan's Highway Capacity Manual, it is assumed that scooters concentrate at the scooter-waiting zone and their discharge do not affect the vehicles behind. However, in observations, scooters and other vehicles may mix up in the queue. This study proposed a new factor, Queue Pattern Entropy (QPE), which can describe the vehicle stopping sequence and queue pattern formed by different vehicle compositions.

Microscopic vehicle trajectory data collected from Unmanned Aerial Vehicle (UAV) is used in this study to gain insights into the interactions between vehicles. The dataset allowed us to observe traffic characteristics such as lateral movement, discharge order, and discharge times of the mixed traffic flow. Furthermore, a regression analysis is proposed to construct a discharge time estimation model under mixed-traffic condition. Linear and non-linear structure has been calibrated and compared to the model without QPE. Both forms of the model shows that the QPE is beneficial and superior to the base model. Compared with previous models in the literature, our model with QPE can effectively describe the queue pattern and attain less bias on the discharge time estimation.

Keywords: discharge time estimation, queue pattern, mixed traffic flow, discharge characteristics.

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在交通大學這五年外加半年的日子裡，我所記憶的東西已由彩色轉黃了。我會說大學是快樂的學習，跌跌撞撞也沒有太大的問題，研究所就不同了，深度的學習，自我的要求，是這一年在國內一年在英國對自己狀態的改變；我不再天真，也不再驕傲；我知道在未來裡我需要的是更多的社交上與專業上的技巧，更銳利的角度，更迅速的效率才可以生存，就如同球場上，當你不認真的時候你已經輸了。最後，我的家人們，謝謝爸媽資助我從小到大的學業，讓我能在這過程接觸到很多知識並能忍受這一個常常不會主動回報動態讓你們擔心的兒子。

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2018 年 1 月

於交大綜合一館

KI Lab

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Chapter 1 Introduction

1.1 Background

The mixed-traffic condition is common in most of the developing countries. The appearance of the motorcycle dependent city (MDC) such as Hanoi and Bangkok shows the urban city suffered from severe congestion, accident, and pollution due to the mixed-traffic condition. In Taiwan, there has been a growing increase in the number of scooter registration by 16% in the last decade (Ministry of Transportation and Communication, 2016). The large numbers of scooters make the road condition more congested and increase the complexity of the interaction between vehicles. According to the latest statistical data from Taiwan’s Ministry of Transportation and Communication (MOTC) in 2016, there are 58.1 scooters per hundred people. Despite for the popularity of scooters because of its convenience, low price, and mobility, it also causes some challenges in the management and control of mixed traffic flow.

The mass amount of scooters has a great impact on the traffic. For example, scooters can squeeze into the gap inside the queue that impede the potential movement of the passenger cars; they can easily change their lateral position in the same lane during the flow propagation and the formation of the standing queue. Even during the discharging process at the junction, the scooters can impede some of the larger vehicles since they possess high acceleration and tend to move forward. The above situation will cause the traffic condition to be chaotic and interrupt the movement of the passenger cars on the artery. To lower the influence of scooters’ behaviours, MOTC in Taiwan set up a scooter waiting zone at downstream along the road to avoid the potential conflicts during discharging. The scooter waiting zone can separate part of the scooters from car flow when the flow is about to start up and increase the efficiency of the discharge process. However, the number of scooters may exceed the waiting zone due to different location of the junction and this measure can only deal with the standing queue.

The discharge analysis under mixed-traffic condition is critical in the field of traffic engineering and traffic control. High proportion of scooters and mixed-traffic between passenger cars and scooters are typical traffic flow conditions in some Asian developing countries. In mixed traffic flow, scooters mix up with passenger cars on the urban arterials and cause traffic issues and conflicts because of the differences in the traffic characteristics such as desired speed, acceleration rate, gaps etc of the different vehicle types. To improve the traffic conditions by reducing the loss time, the estimation of discharge time of the queuing vehicles is better than the measuring of the saturation flow rate. A well-estimated discharge time could be utilised in many applications such as capacity estimation or phase design for signalised intersections.

Under the mixed-traffic condition, the estimation of the saturation flow rate became complicated. Taiwan’s Highway Capacity Manual (HCM) provided a model for the estimation of saturation flow based on the assumption that a number of scooters at the scooter waiting zone does not affect the discharge of vehicles in behind. In fact, when there are too many scooters which exceed the storage capacity of the scooter-waiting zone, scooters spill back and stay in between the passenger cars. It is observed that the sequence and pattern of the stopped vehicles affect the discharging behaviour and thus discharge time of the mixed traffic platoon, implying that using solely number of scooters and number of passenger cars may not accurately reflect the discharging time. Variations in discharge time and discharge capacity are introduced due to different queue pattern of mixed vehicles, and they could be important for the design of effective traffic signal control.

The research on discharge under mixed-traffic condition is important. As the growing traffic in the urban area. It is expected that a more accurate and effective method of solving the mixed-traffic problem can be proposed and applied to the real-world implications.

1.2 Objectives

The aim of this study is to investigate the discharge behaviour of straight through vehicles under the mixed-flow traffic condition with passenger cars and scooters at signalised intersections. The analysis is based on detailed microscopic vehicle trajectory data extracted from videos collected from drone, which provides a wider view of the study area and the occlusion of vehicles in images is avoided. A model is proposed for the estimation of queue discharge time, in which the patterns of stopped vehicles in the queue is an important feature of the mixed-flow traffic. An accurate estimation of discharge time can provide implications and be used for better design of traffic signal control with progression under Taiwan's mixed traffic condition. It is expected that the results of the model can have a better prediction on the discharge time and be able to capture the essence of the chaotic mixed-traffic condition.

To attain this goal, there are several objectives needed to be done in the following:

1. To depict the discharge behaviour and the influence of the stopping queue patterns on discharging time of stopped queues with mixed traffic.
2. To propose a discharge time estimation model considering the patterns of the queue with mixed vehicles.
3. To evaluate the performance of the proposed model by comparing with the models proposed in previous studies.

1.3 Thesis Organization

The thesis structure is organised as follows. Chapter 1 depicts the background of discharge time estimation and the objectives of this thesis. Chapter 2 provides literature review on the discharge characteristics for homogeneous traffic and mixed traffic flow. Chapter 3 describes the methodology of this research, including the model formulation for the queue pattern. Chapter 4 describes the data collection process for microscopic traffic trajectory data and the characteristics of traffic data. Chapter 5 presents model calibration and validation as well as the model comparison. Finally, the results are concluded and the recommendation for future studies are given in Chapter 6.

The steps and flow of this study is shown in Figure 1.3.1 below.

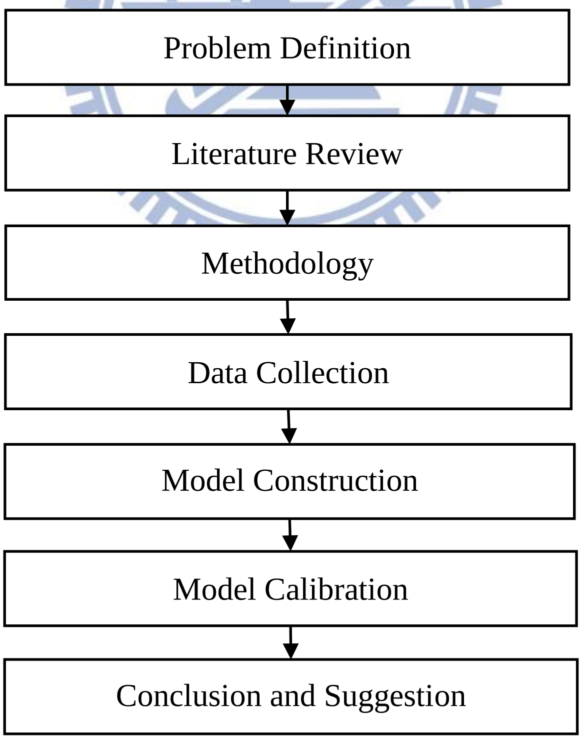


Figure 1.3.1 Flow chart of this study

Chapter 2 Literature Review

Discharge is defined as the action of the vehicle leaving the queue. According to the Institute of Transportation (2011) in Taiwan, discharge is the process of vehicles leaving the queue and entering the junction as the green onset. This study defined the process of discharge as, when a traffic signal turns green; the vehicle starts up from its queue position and passes through the stop line entering the junction.

There are several terms related to discharge such as discharge time, discharge rate, and discharge headway. They are slightly different but necessary when studying the capacity of the intersections. Discharge time is the time it takes for a vehicle to finish this process; discharge rate is the reciprocal of discharge time, meaning the numbers of vehicle discharged per time-unit; discharge headway is the time difference of discharge time between the sequence vehicles.

Previous studies indicated that most research focused on the discharge of homogeneous traffic flow, but great effort has been devoted to the study of mixed-traffic flow as the situation in the developing countries in recent years, different from those countries, which have fewer scooters. The estimation of the discharge time will further influence the estimation of the intersection capacity, providing a critical reference on designing the signal for the junction. In this chapter, it will first review the queue formation process to introduce the origin of the queue. Secondly, introduce the characteristics of discharge. Then, the mixed flow discharge time estimation of the highway capacity manual from Taiwan and some literature related to the estimation of discharge time under homogeneous and mixed-traffic flow. Finally, an extra section to review a mathematical tool of entropy, which is widely used in the academia to discuss the disorder and chaos condition of a system.

2.1 Queue Formation Process

The queue formation under mixed-traffic condition is more complicated than the homogeneous traffic flow. In general, the production of a queue is due to the situation of the traffic flow encountered a bottleneck. The decline of the flow movement formed a queue. Ramezani and Benekohal (2011) analysed and discussed the base queue formation and dissipation on the highway. On the other hand, in urban arterial, Lee and Wong (2016) described the formation of the mixed-traffic queuing vehicle in Taiwan by simulating the queue formulation process of scooter under mixed-traffic flow with the BikeSim simulator. The scooter usually squeezed through the gaps between vehicles and tried to move to the front of the queue, while passenger cars queued up within the lane markings. Figure 2.1.1 depicts the stopping positions and the distribution of scooters and passenger cars at an intersection based on empirical data, in which scooters are represented by the smaller boxes while passenger cars are represented by the larger ones. It shows that the distribution of the queuing vehicles under mixed-traffic flow could be complicated.

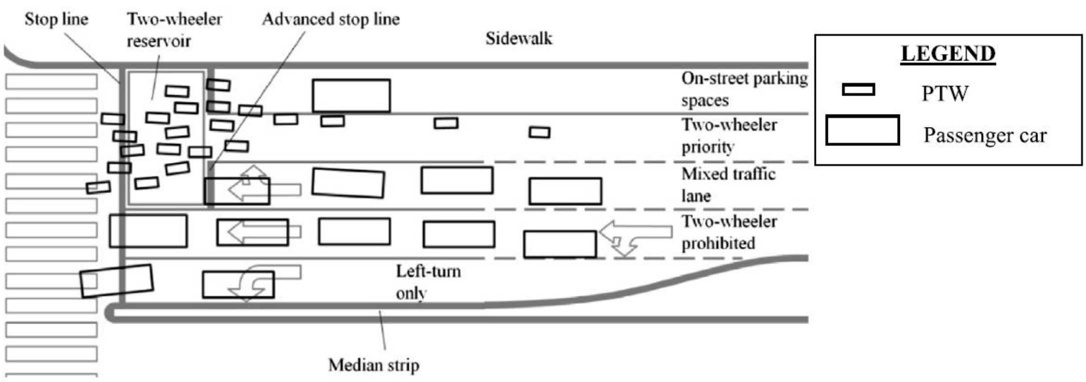


Figure 2.1.1 Formation of queues at an intersection (source: Lee and Wong, 2016)

2.2 Discharge Characteristics for Homogeneous Traffic Flow

According to the U.S. Highway Capacity Manual (Transportation Research Board 2000), the discharge can be divided into 3 stages. At the beginning, when the red time is about to end and turn into green, the queuing vehicle will start to move and pass the stop line. In this stage, due to the late reaction of the driver to the signal, the vehicle will start to pass the stopline slowly. After the 4th or 5th passenger cars had entered the intersection, the discharge rate will reach a steady state, which is also known as saturation flow rate. When the queue is all clear, the discharge rate will decline. As the green time is over, the vehicles will choose to stop, then another queue will form up. Figure 2.2.1 showed the changing process of the discharge rate.

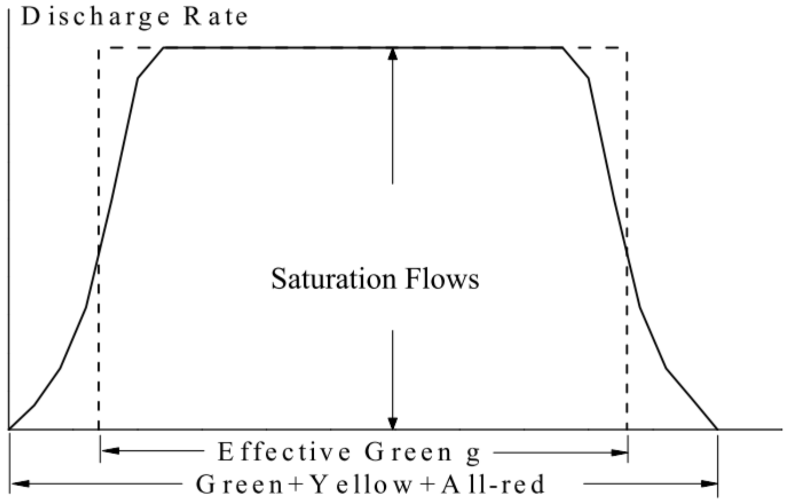


Figure 2.2.1 The change of the discharge rate (source: Lin and Tseng, 2005)

The literature on capacity and level-of-service analysis of signalised intersections shows a variety of approaches and methodologies based on the concept of saturation flow. They assumed that after the green onset, the discharge rate soon would reach a steady state. However, it has been found out that the observed queue discharge behaviour is often contradicted to the original estimation used in U.S. Highway

Capacity Manual (Transportation Research Board 2000). Therefore, continuing using the traditional model will have severely bias on the implications. Lin and Tseng (2005), Lin and Thomas (2005) used field data collected in Taiwan and the United States to analyse the discrepancies between the observed queue discharge behaviours and the saturation flow model as well as discussing the implications of the continuing use of saturation flow for capacity estimation. It is demonstrated that the discharge rate in Taiwan and United States kept rising after the green onset (as shown in Figure 2.2.2 and Figure 2.2.3). It is contradicting to the traditional saturation flow model. The errors in the estimated delays will, in turn, lead to poor decisions in the planning. A better alternative is to estimate the number of queuing vehicles in each signal phase. The IOT in Taiwan employed this approach to revise Taiwan Area Highway Capacity Manual.

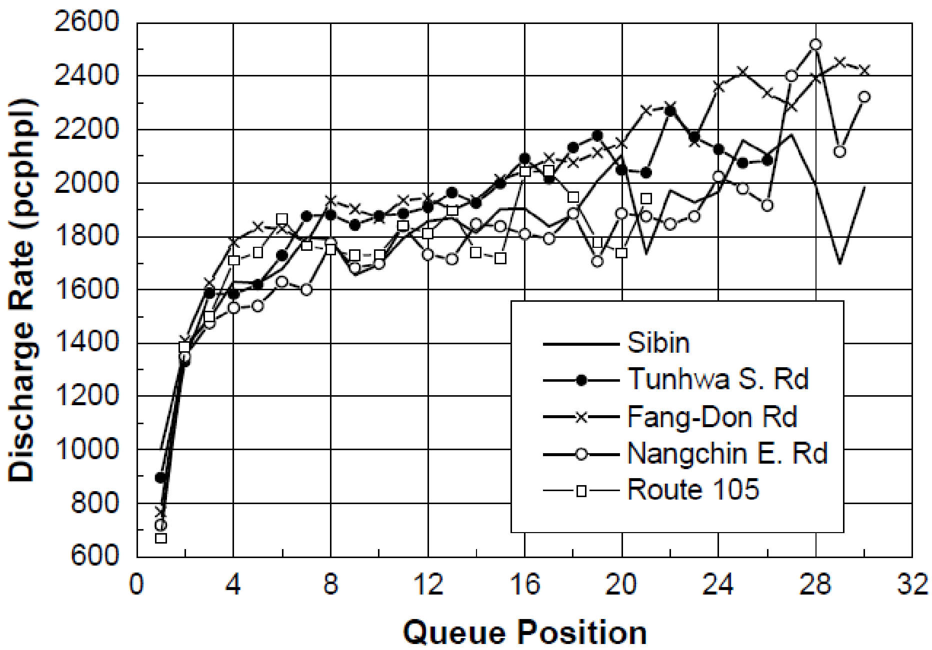
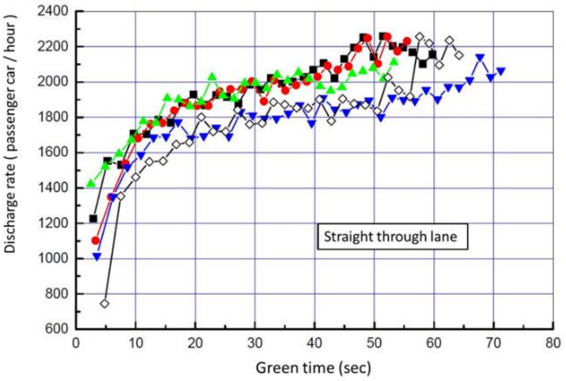
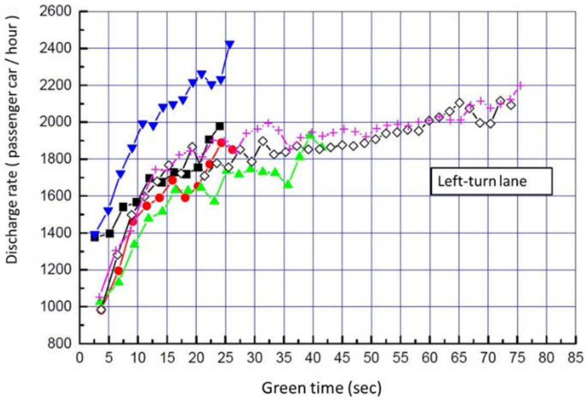


Figure 2.2.2 Discharge characteristics of passenger car at intersection selected from Taiwan (source: Lin and Thomas, 2005)



(a) Discharge characteristics of the passenger cars in straight through lane



(b) Discharge characteristics of the passenger cars in left-turn lane

Figure 2.2.3 Discharge characteristics of passenger cars (source: Taiwan’s HCM, 2011)

The discharge characteristics of the scooter vary from the passenger cars and behave differently under different traffic environment. For example, under scooter exclusive lane, the discharge rate will reach a stable condition after green onset 8 to 10 seconds (Chang, Tseng and Cheng, 2007). The discharge characteristics is shown in Figure 2.2.4. For the scooter traffic flow with a 3 metres lane width, there exists a saturation flow and the scooter flow will be stable after 12 seconds (Tang, 1999). However, if the flow is not large enough, the discharge rate may not be able to reach a stable condition.

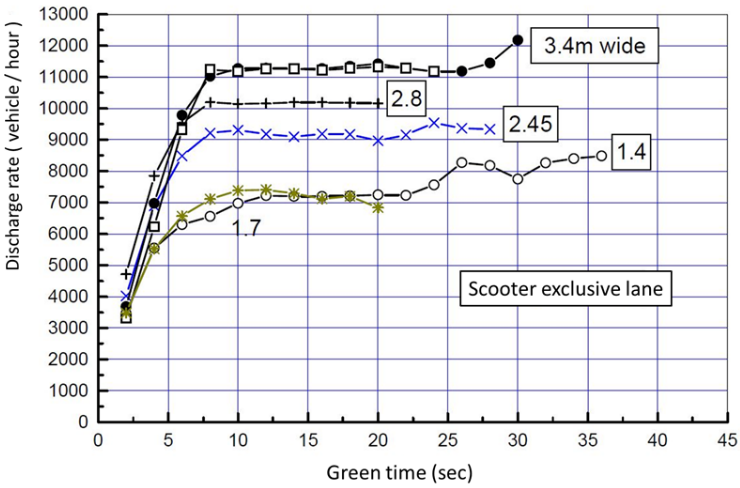


Figure 2.2.4 Discharge characteristics of scooter exclusive lane (source: Taiwan’s HCM, 2011)

Besides the geometry layout or the type of the lane, the slope of the divided urban lane also affects the discharge process. Tseng et al. (2015) collected 7 different locations field data and tried to calibrate the slope adjustment factor used in the saturation flow estimation model. It shows that the impact of the slope on the discharge process is severe than the estimation from the U.S. HCM. The discharge rate became steady as the green time increased.

Other than using the traditional way of estimating the saturation flow rate, Akçelik and Besley (2002) proposed the exponential function to estimate the relevant discharge parameters. The model can estimate the parameter based on the time and the extreme value of discharge rate, queue discharge, and discharge headway, giving the estimation of the intersection capacity more flexible to be adapted to the signal control.

The estimation of the saturation flow rate often been used in designing the signal phases. However, the estimation from the saturation flow rate often contradict to the phenomenon of the rising discharge rate. Chang, Tseng, and Lin (2007) analyse the cause of the bias on the estimation and the discovered a method to adjust the existing model on estimating the suitable cycle by calculating the V/S ratio of the field data and the increase ratio of the discharge vehicles.

Traditional research on discharge characteristics mainly focused on the passenger cars or scooters only. The interaction between passenger cars is much simple than considering the interaction between different modes. They discussed the differences of discharge time under various types of geometry condition and the setting of the signal control. In some of the study, they even dig into the microscopic approach by observing the interaction between each vehicle.

Lin, Tseng, and Su (2004) discovered that the steady saturation flow may not easy to observe and there existed different discharge condition in the same intersection but with different lane. For example, the vehicle under left-turn and straight-through lane have totally different of discharge rate. Tseng, Chang, and Chen (2006) discussed the queue discharge characteristics of the unopposed left turns. They only considered passenger cars as their object and discovered that the discharge rate did not reach a steady state after 6 vehicles had passed. The average discharge headway after the 4^{th} passenger car has significant correlation with the left turn speed and the longer length of the left turn area. To achieve a better estimation of the capacity of a lane, they did not use the saturation flow but the number of passenger car discharged each cycle. Within this relationship, they added on the green time and the longer length of the left turn area to estimate the number of passenger car discharged each cycle. The model was quite convenient and practical for the user to get a quick estimation of the number discharged each cycle.

Wu (2007) and Hsu (2007) also focused on the unopposed left-turn vehicles and straight through vehicles separately with a microscopic approach to construct the model of discharge headway between each vehicle, in ordered. The effect of different headway was also taken into account. They divided the microscopic discharge model into 2 parts. One is the unstable traffic flow, which is also the initial discharge of the queuing vehicles. To analyse the discharge behaviour more precisely, they constructed the discharge model to the specific ordered of cars. Another is the stable traffic flow. Stable traffic flow is the steady state after several vehicles had entered the intersection; the discharge rate will gradually converge to a specific value.

Under the condition of unopposed left-turn, some vehicle may try to enter the intersection to turn early illegally. Wu (2007) also considered this event into his model to compare the difference between legally and illegally entering the intersection. The study revealed that if the vehicle tries to enter the intersection earlier and illegally leaves the queue had significant difference to the one without such condition. The behaviour of the former vehicle that has illegally entered the intersection also has an impact on the following vehicles. As the stopping headway between 2 vehicles gets longer, their discharge headway grows longer.

Hsu (2007) separately discussed the situation of whether there existed a scooter waiting zone of the straight through vehicle lane. She considered those different types of vehicles, stopping headway, the behaviour of start-up earlier and the impact of scooter's density to formulate the model of the lane with a scooter waiting zone. However, in the condition without the scooter waiting zone, the effect of start-up earlier is different in the second vehicles.

To sum up, there are studies that emphasis on the discharge of homogenous traffic flow. They tend to categorise the traffic environment or decompose the car queue into several units such as the headway between vehicles or a specified component to discuss the discharge time. The results of the constructed model are very delicate but the required data input is often too detail, which is complicated and is less practical when it comes to implications. The literature reviews of homogeneous traffic characteristics are summarised in Table 2.2.1.

Table 2.2.1 Literature summary for discharge characteristics under homogeneous traffic condition

Author	Year	Traffic type	Model	Variables	Data amount	Results
Lin, Tseng, & Su	2004	homogeneous	saturation flow rate	● Number of cycles, ● Expected number of discharged vehicles	8 sites	Improved accuracy of capacity estimation
Tseng, Chang, & Chen	2006	homogeneous	discharge number of vehicles under left-turn	● Green time, ● The longer length of the left turn area.	15 intersections, 1512 cycles	Applied to attain the estimated discharge number of vehicles
Wu	2007	homogeneous	discharge headway under left turn	● Legally enter the junction, ● Illegally enter the junction, ● Headway combination, ● Related distance parameters.	2 intersections, 998 vehicles	Construct the ordered vehicle discharge headway model and proved the difference between estimation and actual value is insignificant.
Hsu	2007	homogeneous	discharge headway	● Legally enter the junction, ● Illegally enter the junction, ● Headway combination, ● Scooter density in the scooter waiting zone, ● Related distance parameters.	2 intersections, 2330 vehicles	Construct the ordered vehicle discharge headway model with R^2 from 0.5 to 0.8

2.3 Discharge Characteristics for Mixed-traffic Flow

2.3.1 Discharge Capacity in Taiwan's Highway Capacity Manual

The present study on estimating the discharge time under mixed-traffic condition in Taiwan can be found in Taiwan's Highway Capacity Manual (2011). In section 13.5.4, it described the method of how to estimate the lane capacity under mixed-traffic condition (as shown in the following formula).

$$\mathrm{c} = \frac{3600}{C}\sum_{i=1}^{n}(M + N_g)_i f_g f_b f_S f_P$$

c	:	lane capacity of right turn / through movement under mixed traffic (vehicles/hours)
C	:	cycle length (seconds)
n	:	number of the phase
M	:	number of the scooters in the scooter waiting zone
N_g	:	number of the discharged vehicles in the residual green time
f_g	:	gradient adjustment factor
f_b	:	bus stop adjustment factor
f_S	:	roadside parking adjustment factor
f_P	:	pedestrian conflict adjustment factor

Inside the formulation of the capacity, the number of the scooter stopping in the scooter waiting zone could be estimated by the area of the waiting zone and the ratio of the area occupied by the scooters. For Ng, its value is estimated by a 3 layer ANN model (as the following formula) with nine variables as shown in Table 2.3.1, considering the residual green time, the combinations of the turning ratio with different traffic mode, and lane width. The calibrated variables required several field data, which is considered more complicated to measure when the traffic flow is massive.

$$N_g = \frac{140}{1 + e^{-Y}}$$

$$Y = -\frac{2.4821}{1 + e^{-S_1}} - \frac{1.7453}{1 + e^{-S_2}} - \frac{8.000}{1 + e^{-S_3}} + \frac{10.848}{1 + e^{-S_4}} - 8.0618$$

$$S_i = \left[\sum_{j=1}^{8} A_{ij} X_j\right] + A_{i9} \qquad \text{i} = 1,2,3,4$$

Table 2.3.1 Affecting factors of number of the discharged vehicles in the residual green time

Affecting factors		Observations	
Variable	Definitions	Range	Mean value
X_1	Residual green time after the discharge of the last scooter in the scooter waiting zone (divided by 200)	Residual green time: 9.9~80.1 X_1= 0.05~0.40	--
X_2	Ratio of the straight through small vehicle	0.016~0.459	0.099
X_3	Ratio of the right-turn small vehicle	0.014~0.365	0.112
X_4	Ratio of the straight through scooter not side by side with heavy or small vehicle	0.131~0.805	0.571
X_5	Ratio of the right-turn scooter not side by side with heavy or small vehicle	0.000~0.204	0.057
X_6	Ratio of the straight through heavy vehicle	0.000~0.076	0.017
X_7	Ratio of the right-turn heavy vehicle	0.000~0.152	0.017
X_8	Lane width (metre) divided by 10	Lane width: 3.5~5.2 X_8=0.35~0.52	--
X_9	Ratio of the scooter side by side with the heavy or small vehicle	0.026~0.229	0.126

On the other hand, the situation of the traffic flow that only consists of scooters can applied with the estimation method on scooter exclusive lane. The lane capacity estimation of general condition happened under mixed-traffic condition can be solved.

2.3.2 Discharge Characteristics and Factors

Different from the United States and Europe, mixed-traffic flow is more common in developing countries in Asia. It is the features of convenient and cheaper price that lead to the growing demand of using such mode. In these countries, the proportion of the scooters are high and the composition of vehicles made the traffic condition more complicated which is the reason why there is more study focus on the mixed-traffic and heterogeneous traffic flow.

In Taiwan, in order to solve the problem of the high volume traffic, the ministry of transportation set up a waiting zone at the front of the lane for scooter exclusively. Its function is to separate the scooter from passenger cars. The scooter at the front of the lane can speed up and leave the queue without affecting upstream discharge. Chang, Lin, and Tseng (2008) used the data collected from Taipei to study the discharge characteristics of straight-through/right-turn lanes with two-stage left-turn zone and waiting zone. They found out that the number of scooters in the two-stage left-turn waiting zone per meters has a significant linear relationship with discharge time. However, the distance from waiting zone to the upstream still have some spaces; it will cause no effect on the upstream discharge condition. Compared with the left-turn waiting zone, the waiting zone has less demand. In some situation, scooters may not be able to cover the entire waiting zone. The discharge characteristics are also like the left-turn waiting zone. They analysed the discharge characteristics of the upstream and used the artificial neural network (ANN) to estimate the discharge numbers of vehicles in the residual green time. Furthermore, to estimate the capacity. P, Varghese, and R (2016) also used the ANN method by considering approach width, effective green time, degree of saturation, arrival rate and so on to determine delay at signalised intersections under mixed-traffic condition.

To solve this issue, many researchers have proposed various methods to depict the mixed-traffic conditions. Instead of using the ANN method, Lan and Chang (2015) tried to model and validate the propagation of the mixed-traffic between urban intersections. They validated some of the base properties of the mixed traffic flow including the discharge process, lane choice and travel time estimation etc. Nevertheless, there is no further discussion and validation on the interaction of the queuing vehicles.

Another way to estimate the intersection capacity is by PCU. The previous study revealed that the motorbikes crossing the stop line in the first 6s of effective green time had a pcu value of 0 and those crossing the stop line later in the cycle had a PCU value that varied from 0.53 to 0.65. Powell (2000) used the amended first-order macroscopic approach to represent the scooter behaviour. The study focuses on predicting the QFLIER, which means the number of scooters discharged in the first 6 seconds of the effective green time. First, find out at when the motorbikes are likely to be the QFLIER by the time-distance diagram. Second, take into account the possibility of the later in motorbikes of becoming a QFLIER. Last, consider the lane width, number of lanes and the number of vehicles per cycle into the model to get the final output. The model was tested with the data from Malaysia, Thailand where the scooters proportions are high. The model could be used to assess signal timings at new or modified isolated intersections. Instead of using the PCU, Nguyen (2016) introduced a method of using the Motorcycle Unit (MCU) to propose saturation flow model estimating an value on the approach to an intersection.

Minh and Sano (2003) investigated and analysed the effects of scooters at the signalised intersection. The study indicated that the scooters effects strongly in saturation flow. The increase number of scooter or the ratio of scooter will raise the saturation flow as well. In addition, the degree of the scooter impeding the passenger car is examined and constructed as a model. The number of the scooter will affect the headway of the passenger cars. Similar research had been conducted in Ghana by Adams, Zambang, and Opoku-Boahen (2015); the average headway doesn't only depend on the number of scooters in the flow but the performance and the relative position between the vehicles.

Some of the research tried to decompose and inspect the arrangement of the queuing vehicles. It is confirmed that the relative position of the vehicles does affect the discharge time. Nakatsuji, Hai, Taweesilp, and Tanaboriboon (2001) quantified the impacts of scooters by classifying the relative position of the scooter into 5 patterns as shown in Figure 2.3.1.

- Pattern 1: No scooter is in front of or alongside a passenger car (P-1).
- Pattern 2: Scooter is alongside the following car, on either left or right side (P-2).
- Pattern 3: Scooter is between 2 passenger cars although not directly in front of the follower (P-3).
- Pattern 4: 2 or more scooters are alongside passenger cars but not directly in front of the follower (P-4).
- Pattern 5: Scooter is situated between 2 passenger cars, just in front of the follower (P-5).

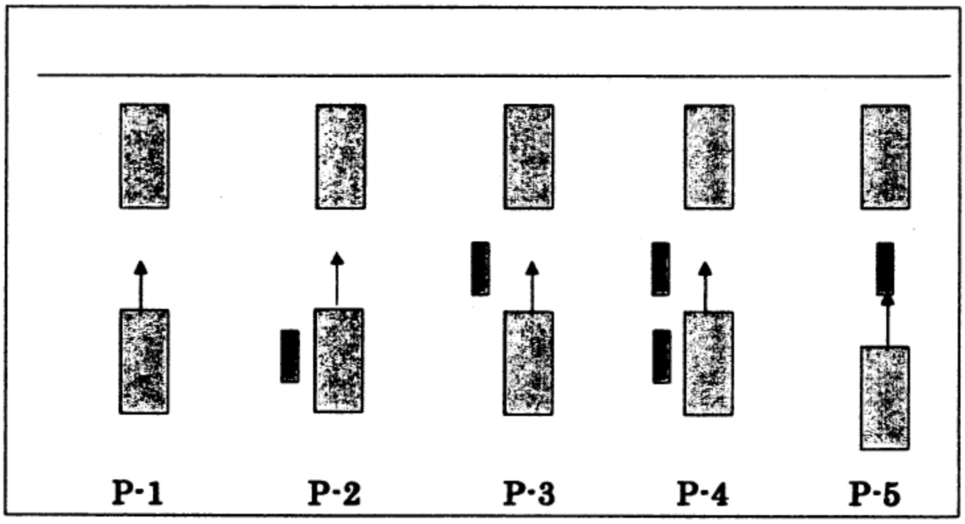


Figure 2.3.1 Relative Position of scooters to Passenger Cars for saturated headway analysis (source: Nakatsuji, Hai, Taweesilp, and Tanaboriboon, 2001)

It revealed the fact that the relative position between passenger cars and scooters has a crucial effect on saturation flow. The impact of the pattern had on the headway is P5 > P4 > P3 > P2 > P1. The scooter has more influence on the passenger car as they are in front of the car rather than alongside the cars. A key limitation of this research is that the model cannot fully represent the headway characteristics and lack of aggregating the pattern together to form a proper model.

On the other hand, Chang (2004) separated the queue into 3 parts: scooters, mixed queue and car queue combination to study the scooters queue impact on the capacity. He found out that under the same amount of scooters, the density of scooter queue has no impact on the discharge time. To estimate the capacity of mixed traffic flow lane, he focused on estimating the discharged number of vehicles. Under the same amount of scooters but different queuing patterns, the capacity of lanes varies due to the discharge time of increase one row of queuing scooters, the average headway of cars under the intervention from the scooter stopped at the roadside and the average headway of cars without intervention.

By estimating the discharge time directly, Huang (2015) separated the queue pattern into seven models to estimate the discharge time of each part. He discovered that the length of the mixed flow and scooters' occupancy ratio has an impact on the discharge time. The length of the mixed flow had significant correlation to the discharge time. To improve the discharge condition of the intersection, he suggested to decrease the growth of the mixed flow queue.

Most studies focused on scooter's behaviour discussing the car following and lane changing model with the microscopic approach. Less research studied discharge at the intersection with the microscopic approach. Cheng (2014) tried to build a safety space based microscopic discharge model. Safety space was defined as the minimum distance to the affecting vehicles accepted by the moving scooters. He used the acceleration, aggressive degree, interaction between vehicles to construct the scooter's discharge time model. Then simulate the process of how scooters discharge at the intersections. The simulation consists two parts. First, calculate the acceleration and the rejected acceleration caused by the surrounding vehicles. Second, scooters will try to avoid collision, so the calculation of emergency acceleration is necessary, in addition, the safety acceleration under normal condition. Last, choose the proper acceleration value to use. The model he built was for straight discharge only.

The project: Development of mixed-flow simulation technology-behaviour of motorcycles (Wong et al, 2015) from the Ministry of Transportation and Communications focused on analysing the behaviour of motorcycles. They used the aerial photography to collect the data and tried to model the act of motorcycles. There were several research including lane choice model, reaction to bus model, intersection position choice model, and the discharge time model. This research originated from the part of this project. The discharge time model in the project separated the mixed-flow queue into 3 segments to construct the model.

Some research focused on the characteristics of the lack of lane discipline to analyse the behaviour of the mixed-traffic flow. Spyropoulou and Sermpis (2009) introduced a notional lane to describe the space between marked lanes that is used by the scooters. They found out that the scooters would ride on the marked and notional lane just to travel in an efficient way. They also found out that the way passenger car move was depended on the movement of the scooters next to them. Last, the observed saturation flow at the intersections was lower than the values calculated from the well-established method.

The most complicated mixed-traffic flow can be observed in India. Dey, Nandal, and Kalyan (2013) discussed the base discharge condition and parameters in India. They found out that the clearing speed of vehicles do not differ significantly by category of vehicle. Radhakrishnan and Ramadurai (2015) examined the factors affecting the discharge headway under heterogeneous traffic flow condition that is characterised by mixed vehicle composition and the lack of lane discipline. However, the variables used in this literature were only suitable for India since they had more than 3 types of vehicle driving on the artery. The study also considered the effect of vehicle types, lateral position on the roadway, and the green time. All these factors were found to be significant. Patel, Dhamaniya, and Katti (2015) proposed the dynamic PCU based on the speed and the projected area of the vehicle and compare the value with the past research. Chand, Gupta, and Velmurugan (2017) constructed the model based on dynamic PCU. They further examined the dynamic PCU under different vehicle classes.

Past research tried to construct model to capture the discharge characteristics under the mixed-traffic condition, however, the effectiveness is limited. Some of the studies only considered the scooters alone, which neglected the impact between different modes. Some of the studies used the method of calibrating new values of PCU to update the data input for the estimation of junction capacity but ignored the variation of the PCU under different location and condition. However, some of the study light up the path by decomposing the stopping queue, which shows the initial progress on the mixed-traffic discharge time estimation; the condition included in the study is mostly focused on the longitudinal position and arrangement of the vehicles, lack of a systematic way to describe and analyse the order less state of the mixed-traffic condition. This research will try to capture the order less state by exploring the stopping queue pattern. The literature reviews of mixed-traffic flow are summarised in Table 2.3.2. Table 2.3.3 is the literatures of mixed traffic categorised by the type of variable

Table 2.3.2 Literature summary for discharge characteristics under mixed-traffic condition

Author	Year	Traffic type	Model	Variables	Data amount	Results
Chang, Lin, and Tseng	2008	mixed-traffic	No. of discharge vehicle under residual green time	● Ratio of turning ratio and vehicle combination, ● Lane width, ● Residual green time.	9 intersections, 370 cycles	Using ANN method to estimate the discharge numbers of vehicles in the residual green time with RMSE of 1.09 to 1.38 veh.
Lan and Chang	2015	mixed-traffic	arterial signal progression model	● Occupied spaces for cars and scooters, ● Discharge rates for cars and scooters in non-mixed traffic condition	2 consecutive intersections	using field data to calibrate the model and offer insight to the mixed traffic flow
Powell	2000	mixed-traffic	QFLIERS	● Average lane width, ● No. of lanes, ● No. of cars, ● No. of vans, ● No. of QFLIERS from first order macroscopic model	10 links, 546 cycles	Using amended first order macroscopic approach. All the variables are significant, $R^2$is 0.87
Minh and Sano	2003	mixed-traffic	saturation flow rate and start up loss time	● Lane width, ● No. of scooters, ● Vehicle PCU	7 intersections	influence of scooters on the saturation flow rate is observed, R^2=0.79
Adams, Zambang, & Opoku-Boahen	2015	mixed-traffic	saturation flow rate	● Vehicle PCU, ● Vehicle headway, ● Scooters percentage	3 intersections, 267 vehicles	Greater % of scooters at the intersection, less average headway. R^2=0.58

Author	Year	Traffic type	Model	Variables	Data amount	Results
Nakatsuji, Hai, Taweesilp, & Tanaboriboon	2001	mixed-traffic	saturated headway and start up loss time	● Vehicle pattern, ● Vehicle headway	2 intersections, 2504 vehicles	all the variables are significant, R^2 is around 0.46 to 0.82
Chang	2004	mixed-traffic	discharge No. of vehicles in effective green time	● No. of rows of the scooter queue, ● No. of cars affected by scooters, ● Green time, ● Lane width, ● Related discharge time	3 intersections, 297 cycles	estimate the discharge numbers of vehicles in the residual green time
Huang	2015	mixed-traffic	discharge time	● No. of the vehicles (cars, scooters), ● Queue length of vehicles (cars, scooters)	1 intersection, 72 cycles	construct 7 models and the R^2 is around 0.79~0.90
Cheng	2014	mixed-traffic	discharge rate and speed (simulation)	● Vehicle position, ● Safety threshold, ● Aggressiveness factors, ● Speed, ● Acceleration	1 intersection, 6 cycles	Simulation model with a MAPE of 5%, RMSE of 1.03 veh.
MOTC	2015	mixed-traffic	discharge time	● No. of the vehicles (cars, scooters), ● Queue length of vehicles (cars, scooters), ● Lane width	5 intersections, 166 cycles	construct 7 models and the R^2 is around 0.84~0.92

Author	Year	Traffic type	Model	Variables	Data amount	Results
Spyropoulou and Sermpis	2009	mixed-traffic	saturation flow rate and start up loss time	● Marked and notional lane, ● Vehicle's PCU	1 intersection, 10 hours	The proportion and the number of scooters influence the start lag of passenger cars
Radhakrishnan and Ramadurai	2015	mixed-traffic	discharge headway	● Vehicle types, ● Vehicle lateral position (median, nearkerb)	3 intersections, 15787 vehicles	all the variables are significant, R^2 is around 0.2 to 0.38
Nguyen	2016	mixed-traffic	saturation flow rate	● Vehicle types, ● Turning movement, ● Lane width	11 intersections	Construct pure scooter flow and define the motorcycle unit. Set up the standard to calculate the value.
P, Varghese, & R	2016	mixed-traffic	Field Delay Adjustment Term	● Cycle time, ● Effective green time, ● Flow, ● Degree of saturation flow, ● Turning movement	11 intersections, 16 approaches,	construct and adjust the ANN model, compared the delay estimation with past study
Patel, Dhamaniya, and Katti	2015	mixed-traffic	discharge rate and dynamic saturation flow	● Width of the approach, ● Share% of the scooters, ● Ratio of the arrival rate % to width of approach	4 intersections, 40 cycles	decide the dynamic PCU and derived 2 approaches to estimate the saturation flow
Chand, Gupta, and Velmurugan	2017	mixed-traffic	saturation flow rate	● The speed ratio and space ratio of the passenger car to the target vehicle	4 intersections, 280 cycles	Develop dynamic PCU. Compare the saturation flow estimation with previous study

Table 2.3.3 discharge characteristics related literatures categorised by variable types

Author	Year	Variable types				
		No. of vehicles	PCU	Lane width	Queue pattern	Queue length
Chang, Lin, and Tseng	2008	✓		✓		
Lan and Chang	2015	✓				✓
Powell	1997	✓	✓	✓		
Minh and Sano	2003	✓	✓	✓		
Adams, Zambang, & Opoku-Boahen	2015	✓	✓			
Nakatsuji, Hai, Taweesilp, & Tanaboriboon	2001		✓		✓	✓
Chang	2004	✓		✓	✓	✓
Huang	2015	✓			✓	✓
Cheng	2014					
MOTC	2015	✓		✓	✓	✓
Spyropoulou and Sermpis	2009		✓			
Radhakrishnan and Ramadurai	2015					
Nguyen	2016		✓	✓		
P, Varghese, & R	2016	✓				
Patel, Dhamaniya, and Katti	2015	✓	✓	✓*		
Chand, Gupta, and Velmurugan	2017	✓	✓	✓*		

* the width is based on the approach width, not lane.

2.4 Entropy used in Traffic Problem

The aim of this study is to design the parameter to describe the relative position of vehicles and their complex environment. To measure the chaos degree of the queue, entropy was a critical tool. Entropy was first introduced to the field of physics, to measure the change of the heat. It was applied to several fields of science, such as biodiversity in the biology, thermo-economics, information theory, and so on. In transportation, it had been applied to many measures. Chang and Lee (2007) used the entropy to measure the variety of the driving action taken by the driver. There are 500 combinations of the driving action in total. The more frequent happened on specific type or action, the lower the entropy is. Chiou and Hsieh (2012) used entropy to adjust the PCE value under the Cell Transmission Model of the mixed-traffic flow; they tried to describe the competition of the different mode on space and time. The entropy here is the proportion of the mixed traffic flow, which is a reference to the dynamic composition and arrangement of the vehicle types. The more simple the traffic composition is the lower entropy value is.

This study adopted the concept of entropy in the theory of information science to measure the complexity of the queue before the green onset. Entropy in the information science was denoted as the total amount of surprise brought about by every unexpected event. The equation below is one of the calculation method of entropy under a discrete set of probabilities P_1 to P_n.

$$\mathrm{H} = -\sum P_i \log P_i$$

The value of H is between 0 and 1. It’s a probability function which can represent the chaos of a system.

The topic of discharge time has been studied for many years. In the homogeneous traffic flow, past research discussed the discharge headway and discharge rate under different geological design and tried to construct the model considering the traditional characteristics of discharge rate. In the mixed-traffic flow, studies had shown that the area of the waiting zone has effect on discharge time. Many research tried to build the model by considering the proportion of scooters, the length of queue or the interaction between each vehicle. However, most studies discussed the discharge behaviour of pure traffic flow and mix traffic flow including the movement during discharge. There were few studies focused on the discharge of the mixed-traffic flow with the queuing pattern. This research wants to study the discharge behaviour and the discharge time of mixed traffic flow considering the stopping pattern.

Chapter 3 Methodology

To capture the discharge characteristics of the mixed-traffic flow, Wong et al (2015) separated the stopping queue into 3 parts: (1) scooters in front of passenger cars; (2) scooters are alongside the passenger cars (on either right or left side); and (3) no scooters stop alongside the passenger cars. The discharge time estimation model on mixed-traffic flow was built under this framework. However, in the real world, it is not easy for people to collect these information directly. Based on directly observing the fact of the traffic flow in the urban area, this study tries to simplify the model by introducing an aggregate index presenting the chaotic condition of the relative position between scooters and passenger cars, which improve the original model structure.

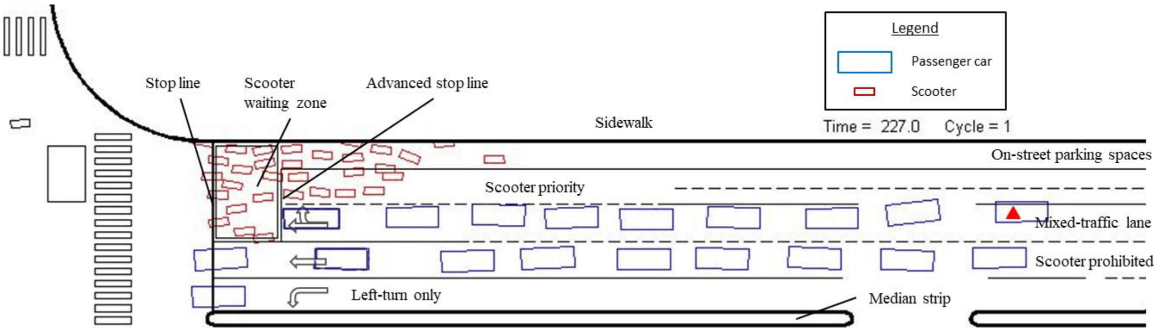
Measuring the complex traffic environment is an important issue for mixed-traffic flow. In this chapter, this research will first introduce the problem description. Second, the core of this research: the queuing pattern entropy and the behaviour of vehicles. Finally, the construction of the mixed-traffic flow discharge model. The variables used in the model and the calculation standard of the variables.

3.1 Problem description

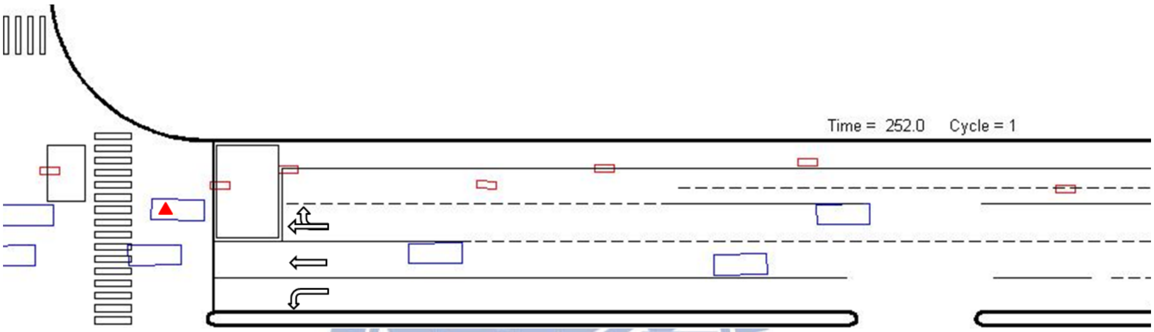
Discharge time is the essential information for the transportation designer or decision maker to modify the signal time steps. The accuracy of the discharge time estimation related to the efficiency of the intersections. The improvement to the estimation of discharge time on mixed-traffic flow was the aspect of what this study concerned.

The discharge time in this study is defined as the time during the whole queuing vehicles in a cycle to pass the stop line and enter into the intersections. The Figure 3.1.1

illustrates the discharge of the 3rd lane. It took 25 seconds (time from 227 seconds to 252 seconds) to discharge the whole queue (see the vehicle marked with a triangle).



(a) One second before the green onset(the last vehicle is marked with a triangle)



(b) The whole queue discharged(Marked vehicle passed the stop line)

Figure 3.1.1 Discharge time demonstration

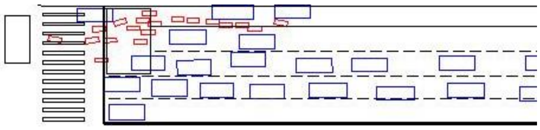
3.2 Model Formulation

Before constructing the discharge time estimation model, the affecting factors must be discussed. Taiwan's HCM (2011) described the related factors influencing discharge time in an intersection that includes the parameters of cycle length, signal planning, traffic composition, geometric patterns etc. Table 3.2.1 shows the affecting factors of discharge time categorised by Taiwan's HCM into signal control, traffic composition, road factors, and other factors. Nevertheless, in this research, traffic parameters obtaining from each videography data based on per lane in a cycle are considered except for factors of signal control and the number of lanes.

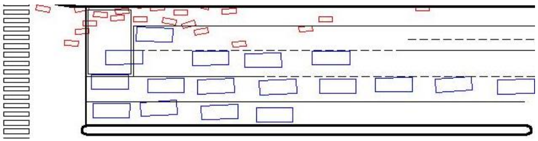
Table 3.2.1 Affecting factors of discharge time in Taiwan's HCM

Categories	**Factors**
Signal control	Signal plan, phase
Traffic composition	Vehicle type, turning ratio
Road factors	Number of lane, lane width, exclusive lane, gradient
Other factors	Driver behaviour, weather.

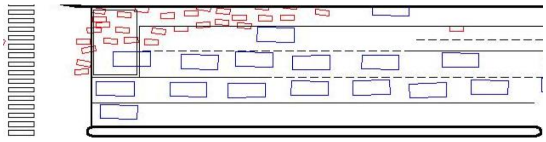
Previous studies tried to capture the characteristics of the mixed flow discharge. Some of them classified the relative position between scooters and passenger cars into several patterns. It seems to exist uncertain situation to distinguish whether the vehicle belongs to which pattern of the queue. Some of the queue arrangement extracted from the data is depicted in Figure 3.2.1. (a), (b), and (c) is the scenario of the scooter at the front and alongside the passenger car. The difference of the arrangement depends on the number of the scooters, the arrangement of the scooters, and the stopping point of the passenger cars. Passenger cars may invade the scooter waiting zone or not. (d) illustrated the condition of the scooters scattered in the passenger car queue. (e) and (f) depicted the situation of a large number of scooters near the passenger car. The position of the passenger cars (near the marker or in the middle of the lane) decides the arrangement of the scooters.



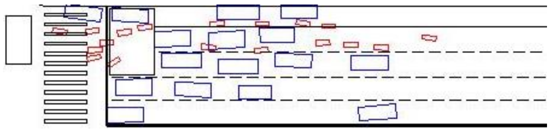
(a) Scooters are alongside and in front of passenger cars (case i)



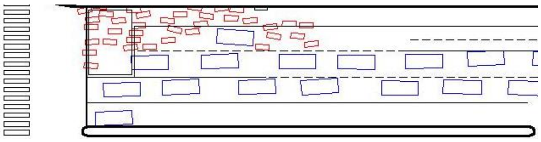
(b) Scooters are alongside and in front of passenger cars (case ii)



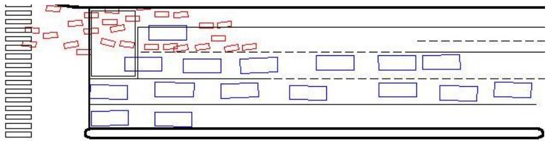
(c) Scooters are alongside and in front of passenger cars (case iii)



(d) Scooters are in between passenger cars.



(e) Scooters surround the passenger car



(f) Scooters fully surround the passenger car.

Figure 3.2.1 Different types of queue arrangement

The queuing arrangement can be viewed as the order less degree of a queue. As the queuing arrangement became more disorganised, the interaction between vehicles will become more complex, thus increase the discharge time. Besides the basic variables needed to be considered in the model, the queuing pattern index demonstrating in chapter 3.2.1 is designed for constructing discharge time estimation model.

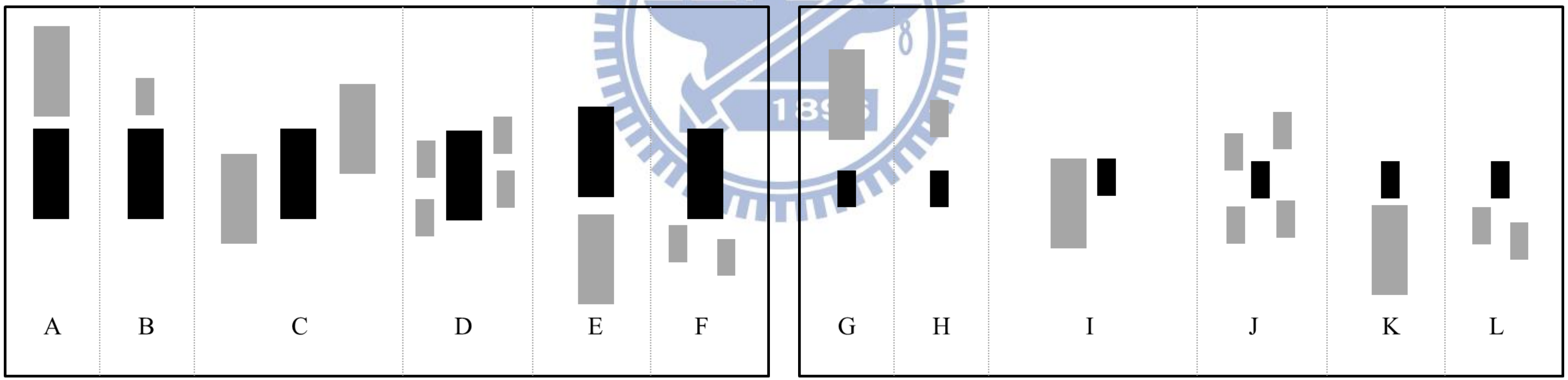
3.2.1 Queue pattern entropy

The relative condition of scooters and passenger cars is what the research concerned. Most research considered the attributes of the vehicle and the cause-effect of the surrounding environment, such as vehicle numbers, turning ratio, lane width, slope gradient, time steps etc. Few had discussion on the effect of the stopping queue patterns and the vehicle compositions. To find out what happened during the discharge process, the study tries to analyse the cause and effect happened during the discharge period through direct observation. The situation happened during the discharge process is shown in Table 3.2.2. All the cause and effect situation is based on the rule of first in first out (FIFO).

Table 3.2.2 The effect on different configuration of queuing vehicles (queue position)

Vehicle types / Direction	Passenger Cars		Scooters	
	Affecting factors	Results	Affecting factors	Results
Front	Passenger car (**situation A**)	● No significant impact. To avoid the deceleration after start up, cars usually start up after the front vehicle move on for a distance. ● Car following	Passenger car (**situation G**)	● Scooters are situated behind or between passenger cars. ● They will firstly follow up the front car, and then decide whether to overtake the front car or slowly follow up the front vehicle. ● In contrast to car following, scooters' overtaking action can shorten the discharge time.
	Scooter (**situation B**)	● Scooters' start-up speed is higher. ● Their influence on the following passenger cars depends not only on how many scooters stopped in front of leading car but also on how close the two motorised vehicles are.	Scooter (**situation H**)	● High density of scooters has the great impact on their forward motion. ● However, scooters with higher start-up speed have few influences on followers during queue discharge.
left/right side	Passenger car (**situation C**)	● Passenger cars move in a constrained space depending on lane-width. ● Turning proportion of intersection traffic demand will influence the passenger cars.	Passenger car (**situation I**)	● Scooters always get closer to the passenger cars with lower start-up speed during queue discharge in order to quickly pass through the signalised intersection. ● Therefore, distance between scooters and passenger cars has less impact on the rider.

	Scooter (**situation D**)	● Scooters are capable of zigzag manoeuvres due to its shapes and behaviours. ● Passenger cars considering the safety risks will start up slowly during the discharge period.	Scooter (**situation J**)	With higher start-up speed and zigzag manoeuvres, scooters always only pay attention to gap between front scooters or nearby riders’ forward action.
Back	Passenger car (**situation E**)	Vehicles probably ignore the action of another vehicle behind before the green onset.	Passenger car (**situation K**)	Vehicles probably ignore the action of another vehicle behind before the green onset.
	Scooter (**situation F**)		Scooter (**situation L**)	



(a) Discussing a passenger car (b) Discussing a scooter

Figure 3.2.2 the illustration drawing of different configuration of queuing vehicles (queue position)

As has been discussed, there are some main factors that affect the discharge in the mixed-traffic flow.

1. Start-up speed:

   The start-up speed of scooters and passenger cars are very different. Scooters are faster and relatively aggressive, their behaviour is the critical parts to disturb during queue discharge. Passenger cars are slower, they are always affected by these small motorised vehicles.

2. Queue arrangement:

   There exists different effect between each configuration (either in front of or on right/left side). Some traffic phenomenon can be observed that, under condition of same queue length and same speed of queuing vehicle, the discharge time is longer if the scooters queue up in order with passenger cars, instead of being alongside the passenger cars. This is the main factors that affect the discharge time in a mixed-traffic situation to be longer than the regular traffic flow.

3. Interaction during discharge process:

   The interaction between vehicles while discharging is also important but hard to quantify. It is also not easy for the operator to collect such information aside the road. The movement of the scooters in the queue will affect other vehicles since their high mobility give them the opportunity to decide whether to overtake the nearby vehicles. However, these often severely influence other vehicles.

Figure 3.2.2 illustrates how different configuration of relative position will influence the specific vehicle during the discharge process, nevertheless, the degree of the effect of each situation is not easy enough to quantify but it can be observed easily.

For passenger cars, their affected level by other vehicles is situation D > A = B = C. The scooters on the left or right side have greater influence to the passenger cars. Since the quantity of the queuing vehicles, especially passenger cars, is the main element to affect discharge time, and their moving in a constrained space depending on the lane-width, the other situations have little influence on them.

For scooters, their affected level by other vehicles is situation G > H = I > J. Scooters are between two passenger cars or just behind a car will be affected severely by cars. Scooters have to make decision whether to keep following, shift leftwards, or shift rightwards to overtake the front car. It takes more discharge time than other situation. Situation H and J have similar degree of effect to the discharge process because the effect between the same vehicle types is lower. Situation I is the less power of effect to the discharge process, in addition, scooter's start up speed is higher than cars that cars have almost no influence on scooters.

The influence of the vehicle nearby will affect the decision of the vehicles. For passenger cars, the vehicle at the front and the scooter on the left/right side will influence their driving behaviour during the discharge process. For scooters, the vehicles at the front and the passenger cars on the left/right side is what they will concern the most during the discharge process. Since the passenger cars are the largest vehicle in the observed lane. The vehicles at the front and left/right side of each passenger car can be deemed as a region or an area. The existence of the vehicles in the region forms the structure of the queue arrangement in the lane. More region is occupied, the more complex the queue structure is. In addition, the more scooters in each nearby region will strengthen the impedance or the impact of delay while discharging. It is necessary to consider both vehicle composition and the queue arrangement when constructing the variable to adjust the discharge time.

Through observation, the study found out that before the green onset, the queue arrangement is critical to discharge under mixed-traffic flow. The discharge time estimation model should include the status of the queue arrangement. The variable that can include the queue arrangement will be discussed in the following section.

3.2.2 Model building

To construct the discharge time (*Dt*) estimation model, the study used 2 kinds of multiple regression models to estimate the discharge time and compare the efficiency. One is the general linear regression model, the other is the non-linear regression model. Considering the variables that will affect the discharge process, the following formulations (1) is the base model without considering the QPE, (2) is the linear model with QPE, and (3) is the nonlinear model considering QPE to describe the discharge time:

Model 1a: Linear model (without QPE)

$$Dt = const. + \beta_1 n_{scooter} + \beta_2 n_{car} + \beta_3 q_{length} \quad \text{— (1)}$$

Model 1b: Linear model (with QPE)

$$Dt = const. + \beta_1 n_{scooter} + \beta_2 n_{car} + \beta_3 q_{length} + \beta_4 QPE \quad \text{— (2)}$$

Model 2: Non-Linear model (with QPE)

$$Dt = const. + (\beta_1 n_{scooter} + \beta_2 n_{car} + \beta_3 q_{length})\, e^{\beta_4 QPE} \quad \text{— (3)}$$

Where

Dt	:	Discharge time of the queuing vehicles
$n_{scooter}$	:	Number of scooters
n_{car}	:	Number of passenger cars
q_{length}	:	The length of the whole queue per lane
QPE	:	queuing pattern entropy; disorganised degree of queue per lane

Model 1a is constructed according to past research that the number of vehicles and the length of the queue will affect the discharge process. Model 1b deemed the relationship of each variable as an additive to the discharge time. For Model 2, the QPE variable is deemed as a correction term to the discharge time, which can adjust the entire queue discharge time due to the order less condition under the same number of vehicles.

The variable used in the regression model are shown in Table 3.2.3. Traffic combinations are presented by number of the vehicles. Queue length is the length of all the vehicles in the same lane. Queuing pattern entropy (QPE) was used to depict the complexity of the queue arrangement. Combined with vehicle numbers, the study discusses the density of the queue.

Table 3.2.3 Variables descriptions

Variables	**Meaning**	**Descriptions**
D_t	Discharge time	The time for the entire queue pass through the stop line.
$n_{scooter}$	Number of scooters.	The number of the scooters per lane per cycle.
n_{car}	Number of cars.	The number of the passenger cars per lane per cycle.
q_{length}	Queue length.	The queue lengths of the lane of cycles.
QPE	Queuing pattern entropy.	The chaos degree of stopping queue per lane per cycle.

➢ Discharge time(D_t)

Discharge time is the time for the queue to pass through the stop line. The time is calculated as the green onset until the last vehicle of the queue to pass through the stop line.

- Number of scooters ($n_{scooter}$)

The amount of the scooters in the queue per lane per cycle. Scooter's arrangement in the queue is the main factors that affect the discharge under the mixed-traffic flow. More scooters may contribute to the discharge time but the arrangement of the vehicles also affect the discharge time. The variable can only represent the general expectation to the fact of more vehicles causing more discharge time.

- Number of cars (n_{car})

The amount of the passenger cars in the queue per lane per cycle. Passenger cars under similar headway almost equal to the queue length. However, the headway between each passenger car is different from each driver. The combination of the amount of passenger car with queue length can certainly contribute some effort to the discharge time.

- Queue length (q_{length})

Queue length is defined from the stop line to the last vehicle of the queue. Longer queue length takes more time to discharge than the shorter one. The original model separates the queue into 3 segments to represent the degree and condition of the mixed-traffic flow. This study removes the function and comes up with a new variable QPE index to demonstrate the features of the mixed flow.

- Queue pattern entropy (QPE)

To describe the chaos or the complexity of the mixed traffic flow, the order of vehicles and the combination of the vehicle types should be considered. Therefore, the QPE index was developed for the improvement of discharge time estimation under mixed-traffic flow.

The idea of the QPE index came from entropy and the inspired by Chiou and Hsieh (2012). The chaos of the stopping queue can be divided into each region in the queue space and related to the type of the vehicles. The QPE index considered the traffic composition and the queue arrangement. In addition, the queue arrangement can be decomposed into four regions as depicted in Figure 3.2.3.

Region 1: The space in front of the 1st passenger cars, from the stop line to the passenger cars. Only consider the scooters stopped at the front of the leading passenger cars.

Region 2: The space on left or right side of each passenger cars, from passenger cars to the lane markings. Only consider the scooters stopped aside passenger car.

Region 3: The space behind each passenger cars. Only consider the scooter queued up behind passenger cars.

Region 4: Passenger car queue (passenger car itself).

The size of Region 1 is not fixed. The size of Region 2 is restricted to the lane width. For Region 3, the size depends on the distance between each passenger cars; the space of the last vehicles is defined by the queue (the last vehicle’s speed in the queue should be under 5km/h in 3 seconds before the lights turn green).

For QPE index, R_{i} is the traffic composition of each region, which is calculated as the information entropy. The value of QPE index is between 0 and 1.

$$R_{\mathrm{i}} = \frac{n_i + N_i \times e}{n + N \times e}$$

$$\mathrm{QPE} = \frac{-\sum_i^k (R_i \times \log R_i)}{\log(k)}$$

Where

R_i ： The ratio of the vehicle composition under the i$^{\text{th}}$ region

n ： Number of scooters in the lane

n_i ： Number of scooters in region i

N ： Number of passenger cars in the lane

N_i ： Number of passenger cars in region i

e ： The area ratio of passenger car on scooter (e=7)

k ： Number of the regions (k=4)

QPE ： Queuing pattern entropy; the chaos degree of the queue per lane.

The area ratio of passenger car on scooter (close to 7) is according to the assumption of the length and width of the vehicles (scooter: 1.6m*0.6m, passenger car: 4.3m*1.65m). If the scooter occupied more than one region, the scooters belongs to the region where their head located in.

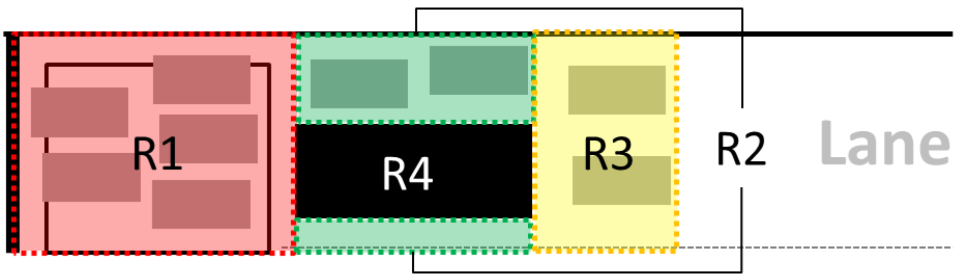


Figure 3.2.3 Queue pattern illustration

All the variables above are used to regress the discharge time. The following section will pick one of the data as the sample to demonstrate how the QPE is calculated.

The data used here is the 4th lane of 2nd cycle from the validation used location A. The reference for the calculation standard is depicted as shown in Figure 3.2.4.

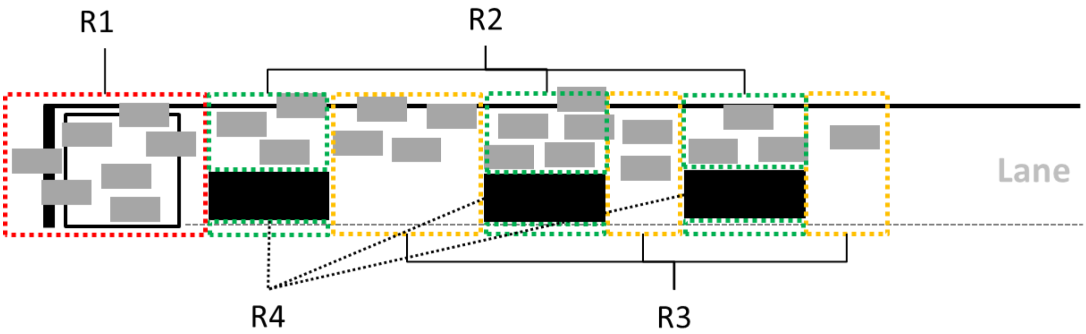
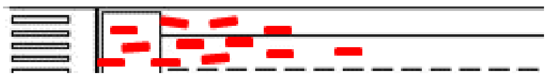
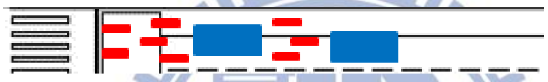


Figure 3.2.4 QPE calculation demonstration

The entire queuing area is $n + N \times e$ which is 25+3*7=46. For R1, there are 7 scooters at the very front queue, implying the R1 to be 0.1521. For R2, which is the aggregated spaces aside the passenger cars, has 11 scooters in total (11 scooters divided by 46 = 0.2391). For R3, the scooters between and the back of the passenger cars, has a value of 7 scooters divided by 46 equals 0.15. For R4, the passenger cars itself is 0.46 (3*7/46). After judging the area and the amount of the vehicle which related to the pattern, the QPE variables can be calculated. In this example, the QPE value is 0.9185.

Table 3.2.4 is the demonstration of the calculated QPE with the queue scenarios summarised from the data. For the no.1 and no.2 queue pattern indicated the situation of pure scooters and pure passenger cars (the value of QPE for both are 0), that is, there is no any interaction between scooters and passenger cars and the distribution of the vehicle is simple. No.3 to No.7 depicts several queue patterns which are easy to observe in the reality. No.8 shows the extreme condition of the queue as the passenger car is surrounded by the scooters, which represent the typical example of the mixed-traffic flow. To reach the maximum value of QPE, the value in each region should be around 0.25.

Table 3.2.4 Demonstration of the QPE with queue data

No.	Vehicle combination	Queue scenario	R1	R2	R3	R4	QPE
1	Scooter only		1	0	0	0	0
2	Car only		0	0	0	1	0
3	Mixed		0.22	0	0	0.78	0.38
4	Mixed		0	0.16	0	0.84	0.32
5	Mixed		0	0	0.22	0.78	0.38
6	Mixed		0.19	0.14	0	0.67	0.62
7	Mixed		0.23	0	0.14	0.64	0.65
8	Mixed		0.19	0.16	0.22	0.43	0.94

Chapter 4 Data Collection and Analysis

The data collected for the analysis under the mixed traffic flow required several procedure before the model calibration. In this chapter, the study will introduce the geometry information of the location, the method to collect the data. Then, the descriptive statistics of the data. Last, the characteristics of the collected data such as the lateral movement and the discharge order analysis. The analysis on the data will provide the study an insight to the behaviour and action of mixed-traffic flow.

4.1 Data collection and compilation

Aerial videography approach is adopted to collect the traffic data. The database of video is filmed by MOTC's report "Modelling driving behaviour of motorcycles in mixed traffic: empirical study and model development". (Wong et al., 2015).

This study aims to construct the discharge time estimation model by analysing aerial video. In addition, accurate information can have made great efforts on discharge behaviour modelling. Compared with traditional traffic data collection skills, unmanned aerial vehicle (UAV) video image processing is an alternative new technology, offering opportunities to perform under complex situations. Traditional data collection on observing the discharge headway only record the successive headway by the stop line and fail to capture the interaction between the vehicles. The UAV video image processing provides more precise traffic parameters without any angular deviation for the wider area than other sensors. In addition, there is no interference to the observed vehicles.

Using video filmed by UAV, traffic data can be captured over a certain road length, obtaining microscopic characteristics of individual vehicle trajectories and extracting behaviour information under mixed traffic situation. Trajectory Extractor (Lee, Polak, and Bell, 2008) is used to record vehicles' trajectory data by clicking position of each motorised vehicle in a second, extracting the trajectories since the vehicle entered the road until it left the intersection. Each data point includes vehicle's type, speed, acceleration, direction, and angle. By transforming the scale, the position in reality can be calculated.

In terms of site selection, there are some requirements needed to follow: (1) existing waiting zone for scooters beyond the stop line; (2) signalised intersection; (3) enough queue length forming up after red time so that the discharge behaviour can be observed, which means volume of scooters and passenger cars should be large enough to analyse QPE index.

Intersections are selected on Xiao-dong road and Sheng-li Road in Tainan, Taiwan. Xiao-dong road is one of the arterials in Tainan; it is near the National Cheng Kung University and hospital. It intersects two major roads, Xiao-dong road and Linsen road, signalised with a pre-timed phasing scheme. Moreover, we collected westbound and eastbound traffic data. On the other hand, the second one intersects two major roads, Xiao-dong road and Sheng-li Road. The detail of these locations' geometry information is described in Table 4.1.1. Scooters follow a two-stage left turn at these three intersections.

Table 4.1.1 Geometry information of the 3 location

<table>
<tr><td colspan="3">location</td><td>A</td><td>B</td><td>C</td></tr>
<tr><td colspan="3">Traffic direction</td><td>westbound</td><td>eastbound</td><td>westbound</td></tr>
<tr><td colspan="3">Intersection</td><td>Xiao-dong road and Linsen road</td><td>Xiao-dong road and Linsen road</td><td>Xiao-dong road and Sheng-li Road</td></tr>
<tr><td colspan="3">Approach width</td><td>15</td><td>15</td><td>15</td></tr>
<tr><td colspan="3">Number of lanes</td><td>4</td><td>4</td><td>4</td></tr>
<tr><td rowspan="4">Lane width</td><td colspan="2">1st lane</td><td>3</td><td>3</td><td>3</td></tr>
<tr><td colspan="2">2nd lane</td><td>3</td><td>3</td><td>3.3</td></tr>
<tr><td colspan="2">3rd lane</td><td>3</td><td>3</td><td>3.3</td></tr>
<tr><td colspan="2">4th lane</td><td>5.5</td><td>5.5</td><td>5.4</td></tr>
<tr><td rowspan="5">Roadside parking lot</td><td rowspan="2">Number</td><td>1st group</td><td>4</td><td>6</td><td>3</td></tr>
<tr><td>2nd group</td><td>2</td><td>8</td><td>3</td></tr>
<tr><td rowspan="2">Location</td><td>1st group</td><td>12m to stop line</td><td>12m to stop line</td><td>10m to stop line</td></tr>
<tr><td>2nd group</td><td>85m to stop line</td><td>50m to stop line</td><td>75m to stop line</td></tr>
<tr><td colspan="2">Width</td><td>2.5</td><td>2.5</td><td>2</td></tr>
<tr><td rowspan="3">Scooter waiting zone</td><td colspan="2">Width</td><td>6</td><td>6</td><td>5.5</td></tr>
<tr><td colspan="2">Length</td><td>7</td><td>7</td><td>7</td></tr>
<tr><td colspan="2">Location</td><td colspan="3">3rd and 4th lane</td></tr>
<tr><td rowspan="4">2-stage scooter waiting zone</td><td colspan="2">length</td><td>5</td><td>5</td><td>4.6</td></tr>
<tr><td colspan="2">Width</td><td>3</td><td>3</td><td>2.8</td></tr>
<tr><td colspan="2">Distance to the stop line</td><td>10</td><td>10</td><td>10</td></tr>
<tr><td colspan="2">location</td><td colspan="3">4th lane</td></tr>
</table>

Traffic data were collected on weekdays during the peak and off-peak evening period, and traffic composition comprises passenger cars, scooters and buses. The cycle which includes buses were not considered in this study. The original traffic video data at three intersections contained uncompleted cycle, poor quality or fisheye lens distortion problems, these biased data need to be excluded or calibrated. Therefore, 15-minute video split into three or four pieces, and each video segment is determined by complete cycle in order to reduce unexpected error in model construction. For location

A, the effective data length is 3455s with 25 complete cycles. For location B, the effective data length is 3508s with 25 complete cycles. For location C, the effective data length is 2283s with 18 complete cycles. The statistics of each mode is in Table 4.1.2.

Figure 4.1.1 Aerial image of Location A

Table 4.1.2 Statistics of the data collected

	Vehicle observed Number (%)			
	Location A	Location B	Location C	Subtotal
Scooters	465 (77.4%)	319 (65.9%)	268 (71.7%)	1052 (72.1%)
Passenger cars	136 (22.6%)	165 (34.1%)	106 (28.3%)	407 (27.9%)
Total	601 (100.0%)	484 (100.0%)	374 (100.0%)	1459 (100%)

4.2 Descriptive Statistics Analysis

The 3 chosen intersections in Tainan have 4 lanes. Lane 1 and 2 are the inner lanes, only consist of the passenger cars for the exclusive left turn and straight forward; lane 3 and 4 are the outer lanes which have the scooter waiting zone at downstream. Naming the inner lane as the 1st lane, the second inner lane as the 2nd lane, and so on. To analyse the effect of the mixed-traffic flow condition, this study only focuses on the 3rd and 4th lane.

The base information of the 3 chosen intersections include queue length, discharge time, number of vehicles in each lane per cycle, displayed separately in Table 4.2.1, Table 4.2.2 and Table 4.2.3. The queue can be divided into 3 segments. The front scooters form the first queue; the mixed queue start from the passenger cars and end with the last scooters; the third segment is the passenger cars queue. In the figure of queue length, d1 represents the length of the front scooters queue, d2 is the length of the mixed queue and d3 is the length of the residual passenger cars. In the figures of the discharge time, t1 is the discharge time of the front scooters, t2-mc is the discharge time of the scooters mixed up with the passenger cars, t2-car is the discharge time of the passenger cars mixed up with the scooters, t3 is the discharge time of the rest of the car queue. Likewise, the notation is similar in the figures of Numbers of the discharge vehicles.

In terms of queue length of each lane per cycle period, through comparing the video recording the signal timing on the ground with the aerial video, the study can obtain the exact discharge time of each cycle. In addition, all the markings and explicit object relative position and length had been collected with a rangefinder to assure the queue length is accurate.

According to the obtained data, Lane 2 has the most cars, and for Lane 4 the queue is mostly motorcycles. When the space for the motorcycle is full, the cars coming up will mix up with the motorcycles. As for discharge time of each lane per cycle, if the former vehicles in the queue spend more time at starting up, it will cause the later vehicle to delay. In Lane 1, passenger cars spend lots of time on making a left turn, causing the discharge time to be longer than others. Compare Lane 4 and Lane 3, it shows that the discharge time takes more in the mixed queue than the pure cars queue. For number of the vehicles at the intersection, although a number of cars in Lane 1 is smaller than Lane 2, it takes more discharge time than Lane 2 due to the times for making the left-turn movement. From Lane 4, the numbers of vehicles are extremely high, but the discharge time it takes has a wide variation. The number of vehicles and discharge time is not a linear relationship but only form a positive correlation.

Table 4.2.1 Data of location A

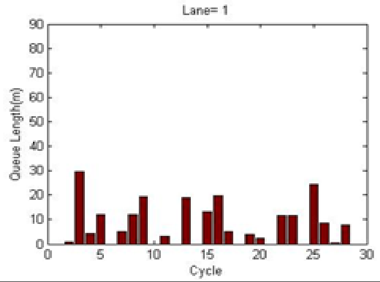
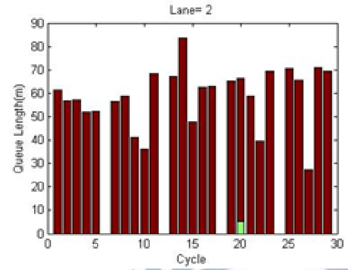
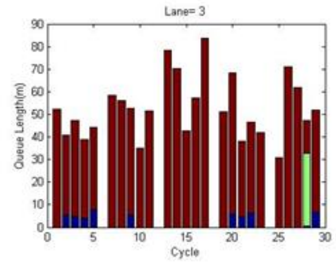
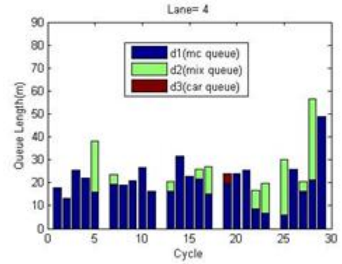
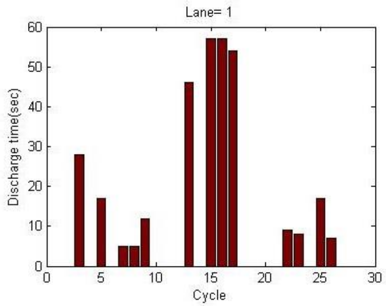
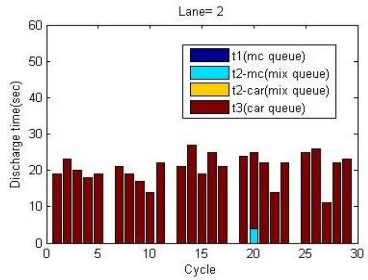
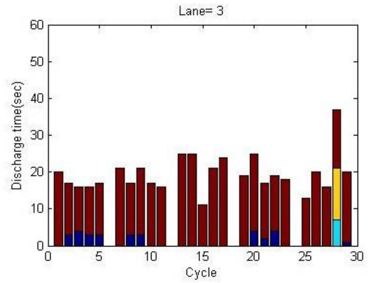
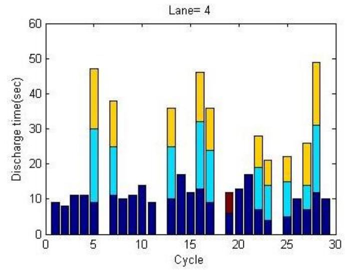
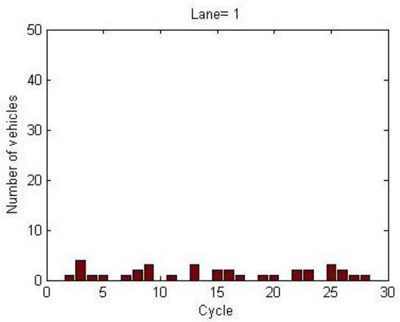
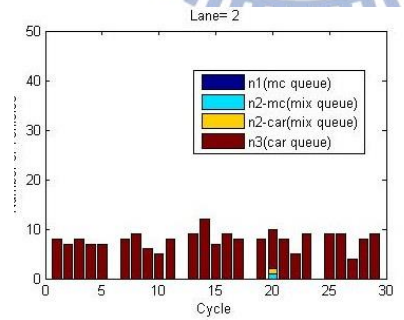
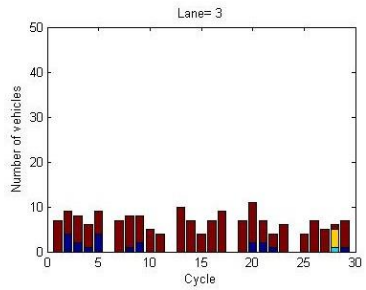
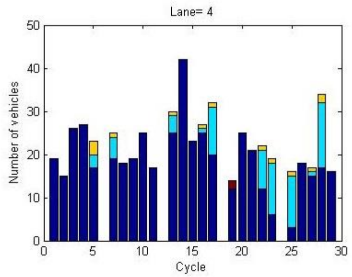
Location A	Lane 1	Lane 2	Lane 3	Lane 4
Queue length				
Discharge time				
Number of the vehicles				

Table 4.2.2 Data of location B

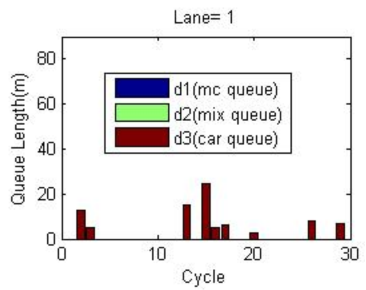
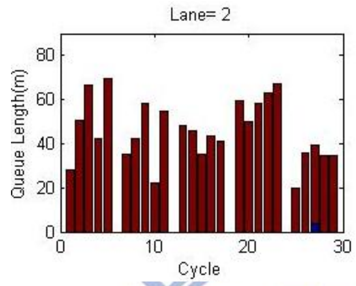
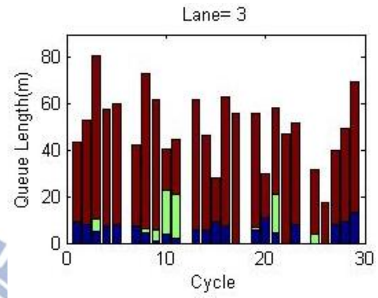
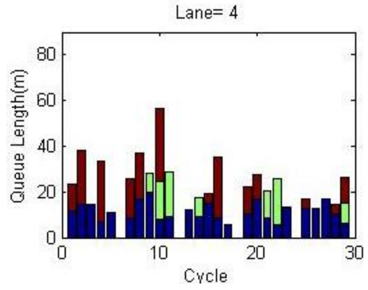
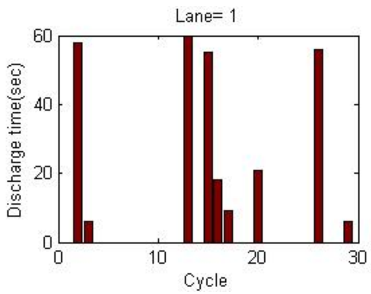
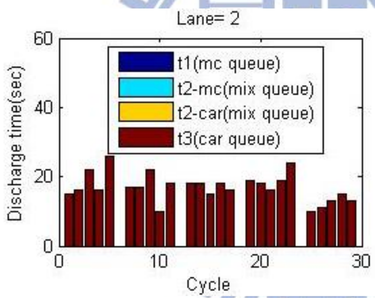
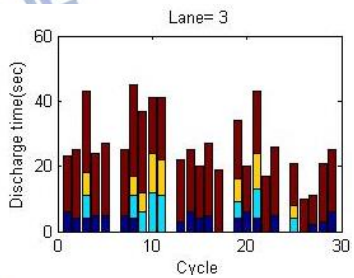
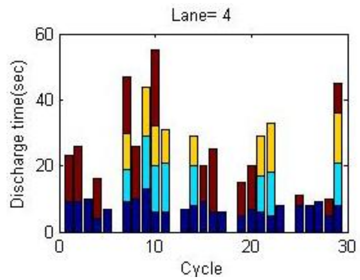
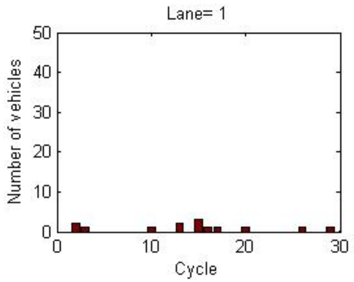
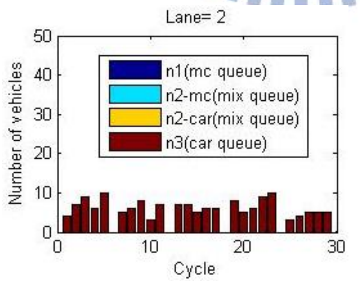
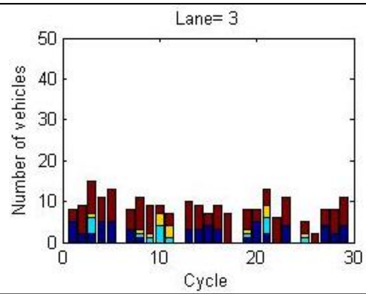
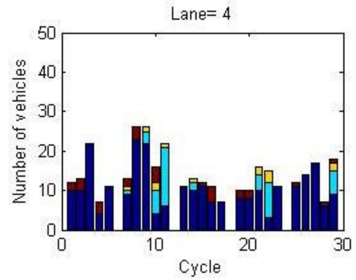
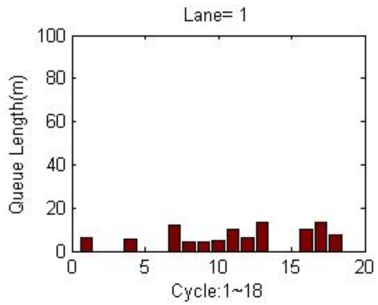
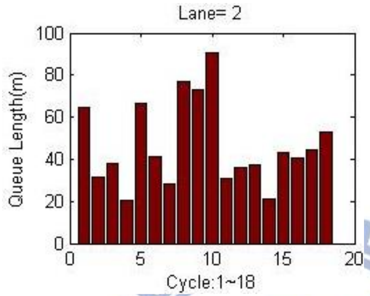
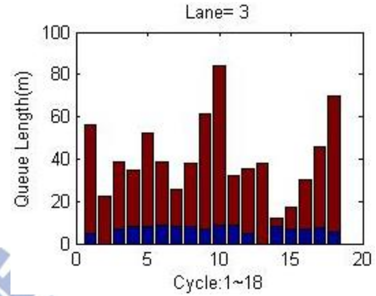
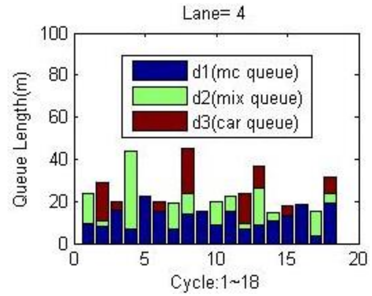
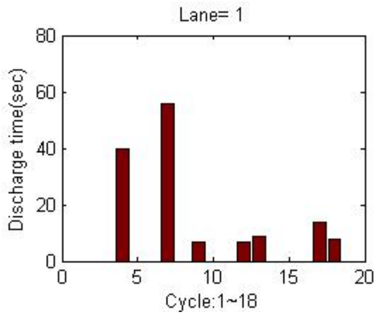
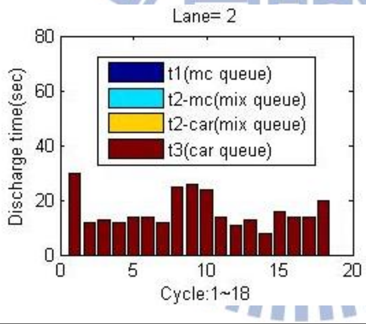
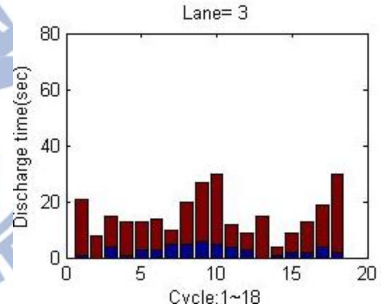
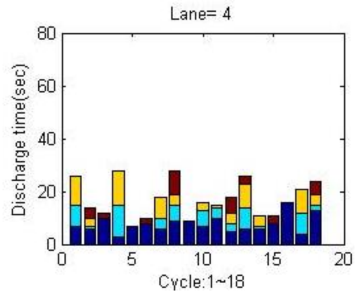
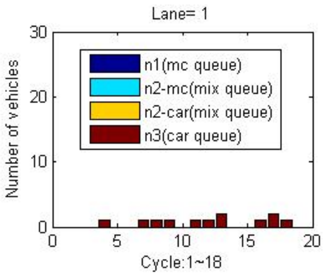
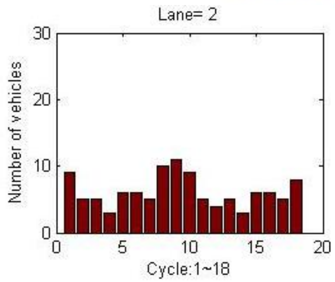
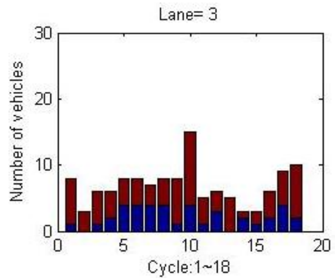
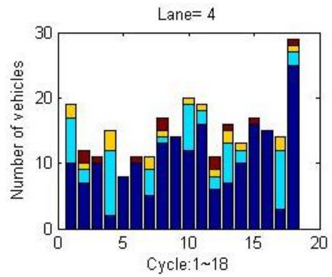
Location B	Lane 1	Lane 2	Lane 3	Lane 4
Queue length				
Discharge time				
Number of the vehicles				

Table 4.2.3 Data of location C

Location C	Lane 1	Lane 2	Lane 3	Lane 4
Queue length				
Discharge time				
Number of the vehicles				

The data collected from location A, B and C had been processed and grouped to provide more objective choices data. To explore and model the basic mixed-traffic discharge time, the data used for model calibration only consider the straight through traffic on lane 3 and 4. The cycles consists of right turn movement had been removed in order to simplify the research (18 samples in total had been removed). Therefore, there are 40 valid samples from location A, 44 valid samples from location B, and 34 valid samples from location C. Table 4.2.4 summarises the variables in the regression model of discharge time estimation. Descriptive statistics showed the mean, standard deviation, minimum and maximum for each variable in the model. There are 118 cycles included in the modelling procedure. The number of the scooters and passenger cars are widely variate due to the traffic environment. For the queue pattern entropy, the minimum of 0 reveals that the condition of homogeneous traffic flow exist and for the maximum of a 0.99 means that the extreme cases of mixed-traffic flow do exist in the data.

Table 4.2.4 Descriptive statistics for calibration used data

Sample :118				
Variables	Mean	Standard deviation	Maximum	Minimum
no_scooter	9.20	9.28	44	0
no_car	3.38	2.66	11	0
q_length	34.50	17.03	84.12	4.66
QPE	0.26	0.26	0.99	0

4.3 Data Characteristics

Traditional recognition to the discharge process indicated that the discharge will reach the stable condition after several passenger cars entered the intersection. However, under the mixed-traffic condition, there are argument and evidence point out the fact contradicting to the original recognition to the discharge process. The data of the discharge headway by lane are shown in the Appendix I Discharge headway data. Figure 4.3.1 is the average discharge headway of the collected data. It reveals that after the 9th~11th vehicles, the discharge headway will gradually become unstable. The cause of this phenomenon should be inspected from the lateral and longitudinal movement.

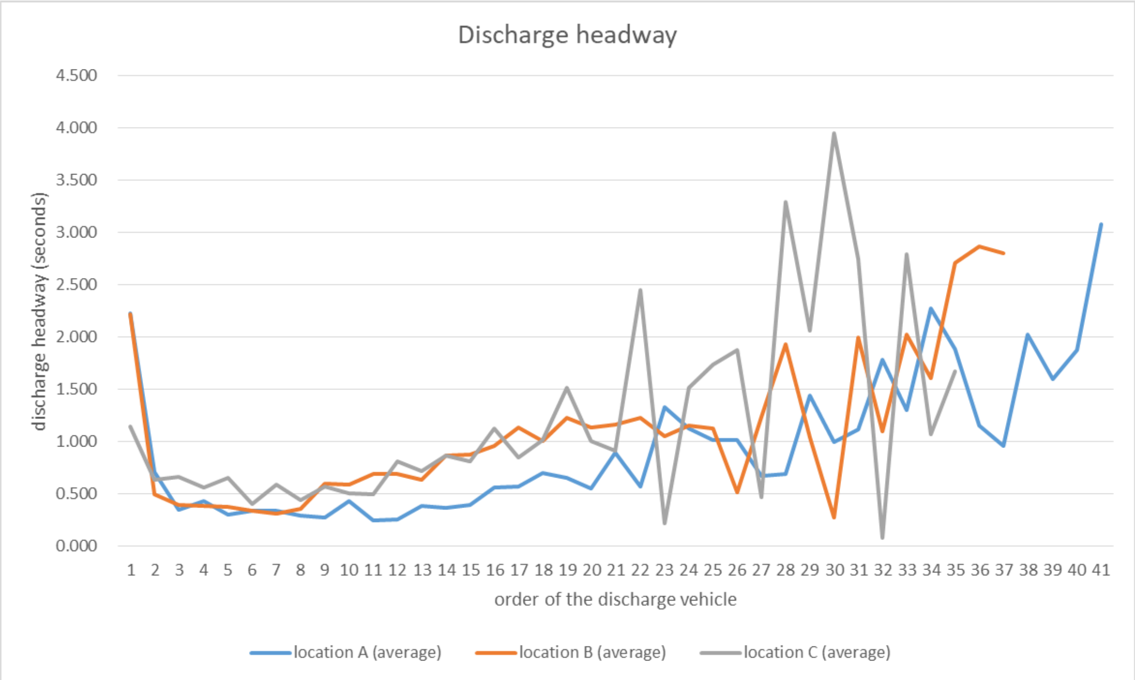
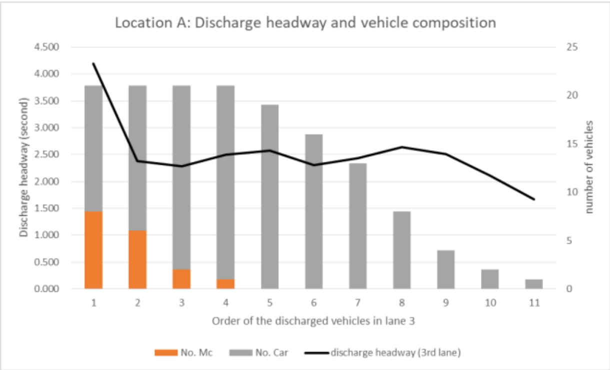
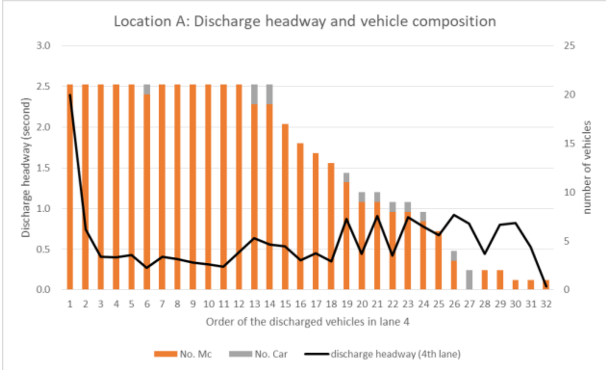


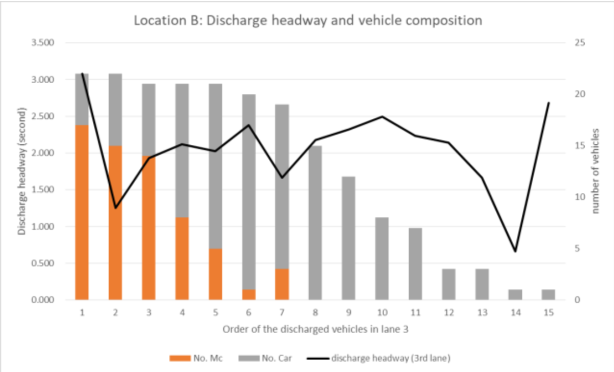
Figure 4.3.1 Average discharge headway of the observed location



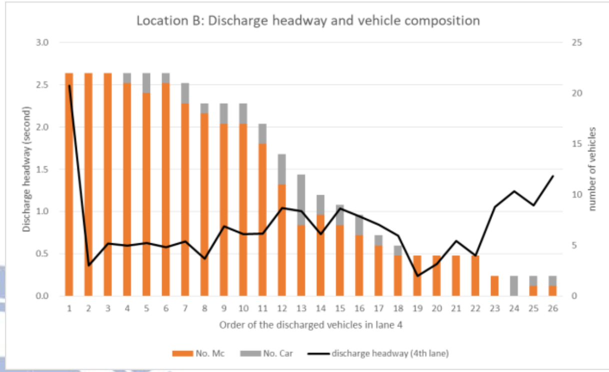
(a) 3rd lane of location A



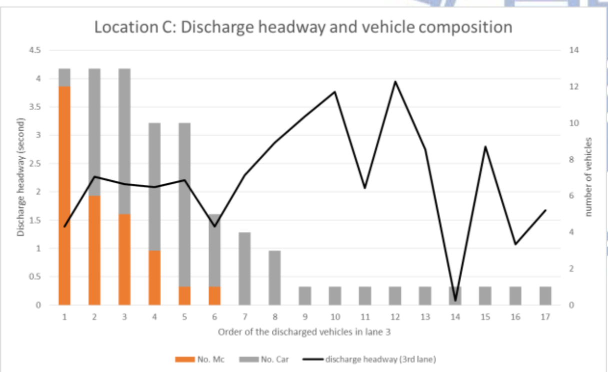
(b) 4th lane of location A



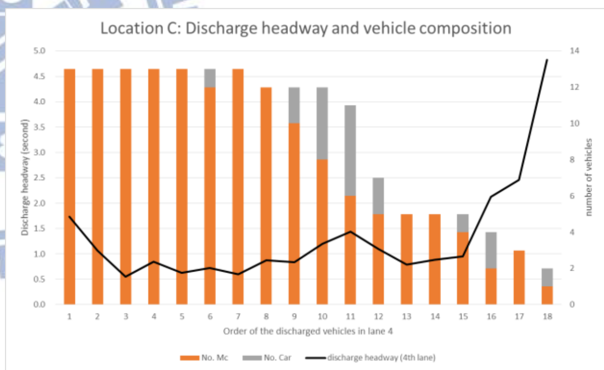
(c) 3rd lane of location B



(d) 4th lane of location B



(e) 3rd lane of location C



(f) 4th lane of location C

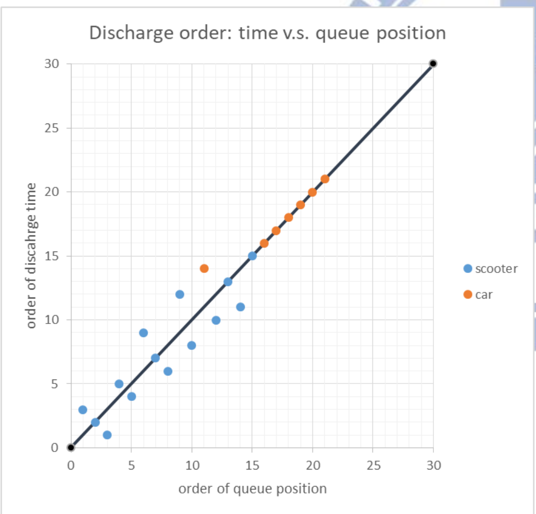
Figure 4.3.2 Discharge headway and vehicle composition of the selected location

Figure 4.3.2 is the discharge headway and the vehicle composition of each location. It shows that different location and different lane possesses different discharge headway. The main y-axis is the discharge headway; the sub y-axis is the number of the vehicles in the observed vehicle position; the x-axis is the order of the vehicle in the queue passing through the stop line (exclude their lateral location). The cause of the variation between different lane may be the characteristics of vehicles and the impact of lane width of lane3 (near 3 meters) and lane 4 (around 5.5 meters). The wider the lane width is the shorter the discharge headway is. Some interesting facts can be observed. The discharge headway is affected by its position and the probability of whether the vehicle is a scooter or a passenger car. The scooter usually passed the stop line before the passenger car that the discharge headway is short. As the probability of the passenger car passed through the stop line is increased, the headway began to rise and fluctuate. The overall variation in the discharge headway cannot be deemed as a stable traffic flow.

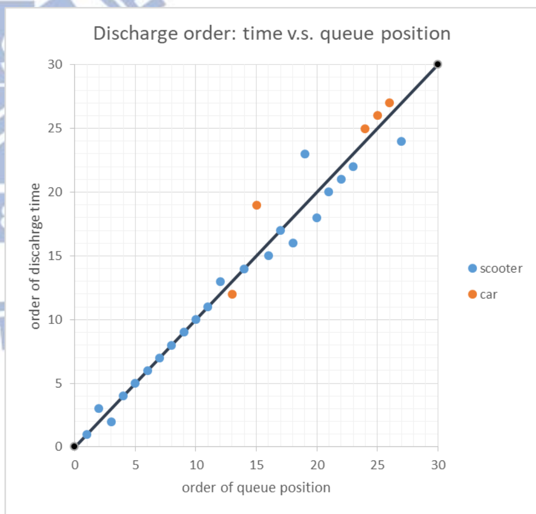
The cause of the chaotic mixed traffic condition comes from the interaction between the vehicles and the movement during the discharge process. The behaviour can be observed from 2 perspectives. One is the order of the vehicles passing the stop line compared to the order of the queue. The other is the lateral movement of the vehicles during the discharge process.

The behaviour of the discharged vehicle in the longitudinal direction can be inspected by comparing the order of the vehicle passing the stop line with the queue. If the queue can be discharged smoothly, it should obey the rule of First In First Out (FIFO). Under mixed traffic flow, due to different start up speed and acceleration, the vehicles often exists different order when entered the intersection. As depicted in Figure 4.3.3, each figure reveals different situation observed from the queuing vehicles. (a) shows the general behaviour of scooter on the road, they don't have much recognition to the lane and can pass through the intersection as soon as possible. The passenger cars cannot that they can only discharge in order. (b) illustrates an interaction of cars and scooters. Scooters can overtake the cars when discharging. (c) shows that the scooters' high mobility interfere the movement of the passenger cars. On the other hand, there is also a possibility for the cars to impede scooters' movement.

The condition of the overtaking during the discharge process can be analysed by calculating the proportion of the vehicle possesses relative small order on the discharge position. The overtaking ratio is defined as the proportion of the queuing vehicles that occurred the overtaking action. The occurrence of the overtaking will influence the discharge process. The maximum value of the overtaking ratio will not exceed 50% since the action of overtaking required at least two vehicles. For Figure 4.3.3, (a) is 29%, (b) is 33%, (c) is 45%, and (d) is 32%. The higher taking ratio is the more complicated discharge condition the queue is. The distribution of the overtaking ratio is depicted in Figure 4.3.4. There are 64% of the data has the overtaking ratio above 30%. Overall, most of the overtaking action is complete by the scooters showing that the overtaking of scooters during discharge is quite common in mixed-traffic.



(a) Case I



(b) Case II

(c) Case III (d) Case IV

Figure 4.3.3 FIFO comparison of the discharge process

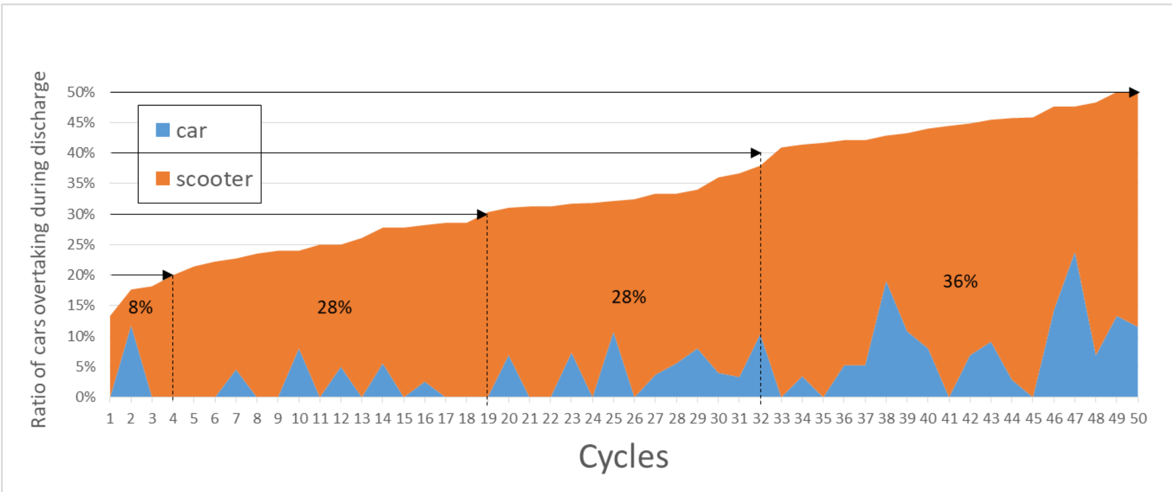


Figure 4.3.4 The ratio of overtaking between passenger cars and scooters

During the discharge process, some vehicles will shift left or right for a small distance; this behaviour will further influence the movement of the later vehicles. Figure 4.3.5 is the distribution of the lateral movement including left and right movement; there are 886 scooters and 275 passenger cars in total. For scooters, around 34% lateral movement is above 1 metre. For passenger cars, nearly 6% lateral movement is above 1.5 metre. Since the scooters are relatively small vehicles but 34% of it has lateral movement above 1 metre from its starting point causing the interruption of the flow in the traffic stream. To examine this behaviour, the lateral movement from the point of the queuing position to the stop line is illustrated in Figure 4.3.6. Passenger cars usually stay in the same lane under the discharge process. For the scooters, the variation of the lateral movement compared with the passenger car is large. The results verified the situation of the scooters' lateral movement that they tend to find the gap for them to pass the artery quickly. In some extreme cases, they may enter the other lane. In summary, the high proportion of the lateral movement and the ratio of overtaking occurred during discharge process complex the discharge condition in the mixed-traffic flow.

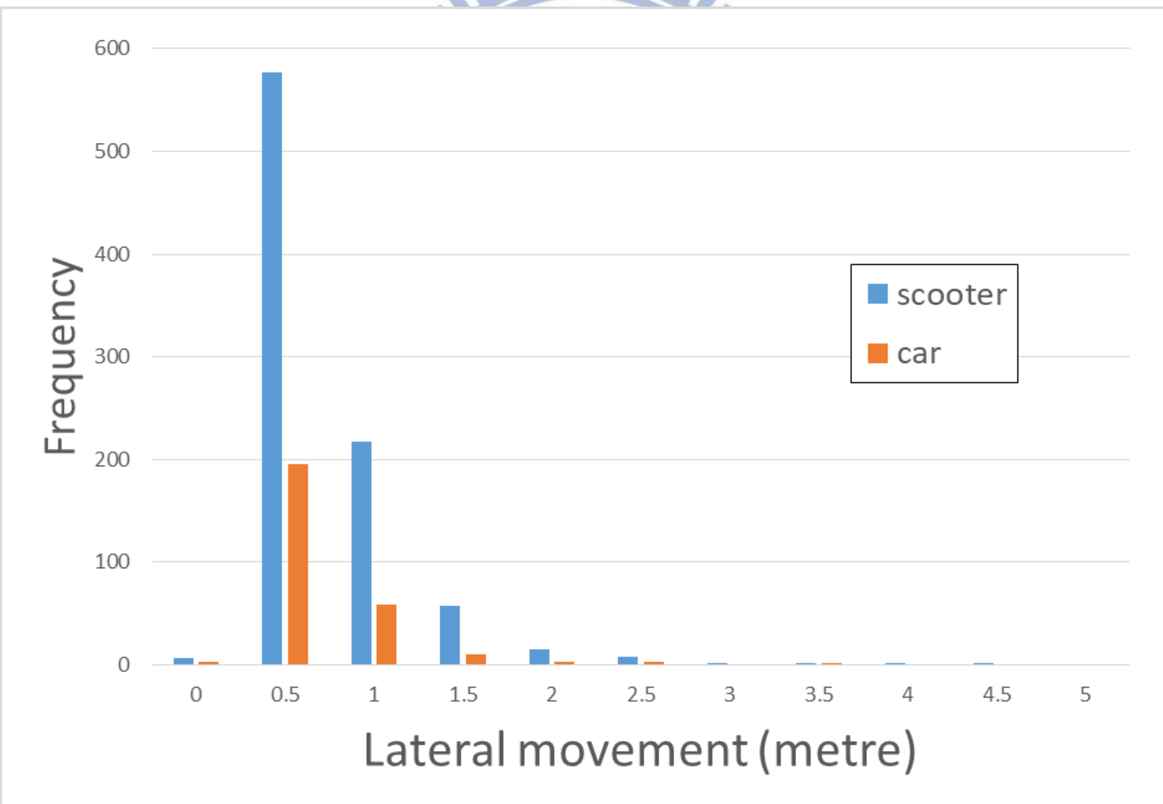
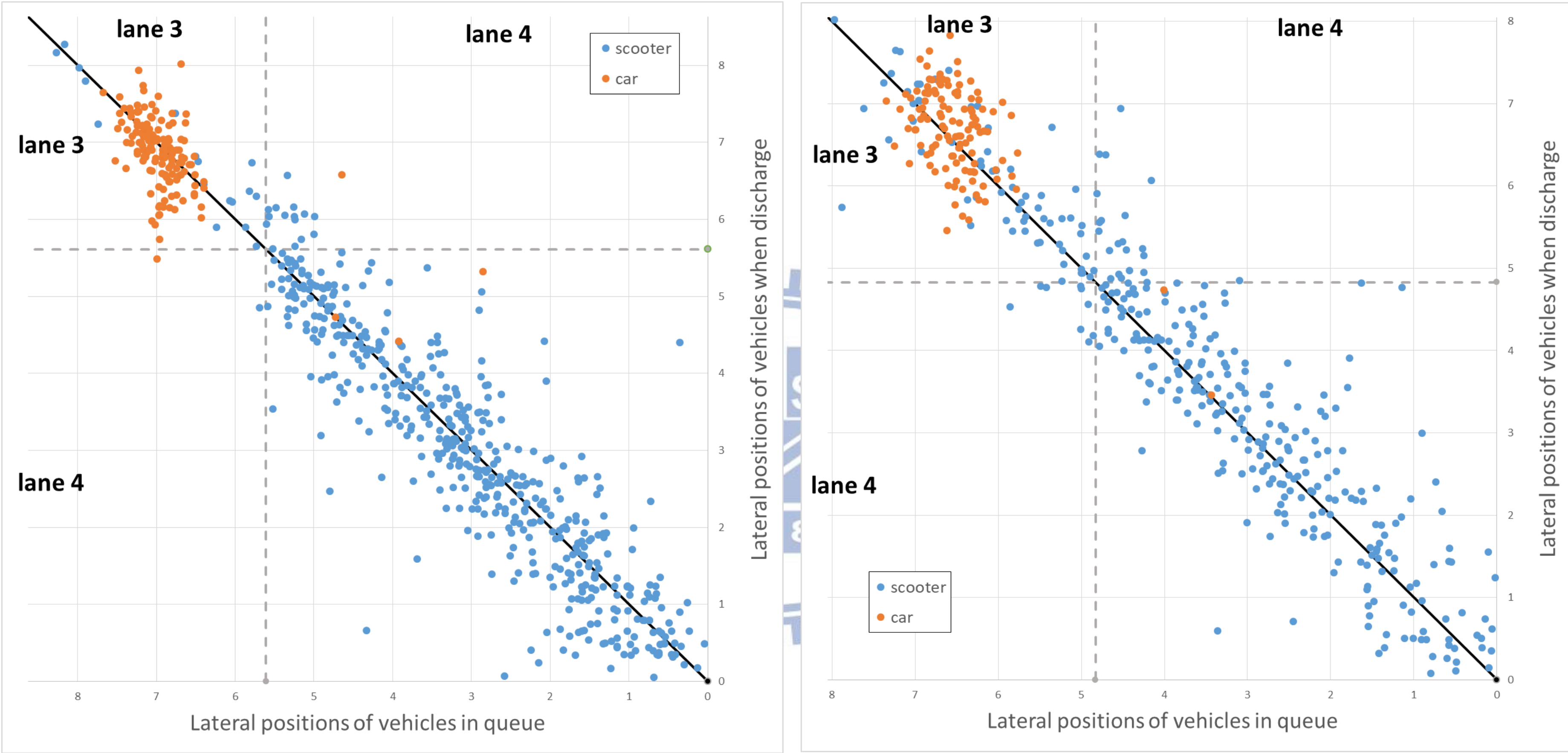


Figure 4.3.5 Frequency of lateral movement



A. Lateral movement of location A

B. Lateral movement of location B

Figure 4.3.6 Lateral movement of the vehicles

Chapter 5 Empirical Analysis

Discharge time is an important issue for signal control, especially under mixed-traffic flow. The parameter, QPE index, is designed to demonstrate the characteristics of vehicles' relative position during queue discharge, which improves the accuracy of estimation model. In this chapter, firstly, construct both the linear and non-linear model implemented to estimate discharge time and compare with the existing discharge model. A validation process is conducted on the model to measure the performance and compared to the original model built in Wong et al (2015).

5.1 Model Calibration

To evaluate the effect of the queue pattern entropy (QPE) on the discharge time, a regression analysis is adopted to the traffic data with presenting chaotic environment of scooters and passenger cars. According to the previous literature, the study firstly considered the model with regular variables, such as the number of scooters, the number of passenger cars, and the queue length. These parameters have great influence on the discharge time. Table 5.1.1 presents a summary of the regression analysis without using a parameter, QPE index.

Table 5.1.1 Regression analysis without queue pattern entropy

Variable name	Coefficient estimate	Standard error	t-statistics	p-value
$constant$	3.51	0.60	5.80	0.000***
$n_{scooter}$	0.22	0.03	7.36	0.000***
n_{car}	1.02	0.22	4.56	0.000***
q_{length}	0.18	0.03	5.91	0.000***
Observations: 118 R^2: 0.853 adjusted R^2: 0.849				

* Significant at 10% level; ** Significant at 5% level; *** Significant at 1% level

All the variables which are significant at the 1% level indicate their necessity to the discharge time estimation model. According to the result of regression, discharge time estimation model without queue pattern entropy can be expressed as follows:

$$Dt = 3.51 + 0.22\, n_{scooter} + 1.02\, n_{car} + 0.18\, q_{length}$$

The 1.02 of coefficient of the number of car (n_{car}) is the critical variables that it almost dominates the results of the model. The number of the scooters ($n_{scooter}$) and the length of the queue (q_{length}) support the model. All sharing a positive sign reveals a logical relationship with the discharge time. The model has an adjusted R^2 of 0.849 which is quite well to capture the base component of the discharge time.

Table 5.1.1 Linear regression analysis with queue pattern entropy

Variable name	Coefficient estimate	Standard error	t-statistics	p-value
$constant$	3.02	0.62	4.90	0.000***
$n_{scooter}$	0.18	0.03	5.45	0.000***
n_{car}	0.85	0.23	3.74	0.000***
q_{length}	0.21	0.03	6.59	0.000***
QPE	2.20	0.82	2.67	0.009***
Observations: 118 R^2: 0.861 adjusted R^2: 0.856				

* Significant at 10% level; ** Significant at 5% level; *** Significant at 1% level

As presented in Table 5.1.1, the adjusted R-squared value of the linear model with queue pattern entropy (QPE) is 0.856. According to the result of regression, discharge time estimation model with queue pattern entropy (QPE) can be expressed as follows:

$$Dt = 3.02 + 0.18\, n_{scooter} + 0.85\, n_{car} + 0.21\, q_{length} + 2.20\, QPE$$

All the signs of the variables were logical. The p-value of each variable is significant. Besides the number of cars (n_{car}), the queue pattern entropy (QPE) has the highest coefficient of all the variables with a value of 2.20. It means that the QPE will increase no more than 2.2 seconds to the estimated discharge time. Compared the model without QPE with the linear model (with QPE), it shows that the later model have higher explanation on the data. The R-square increased by 0.08%. For the estimation bias as show in Table 5.1.2. The bias has decreased and shows that the queue pattern entropy does improve the existing model.

Table 5.1.2 Model comparison with or without QPE

Model	Model(without QPE)	Model(with QPE)
MAE	1.5335	1.4413
MAPE	0.1147	0.1069
RMSE	2.0235	1.9623

The relationship between actual value and the estimation is depicted in Figure 5.1.1, the estimations are evenly distributed. Lane 3 tends to have longer discharge time because Lane 3 usually has more passenger cars and the less mixed-traffic condition than Lane 4.

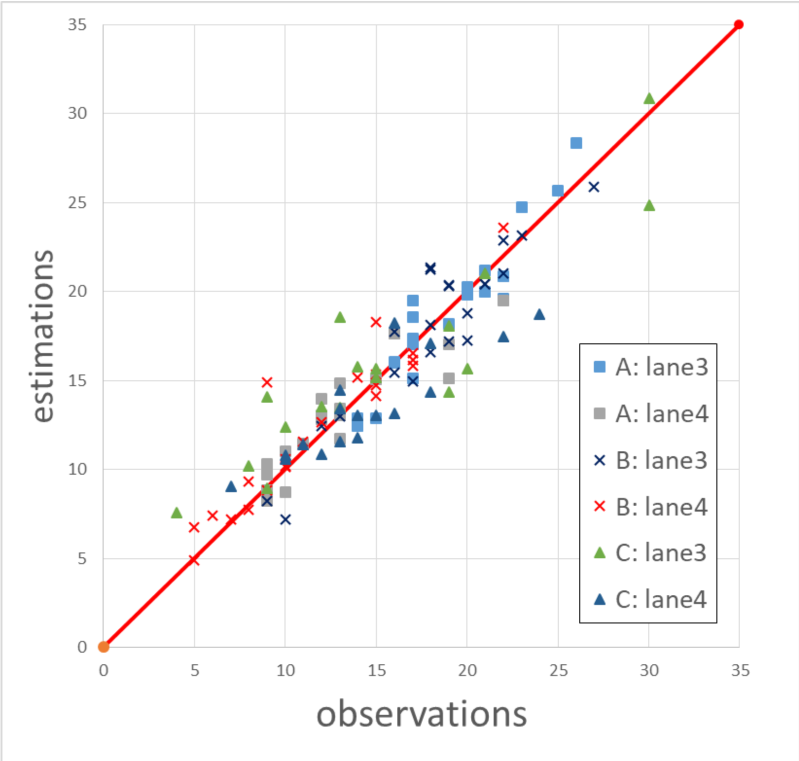


Figure 5.1.1 Linear model with QPE index

Table 5.1.3 Non-linear regression analysis with queue pattern entropy

Variable name	Coefficient estimate	Standard error	t-statistics	p-value
$constant$	3.53	0.59	6.02	0.000***
$n_{scooter}$	0.17	0.03	4.92	0.000***
n_{car}	0.83	0.21	3.91	0.000***
q_{length}	0.20	0.03	6.87	0.000***
QPE	0.21	0.08	2.62	0.010***
Observations: 118 R^2: 0.861 adjusted R^2: 0.856				

* Significant at 10% level; ** Significant at 5% level; *** Significant at 1% level

Table 5.1.3 is the calibrated result of the non-linear model. The adjusted R-squared value of the non-linear model is 0.861, which is the same as the linear model. According to the result of non-linear regression, the discharge time estimation model with queue pattern entropy (QPE) can be expressed as follows:

$$Dt = 3.53 + (0.17\, n_{scooter} + 0.83\, n_{car} + 0.20\, q_{length})\, e^{(0.21\, QPE)}$$

All the signs of the variables were logical. The p-value of each variable is significant. Unlike the linear model, the queue pattern entropy (QPE) become the correction term of the discharge time. The existence of the mixed-traffic can affect the discharge time with the power of the exponential term. If the QPE is 0, the output of the exponential term would be 1 (e^0), which means there is no mixed-traffic condition in the queue and the impact of estimation only based on the numbers of vehicles and queue length. If the QPE is 1, the output of the exponential term would be 1.23 ($e^{0.21}$). The discharge time would increase by 23% compared with the queue without mixed traffic. With QPE, the change of the discharge time varies from 1 to 1.23 times of the original explanation on the discharge time. The relationship between observations and the estimations is depicted in Figure 5.1.2, the estimations are evenly distributed. Compared to the results of the linear model. It shows less difference between the models.

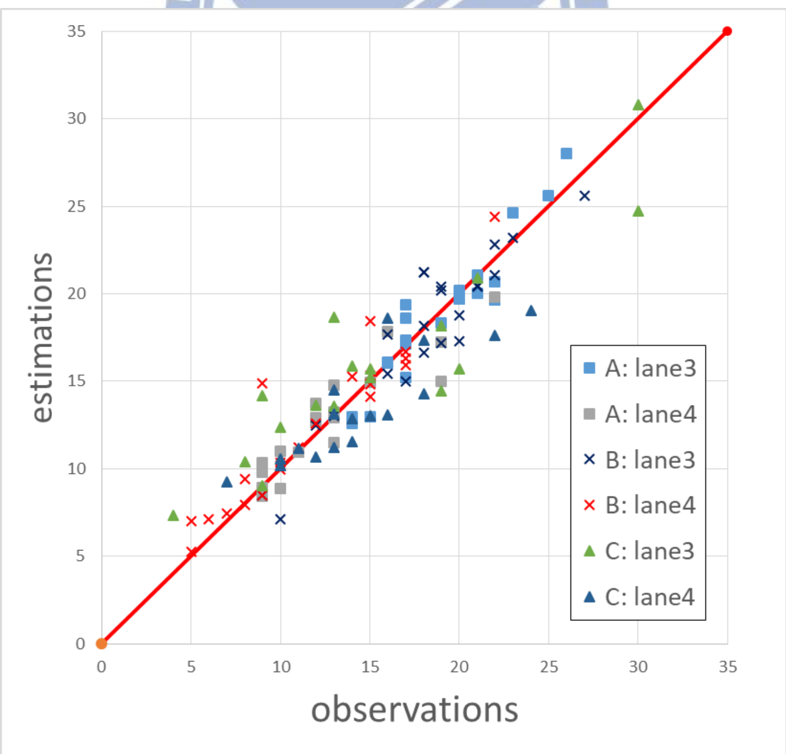


Figure 5.1.2 Non-linear model with QPE index

5.2 Model Comparison

The aim of the model is to capture the order less condition under mixed traffic. To investigate the capability of the model, the comparison with the model developed from HCM and Wong et al. (2015) is conducted. Before comparing the models, there is some method to measure the accuracy of the forecasting model. The mean absolute error (MAE), mean absolute percentage error (MAPE), and root mean square error (RMSE). The lower the indicator is, the more accurate the model is.

The data source is the same as the one used in Wong et al. (2015). In the project, the queue length was separated in order to capture the effect of the mixed flow. Table 5.2.1 shows the calibration results of the model after considering the effect of queue patterns, all the indicator decrease. However, including queuing pattern entropy into the model not only can lower the number of the variable used in the model but also lower the bias of the estimation. It is noteworthy that the non-linear model has a less bias in MAE and MAPE but the R-square is the same.

Table 5.2.1 Calibrated model comparison

Model	Wong et al. (2015)	Model (linear)	Model (non-linear)
MAE	1.4649	1.4413	1.4240
MAPE	0.1102	0.1069	0.1056
RMSE	1.9533	1.9623	1.9622
R^2	0.863	0.861	0.861

The validation of the model is conducted with other database collected from the location A and B. A total of 78 samples was used to validate the model results. Table 5.2.2 is the validated result of the indicators of both models. Compared with the calibrated results, all the indicators reveal the outcome of the model built by this research is stable.

Table 5.2.2 Validated model comparison

Model	HCM (2011)	Wong et al. (2015)	Model (linear)	Model (non-linear)
MAE	9.4219	1.8753	1.7630	1.7594
MAPE	0.6657	0.1516	0.1451	0.1445
RMSE	10.2010	2.3039	2.2318	2.2329

Figure 5.2.1 is the comparison of the differences between the estimation and the actual value of the 4 models. It shows that except the model provided by the HCM, all the other model are similar and the estimation of the discharge time is acceptable. The dotted line is the observed discharge time; the solid line is the estimation from each of the model. It shows that all the models are similar and the estimation of the discharge time is acceptable. It can be observed that the model with the queuing pattern entropy has lower differences between the estimation and the actual discharge time. The bias has been shortened. For the models with QPE, it revealed that there are fewer differences between the structure of linear and non-linear.

The calculation method of the HCM is mentioned in section 2.4.1. To compare with the proposed model, the Taiwan Highway Capacity Software (THCS, 2015 version) was applied to generate the output of discharge time. In THCS, it required the user to input the signal phase setting, geometry setting, and the traffic flow. In signal phase setting, the cycle time is 130 second. In geometry input, the lane type, lane width, and solid division had been set according to the parameter from section 4.1. The arrival pattern of the vehicles is set to be intensive. The occupancy ratio of the scooter waiting zone is set as the default (60%). In the traffic flow input, THCS required the user to input the proportion of each kind of vehicle based on their turning movement. The peak hour factor is set to be 1. All the input requirement is based on the formulation from the HCM.

Compared with other methods, the results are far lower than the estimation. The cause is, in HCM, the scooter is supposed to queue up in the waiting zone and these scooters possess no impact on the discharged queue. However, through the observation of the collected data, the scooter at the front of the queue does influence the queue. In addition, the discharge time in HCM mainly depends on the proportion of passenger cars. When calculating the discharge vehicles in the residual green time, the increased proportion of the scooters will result in the decrease of the estimation. The discharge time is thus underestimated.

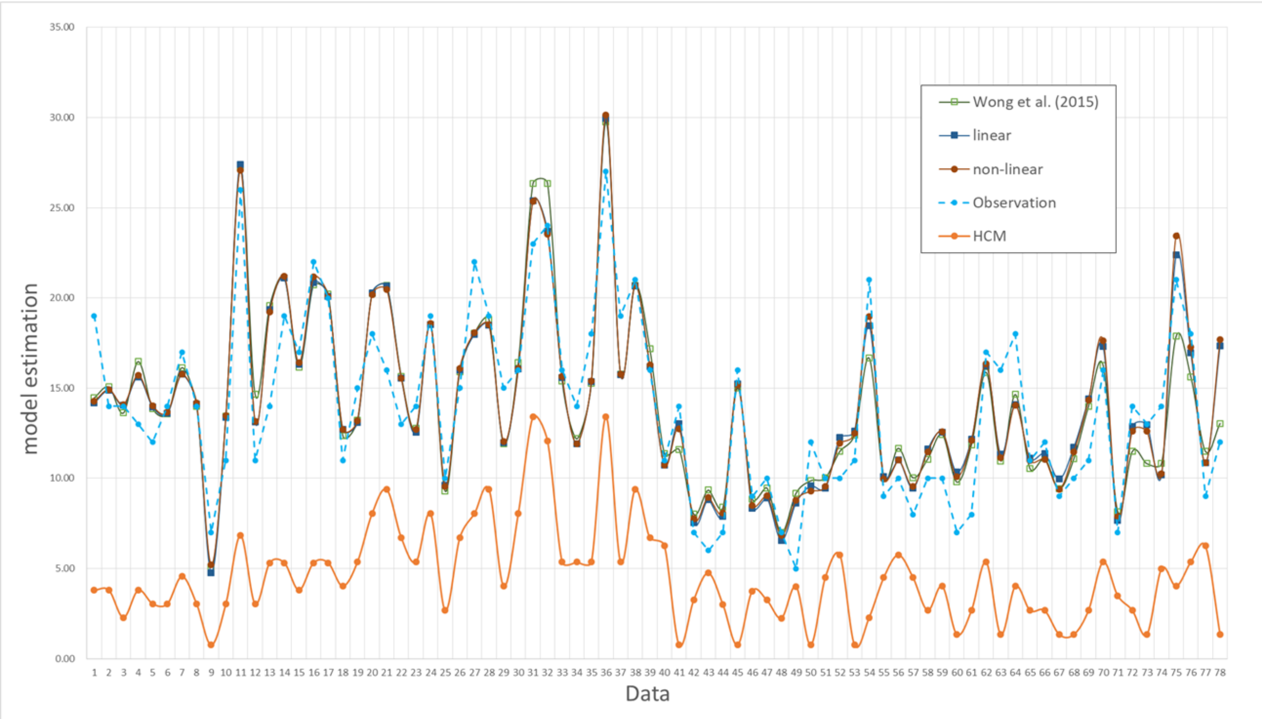


Figure 5.2.1 Observation vs. estimation model comparison

Table 5.2.3 Validated model comparison by lane

model	lane	MAE	MAPE	RMSE
Wong et al. (2015) discharge time model	3	1.89	0.12	2.35
	4	1.86	0.18	2.26
Linear discharge time model	3	1.75	0.11	2.23
	4	1.78	0.18	2.23
Non-linear discharge time model	3	1.72	0.11	2.19
	4	1.80	0.18	2.27
HCM: THCS software (signalised intersection service level analysis)	3	10.69	0.66	11.07
	4	8.16	0.67	9.24

Table 5.2.3 is the validation results of each model by lane. The model can be discuss by lane-based level. It shows that there exists some difference when comparing the model under different lane. In the model from Wong et al. (2015), the difference between the outer lane and the 3rd lane is small. As illustrated in Figure 5.2.2, the data from 1~39 is lane 3 and 40~78 is lane 4. It shows that the estimation match to the trend of the observation but in the data of lane 4, there exist a larger bias.

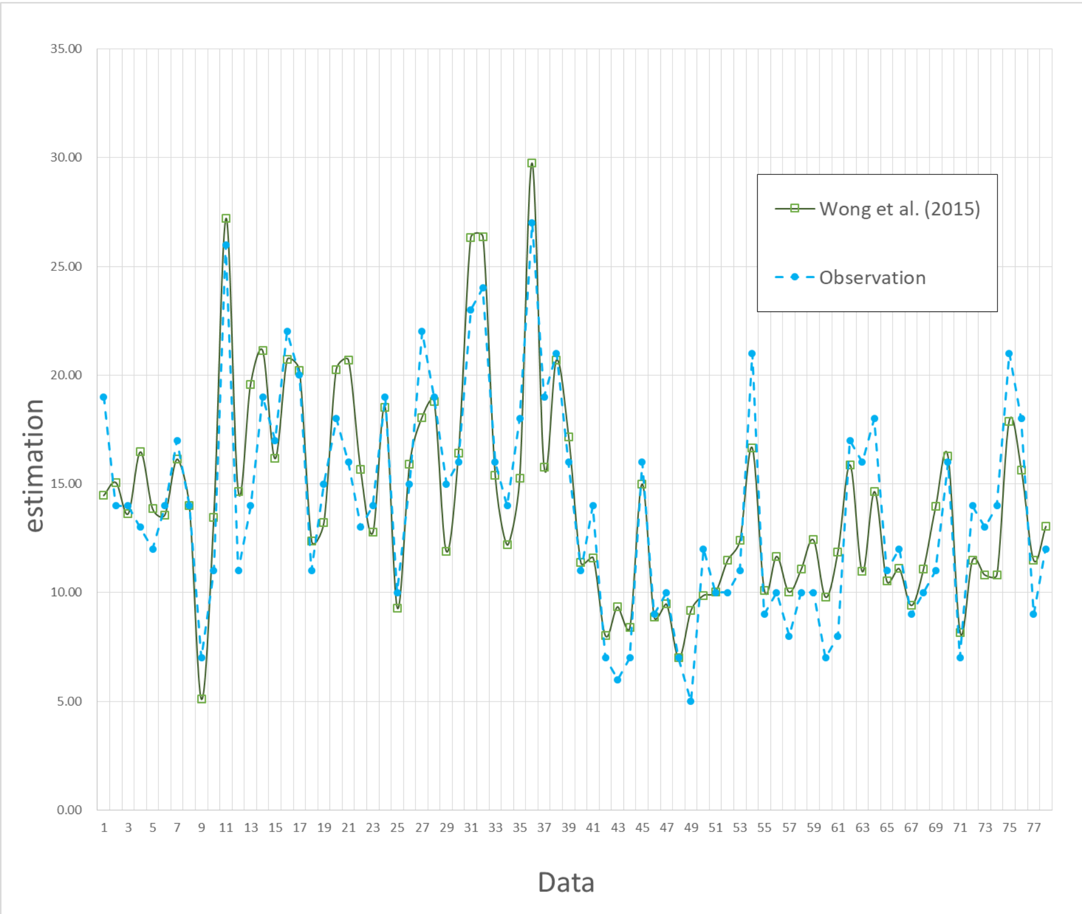


Figure 5.2.2 Wong et al. (2015) discharge time model (validated)

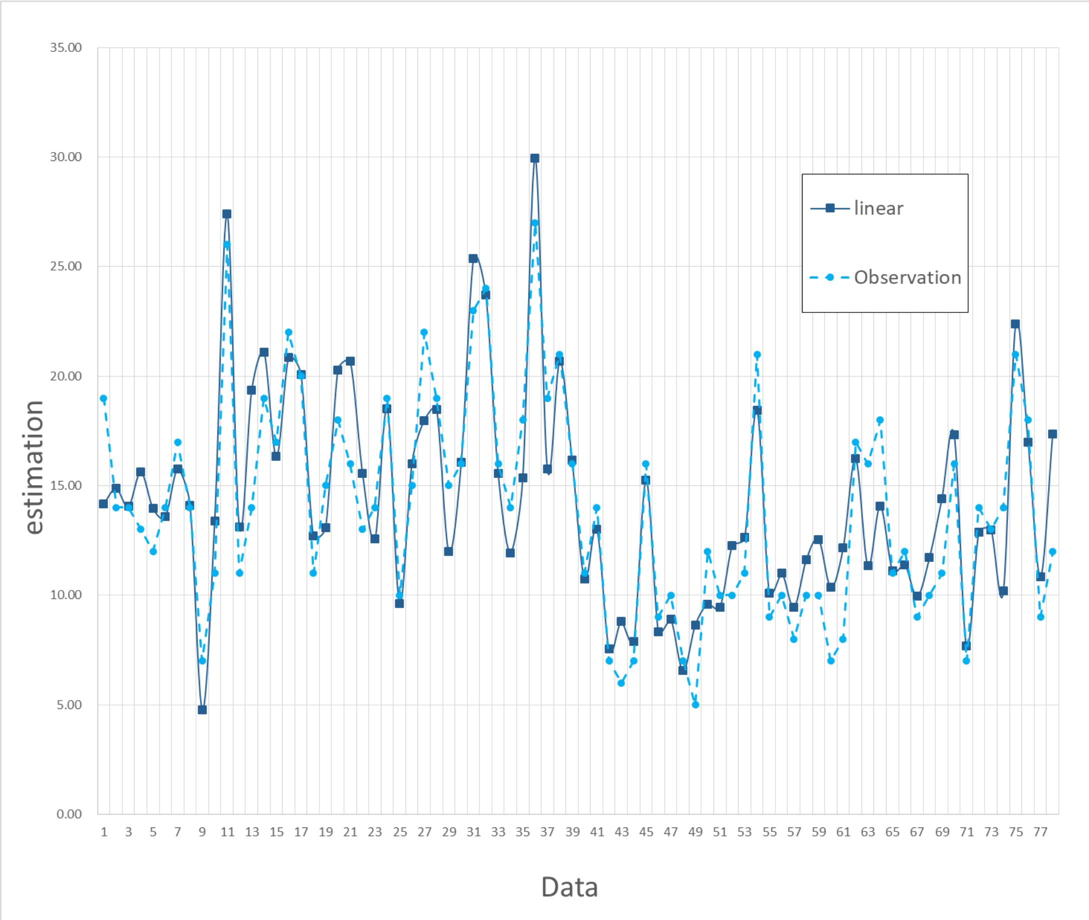


Figure 5.2.3 Linear discharge time model (validated)

In linear model, all the indicators are better than the model from Wong et al. (2015). The RMSE decreased by 0.03~0.12. Figure 5.2.3 shows the distribution of the linear model. The queue in the 4th lane is usually shorter than the 3rd lane. The results are still quite well that most of the results are close to the estimation.

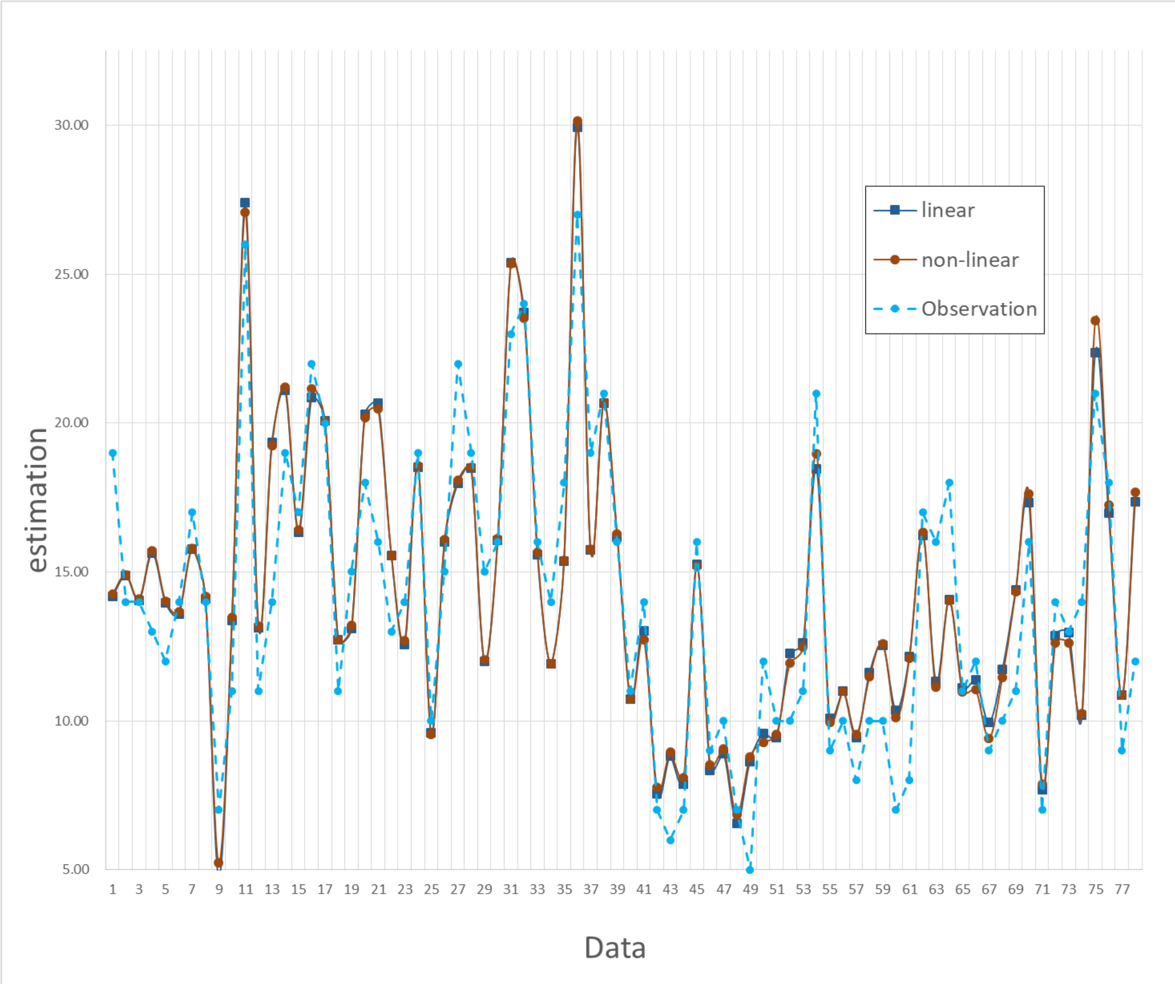


Figure 5.2.4 Linear v.s. Non-linear discharge time model

Table 5.2.3 and Figure 5.2.4, the model effect on the lane 3 and lane 4 is different. Lane 3 has less bias than lane 4. Comparing the linear and non-linear model under lane-based level, the results show no significant differences between both linear and non-linear model during the calibration and validation. Both structures can be used to revise the past model but more effort can be put on the non-linear model such as calibrating the model with other locations data.

After introducing the queuing pattern entropy to the model, all the indicators have better performance than the original model in Wong et al. (2015). In other words, the model of the research can overtake the previous model to describe the discharge time of the mixed-traffic flow. Although the estimation is similar but the model proposed in this research can estimate the discharge time with fewer variables and the structure of the model had been simplified. The research separates the validation data based on the location of the lane and found out that there still exists slightly differences on different lane's discharge but for a general estimation, the outcome is quite well.

Chapter 6 Conclusions

Recently, there are increasing interests in the study of mixed-traffic flow problems. This study investigates the discharge characteristics of mixed traffic flow with scooters and passenger cars at signalised intersections. It revealed that the model built in the past tried to construct the model based on the interaction between vehicles and considered the traffic composition and the way the vehicle queues up. Nevertheless, there is no study that can successfully develop a variable that is capable of describing the traffic composition and the queue pattern of the vehicles. Some findings from this study are summarised as follows:

1. As different from previous studies, this study makes use of drones to collect traffic videos for a wide study area, and an extraction tool is used to obtain microscopic vehicle trajectory data. The microscopic vehicle trajectory data offers new opportunities in observing the characteristics and interactions of mixed vehicles in the traffic.

2. This study analyse and discuss the behaviour of the vehicles during the queuing period. The results reveal the fact that the relative position of the vehicles will influence their reaction during the discharge procedure, especially related to the front vehicles. Under mixed flow, the change of the discharge order and queuing order often happened on the scooters; over 60% of the observations have occurred overtaking action above 30%. The lateral movement of the scooters will impede the flow of the discharge process; around 30% of the scooters have lateral movement over 1metre. In addition, It revealed that after the 9th~11th vehicles, the discharge headway will

gradually become unstable. The condition of the mixed flow needs to be valued.

3. The concept of the entropy from the information theory was applied to calculate the probabilities of the queue arrangement combined with the traffic composition. The queue pattern entropy (QPE) is designed to demonstrate the characteristics of vehicles' relative position during queue discharge. The QPE would be 0 when the queue only consists passenger cars or scooters. For the case of the maximum QPE value, which represents the most chaotic condition (scooters mixed up with the passenger cars entirely) of the mixed-traffic. The study then proposes a discharge time estimation model considering the patterns of the queue with mixed vehicles.

4. This study evaluates the performance of the proposed model by comparing with the models proposed in previous studies. After model calibration and validation process, the result revealed that both the linear and non-linear models can reduce Wong et al. (2015) model’s variable from 6 to 4 as well as simplified the model structure. The value of MAE, MAPE, and RMSE is around 1.76, 0.15, and 2.23; which is the lowest compared with other models. The comparison with HCM has been validated and investigate the cause of the underestimation on the discharge vehicles.

There are some suggestions for the future study as for the academia interested in developing the discharge time estimation under mixed-traffic flow condition:

1. The traffic composition of the discharge model only considered the passenger cars and scooters. Buses and other heavy vehicles are excluded from the model, therefore, future study can relax the constraint of this model to a

broader defined vehicles such as the traffic condition in India. The heterogeneous traffic in India consists at least 8 kinds of vehicles on road. How to deal with the influence of the various kinds of vehicle is the critical part of this problem statement.

2. Different turning function of the target lane should have different influence on discharge. For example, the right turn of the passenger cars will not only affect the later traffic but also the nearby lane. Future study can analyse and compare the cause of the differentiation, internalised the effect by constructing another variable.
3. The entropy in physics is used to describe a state of a system. The more chaotic the system is the higher value the entropy is. However, in queue discharge, the traffic flow has directional factors that the concept of QPE is not able to differentiate the difference of the discharge time on the queue. There may exist an influence on the discharge time due to different order of the queue pattern.
4. The adjustment or the improvement of the capacity estimation can be used to revise the existing model in HCM. In HCM, the deterministic estimation methods only require the number or proportion of the vehicle as well as the turning movement ratio. However, it has been proved that the queue patterns of the mixed traffic do influence the discharge time differently. If the variation of the queue pattern is high, it may lead to inaccurate estimation of the discharge time. The HCM could consider the stochastic effect such as the queue pattern entropy (QPE) to reduce the bias on the estimation.

References

Adams, C. A., Zambang, M. A. M., & Opoku-Boahen, R. (2015). Effects of Motorcycles on Saturation Flow Rates of Mixed Traffic at Signalized Intersections in Ghana. International Journal of Traffic and Transportation Engineering, 4(3), 94-101.

Akçelik, R., & Besley, M. (2002, June). Queue discharge flow and speed models for signalised intersections. In Transportation and Traffic Theory in the 21st Century: Proceedings of the 15th International Symposium on Transportation and Traffic Theory, Adelaide, Australia, 16-18 July 2002 (pp. 99-118). Emerald Group Publishing Limited.

Chand, S., Gupta, N. J., & Velmurugan, S. (2017). Development of Saturation Flow Model at Signalized Intersection for Heterogeneous Traffic. Transportation Research Procedia, 25, 1665-1674.

Chang, C. F. (2004). Effects of motorcycle queueing length on lane capacity at signalized intersections(號誌化路口機車車隊等候長度對混合車道容量影響之研究). M.S. Thesis, Department of Transportation Technology and Management, National Chiao Tung University. (in Chinese)

Chang, C. W., Lin, F. B. and Tseng, P. Y. (2008). Queue discharge characteristics and analytical models of shared straight-through / right-turn lanes with left-turn zone and waiting zone(設置機車待轉區及停等區之直行右轉共用車道疏解特性與分析模式). Transportation Planning Journal Vo1. 37 No. 3, 263 – 284.

Chang, C. W., Tseng, P. Y. and Cheng, C. M. (2007). Estimation of actual discharge width and capacity of exclusive motorbike lanes (機車專用道實際使用疏解寬度及容量估計之研究). Transportation Planning Journal Vo1. 36 No. 3, 371 – 392.

Chang, C. W., Tseng, P. Y. and Lin, F. B. (2007). Influences of Queue Discharge Characteristics on Signal Cycle Length for Signalized Intersections(停等車疏解特性對號誌週期長度之影響). Journal of the Chinese Institute of Transportation, 19(4), 363-382.

Chang, S. H., & Lee, D. Y. (2007). Driving environment complexity of mixed traffic flow. Journal of the Eastern Asia Society for Transportation Studies, 7, 2261-2273.

Cheng, H. K. (2014). Microscopic motorcycle discharging model at mixed traffic flow signalized intersections (混合車流號誌化路口微觀機車紓解模型之建立). M.S. Thesis , Department of Civil Engineering, College of Engineering, National Taiwan University. (in Chinese)

Chiou, Y. C., & Hsieh, C. W. (2012). Mixed traffic cell transmission models: Development and validation (混合車流格位傳遞模式之建立與驗證). Journal of the Chinese Institute of Transportation, 24, 245-276. (in Chinese)

Dey, P. P., Nandal, S., & Kalyan, R. (2013). Queue discharge characteristics at signalised intersections under mixed traffic conditions. European Transport, 55(7), 1-12.

Hsu, M. C. (2007). A study on ordered straight vehicles microscopic discharging models at the signalized intersection (號誌化平面交叉路口序別直行車微觀疏解模式之研究). M.S. Thesis, Department of Transportation Technology and Management, National Chiao Tung University. (in Chinese)

Huang, Y. C. (2015). Discharging Time Estimation Models for the Mixed Traffic Flow at Signalized Intersections (混合車流號誌化路口疏解時間預測模式之研究). M.S. Thesis, Department of Transportation and Logistics Management, National Chiao Tung University. (in Chinese)

Institute of Transportation (2011). Taiwan Area Highway Capacity Manual (台灣高速公路容量手冊). Ministry of Transportation and Communication, Taipei, 2011. (in Chinese)

Lan, C. L., & Chang, G. L. (2015). Empirical Study of Scooter–Vehicle Mixed Traffic Propagation on Urban Arterials. Transportation Research Record: Journal of the Transportation Research Board, (2491), 32-42.

Lee, T. C., & Wong, K. I. (2016). An agent-based model for queue formation of powered two-wheelers in heterogeneous traffic. Physica A: Statistical Mechanics and its Applications, 461, 199-216.

Lin, F. B. and Tseng, P. Y. (2005). Fallacies and implications of conventional saturation flow model of queue discharge behavior at signalized intersections. Journal of the Eastern Asia Society for Transportation Studies, Vol. 6, 2005, 1610 – 1623.

Lin, F. B., & Thomas, D. (2005). Headway compression during queue discharge at signalized intersections. Transportation Research Record: Journal of the Transportation Research Board, (1920), 81-85.

Lin, F. B., Tseng, P. Y., and Su, C. W. (2004). Variations in queue discharge patterns and their implications in analysis of signalized intersections. Transportation Research Record: Journal of the Transportation Research Board, (1883), 192-197.

Minh, C. C., & Sano, K. (2003). Analysis of motorcycle effects to saturation flow rate at signalized intersection in developing countries. Journal of the Eastern Asia Society for Transportation Studies, 5, 1211-1222.

Nakatsuji, T., Hai, N. G., Taweesilp, S., & Tanaboriboon, Y. (2001). Effects of motorcycle on capacity of signalized intersections. Infrastructure Planning Review, 18, 935-942.

Nguyen, H. D. (2016). Saturation flow rate analysis at signalized intersections for mixed traffic conditions in motorcycle dependent cities. Transportation Research Procedia, 15, 694-708.

Patel, P. N., Dhamaniya, A., & Katti, B. K. (2015). Effect of Mixed Traffic Characteristics on Saturation Flow and Passenger Car Units at Signalised Intersections. EUROPEAN TRANSPORT-TRASPORTI EUROPEI, (59).

Powell, M. (2000). A model to represent motorcycle behavior at signalized intersections incorporating an amended first order macroscopic approach, Transportation Research Part A, No. 34, 497 – 514.

Preethi, P., Varghese, A., & Ashalatha, R. (2016). Modelling Delay at Signalized Intersections under Heterogeneous Traffic Conditions. Transportation Research Procedia, 17, 529-538.

Radhakrishnan, S. and Ramadurai, G. (2015). Discharge headway model for heterogeneous traffic conditions. Transportation Research Procedia 10 (2015) 145 – 154.

Ramezani, H., & Benekohal, R. (2011). Analysis of Queue Formation and Dissipation in Work Zones. Procedia-Social and Behavioral Sciences, 16, 450-459.

Spyropoulou, I. and Sermpis, D. (2009). Performance of junctions with a high motorcycle proportion. Proceedings of the ICE-Transport, 162(2), 63-69.

Tang, R. Y. (1999). Study of the Lane Width and Discharging Pattern on Intersection for Motorcycle Lane (機車車道寬度與路口疏解型態之研究). Ministry of transportation and communications.

Transportation Research Board (2000) Highway Capacity Manual. Transportation Research Board, National Research Council, Washington, D. C.

Tseng, P. Y. et al. (2015). The grade adjustment factor of queue discharge behavior on divided urban streets (中央實體分隔路型停等車疏解能力之坡度調整因素). Transportation Planning Journal, 44(2), 145-167.

Tseng, P. Y., Chang, C. W. and Chen, W.B. (2006). Queueing discharge characteristics of unopposed left turns (無衝突左轉停等車之疏解特性). Transportation Planning Journal Vol. 35 No. 2, June 2006, 233 –260.

Wong, K. I. et al. (2015). Development of mixed-traffic simulation technology - behavior of motorcycles (混合車流模擬技術研發－機車行為研究). Ministry of Transportation and Communications, Taipei, 2015.

Wu, C. Y. (2007). A study on ordered unopposed left-turn vehicles microscopic discharging model at the signalized intersection (號誌化平面交叉路口序別無衝突左轉車微觀疏解模式之研究). M.S. Thesis, Department of Transportation Technology and Management, National Chiao Tung University. (in Chinese)

Appendix I Discharge headway data

The following table is the discharge headway of the selected site. Table A1 is the discharge headway on lane3. Table A2 is the discharge headway on lane4. The headway is calculated based on the sequential vehicle passed through the stop line. The information includes the mean, standard deviation, sample size, and the proportion of the scooters.

Table A1 Discharge headway on lane 3 of the 3 locations

Discharge order	location A				location B				location C			
	mean (s)	S.D. (s)	sample	Scooter (%)	mean (s)	S.D. (s)	sample	Scooter (%)	mean (s)	S.D. (s)	sample	Scooter (%)
1	4.19	1.96	21	0.38	3.08	1.56	22	0.77	1.38	1.01	13	0.92
2	2.38	1.18	21	0.29	1.25	1.08	22	0.68	2.26	1.90	13	0.46
3	2.28	1.07	21	0.10	1.93	1.85	21	0.67	2.14	1.11	13	0.38
4	2.49	1.00	21	0.05	2.12	2.26	21	0.38	2.08	1.20	10	0.30
5	2.57	1.13	19	0.00	2.03	1.79	21	0.24	2.20	0.85	10	0.10
6	2.30	0.73	16	0.00	2.38	1.24	20	0.05	1.39	0.83	5	0.20
7	2.44	0.99	13	0.00	1.67	0.73	19	0.16	2.29	0.58	4	0.00
8	2.64	1.08	8	0.00	2.18	0.74	15	0.00	2.87	1.13	3	0.00
9	2.51	0.84	4	0.00	2.32	0.84	12	0.00	3.33		1	0.00
10	2.11	0.62	2	0.00	2.49	1.16	8	0.00	3.77		1	0.00
11	1.67		1	0.00	2.24	0.47	7	0.00	2.06		1	0.00
12					2.14	0.62	3	0.00	3.95		1	0.00
13					1.67	1.71	3	0.00	2.75		1	0.00
14					0.66		1	0.00	0.08		1	0.00
15					2.68		1	0.00	2.80		1	0.00
16									1.07		1	0.00
17									1.67		1	0.00

Table A2 Discharge headway on lane 4 of the 3 locations

Discharge order	location A				location B				location C			
	mean (s)	S.D. (s)	sample	Scooter (%)	mean (s)	S.D. (s)	sample	Scooter (%)	mean (s)	S.D. (s)	sample	Scooter (%)
1	2.39	0.99	21	1.00	2.49	1.11	22	1.00	1.74	1.27	13	1.00
2	0.75	0.59	21	1.00	0.36	0.35	22	1.00	1.07	0.49	13	1.00
3	0.40	0.39	21	1.00	0.62	0.49	22	1.00	0.55	0.51	13	1.00
4	0.40	0.28	21	1.00	0.60	0.58	22	0.95	0.84	0.57	13	1.00
5	0.43	0.31	21	1.00	0.63	0.58	22	0.91	0.63	0.91	13	1.00
6	0.27	0.25	21	0.95	0.58	0.68	22	0.95	0.72	0.49	13	0.92
7	0.41	0.31	21	1.00	0.65	1.10	21	0.90	0.60	0.40	13	1.00
8	0.38	0.31	21	1.00	0.44	0.36	19	0.95	0.88	0.70	12	1.00
9	0.33	0.27	21	1.00	0.83	1.04	19	0.89	0.84	0.67	12	0.83
10	0.32	0.21	21	1.00	0.73	0.68	19	0.89	1.20	0.99	12	0.67
11	0.29	0.20	21	1.00	0.74	0.72	17	0.88	1.44	1.33	11	0.55
12	0.46	0.33	21	1.00	1.04	1.02	14	0.79	1.09	1.28	7	0.71
13	0.63	1.33	21	0.90	1.00	0.87	12	0.58	0.79	0.51	5	1.00
14	0.56	1.14	21	0.90	0.73	0.58	10	0.80	0.89	0.33	5	1.00
15	0.53	0.35	17	1.00	1.04	1.19	9	0.78	0.95	0.67	5	0.80
16	0.36	0.43	15	1.00	0.94	0.89	8	0.75	2.12	1.13	4	0.50
17	0.45	0.33	14	1.00	0.84	0.83	6	0.83	2.46	2.93	3	1.00
18	0.35	0.40	13	1.00	0.71	0.94	5	0.80	4.83	3.25	2	0.50
19	0.87	0.93	12	0.92	0.24	0.37	4	1.00				
20	0.44	0.30	10	0.90	0.38	0.30	4	1.00				
21	0.91	1.17	10	0.90	0.65	0.29	4	1.00				
22	0.42	0.32	9	0.89	0.48	0.26	4	1.00				
23	0.89	0.41	9	0.89	1.06	0.06	2	1.00				
24	0.78	0.65	8	0.88	1.24	0.50	2	0.00				
25	0.67	0.37	6	1.00	1.07	0.39	2	0.50				
26	0.92	1.08	4	0.75	1.42	1.90	2	0.50				
27	0.82	0.35	2	0.00								
28	0.45	0.48	2	1.00								
29	0.80	1.04	2	1.00								
30	0.82		1	1.00								
31	0.53		1	1.00								
32	0.05		1	1.00								