MICROSCOPIC SIMULATION ON THE OPERATION AND CAPACITY OF TOLL PLAZA IN MALAYSIA

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MICROSCOPIC SIMULATION ON THE OPERATION AND CAPACITY OF TOLL PLAZA IN MALAYSIA

by

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LIST OF ABBREVIATIONS

ACMs	Automatic coin machines
AM	Ante meridiem
ATC	Automatic toll collection
AVI	Automatic vehicle identification
CCTV	Closed-circuit television
CSC	Contactless smart card
DVR	Digital video recorder
DVUs	Driver-vehicle units
ETC	Electronic toll collection
HGV	Heavy goods vehicle
MHA	Malaysian highway authority
HOV	High occupancy vehicle
MOE	Measure of effectiveness
MTC	Manual toll collection
ORT	Open road tolling
PM	Post meridiem
UPS	Uninterruptible power supply

LIST OF SYMBOLS

C	Capacity
D	Difference between the observed and simulated MOE
H	Average headway of ETC
h	Hour
L_{stop}	Stop sight distance
n	Number of simulation runs
s	Second
t	t-test
T_i	Inter-vehicle time
V	Speed limit of the ETC lane
vph	Vehicle per hour

SIMULASI MIKROSKOPIK KE ATAS OPERASI DAN KAPASITI TOL PLAZA DI MALAYSIA

ABSTRAK

Perisian simulasi lalu lintas mikroskopik mempunyai beberapa kegunaan seperti penilaian prestasi, penambahbaikan pelan, operasi kawalan lalu lintas, reka bentuk dan pengurusan kemudahan pengangkutan. Kajian ini membentangkan penggunaan perisian simulasi lalu lintas terkenal, VISSIM dalam operasi lalu lintas bagi plaza tol di Malaysia. Kajian ini menilai keseluruhan operasi tol terhadap dua jenis plaza tol yang bersistem tertutup di lebuhraya Malaysia bagi mendapatkan pembolehubah yang mempengaruhi operasi tol. Pembolehubah ini memberi kesan terhadap keupayaan plaza tol yang sebenar dari segi purata dan panjang beratur yang maksimum. VISSIM telah digunakan untuk membina model plaza tol laluan utama dan plaza tol laluan susur iaitu masing-masing plaza tol Juru dan plaza tol Jawi, untuk mengkaji operasi tol serta kapasiti yang sebenar. Bagi tujuan simulasi operasi di tol plaza data mikroskopik untuk setiap kenderaan yang tiba dan berlepas dari plaza tol telah di perolehi melalui rakaman video. Rakaman video telah diambil daripada dua sumber. Sumber pertama adalah daripada kamera CCTV yang telah dipasang manakala sumber kedua adalah daripada kamera-kamera CCTV pihak PLUS yang terdapat di lorong tol. Data yang dikumpul di plaza tol Juru dan Jawi adalah berbeza dari segi bilangan lorong, konfigurasi lorong, bayaran tol, lokasi lebuh raya, permintaan lalu lintas, serta ciri-ciri komposisi lalu lintas. Model-model plaza tol ini kemudiannya telah ditentukur mengikut keberkesanan ukuran dan parameter penting supaya sepadan dengan operasi di plaza tol yang sebenar. Keputusan menunjukkan bahawa masa perkhidmatan adalah parameter yang paling penting untuk menilai operasi

di plaza-plaza tol. Selain itu, masa perkhidmatan untuk memasuki plaza tol adalah jauh lebih rendah berbanding masa perkhidmatan untuk keluar tol. Dapatan kajian menunjukkan bahawa peratusan aliran lalu lintas bagi kenderaan berat mempunyai kesan yang besar terhadap panjang beratur di plaza tol Juru dan Jawi. Selain daripada itu, model-model tersebut juga telah digunakan untuk meramalkan operasi plaza tol-plaza tol pada masa hadapan iaitu setelah kutipan tol secara elektronik (ETC) dilaksanakan sepenuhnya. Dapatan-dapatan ini menunjukkan bahawa pelaksanaan ETC penuh pada bahagian masuk di kedua-dua plaza tol Juru dan plaza tol Jawi tidak menambah baik operasi plaza tol. Walau bagaimanapun, pelaksanaan ETC penuh di pintu keluar telah menambah baik operasi tol dengan lebih ketara. Telapi, pelaksanaan ETC penuh di pintu keluar Plaza Tol Jawi telah mempengaruhi secara negatif panjang barisan di lorong-lorong Touch 'n Go dan Smart TAG disebabkan oleh kedudukan persimpangan lampu isyarat yang berhampiran dengang plaza tol Jawi. Kajian ini telah membenkan dua sumbangan kepada operasi trafik di plaza tol. Sumbangan pertama ialah berkaitan ramalan operasi trafik di plaza tol pada masa akan datang selepas pelaksanaan sistem kutipan tol elektronik sepenuhnya di plaza tol konvensional. Sumbangan kedua ialah berkaitan anggaran kapasiti sebenar di plaza tol konvensional.

MICROSCOPIC SIMULATION ON THE OPERATION AND CAPACITY OF TOLL PLAZA IN MALAYSIA

ABSTRACT

Microscopic traffic simulation software has several applications, such as performance evaluation, plan improvements, traffic operation control, design, and transportation facility management. This study presents the application of the well-known traffic simulation software VISSIM in the operation of toll plazas in Malaysia. This study evaluates the overall toll operation of two types of closed system toll plazas in the Malaysian expressway to gain insight into the variables that influence toll operations, which in turn affect the actual capacity of toll plazas in terms of average and maximum queue length. VISSIM was used to build toll plaza models for the mainline and ramp toll plazas which are Juru and Jawi respectively, to study their toll operations and actual capacities. In order to simulate the toll operations at toll plazas, microscopic data were obtained for each vehicle arriving and departing the toll plazas through video recordings. Video recordings were taken from two sources. The first source was from the installed CCTV and the second source was from the PLUS CCTV cameras at the tollbooths. The collected field data of the Juru and Jawi toll plazas differed in terms of number of lanes, lane configuration, toll base fee, expressway location, traffic demand, and traffic composition characteristics. The toll plaza models were then calibrated according to the measure of effectiveness and key parameter to match real world toll operations at toll plazas. Results revealed that service time is the most important parameter for evaluating the toll operation of toll plazas. Moreover, service time for entry is much lower than the service time for exit. The findings indicated that the percentage of heavy vehicles in traffic flow has a significant impact on the queue lengths at the Juru and Jawi toll plazas. Apart from that, the models were used to predict the operation of toll plazas in the future upon implementation of full electronic toll collection (ETC). The results indicated that the implementation of full ETC at the entry of both the Juru and Jawi toll plazas did not improve the operations of the toll plazas. However, the implementation of full ETC at the exit significantly improved the toll operations. But, the implementation of full ETC at the exit of the Jawi toll plaza has negatively influenced the queue lengths of Touch 'n Go and Smart TAG lanes due to the location of the signalised intersection which is near to Jawi toll plaza. The study has managed to contribute to two major findings at the traffic operations at toll plaza. The first contribution is on the prediction of traffic operation at the toll plaza in the future after the implementation of full electronic toll collection system at conventional toll plazas. The second contribution is on the estimation of the actual capacity of the conventional toll plazas.

CHAPTER ONE
INTRODUCTION

1.1 Background

Highways and expressways provide support for local, regional, and national transportations of services and goods, and they are indispensable to economic activities because it would be impassable for modern lifestyle to continue without them. Many activities such as work, education, shopping, tourist, and social activities are generating a demand for trips.

Congestions normally occur when drivers are commuting from home to work and back again. Furthermore, the presence of toll plazas at the expressway slows down the traffic thus creating traffic congestion and jams during rush hours.

There are many existing toll plazas in Malaysia and they are increasing in number in Malaysian expressways because of the process of development, which mean more congested points on the expressway. Traffic congestions at these facilities have become a serious problem in Malaysia.

Malaysian toll plazas are considered as conventional toll collections in which the most common method of toll collection is manual. A toll collector/ attendant is required at the tollbooth to collect cash, dispenses change (if any), issue ticket and receipt to patrons (upon request), and also complete the electronic transactions in a multiclass lane.

The toll lanes in Malaysian toll plazas are mainly divided into three types according to vehicle class and mode of payment: mixed mode, Touch 'n Go, and Smart TAG lanes. The most congested lane is the mixed mode lane, where most of the long queue lengths occur during the peak hours.

The application of traffic simulation software has become a very popular tool for traffic analysis in recent years. Therefore, in order to investigate the operation and capacity of toll plaza in Malaysia, microscopic simulation approach was adopted. By using the microscopic traffic simulation software, traffic engineers and planners are capable of visually observing the problem areas in the network. Also, these software are capable of providing many useful output data for analysis, like queue length, delay, travel time, etc.

The microscopic traffic simulation software, VISSIM, was selected to simulate the selected toll plazas in this study. It is capable of analyzing the operation of toll plazas and the behavior of different types of vehicles at the area of the toll plazas. VISSIM displays the simulated traffic flow with 3D animations, as well as large amount of output data.

1.2 Problem statement

The increased use of tollways and their associated toll plazas is a continuing trend in Malaysia due to increasing number of vehicles along federal routes, opening of major ports and airports, and increasing population in major cities and towns. One of the major reasons for traffic congestions in expressways is because of the conventional toll collection at the toll gates. Every vehicle that passes through a toll plaza experiences certain delays depending on type of payment and queues start building up when traffic volume for one payment type exceeds the capacity of the plaza for one or all of the payment types.

A toll plaza is a structure built on an expressway where every vehicle has to pass through to make a payment, which is a reason for severe traffic congestion occurring during peak hours. As such, toll plazas are considered as a unique component of a transportation system, which requires a special analysis for an in-depth understanding of the operation of toll plazas and identifying factors affecting the operations of toll plazas such as upstream traffic volume, traffic composition, service time, number of toll lanes, toll lane capacity, and desired speed.

Due to complexity in analytically analyzing the operations of toll plazas, analyses of toll plazas using microscopic simulation software drew attention in recent years. It is often used as an alternative or complementary tool for analytical methods and procedures for road traffic facilities, and, more importantly, for prediction of future performance based on forecasted or expected changes in vehicle travel demand patterns or potential operational strategies.

Toll plaza in Malaysian expressways system is an interesting subject to be studied due to two reasons. Firstly, traffic along the expressway is heterogeneous with mixed vehicle composing of car, small lorry, truck, trailer, and bus. Secondly, the toll collection system consists of both the manual and electronic toll collection, therefore the payment time and operation will vary according to the vehicle class. Furthermore, the automatic vehicle identification (AVI) system has yet to been adopted in Malaysia therefore, vehicles such as small lorry, truck, trailer and bus are prohibited from using the electronic toll lanes. Thus, this study tackles the question of how a toll plaza operates with heterogeneous traffic flow. Moreover, due to the complexity of the traffic operations of conventional toll plazas, it is very important to develop prediction models to calculate the actual capacity of different types of toll lane at the Malaysian conventional toll plazas. Also, for future improvement on the Malaysian expressways system, it is necessary to predict the efficiency of implementing the full electronic toll collection (ETC) system at conventional toll plazas.

Figure 1.1 shows the traffic jam conditions at toll plazas during peak hours in Malaysia.

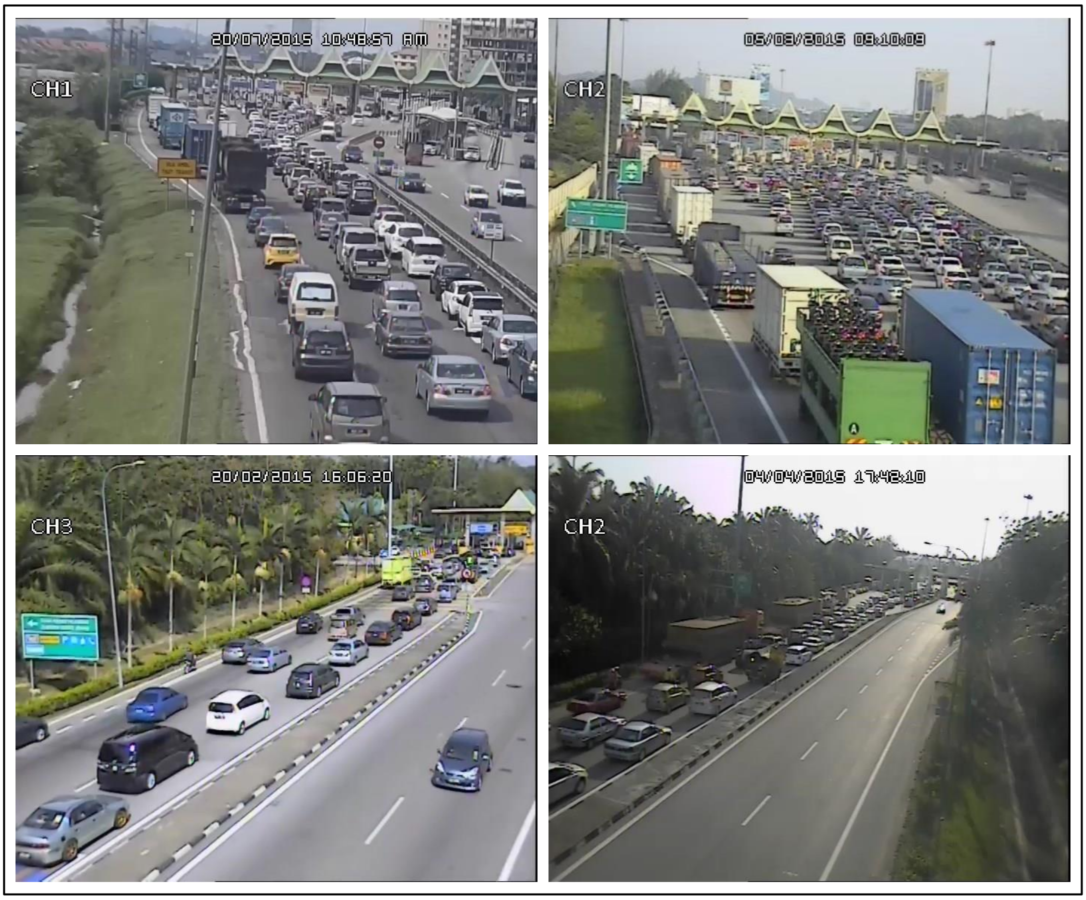


Figure 1.1 Conditions of traffic jam at toll plazas during peak hours in Malaysia. (From the study CCTV recordings)

1.3 Research objectives

The main objective of this thesis is to assess the overall operations of two types of toll plazas in Malaysia using microscopic traffic simulation model VISSIM. The two types of toll plazas are the mainline and ramp toll plazas.

The specific objectives of this thesis are summarized as follows:

1. To investigate the operation and service time for each toll lane type;
2. To examine the effect of traffic composition on queue lengths at toll plazas;
3. To develop equations to calculate the actual capacity of the conventional toll plazas;
4. To predict the effectiveness of implementing a full ETC system of the operation on conventional toll plazas in the future.

1.4 Scope of the study

This study focuses on the assessment of the overall traffic operations of the two types of closed system toll plaza in the Malaysian expressway. The selected toll plazas are the Juru toll plaza (a mainline toll plaza) and the Jawi toll plaza (a ramp toll plaza). Each toll plaza differed in terms of the number of lanes, lane configuration, toll base fee, highway location, traffic demand, and traffic compositions. The video recording approach was used to collect data. The field data collections for each toll plaza are categorized into three categories, layout of toll plaza, traffic, and vehicle characteristics.

A microscopic simulation software called VISSIM was used to build models for the Juru and Jawi toll plazas to study their toll operations and actual capacities. The toll plaza models were calibrated according to the measure of effectiveness (MOE) and key parameter to match real -world toll operations at toll plazas.

Finally, the calibrated toll plaza models were used to examine the effect of heavy vehicles and the effectiveness of full ETC.

1.5 Thesis structure

This thesis is documented in six chapters organized as follows:

Chapter 1 introduces the background of the problem and the objectives of the study.

Chapter 2 provides a literature review of the general overview of toll plazas and discusses different traffic simulation software packages available for modelling toll plazas.

Chapter 3 presents the methodology of this research study and proposed affective parameters on the operations and capacities of toll plazas, describing also the general steps taken to build the toll plaza model using the VISSIM software.

Chapter 4 presents the results and discussion on the findings from data analysis.

Chapter 5 presents the development of toll plaza models and the models simulation outputs.

Chapter 6 presents the conclusions and the recommendations of the study.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter is divided into two main sections. The first section provides a general overview of toll plazas and the second section discusses the different traffic simulation software packages available for modeling toll plazas.

2.2 Toll plaza

A basic understanding on the general operation and configuration of toll plazas is necessary before the discussion of traffic simulation software. The general operation and configuration of toll plazas are based on basic elements that may differ across various plazas.

2.2.1 What is a toll plaza?

Toll plaza is frequently referred to by the media, the public, and even designers as toll lanes, toll barriers, and tollbooths. Actually, a toll plaza is all of these. However, a toll plaza is defined as the area where tolls are collected. This area starts where the approach roadway pavement widens, continues through the toll barrier or collection point, and ends where the pavement returns to the normal roadway cross section (Cherng et al., 2005). Toll plaza can be defined as a structure where every vehicle has to either decelerate or stop to pay toll on an expressway (Dubedi et al., 2012). Figure 2.1 shows a typical toll plaza divided into five areas or zones, which include the approach (transition) zone, the queue area, the toll island or barrier, the recovery (merge) zone, and the departure (transition) zone (Cherng et al., 2005).

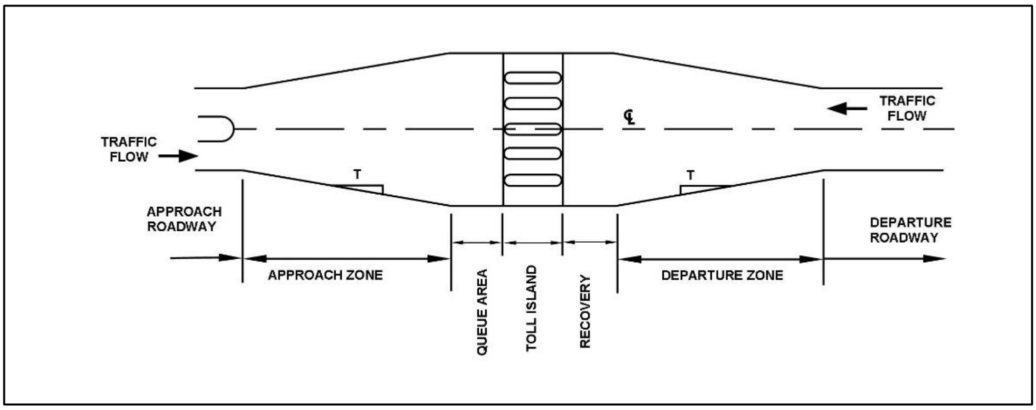


Figure 2.1 A typical toll plaza layout (Pickett et al., 2008).

2.2.2 Types of toll systems

Toll systems are primarily classified into two types according to the operating characteristics of the toll plaza.

2.2.2(a) Open toll system

An open toll system is typically adopted in an urban area or at the edge of an urban area. The local traffic normally uses this facility, and a majority of travelers are committed to this toll system, with a minimum likelihood of switching to the parallel free route (Mathew and Bombay, 2014a). The toll rates in this toll system depend solely on the vehicle classes. Figure 2.2 shows the general layout of an open toll system.

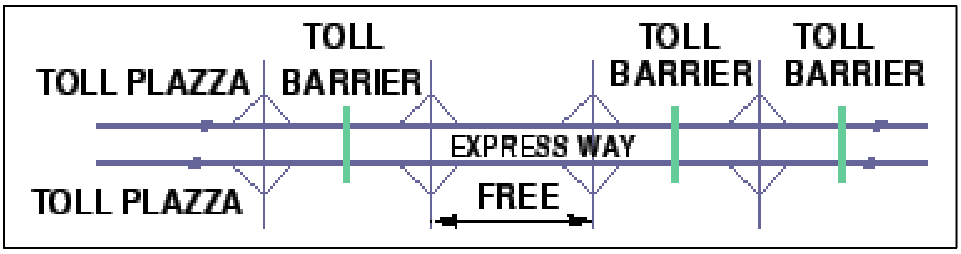


Figure 2.2 Open toll system (Mathew and Bombay, 2014).

2.2.2(b) Closed toll system

No free rides exist in a closed toll system. Plazas are located at all entry and exit points of an expressway. A patron receives a ticket upon entering the expressway. Upon exiting, the patron delivers the ticket to the collector and is charged a scheduled fee from the point of entry to the point of exit based on vehicle class and distance traveled (Mathew and Bombay, 2014a). Figure 2.3 shows the general layout of a closed toll system.

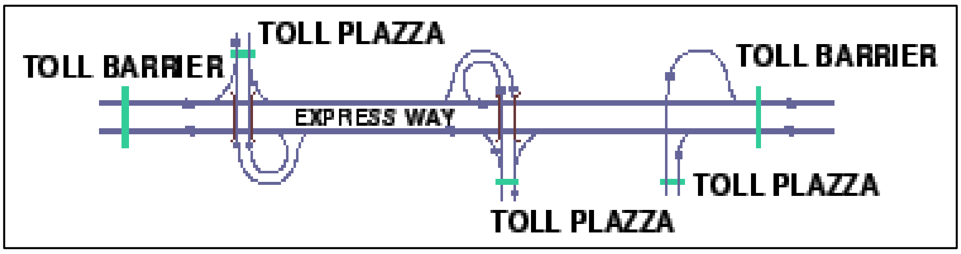


Figure 2.3 Closed toll system (Mathew and Bombay, 2014).

The major differences between the open and closed systems lie in their operating costs and the initial investments in the toll plazas. Furthermore, a closed toll system has only two stops for traveling vehicles, whereas an open toll system can have several stops.

2.2.3 Toll plaza configurations

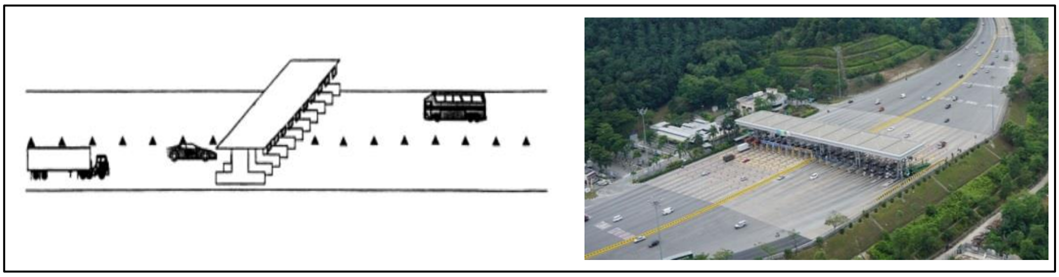
Toll plaza configurations are mainly determined by the toll system type, traffic demand, toll rate schedule, toll collection method, and physical and environmental site constraints. Figure 2.4 shows some of the common toll plaza configurations: a two-way toll plaza barrier, a mainline split toll plaza (two types), a conventional toll plaza split barrier with ETC/ HOV vehicle lanes, and a tandem (staggered) tollbooth. In a tandem (staggered) tollbooth, two or more tollbooth collectors are located in a single lane and serve alternating sets of vehicles at the same time (Hong et al., 2010). The tandem (staggered) tollbooth is a possible solution to expand the capacity of the manual toll lanes or that of the toll plaza in general (Hong et al., 2009).

In Malaysia, a majority of the toll plazas adopt the two-way toll plaza barrier type.

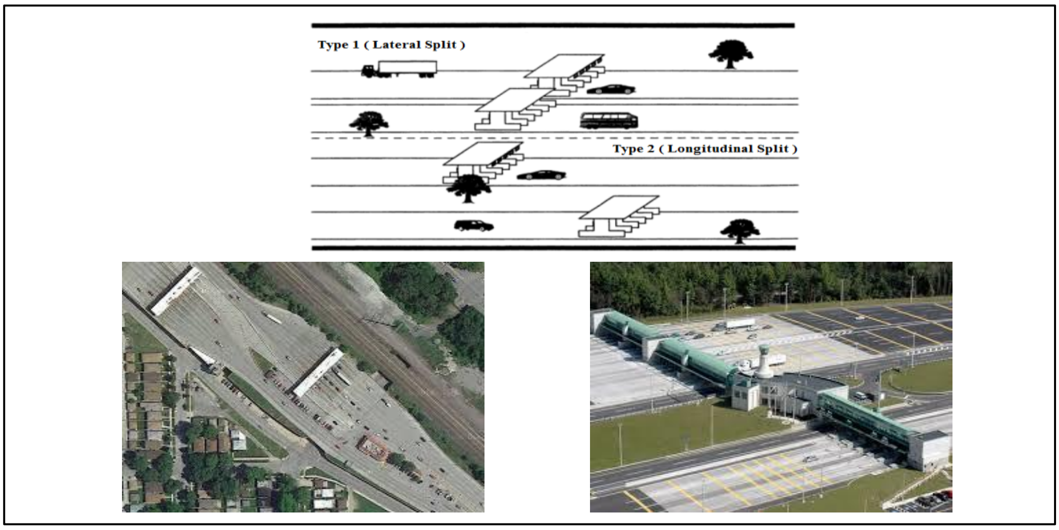
2.2.4 Closed toll system categories

Generally, toll plazas adopting a closed toll system fall into two categories: ramp and mainline. Both can be designed to handle one-way or two-way toll collection. A mainline toll plaza is a series of toll lanes operating perpendicular to the roadway direction. It is used for tunnel facilities, bridges, and toll roads in conjunction with a ramp toll plaza. The selection of which category of toll plaza to adopt depends on the adopted toll collection method (McDonald and Stammer, 2001).

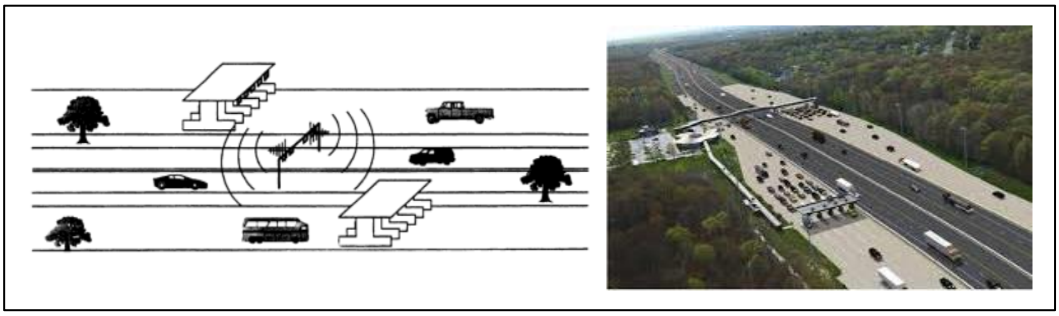
Both ramp and mainline toll plazas can have a split design. For a toll plaza, a split design means two individual toll plazas, each one serving different roadway directions. This design is adopted to maximize the available space or reduce the right-of-way required. This design is usually used if directional traffic peaks occur in a conventional two-way toll plaza. As an alternative to the split toll plaza, median ETC/HOV lanes or bypass lanes have been proposed (Mathew and Bombay, 2014a).



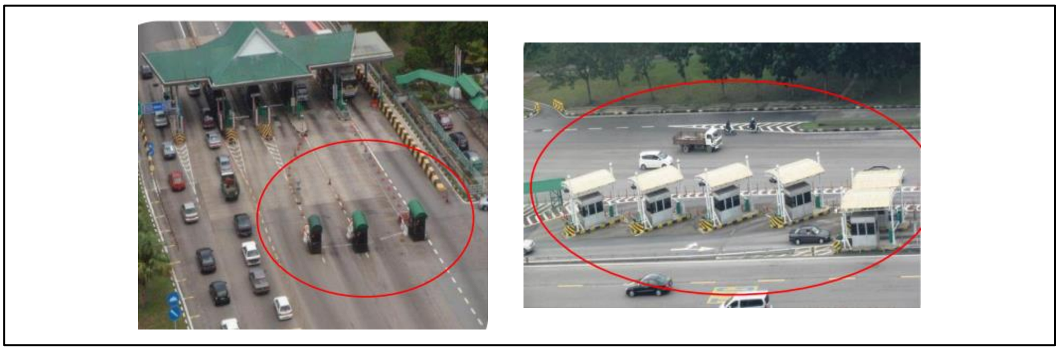
(a) Two way toll plaza barrier



(b) Mainline split toll plaza (2 types)



(c) Conventional toll plaza split barrier-Express with ETC /(HOV) vehicle lanes



(d) Tandem (staggered) tollbooth

Figure 2.4 Typical toll plaza configurations (Pickett et al., 2008).

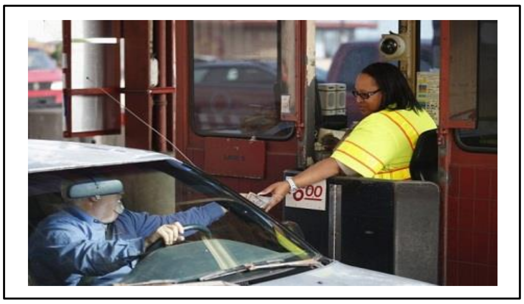
2.2.5 Toll collection methods

The three general toll collection methods (Jack Klodzinski and Al-Deek, 2002a) include manual (cash) toll collection (MTC), automatic toll collection (ATC) by automatic coin machines (ACMs), and electronic toll collection (ETC). MTC (Figure 2.5a), requires a toll collector or an attendant in the booth to receive cash and also make change, provide tickets and coupons, reload card accounts, issue receipts to patrons, and specify the classes of vehicles in multiclass lanes. For ATC using ACMs, as shown in Figure 2.5b, the patron can deposit coins or tokens issued by the operating agency in the ACM basket. ACMs are usually installed in a toll lane designated for a particular vehicle class whose exact cash toll is less than a dollar. Depending on the toll rate, the use of ACMs is more efficient than MTC. Compared with MTC, ATC by ACM reduces processing and transaction times, as well as operating costs (Pietrzyk, 1994).

In ETC (Figure 2.5c), a road pricing concept is implemented to reduce toll paying time, increase the capacity of toll plazas, minimize air pollution, and enhance the convenience and safety of travelers. ETC is accomplished with the use of an automatic vehicle identification (AVI) system (Lee et al., 2008; Sharma, 2014; Venable et al., 1995). As a vehicle equipped with a valid encoded data transponder or tag moves through an ETC lane, the ETC system posts a debit to the account of the patron. The ETC method increases the capacity of a single toll lane by eliminating the need to stop at the tollbooth (Astarita et al., 2001).

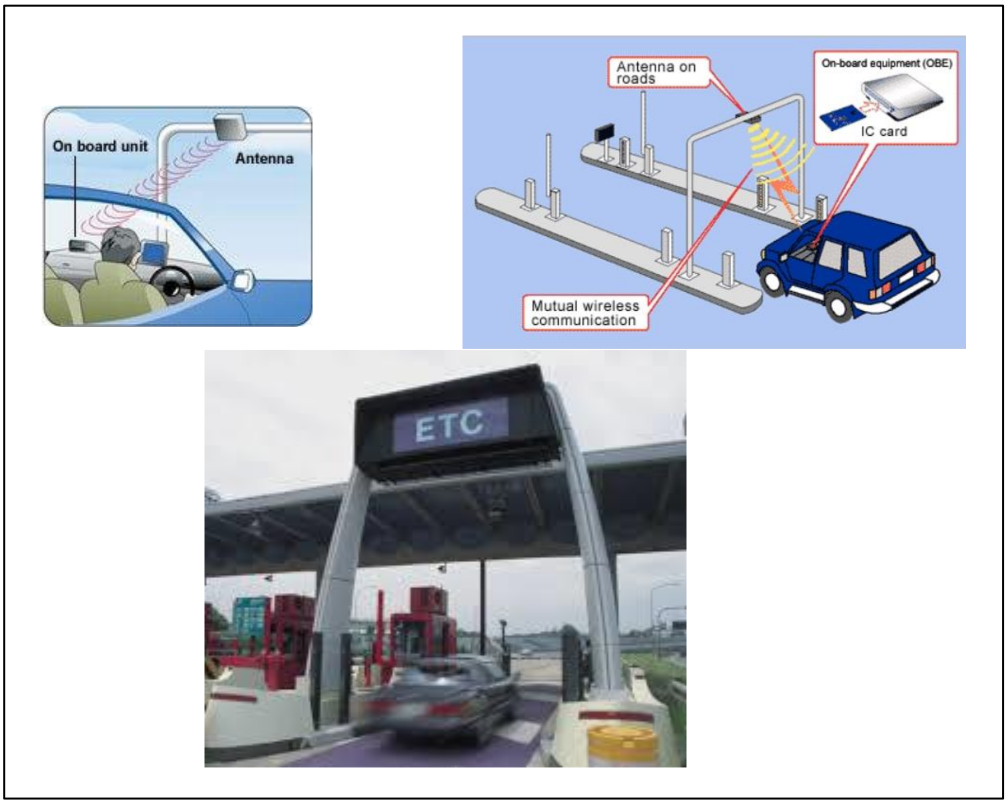
In Malaysia, the toll collection methods are similar to the aforementioned three types with certain modifications. MTC is the most common method used in Malaysia, following the typical collection setup previously mentioned. In the second method, the Touch 'n Go card, which uses contactless smartcard technology, is used as the mode of payment for ETC. A user can continue using the card as long as it is pre-loaded with electronic cash, which can be reloaded at various Touch 'n Go hubs. Touch 'n Go enhances the speed of paying for low-value but high-frequency transactions. Aside from having an advantage in terms of speed, this method is also very convenient for users, who do not need to wait for their change or wait in queue in the cash lane to complete their transactions. However, both the MTC and Touch 'n Go toll collection systems require vehicles to stop to pay.

The third method, which is another form of ETC system uses Smart TAG technology. An on-board unit, which works in combination with the Touch 'n Go card, allows users to pay the toll with drive-through convenience. Smart TAG transmits information between the Touch 'n Go card and the toll system via infrared in the dedicated lane. It allows for non-stop ETC as the system can process payment transactions for passing vehicles running at a maximum speed of 20 km/h. However, the Smart TAG method can be used only in a toll lane designated for a particular vehicle class because it does not use an AVI system.



(a) Manual toll collection (MTC)

(b) Automatic coin machine (ACM)



(c) Electronic toll collection (ETC)

Figure 2.5   Methods of toll collection (Kato, 2001).

2.2.6 Traffic flow process at a toll plaza

Gulewicz and Danko (1995) described a general process for the traffic flow in a toll plaza. The process starts as an arriving vehicle travels from upstream into the approach zone. Once the vehicle reaches the approach zone, it decelerates and starts to scan the toll plaza configuration. The vehicle checks which of the toll lanes matches its desired mode of payment. This lane becomes the initially desired toll lane of the vehicle. As the vehicle travels in the approach lane, it tries to access the approach lane that leads to its initially desired toll lane. Then, as soon as the vehicle reaches the beginning of the queue area (Al-Deek and Mohamed, 2000), the vehicle assesses if any queue exists in its initially desired toll lane. If no queue exists in this lane, it enters the tollbooth and pays the toll. If a queue exists in its initially desired toll lane, the vehicle selects the toll lane with the shortest queue length. The queue may probably build in a toll lane when the number of arriving vehicles selecting that particular toll lane exceeds its capacity. After payment, the vehicle continues with its travel through the recovery zone and then the departure zone. Finally, the vehicle reaches the expressway lanes (Lang et al., 2011). Figure 2.6 shows the general flowchart for traffic flow process at toll plazas in Malaysia.

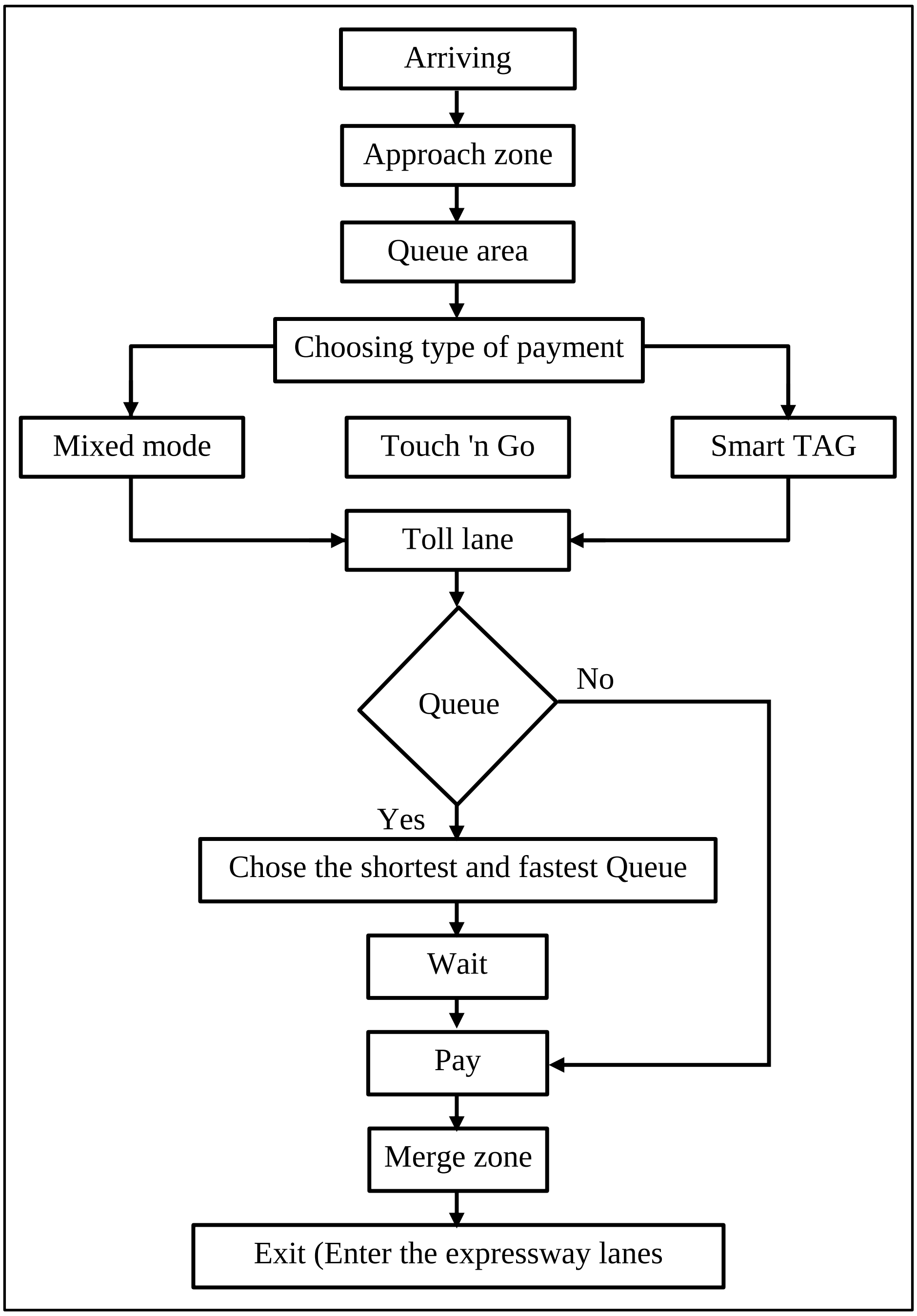


Figure 2.6 General flow chart of traffic flow process at toll plaza in Malaysia.

2.2.7 Operation of toll plaza

Toll plazas are traffic bottlenecks on toll roadways. Every vehicle that passes through a toll plaza experiences certain delays depending on its payment type (Aycin et al., 2010). Delays and queues caused by waiting times at tollbooths are one of the main issues in the relationship between upstream traffic flow and the toll plaza performance, and the evaluation of the operational performance is important for the optimization of the service at toll plazas (Oliveira and Cybis, 2006). The performance of a toll plaza can be significantly influenced by a number of factors, such as service time, number of available toll lanes, vehicle arrival pattern, queue lengths, and driver behavior.

According to Padayhag and Sigua (2003), the key indicators of the performance of a toll plaza include the service times for the different modes of payment, the capacity of the toll lane, and the queuing delay or waiting time of a vehicle. Klodzinski and Al-Deek (2004) presented other important toll lane performance indicators, namely, queue length, throughput, and inter-vehicle time. These performance indicators are described as follows (Boahen et al., 2013; Klodzinski and Al-Deek, 2004):

1. Throughput is the number of vehicles departing from the toll plaza per lane per hour in a direction. (throughput should not be confused with capacity).
2. Capacity is the highest vehicle number a toll lane collection system can process in an hour (Hendrickson and Ritchie, 1998).
3. Inter-vehicle time is the time difference between two consecutive vehicles as they stop to pay the toll at the tollbooth:

$$\text{Inter-vehicle time } (Ti) = \text{Service time} + \text{Vehicle headway} \quad (2\text{-}1)$$

The inter-vehicle time is used to calculate the capacity of a conventional toll lane (AL-Deek et al., 1996).

4. Vehicle headway is the time it takes for a vehicle to proceed from queuing position to a complete stop at tollbooth payment position as soon as the lead vehicle departs from the same tollbooth payment position.
5. Service time is the time a vehicle spends to complete a transaction at the tollbooth until it starts to move. Service time of vehicles need to stop to make the payment consists of two components; transaction time and start-up delay time.
6. Start-up delay is the time from the end of the transaction until the time the vehicle starts moving.
7. Queue length is the number of vehicles queuing in each lane and waiting to be served for an entire hour during peak hours.
8. Total queuing delay is the time spent by all vehicles waiting in queue in toll plaza lanes.

Figure 2.7 shows the service time and inter-vehicle time of vehicles in toll plaza lanes. In the figure, the time taken when vehicles approach the toll plaza, and decelerate until stop at the booth to make the payment, is the service time. Each vehicle has specific service time according to its category. After making the payment, the vehicle will start moving and continue their journey. The inter-vehicle time is the time calculated from the start moving of the first vehicle at the tollbooth until the stopping time of the second vehicle at the same point of the tollbooth.

The average service time spent in a toll system is used as the measure of effectiveness (MOE) to assess the quality of service at toll plazas (Lin and Su, 1994). An estimation of this parameter helps in evaluating the operational performance of a toll plaza. The service time in a toll lane is the main input parameter in the simulation model to represent the toll plaza performance (Klodzinski, J. and Al-Deek, 2002; Zhong et al., 2014).

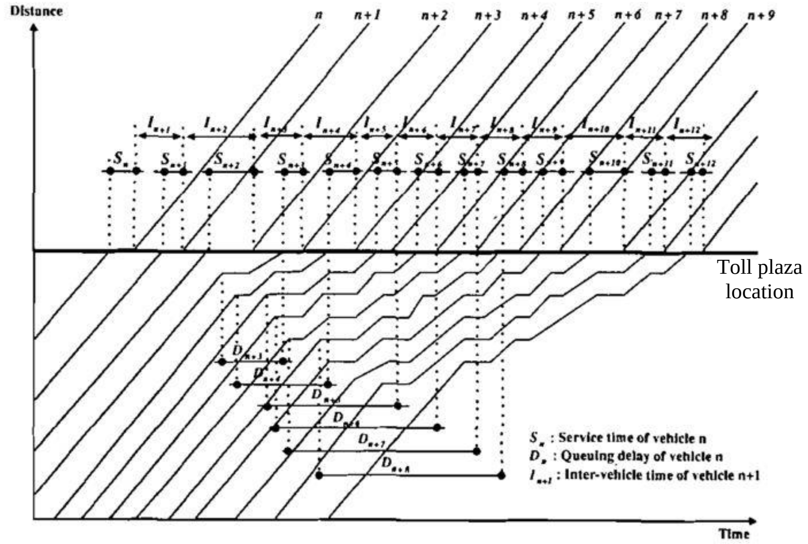


Figure 2.7 Trajectories of vehicles at toll plaza lane (AL-Deek et al., 1996).

2.2.8 Service time and capacity of the toll plaza

Service time, in its general definition, is the time interval between the time when the wheels of a vehicle stop rolling at the tollbooth and the time when they start rolling again. In another words, service time is the time a vehicle spends to complete a transaction at the tollbooth; it does not include the delay time in the queue before entering the tollbooth (AL-Deek et al., 1996; Padayhag and Sigua, 2003).

Service time is an important parameter for the evaluation of the operational performance of a toll plaza. Several factors influence the actual service time in ATC by ACM and MTC, such as the type of vehicle making the payment (Oliveira and Cybis, 2006; Woo and Hoel, 1991; Zarrillo, 1998; Zarrillo and Radwan, 2009), the fee value (Oliveira and Cybis, 2006), the traffic composition (Zarrillo et al., 2002, 1997), the processing efficiency of the ETC technology, and the efficiency of the tollbooth attendant (AL-Deek et al., 1996). These factors are helpful in understanding questions such as why cars have different service times from trucks, or why the vehicles of the same class have different service times for same direction of the travel.

In a conventional tollbooth, service time is measured from the time the vehicle stops at the tollbooth until it starts moving. For non-stop ETC lanes, the vehicle must decelerate within the speed limit while passing through the toll plaza. Given that the ETC vehicle transacts without stopping at the tollbooth, the service time for the ETC vehicle in this case is equal to zero (Zhong et al., 2014).

Service time and move-up time values should represent different vehicles type in a mixed-mode traffic flow. Furthermore, the service time for each vehicle class is obtained by field observation (Aycin et al., 2010).

Service time has the most significant influence on the capacity of a toll plaza (Oliveira and Cybis, 2006; Russo et al., 2010) . Each toll lane type is characterized by its own service time distribution (Astarita et al., 2001).

The capacity of a toll lane is defined as the maximum hourly rate of vehicles that can pass through the toll lane. Generally, the capacity is calculated from the throughput of the toll lane when the toll lane utilization is 100% at the saturated or queued conditions of the upstream traffic flow (Zarrillo, 2000).

Toll plaza capacity depends on:

1. Number of toll lanes at the toll plaza.
2. Type of toll lanes.
3. Traffic composition.
4. Methods of payment.

Usually, traffic flow is a mixture of different types of vehicles that introduce different operations of the toll lanes. These differences cause a variety of service times, furthermore traffic flow which contains a significant number of heavy vehicles will reduce the toll plaza capacity because of their higher service times (Lin, 2001; Lin and Su, 1994).

Although the influence of heavy vehicles on the intersections and highway roadways has been conducted in several studies (Al-Kaisy et al., 2005, 2002; Benekohal and Zhao, 2000; Broaddus and Gertz, 2008; Cunha and Setti, 2011; Dey et al., 2008; Kockelman and Shabih, 2000; Venigalla and Krimmer, 2006), none of these studies present in detail the influence of heavy vehicles on the performance of toll plazas with the use of microscopic traffic simulation. Thus, this thesis investigates the influence of heavy vehicles on the operation of toll plaza.

Capacity of toll lane can be measured in the field that is when the queued condition lasted for a full hour, by counting the vehicles exiting the toll lane. Capacity can also be calculated using the average inter-vehicle time during the saturated hour in which the hour (3600 s) is divided by the average inter-vehicle time (Boahen et al., 2013).

The tollbooth capacity (vehicles per hour or vph) for various collection methods can be calculated simply by Equation (2-2) (Al-Deek et al., 1997; Aycin et al., 2010) :

$$C = \frac{3600}{Ti} \qquad (2\text{-}2)$$

Where:

C = lane capacity (vph).

Ti = average inter-vehicle time (s). It can be calculated for cash, and non-stop ETC toll lanes as follows:

$Ti_{\text{cash}} = t_{\text{service}} + t_{\text{move-up}}$

$Ti_{\text{ETC}} = t_{\text{service}} + t_{\text{headway (ETC)}} = \text{zero} + t_{\text{headway (ETC)}}$

$Ti_{\text{ETC}} = t_{\text{headway (ETC)}}$

Where:

Ti_{cash} = average inter-vehicle time for cash (s).

t_{service} = service time (s).

$t_{\text{move-up}}$ = is the time it takes for the next vehicle in the queue to arrive at the cash booth after the current vehicle completes its transaction.

$t_{\text{headway (ETC)}}$ = vehicle headway for ETC lanes (s).

Average saturation headway for non-stop ETC vehicle is the minimum time interval while the sequential vehicles pass the same lane section. The distance between these two vehicles must be maintained to the stopping sight distance. Therefor the average saturated headway for ETC vehicles can be calculated with relationship to the stopping sight distance by Equation (2-3) (Zhong et al., 2014):

$$H = \frac{L\ stop}{V} \tag{2-3}$$

where:

H = average headway of ETC vehicles (s)

$L\ stop$ = stop sight distance (m).

V = speed limit of the ETC lane (m/s).

Many published studies on toll plaza operations have determined lane capacity according to the collection method and the existing toll plaza facilities. Table 2.1 shows some the results from of these studies.

Table 2.1 Toll plaza lane capacities in some published studies

Authors	Toll collection type	Lane capacity (vph)
Fuller (2011)	Manual passenger car Manual Mixed ACM Ticket entry Mixed Ticket exit mixed ETC Express	416 360 550 506 370 1500
Padayhag and Sigua (2003)	Manual E-pass/Cash E-pass Dedicated E-pass	240 450 1548 1872
Zarrillo et al. (2002)	Manual (not semi-Truck) Manual (semi-Truck) ACM ETC Express	498 138 618 1560
Al-Deek et al. (1997)	Manual ACM Mixed AVI Dedicated AVI Express AVI	350 500 700 1200 1800
Pietrzyk (1994)	Manual ACM Mixed Manual/ ETC Express ETC	350 500 700 1800

2.3 Microscopic traffic simulation software

Generally, traffic simulation software mathematically models traffic system operations in a virtual environment to analyze, evaluate, and understand various real-world traffic operations (Dijk et al., 1999). Traffic simulation software has become a popular and effective tool in traffic engineering for analyzing a wide variety of operations of complex traffic systems under congested conditions, which cannot be adequately studied using analytical terms (Mathew and Bombay, 2014b).

Traffic simulation can be classified into three levels according to the level of modeling detail: macroscopic, mesoscopic, and microscopic. Macroscopic simulation describes entities and their interactions at a low level of detail and models these on a considerably large scale in terms of average flow, speed, and density; thus, it describes the traffic network as a whole. By contrast, microscopic simulation describes both the system entities and their interactions at a high level of detail. Mesoscopic simulation describes the activities and interactions of individual vehicles based on aggregate relationships, falls between macroscopic and microscopic simulations, and uses both macroscopic software and microscopic software (Boxill, 2007; Fellendorf and Vortisch, 2010; Wang et al., 2012). Figure 2.8 shows the macroscopic, mesoscopic, and microscopic levels of communication.

In this study, microscopic traffic simulation is used because toll plaza modeling falls within the microscopic level of simulation.

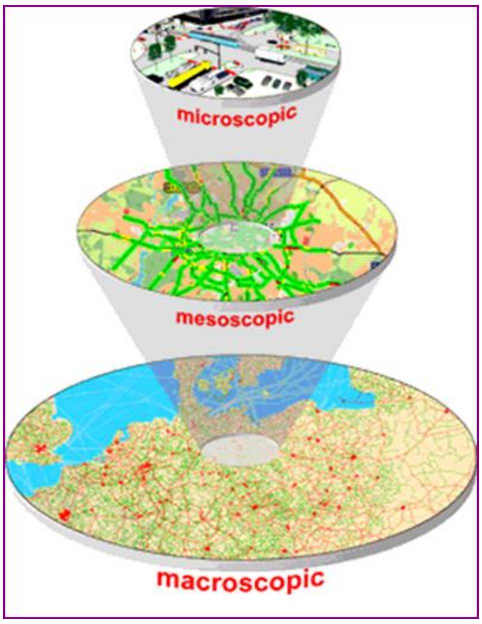


Figure 2.8 The levels of macroscopic, mesoscopic and microscopic (PTV Vision, 2016).

Microscopic traffic simulations can simulate the behavior of individual vehicles within a road network, and these simulations are used to predict the likely impact of traffic pattern changes resulting from proposed commercial developments or road schemes. The models aim to assist transportation municipalities, consultants, public transportation companies, and government transportation authorities.

The traffic flow models used are stochastic discrete, time step based microscopic models, with driver–vehicle units (DVUs) considered as single entities (Papageorgiou and Maimaris, 2012). Microscopic simulation models simulate traffic systems by modeling the interactions between a vehicle and another vehicle on a road and between an individual vehicle and the different features (signs, signals, and roadway geometries) of a road within a traffic flow. The model analyzes these interactions by updating the state (acceleration, deceleration, position, lane position, speed, etc.) of every vehicle on time steps (Barcelo et al., 2004; Boxill, 2007; Li et al., 2011). Microscopic simulation models also simulate the behaviors of individual vehicles with the use of car-following, gap-acceptance, and lane-changing models (Venter et al., 2001). Some microscopic models have a 3D interface, in addition to a 2D interface.

Microscopic models with 3D visualization are powerful tools for helping planners and traffic engineers solve specific traffic problems. Through 3D visualization, the users are provided with virtual, real-world viewpoints (i.e., helicopter, traffic camera, and vehicle) and allowed to view the simulated area in a very rich virtual environment, which contains structures representative of the real world (Boxill, 2007).

A microscopic toll plaza model is unavailable in many of the widely used microscopic traffic simulation software packages. However, even with the absence of a built-in toll plaza model (Ozbay et al., 2006), these software packages have many available tools that can be used to create a toll plaza model. Many researchers have created and developed customized toll plaza models from standard microscopic simulation software packages, as presented in the next subsection.

2.3.1 Toll plaza simulation software

As previously mentioned, the main objective of this thesis is to assess the performance of selected toll plazas. Microscopic traffic simulation software can help users better understand traffic operations at toll plazas. Several microscopic simulation software packages can be used to study toll plazas. This subsection provides a review of previous studies on toll plaza modeling.

2.3.1(a) TPASS

Toll Plaza Animation/Simulation System (TPASS) is one of the first animated toll plaza simulation software. TPASS was developed by Science Application and International Corporation at the University of Central Florida in 1992 (Redding and Junga, 1992). Redding and Junga (1992) proposed a stochastic discrete-event microscopic traffic simulation model to simulate traffic operations at toll plazas, this model combines simulation and visual animation (Al-Deek et al., 2000a), helps traffic engineers and planners quantitatively compare experimental data sets, and allows users to evaluate the simulated scenario through the information presented in visual animations (Russo et al., 2010). Furthermore, TPASS enables users to experiment on different toll plaza configurations and traffic characteristics to determine the resulting waiting time, queue length, and toll revenue. To facilitate analyses, TPASS model divides the toll plaza into three zones, namely, approach zone, transition zone, and toll zone. Furthermore, the

TPASS microscopic model can simulate toll plazas with as many as 10 toll lanes and 5 approach lanes for each direction.

The input parameters for the constructed model include the number of tollbooths, traffic volume, speed of vehicles approaching the toll plaza, and distribution of vehicle classes. The output results of the simulated model include average queuing delay, total queuing delay, maximum queuing delay, and throughput. TPASS simulation software contains lane-changing, car-following, and toll-lane selection algorithms. For the calibration of the TPASS simulation model, Al-Deek et al., (2005) and Redding and Junga, (1992), proposed that the total number of vehicles in queue is the most useful output parameter, whereas Klodzinski, and Al-Deek (2002) proposed that service time has the most significant influence on the simulation model.

TPASS, however, can only model isolated toll plazas; thus, it cannot be utilized to simulate an entire network consisting of numerous toll plazas or intermediate sections between toll plazas.

2.3.1(b) TPSIM

Toll Plaza SIMulation (TPSIM) model was developed by the Transportation System Institute at the University of Central Florida, Orlando, Florida. TPSIM is a stochastic object-oriented discrete-event microscopic simulation model coded using Microsoft Visual Basic 6.0 to provide a PC interface in a Windows 98/NT environment (Al-Deek et al., 2000b). The purpose of TPSIM is to simulate the toll plaza operations at the Holland East toll plaza, which is the busiest toll plaza in the Orlando–Orange County expressway. TPSIM was presented by Haitham Al-Deek in a study about the impact of the market penetration of ETC on the benefit of this technology (Al-Deek et al., 2000b;

Jack Klodzinski and Al-Deek, 2002a, 2002b). TPSIM divides a toll plaza into three zones, namely, approach zone, transition zone, and toll zone.

Simulation with TPSIM model can simulate toll plazas with a maximum of 5 approach lanes up to 10 toll lanes for each direction (Russo et al., 2010). But, TPSIM can simulate five different toll collection methods: manual, ETC, manual/ETC, coin operated, and coin operated /ETC. However, TPSIM can simulate only two vehicle classes: passenger car and truck (Al-Deek, 2001). Figure 2.9 shows the TPSIM animation window for the simulation of the Holland East toll plaza.

TPSIM utilizes different algorithms, including car-following, lane-changing, and a toll-lane selection algorithms. During the morning peak hours on four weekdays, traffic data were collected at the Holland East toll plaza and used as inputs into the TPSIM model. These data were vehicle arrival, queue length, service time, queuing delay, and throughput. The data were extracted from the video cameras placed on top of the Holland East toll plaza canopy, whereas the data that was used for model calibration were queue condition, vehicle delay, lane throughput, and service time. Among the model calibration parameters, service time mainly controlled the performance of the toll plaza (Al-Deek et al., 2000a). The results obtained using the TPSIM microscopic simulation model for the Holland East toll plaza showed that the performance of the toll plaza improves when only 10% of the manual users switch to ETC lanes. Consequently, the average queuing delay is reduced by more than 90 s per vehicle, the total delay (vph) is cut into half, and the throughput (vph) is increased by more than 20% (Al-Deek, 2001). Klodzinski et al. (2008) applied TPSIM in another simulation experiment to evaluate and forecast the impact of a mainline toll plaza without renovation in five years on the traffic operations. The results of the simulation experiment show an increment in the average delay for cash lanes and the inability of the toll plaza to accommodate the entire forecast traffic volume.

However, TPSIM has certain disadvantages. First, it is unsuitable for the simulation of the traffic operations at toll plazas with more than two vehicle classes. Second, TPSIM divides the toll plaza into three zones from upstream until the tollbooths only and simulates the traffic operation only within this boundary; as a result, the traffic operations after the tollbooths, namely, the recovery and departure zones, which are also parts of a toll plaza, are ignored. Finally, the animations present only one direction of toll plaza for each scenario; thus, TPSIM cannot present the entire toll plaza configuration in one scenario.

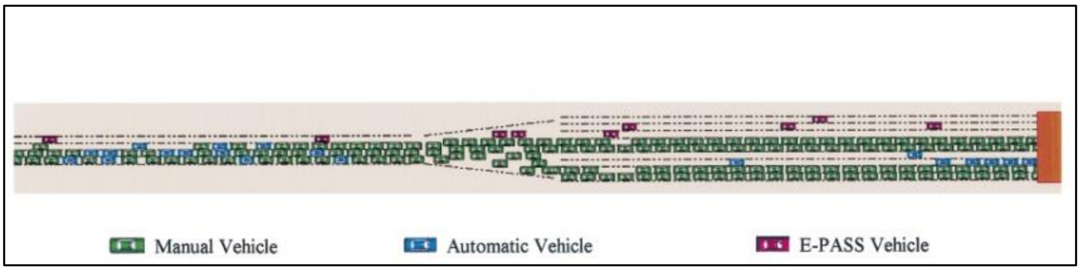


Figure 2.9 Illustrates a snapshot of the TPSIM animation (Al-Deek, 2001).

2.3.1(c) SHAKER

SHAKER is a deterministic queuing model that computes the maximum hourly total throughput of a toll plaza by assigning the vehicles to the toll lanes based on one of the following four lane conditions: lane that has the shortest queue length, lane that provides the appropriate toll collection type to the arriving vehicles, lane that has the least amount of vehicles, and lane that contains the fastest moving queue (Russo et al., 2010). To calculate the hourly throughput, the SHAKER model uses the linear equations for motion and the lane percentage or frequency of occurrence of a vehicle class.

SHAKER was developed by the Center of Advanced Transportation System Simulation at the University of Central Florida. The name of this model is derived from the shaking process used to assign vehicles to lanes to determine the optimum lane configuration (Zarrillo and Radwan, 2009). The shaking process moves vehicles from one lane to another until the correct distribution is established. The correct distribution is based on queue length, hourly throughput, and delay.

SHAKER categorizes vehicles by classes into passenger car and truck; categorizes payment method into manual, ACM, high-speed ETC, and ETC; and categorizes the collected field data into vehicle characteristics (i.e., vehicle class, processing time, lane choice, payment type, departure time, arrival time, and inter-arrival time between vehicles), traffic characteristics (i.e., queue length, throughput and demand), and toll plaza characteristics (i.e., number of lanes, mode of payment, and number of each type of lane).

The field data were collected at four toll plazas located in Florida's Turnpike. To record the traffic characteristics at each toll plaza, four video cameras were installed to capture traffic operation during morning peak hours, which were from 7:00 a.m. to 9:00 a.m., and afternoon peak hours, which were from 4:00 p.m. to 6:00 p.m. All the cameras were activated simultaneously; two cameras were used to capture one direction, and the other two cameras were used to capture the opposite direction. The calibration of the SHAKER model strongly depends on two important parameters: correct vehicle percentage and stop time at tollbooths (Russo et al., 2010; Zarrillo and Radwan, 2009).

One of the important findings revealed by the SHAKER simulation model for the traffic operation of toll plazas is that the maximum throughput is not dependent on the configuration of the toll plaza only or the number of lanes only. The performance of a particular lane is high for a specific composition of approaching traffic but not for another composition of the traffic. In fact, the lane maximum throughput depends on the truck percentage in the approaching traffic and the mode of the payment of the vehicles. The simulation results showed that the toll fee amount also has an impact on the maximum throughput of the cash lane. Toll plazas charging toll fees that are whole numbers, such as $2.00 and $1.00 had shorter stop times than toll plazas charging such toll fees as $2.50 and $0.75. Figure 2.10 shows the graphical user interface of the SHAKER simulation model.

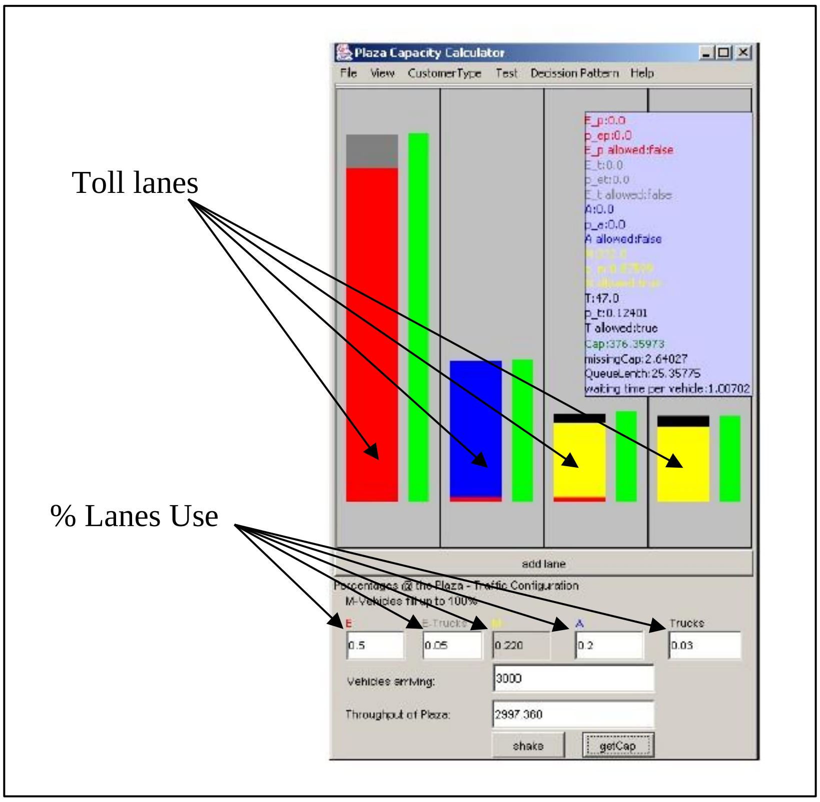


Figure 2.10 A toll Plaza model in SHAKER software (Zarrillo and Radwan, 2009).

2.3.1(d) PARAMICS

PARAMICS is a microscopic freeway and urban traffic simulation software package used to simulate the movement and behavior of individual vehicles in traffic networks. The name of PARAMICS is derived from PARAllel computer MICropic Simulation (Bertini et al., 2002). PARAMICS has the ability to present the simulation model with a 3D visualization interface during the simulation run (Boxill and Yu, 2000; Gardes et al., 2002).

Many studies were conducted using PARAMICS for the simulation of transportation network facilities. PARAMICS have been used in previous studies to evaluate freeway improvement strategies (Gardes et al., 2002), investigate signalized intersections (Liu et al., 2001), examine the local traffic conditions (Lee et al., 2001), determine the impact of high-occupancy vehicles on highways (Abdulhai, 2001), and develop an artificial neural transportation network (Mark et al., 2004). However, only few studies have employed PARAMICS in studying toll plazas; these studies used PARAMICS to develop and calibrate an integrated freeway and toll plaza model for the New Jersey Turnpike (Ozbay et al., 2005a), (Ozbay et al., 2005b), develop a microscopic toll plaza for Holland East toll plaza (Nezamuddin and Al-Deek, 2008), and investigate the impact of ETC lanes on toll plazas (Liu et al., 2011).

The PARAMICS model employs lane-changing and car-following algorithms to simulate the movements of individual driver vehicle units (DVUs). A DVU is a combined representation of the behavior of a driver and the physical characteristics of a vehicle. The parameters of a DVU mainly include mean reaction time, mean target headway, physical dimensions of the vehicle, aggressiveness and awareness, and acceleration and deceleration profile (Nezamuddin and Al-Deek, 2008). Although PARAMICS does not have a default built-in toll plaza model, it has many simulation tools that can be used to simulate a toll plaza (Ozbay et al., 2006). The following parameters need to be entered to establish a toll plaza model:

1. A satellite picture, which is used as an overlay to provide toll plaza information (i.e., geometry of the toll plaza area and the number, width, and length of the toll lanes).
2. Toll plaza configurations, which represent the toll payment lanes according to the toll collection methods (i.e., MTC; ACM; and ETC).
3. Vehicle type: According to the modeling requirements, PARAMICS can define vehicle types according to their modes of payment, namely, MTC, ACM, and ETC (Nezamuddin and Al-Deek, 2008), or according to their classes, namely, passenger car, bus, light duty vehicle, and heavy duty truck.
4. Service time distribution for each vehicle type.
5. Arrival distribution (Ozmen-Ertekin and Ozbay, 2008).
6. Key parameters to make the results more realistic: queue speed, queue gap, mean driver reaction time, mean target headway, and minimum gap.
7. Key parameters for calibration: delay data (Liu et al., 2011), route choice decisions, driver behavior.

The collected data were extracted from the available databases. The data spanned four months, covering typical weekdays. The extracted data consisted of the entry and exit time data for each vehicle and the lane throughput during the morning and afternoon peak hours (Ozbay et al., 2006), however in another study (Nezamuddin and Al-Deek, 2008), only the morning peak hours were considered.

Nezamuddin and Al-Deek (2008) used the GEH (Geoffrey E. Havers) statistic to compare the volumes obtained from the simulation with the observed volumes to verify the operation of the calibrated model.

$$GEH = \sqrt{\frac{2 \times (simulated - observed)^2}{(simulated + observed)}} \quad (2\text{-}4)$$

When:

$GEH < 5$, flows considered a good fit.

If $5 < GEH < 10$, further investigation may require for flows.

If $10 < GEH$, flows cannot be considered a good fit.

In the study of Ozbay et al. (2006), PARAMICS was used to evaluate whether the implementation of E-ZPass at toll plazas had a significant effect on vehicle delays. They found that the time savings at toll plazas could exceed 89% with the implementation of E-ZPass lanes. In the study of Liu et al. (2011), they concluded that the traffic operation of a toll plaza improved after adopting ETC lanes. Figure 2.11 shows the model interface of PARAMICS for toll plaza configurations.

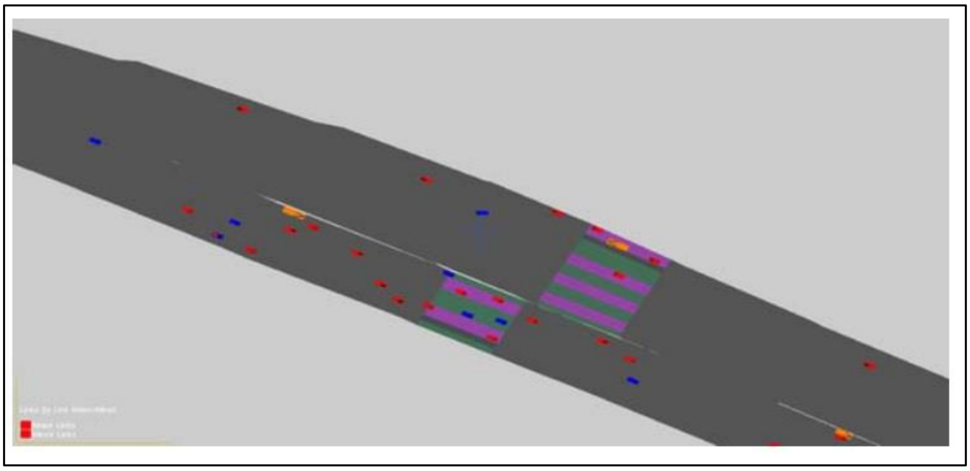


Figure 2.11 Toll plaza configurations in PARAMICS model (Nezamuddin and Al-Deek, 2008)

2.3.1(e) AIMSUN

AIMSUN is the acronym for Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks. It was developed by Transport Simulation Systems to simulate the real traffic conditions on arterial routes and expressways (Barcelo et al., 2004). AIMSUN is a microscopic simulation approach, that is, the behavior of every vehicle in the network is modeled by simulation according to the vehicle behavior models, namely, lane-changing, car-following and gap-acceptance models (Boxill, 2007).

AIMSUN is capable of analyzing any type of a traffic network system with respect to the traffic flow input or origin–destination parameters (Ciuffo et al., 2009). Vehicles are categorized into classes according to vehicle characteristics and physical dimensions. Vehicle characteristics include dynamic parameters, such as deceleration rate, acceleration rate, and maximum desirable speed (Boxill and Yu, 2000). Generally, AIMSUN divides vehicles into four classes: cars, motorbikes, dual rear wheels, and trailers.

The quality of the microscopic simulation model is highly dependent on the accuracy and the availability of the input data. Therefore, three types of input data are required to establish a complete AIMSUN model.

1. Network layout to establish the toll plaza network model and the geometries of its surrounding area by importing the toll plaza aerial image as a background and establishing the number of toll lanes.
2. Traffic demand data; which includes traffic flows for each vehicle class; vehicle class for reserved lanes; vehicle type; toll collection method (i.e., MTC, ACM, and ETC); and delay time, which is defined as the time interval between vehicle stop time at the booth and the time when the boom gate was raised.

3. Traffic control is defined by the input data of ramp metering, that is, the type of metering, namely, location and control metering (flow or delay time). Ramp metering in AIMSUN is used to simulate the drivers stopping or decelerating to pay their tolls in automatic and manual toll lanes. ETC toll lanes were simulated according to the observed speed limits in the field (Poon and Dia, 2005).

The model calibration is usually performed to ensure that the created model accurately represents reality. In AIMSUN, section time is used to calibrate the base model. Section time is the total time taken for a vehicle to pass through the concreted area surrounding the tollbooths (Grigoroudis and Siskos, 2010). T-test was used in model calibration with a 95% level of confidence (Poon and Dia, 2005).

AIMSUN can present quantifiable outputs, such as speeds, flows, queue lengths, occupancies, and travel times. It can also display the saved scenarios in 2D and 3D formats, allowing for a powerful mode to study and understand complex traffic operations (Barcelo et al., 2004).

Poon and Dia (2005) used AIMSUN to construct a traffic model for the Gateway Bridge toll plaza, and the established model can evaluate the performance of tollbooths. The results showed that an increase in the proportion of heavy vehicles influenced the overall toll plaza performance. Furthermore, the increased use of ETC lanes could gradually enhance the overall efficiency of the toll plaza. Spiliopoulou et al. (2010) used an AIMSUN model for the throughput maximization and delay minimization in the Oakland–San Francisco Bay Bridge toll plaza. Figure 2.12 shows the AIMSUN base model for the Gateway Bridge toll plaza.

However, AIMSUN has some limitations in toll plaza modeling. First, the use of fixed delay ramp metering to simulate tollbooth operations cannot sufficiently present the variation in the delay times in the actual operations of tollbooths, particularly those with cash and ACM tolls. Second, the characteristics in the vehicle class library in AIMSUN are specific to European vehicles; thus, these characteristics may not resemble those of Malaysian vehicles. Third, AIMSUN models are calibrated using delay time, section time, and overall throughput, whereas queue length is not taken into account.

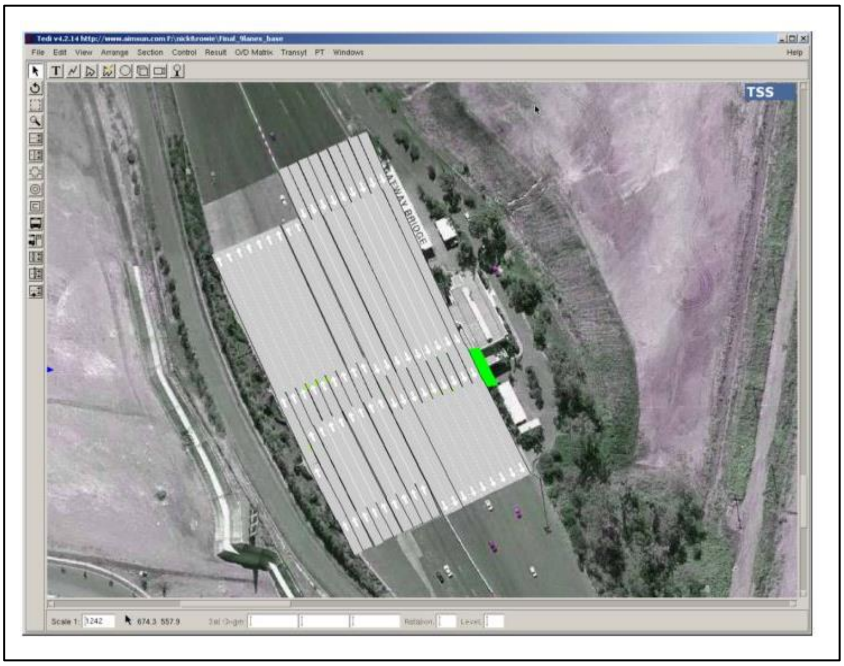


Figure 2.12 AIMSUN base model of Gateway Bridge toll plaza (Poon and Dia, 2005).

2.3.1(f) VISSIM

VISSIM is a microscopic, time increment oriented, and behavior-based multi-purpose simulation tool developed by PTVGROUP, Karlsruhe, Germany for modeling urban and rural traffic (Lelewski et al., 2003). VISSIM is a German acronym for "Verkehr In Städten – SIMulationsmodell," which means Traffic in Towns Simulation in English (Fellendorf, 1994). Currently, VISSIM is receiving increasing worldwide acceptance as a microscopic simulation model in the transportation field. VISSIM was used in various traffic operations in numerous studies, such as studies on toll plazas (Lelewski et al., 2003; Ceballos & Curtis, 2004; Aycin et al., 2010; Yilin, 2013; Aksoy et al., 2014; ZHONG et al., 2014), traffic flows (Doina and Chin, 2005; Qiu et al., 2011; Yang et al., 2014; Zhang et al., 2012), signalized intersections (Leong et al., 2015; Qiao et al., 2012; Xu et al., 2013; Zhou et al., 2014), and freeways and expressways (Bains et al., 2012; Gomes et al., 2004; Huang et al., 2014; Yan et al., 2013). VISSIM is the most common software that can analyze and evaluate a wide range of functionally classified roadways (including toll plazas and railroads) and transit traffic operations, such as traffic composition, lane configuration, transit stops, and traffic signals (AG, 2014; Zhou et al., 2014). It can model traffic operations with various traffic control parameters in 2D and 3D environments (Boxill, 2007). VISSIM models primarily consist of two components that work in parallel: traffic flow simulator and signal generator state. The traffic flow simulator is based on two models:

- Car-following model, which regulates the longitudinal movements of vehicles.
- Lane-changing model, which regulates the lateral movements of vehicles.

Although VISSIM does not include a built-in toll plaza model, it includes many functionalities, such as priority rules, dynamic assignment of vehicle paths, service time distribution, driver behavior, and speed reduction zones, which allow for the development of toll plaza models. VISSIM also provides several MOEs that are relevant to toll plaza analyses, including the following (Ceballos and Curtis, 2004);

1. Average waiting time by vehicle class and lane.
2. Average and maximum queue length by lane.
3. Total throughput by lane.
4. Average processing time.

5. Total system delay.
6. All vehicle delays measured during simulation period.
7. Vehicle travel time per lane.
8. Average speed and density on the approach and exit roadways.

Toll plaza model calibration in VISSIM is focused on comparing the simulation results with the actual operation of toll plazas, the results include (Ceballos and Curtis, 2004);

i. Average waiting time in queue.
ii. Throughput
iii. Average and maximum queue lengths per lane.

The first task in establishing a toll plaza model in VISSIM is to import an aerial image of the toll plaza as a background and use it as an overlay for the network. Figure 2.13 shows the aerial image of the Holland East express toll plaza. Then, the roadway network, which is a complex of links and connectors, must be placed correctly on the image background. At this point, the base data are loaded for simulation. These data are modeled by functions and distributions rather than single values. VISSIM provides five default vehicle types: car, tram, bus, heavy vehicle (i.e., HGV), pedestrian, and bike. From these vehicle types, this simulation software can define new vehicle types, such as a trailer truck, an articulated truck, a standard bus, and an articulated bus. Each vehicle type has a different speed or acceleration behavior (AG, 2014). The tollbooth transactions or the toll collection methods are modeled using stop signs placed on a single lane link. Any transaction type for any vehicle type that needs to stop at the tollbooth can be simulated by using the stop sign dwell time, which can be adjusted to represent the proper service time for a particular vehicle type. By contrast, for vehicles that do not need to stop to complete their transactions, such as vehicles in an E-ZPass lane, they can be simulated by using the reduced speed zone.

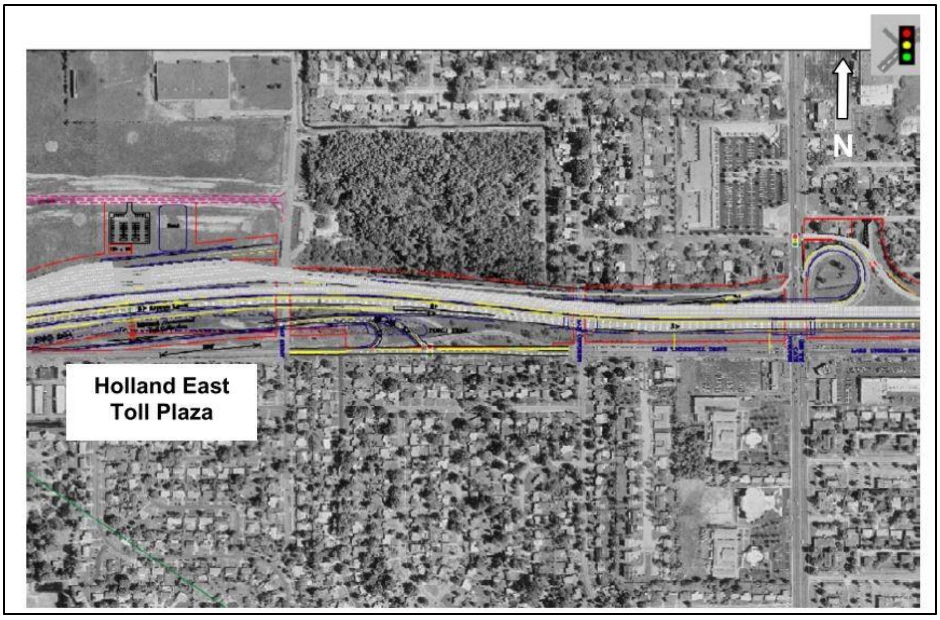


Figure 2.13 Aerial image of Holland East Express Toll Plaza as a background in VISSIM. (Lelewski et al., 2003).

VISSIM has been proven to be a suitable tool for simulating different driver behaviors and complex vehicle interactions in traffic operations in general and in toll plazas in particular (Ceballos and Curtis, 2004). Lelewski et al. (2003) proved that VISSIM could analyze the complex traffic operations at selected toll plazas by describing the methodology that can be used to analyze the operations at a toll plaza using VISSIM. Aycin et al. (2010) used VISSIM to simulate the operations at the Goethals Bridge Toll Plaza and obtain the delay and queue length statistics to be compared with those of their proposed delay methodology for various demand/capacity ratios. Yilin (2013) and Zhong et al. (2014) studied the capacity of a toll plaza by simulating the ETC and artificially mixed toll lanes using VISSIM. Aksoy et al. (2014) utilized VISSIM to generate travel times and delays for Istanbul Fatih Sultan Mehmet Bridge toll plaza to evaluate its performance. A Malaysian study by Hamid (2011) used VISSIM to create the simulation models of selected toll plaza operations in Malaysian expressway and the resulting of this study was found that traffic volumes, toll booths orientation, storage capacity and types of toll service have influence on traffic operations and efficiency of the toll plaza.

However, VISSIM also has certain limitations. It is difficult to handle because of its complexity and brief manual. Establishing a VISSIM model could take numerous hours, even for experienced users, because the traffic parameters and roadway network must be created and defined before running the simulation.

2.4 Summary

A toll plaza is a structure where every vehicle has to either decelerate or stop to pay the toll on an expressway. Therefore, toll plazas are considered bottlenecks on expressways. A toll system has two types according to the operating characteristics of the toll plaza: open toll system and closed toll system. The major differences between these two systems lie in their operating costs and the initial investments in the toll plazas. Toll plazas adopting the closed toll system falls into two categories, namely, ramp and mainline. The toll collection methods are generally categorized into three types: MTC, ATC by ACM, and ETC. Each one of these methods has its own lane configuration and particular vehicle class. A number of factors can significantly influence the performance of toll plazas. Service time has the greatest influence on toll plaza performance; as a result, it influences the capacity of the toll plaza.

The studies mentioned in the literature review are selected based on their relevance to the selected toll plaza type in this study. The selected toll plazas are mainline-closed-system toll plazas located in the Malaysian Expressway System. The main objective of this study is to assess the operation of the selected toll plazas using microscopic simulation software. Therefore, numerous microscopic simulation software packages are reviewed, including TPSS, TPSIM, SHAKER, PARAMICS, AIMSUN, and VISSIM to determine which package is the most suitable to simulate the operation of the selected toll plazas. All the reviewed software packages have respective pros and cons in simulating toll plaza operations. Among the software packages, VISSIM is selected based on the study requirements and the latest research opinions. Many scholars have proven that VISSIM is a suitable tool for the simulation of the traffic operations in toll plazas. Furthermore, VISSIM can simulate various toll collection methods and vehicle classes, whereas the other software packages do not offer these options.

The literature review clearly shows that numerous studies from different countries employ traffic simulation for toll plazas, despite the fact that toll plaza operations in Malaysia are vastly different from those in other countries in terms of system operations and vehicle classification. These gaps serve as the motivation to study the toll plaza operations in Malaysia.

CHAPTER THREE
RESEARCH METHODOLOGY

3.1 Introduction

This chapter describes the methodology used to obtain information on toll plaza traffic operations and its configurations with various steps. Figure 3.1 shows the flowchart of the study methodology and illustrates the general steps to achieve the objectives of the study.

3.2 Site locations

In order to simulate traffic operations at the Malaysian toll plazas, in this study two toll plazas located at the North–South Expressway, which usually experience severe traffic congestion, especially during peak hours because of the presence of toll plazas are selected. Each site differed in terms of number of lanes, lane configuration, toll base fee, expressway location, traffic demand, and percentage of each passing vehicle type.

The first selected toll plaza is the closed system Juru toll plaza located in Bukit Mertajam, Malaysia. The Juru toll plaza is a mainline barrier toll plaza at a distance of 145.7 km at the North–South Expressway. This kind of toll plaza configuration impedes traffic flow on the expressway especially during peak hours.

The second toll plaza is the Jawi toll plaza, which is an entrance/exit ramp expressway (where users enter or exit the expressway). The Jawi toll plaza is located in Nibong Tebal, Penang, Malaysia. This kind of toll plaza configuration does not impede traffic flow on the expressway. However, it represents an important feature of the modern networks because it affects the travel times between origin and destination. Figure 3.2 shows the location for the selected toll plazas.

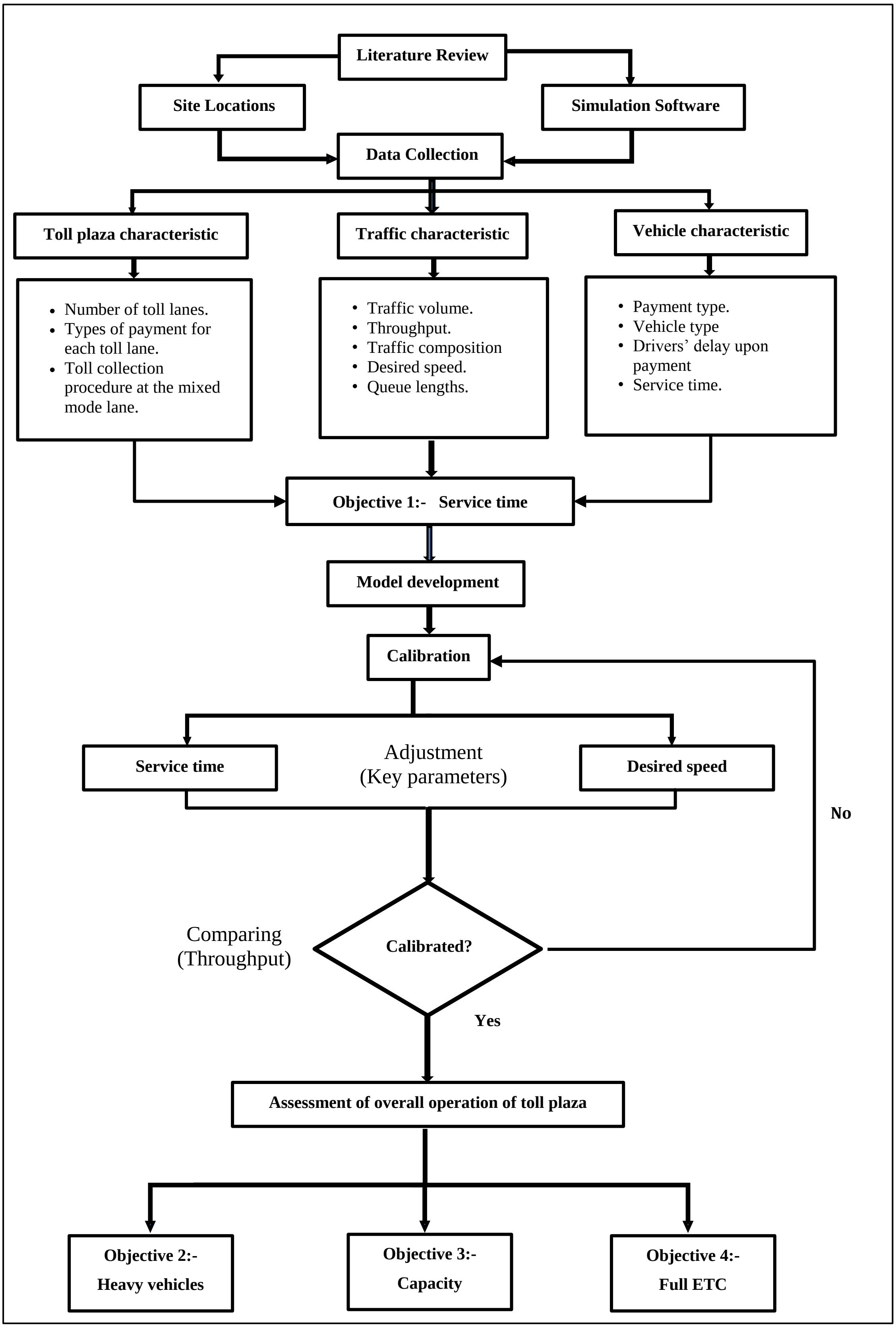


Figure 3.1 Flowchart of the study methodology.

Figure 3.2 Locations of the Juru and Jawi toll plazas.

3.3 Toll plaza configuration

3.3.1 Juru toll plaza

The Juru toll plaza has twenty-three toll lanes. Seven toll lanes are allocated for the entry direction (expressway entry) and 16 toll lanes are allocated for the exit direction (expressway exit). The upstream of the entry and the exit directions are three and two lanes, respectively. Figure 3.3 shows the layout of the Juru toll plaza.

The lanes in the Malaysian toll plaza are mainly divided into two types: first is the single-class lane (specified only for class 1; these lanes are Smart TAG and Touch 'n Go lanes) and the second is the multiclass lane (specified for all types of vehicles including heavy vehicles; these lanes are multiclass lanes for mixed mode toll collection).

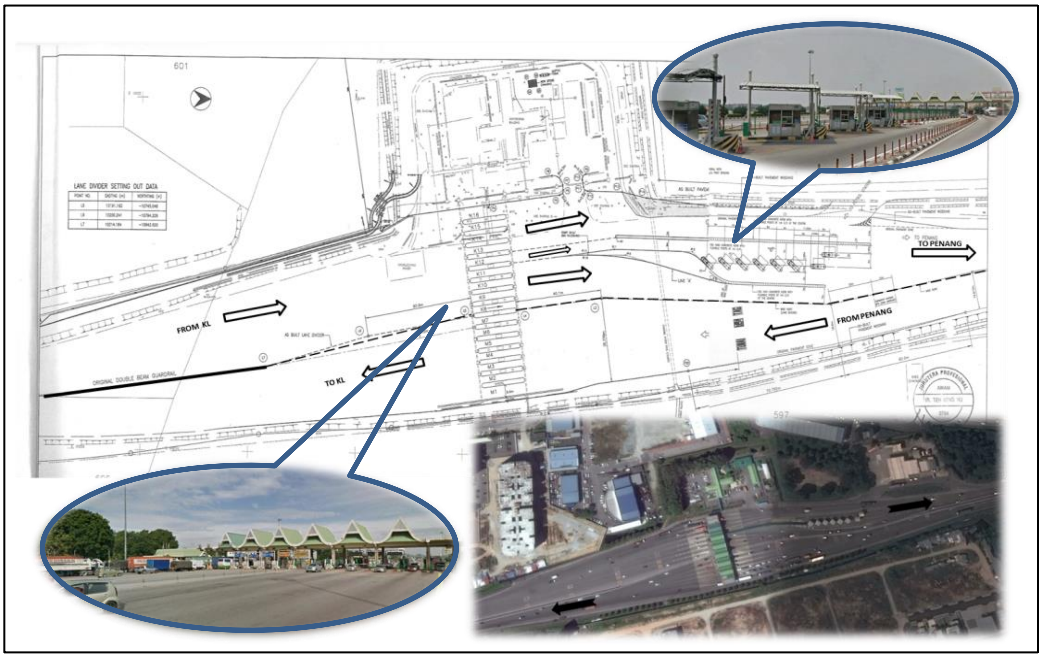


Figure 3.3 The layout of the Juru toll plaza (from PLUS Malaysia Berhad).

The configuration of the Juru toll lanes is shown in Figure 3.4. At the entry direction, M01, M02, and M03 are multiclass lanes for mixed mode payment (ticket and Touch 'n Go). Lanes M04 and M05 are single-class lanes for Touch 'n Go. Lanes M06 and M07 are single-class lanes for Smart TAG. At the exit direction, lanes K08 and K09 are single-class lanes for Smart TAG; lanes K10 and K11 are single-class lanes for Touch 'n Go; lanes K13, K14, K15, and K16 are multiclass lane for mixed mode payment (cash and Touch 'n Go). The K31–K38 staggered lanes are also multiclass lane for mixed mode payment.

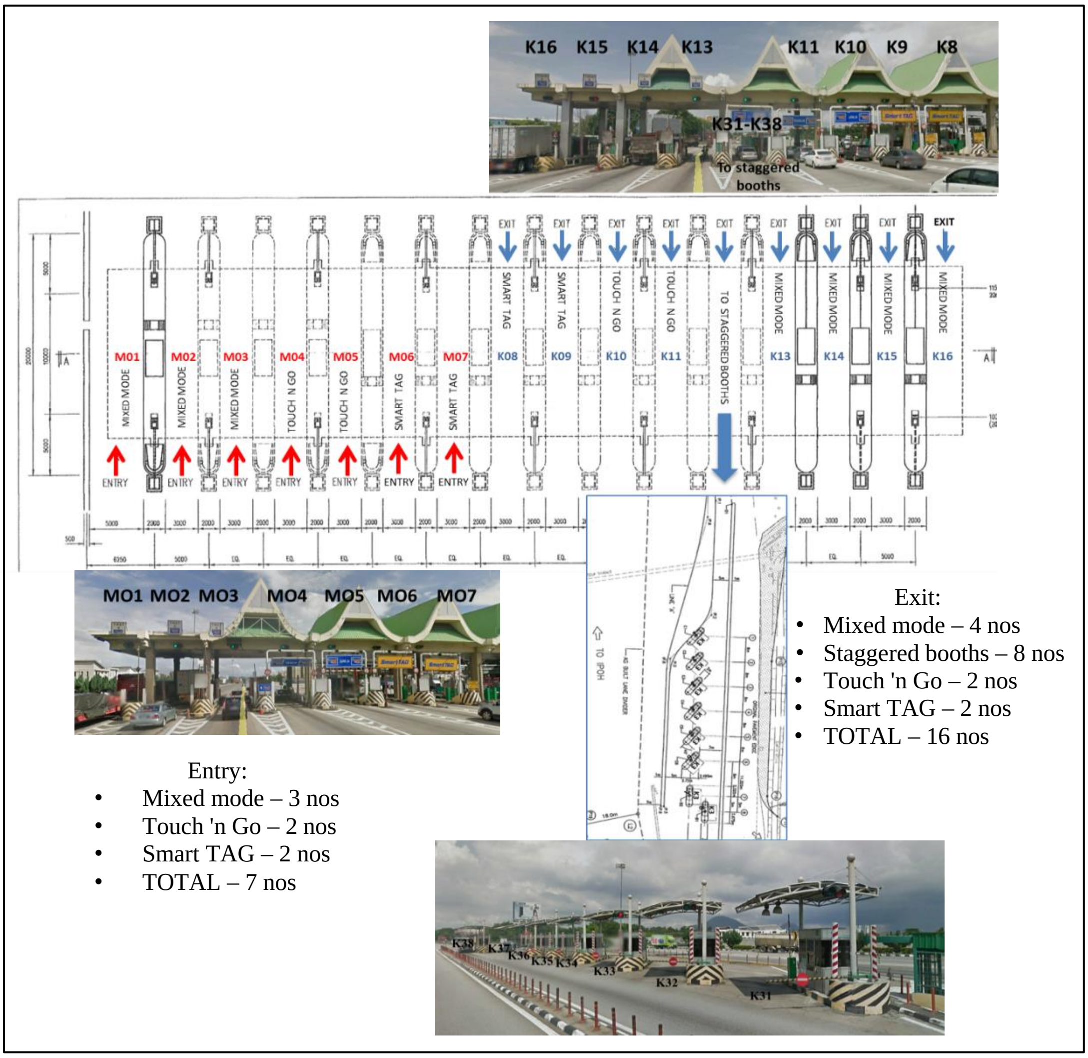


Figure 3.4 Configuration of Juru toll lanes.

3.3.2 Jawi toll plaza

The Jawi toll plaza has eight toll lanes as shown in Figure 3.5. Three and five toll lanes are allocated for entry and exit of the expressway, respectively.

Figure 3.6 shows the configuration of the Jawi toll lanes. At the entry direction, the M01 lane is a multiclass lane for mixed mode payment (ticket and Touch 'n Go), M02 is for Touch 'n Go, and M03 is for Smart TAG; both M02 and M03 are single-class lanes. At the exit direction, lane K04 is a single-class lane for Smart TAG, and K05 is a single-class lane for Touch 'n Go. Lanes K06, K07, and K08 are multiclass lanes for mixed mode toll collection (cash and Touch 'n Go). The upstream of the Jawi toll plaza has two lanes allocated for each direction.

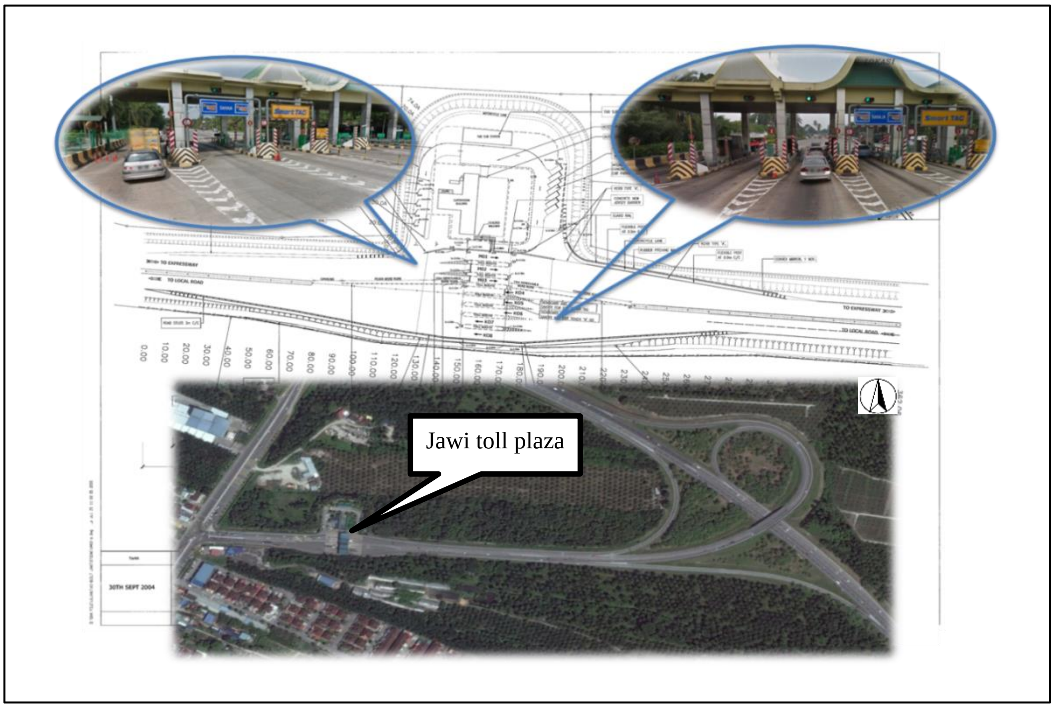


Figure 3.5 Layout of the Jawi toll plaza.

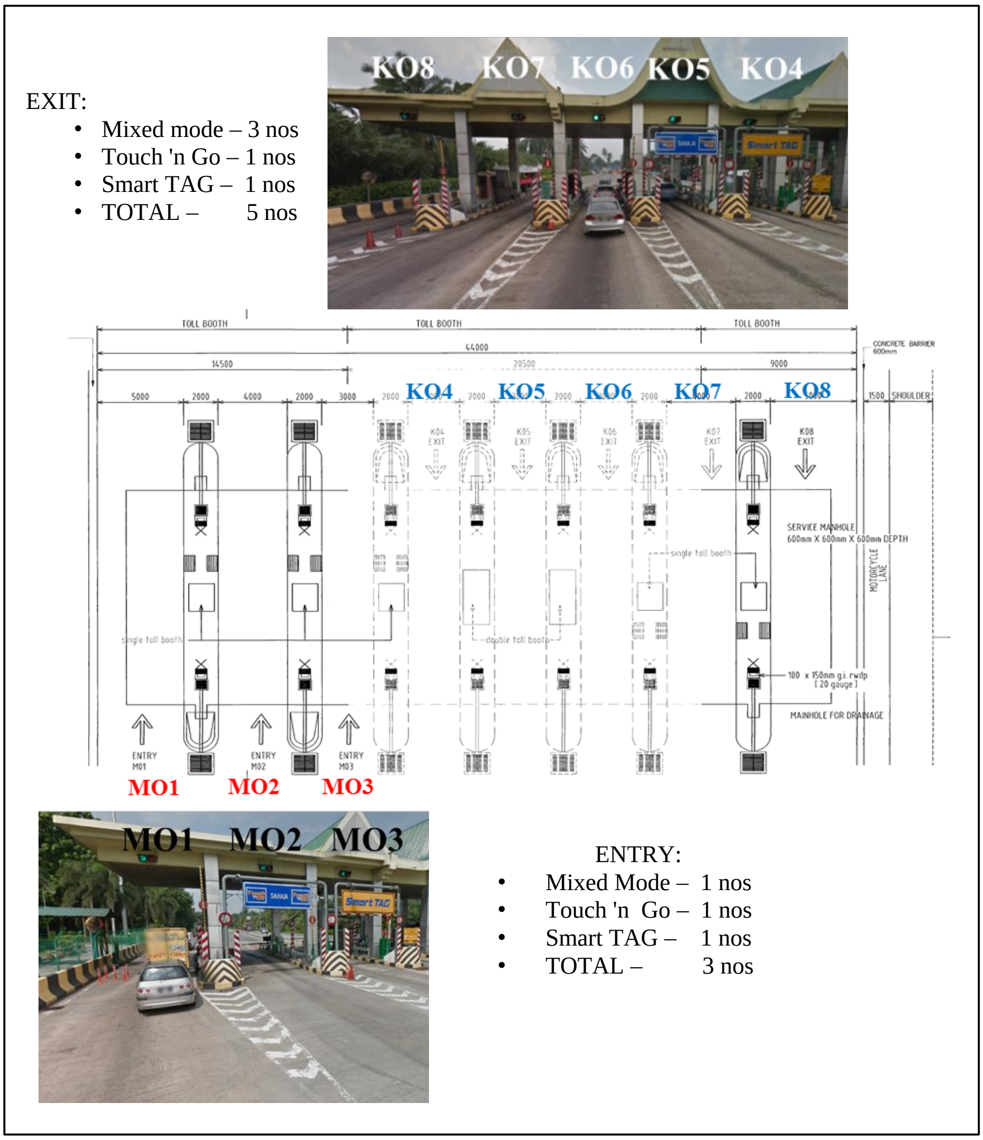


Figure 3.6 Configuration of Jawi toll lanes.

3.4 Tollbooth configuration

Malaysian toll plazas are considered as a conventional toll collection wherein the most common method is the manual toll collection in which a toll collector/ attendant is required at the tollbooth to collect cash, dispense change (if any), issue ticket and receipt to the patrons (upon request), and to also complete the electronic transactions in the multiclass lane. The tollbooth is the main configuration of the manual toll collection in toll plazas. Booth configuration influenced the operation of manual toll collection;

therefore, measurements have been made at the Juru and Jawi tollbooths for the height of the Contactless Smart Card (CSC). Figure 3.7 and Figure 3.8 shows the measurements of the Contactless Smart Card (CSC) at the Juru and Jawi tollbooths, respectively.

Figure 3.7 Measurements of Juru tollbooths.

Figure 3.8 Measurements of Jawi tollbooths.

3.5 Microscopic simulation model VISSIM

A variety of traffic simulation packages is available for studying traffic operations at toll plazas. Each of these simulation packages has pros and cons for simulating the toll plaza operation. Previous literature research studied specific simulation packages in terms of capabilities of modelling the traffic facilities (Fang and Elefteriadou, 2005). The capabilities of these simulation packages differ widely, and selection of the most appropriate model for a given case depends on several factors such as the requirements and characteristics of the site/toll plaza, cost, objectives of the study, and simulation model capabilities for achieving the objectives.

In this study, VISSIM was chosen to simulate the operations at the Juru and Jawi toll plazas. It was proven that VISSIM was a very well-suited tool to simulate the traffic operations at toll plazas and its performance based on the requirements and the objectives of this thesis, and also based on various previous studies conducted around the world. Figure 3.10 shows the general steps taken in choosing the traffic simulation model for this study.

Vissim's traffic flow model is a stochastic, time step based, microscopic model that treats driver-vehicle units as basic entities. The traffic flow model contains a psycho-physical car following model for longitudinal vehicle movement and a rule-based algorithm for lateral vehicle movement. The models deployed are based on Wiedemann's extensive research work. Wiedemann's traffic flow model is based on the assumption that there are basically four different driving states for a driver (AG, 2014):

- Free driving: In this state, the driver seeks to reach and maintain his desired speed. In reality, the speed in free driving will vary due to imperfect throttle control. It will always oscillate around the desired speed.

- Approaching: Process of the driver adapting his speed to the lower speed of a preceding vehicle. While approaching, the driver decelerates, so that there is no difference in speed once he reaches the desired safety distance.
- Following: The driver follows the preceding car without consciously decelerating or accelerating. He keeps the safety distance more or less constant. However, again due to imperfect throttle control, the difference in speed oscillates around zero.
- Braking: Driver applies medium to high deceleration rates if distance to the preceding falls below the desired safety distance. This can happen if the driver of the preceding vehicle abruptly changes his speed or the driver of a third vehicle changes lanes to squeeze in between two vehicles.

For each of the four driving states, acceleration is described as a result of current speed, speed difference, distance to the preceding vehicle as well as of individual driver and vehicle characteristics. Drivers switch from one state to another as soon as they reach a certain threshold that can be described as a function of speed difference and distance. For instance, small differences in speed can only be perceived at short distances. Whereas large differences in speed already force drivers to react at large distances.

The perception of speed differences as well as the desired speed and safety distance kept vary across the driver population.

As the model accounts for psychological aspects as well as for physiological restrictions of drivers' perception , it is called psycho-physical car-following model

The driver behavior parameters that make up the psycho-physical car-following model were broken down into four behavior sub categories, they are: following behavior, lane change behavior, lateral behavior, and signal control behavior. There are two models of car-following models:

- Wiedemann 74: Model suitable for urban traffic and merging areas.

- Wiedemann 99: Model for freeway traffic with no merging areas.

For the purpose of modeling toll plaza operations the Wiedemann 74 model is suitable as the toll plazas had the merging areas.

The Wiedemann 74 model is based on the following parameters:

- Average standstill distance (ax) defines the average desired distance between stopped cars. It has a fixed variation of ± 1m.
- Additive and multiplicative part of desired safety distance (bx_add) and (bx_mult) affect the computation of the safety distance.

The distance d between two vehicles is computed using the following formula:

$$d = ax + bx \tag{3-1}$$

where,

ax: is the standstill distance

$$bx = (bx\_add + bx\_mult * z) * \sqrt{v} \tag{3-2}$$

v: is the vehicle speed

z: is a value of range [0,1] which is normally distributed around 0.5 with a standard deviation of 0.15. This parameter is automatically determined by the stochastic nature of the car following model. The setup of the Wiedemann 74 driving behavior parameter set is showed in Figure 3.9.

The class of vehicles is classified in categories like cars, trucks, buses and bikes. Within each category a particular vehicle model with mandatory technical features like vehicle length, width, acceleration and deceleration rates, and maximum speed is defined. Depending on the purpose of the modeling application data entry of vehicles can be simplified by the specification of distributions of these technical features instead of defining individual vehicle types. The proper distribution of vehicle length reflecting the real vehicle fleet influences the simulation result such as queue length. For most studies vehicle width is irrelevant but modeling-mixed traffic requires the precise definition of the geometric extension of each vehicle type. The vehicle types can be aggregated to a set of vehicles for analysis purpose such as collecting the total travel time of all HOV vehicles.

Vehicles are generated randomly at link entries or at parking lots which may be located in the middle of link segments. Data input flows are defined individually for multiple time periods. As the number of departures in a given time interval [0,t] follows the Poisson distribution with mean = λt, the time gap x between two successive vehicles will follow the exponential distribution with mean 1/λ. λ is measured in vehicles per hour. The probability of a time gap x between two successively generated vehicles can be computed by (Grigoroudis and Siskos, 2010)

$$f(x) = \lambda e^{-\lambda x} \tag{3-3}$$

$$p(X = x) = \frac{e^{-\lambda t} (\lambda t)^x}{x!} \tag{3-4}$$

$$F(x) = 1 - e^{-\lambda x} \qquad , x \geq 0 \tag{3-5}$$

If the defined traffic volume exceeds the link capacity the vehicles are stacked outside the network until space is available. It is noted if the stack is not emptied at the end of the simulation time.

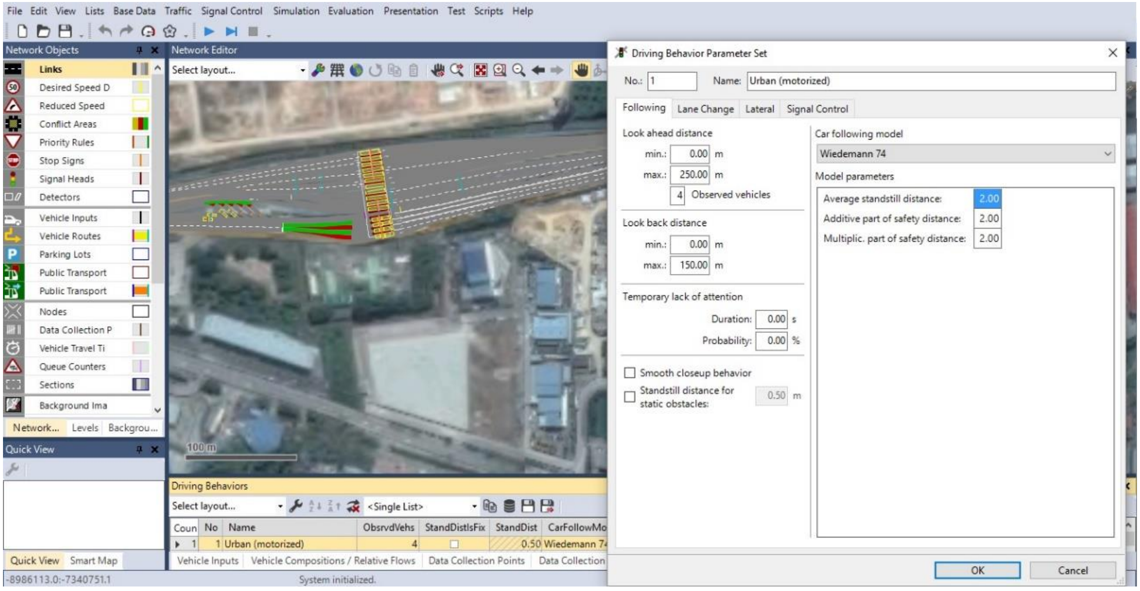


Figure 3.9 Driving behavior parameter setting window in VISSIM – Wiedemann 74

The process of constructing the VISSIM model consists of a systematic series of programing sets that must be addressed to duplicate an actual situation of toll plaza traffic operation. The programming processes of the model were needed to input various field data collections. The quality of the constructed model is highly dependent on the accuracy and availability of the input data (Poon and Dia, 2005). These data were broken down into three major categories: traffic, vehicle, and toll plaza characteristics.

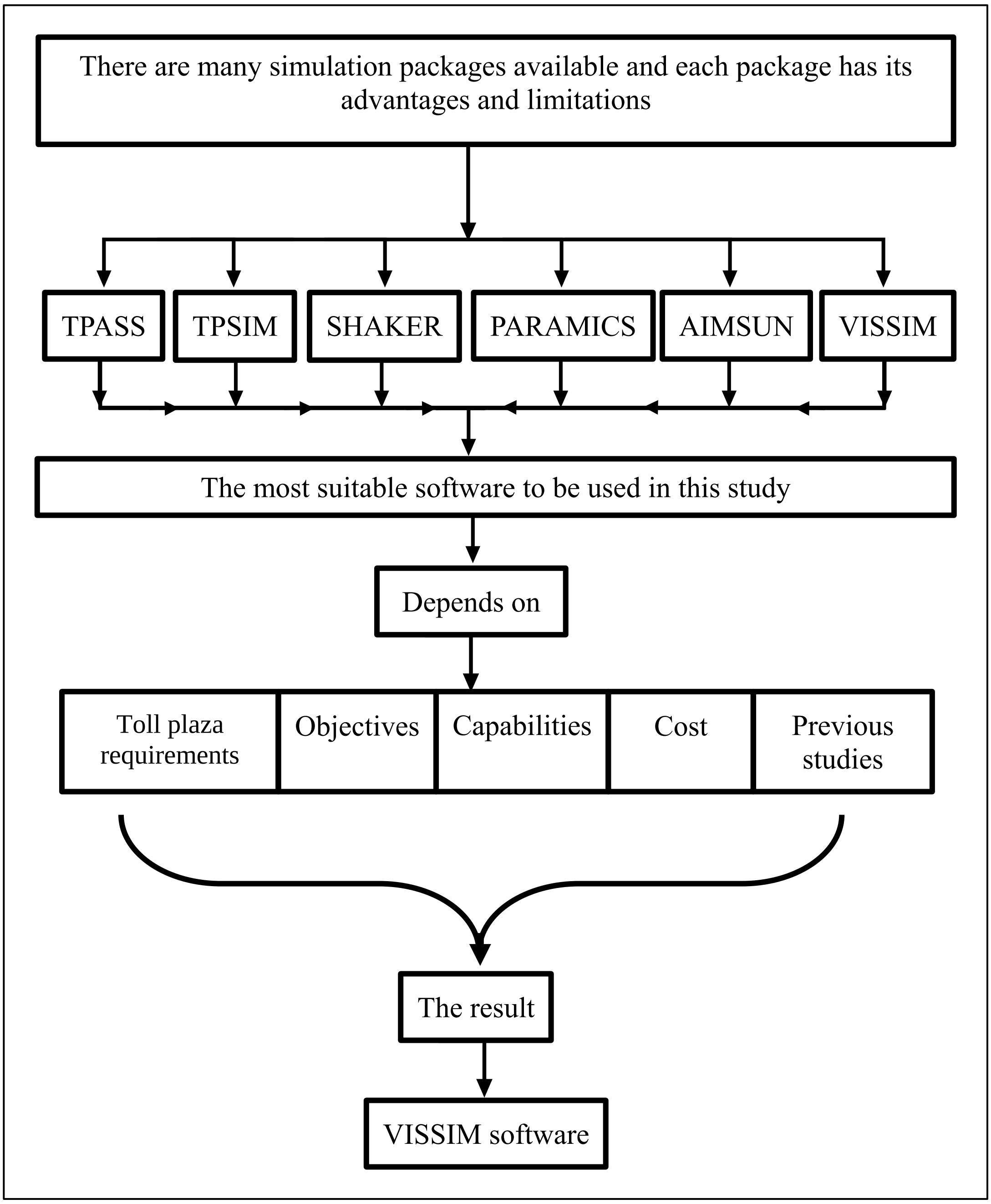


Figure 3.10 Flowchart of Choosing a simulation package.

3.6 Data collection

Generally, field data collection of toll plaza traffic operations is very expensive and time consuming, therefore a balance in collecting enough data needs to be achieved so that the toll plaza model is fit for the purpose and the cost of collecting the field data would also not exceed the budget of the study (Feldman, 2012).

According to the construction requirements of the VISSIM model, the field data collections for each toll plaza were categorized into three categories:

1. Toll plaza characteristics: the number of toll lanes, types of payment for each toll lane and toll collection procedure at the mixed mode lane.
2. Traffic characteristics: traffic volume, throughput, traffic composition, desired speed and queue length.
3. Vehicle characteristics: payment type, vehicle type, drivers' delay upon payment and service time.

To simulate the traffic operation at toll plazas, microscopic field data were needed for each individual vehicle arriving and completing the transaction at the toll plaza. The video recording approach was used to collect field data. Thus, CCTV cameras were needed to be installed at each site to record the traffic operations at the toll plazas. One of the most challenging tasks in this study was the installation of the CCTV cameras at the toll plazas as was needed to choose the most suitable recording system that is within the budget of this study. Another challenging task was to determine the locations and number of cameras needed to clearly record the movement of individual vehicle arriving, as well as during the transaction time at the tollbooths. As a result, after negotiation with the Malaysian Highway Authority (MHA) and the PLUS company, video recordings were taken from two sources. The first source of video recording was from the CCTV cameras installed to record approaching vehicle behavior, traffic composition, traffic volume, queue lengths, and vehicle type. The second source of recording was from the PLUS CCTV cameras. All toll lanes at the toll plazas were provided with CCTV cameras to record each vehicle with its details (vehicle category and the plate number) for 24 hours a day. Furthermore, all the PLUS CCTV cameras are located in the same manner at the toll lanes. Therefore, all extracted data from the videos of PLUS CCTV cameras had same accuracy.

The extracted data from these videos are; throughput, payment type for each vehicle, lane choice, drivers' delay upon payment, vehicle service time, and toll collection procedure at the mixed mode lane.

The CCTV system camera that was required to be installed at both Juru and Jawi toll plazas consisted of one DVR, two Sony 2.8 to 12 mm lens CCTV cameras, one Sony 5 to 50 mm CCTV camera, one UPS, two batteries, and one ground feeder pillar to contain the DVR, UPS, and batteries as shown in Figure 3.11.

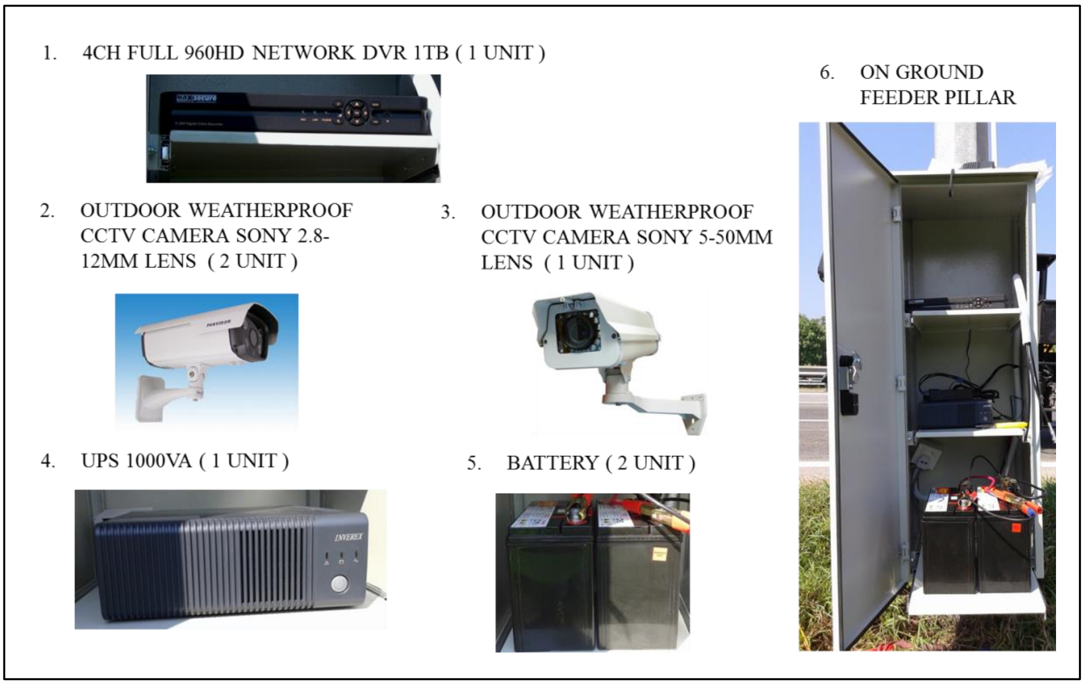


Figure 3.11 Equipment included in the CCTV system.

3.7 Camera configuration

At the Juru and Jawi toll plazas, six cameras were used to capture the upstream and downstream traffic flow and the operations at the toll plaza. All six cameras were simultaneously started, and each one captured a different situation. Three of the six cameras were used to capture one direction, and the other three were simultaneously capturing the opposite direction. Each of the three cameras were installed on a lighting pole. The height of the lighting pole and its selected location gave a clear recording view for the whole toll plaza area. Figure 3.12 shows the locations of the selected lighting poles that were used for the installation of three CCTV cameras in the Juru toll plaza. For the entry and exit directions, the selected lighting pole was at a distance of 384 m and 306 m, respectively, from the Juru toll plaza.

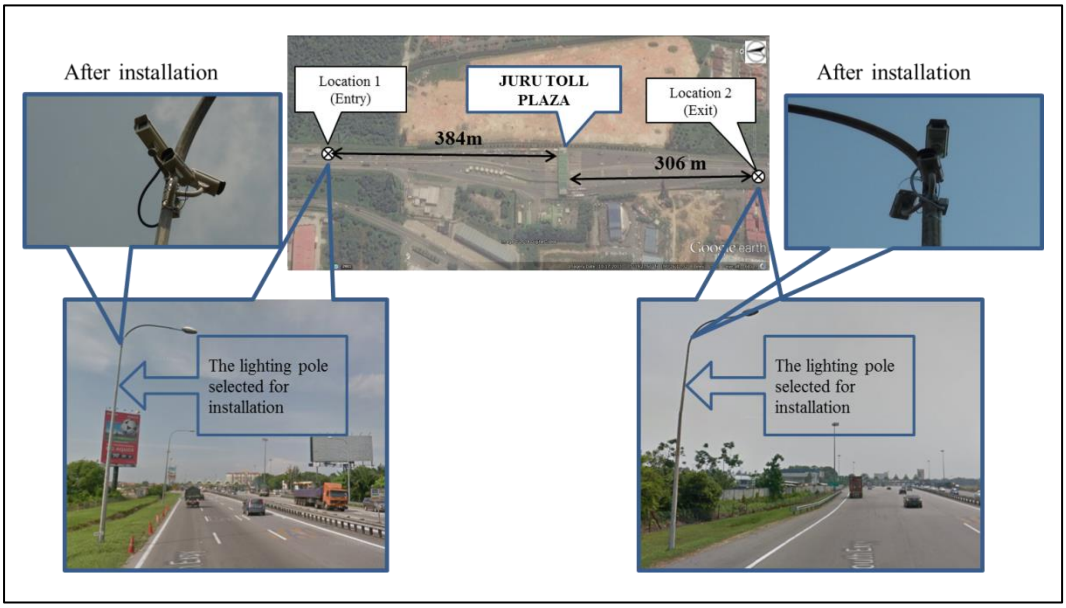


Figure 3.12 Entry and exit locations of the selected lighting poles at Juru toll plaza.

Figure 3.13 shows the locations of the selected lighting poles at the entry and exit directions of the Jawi toll plaza. The locations for the poles at the entry and exit were at distances of 149 m and 173 m, respectively, from the Jawi toll plaza.

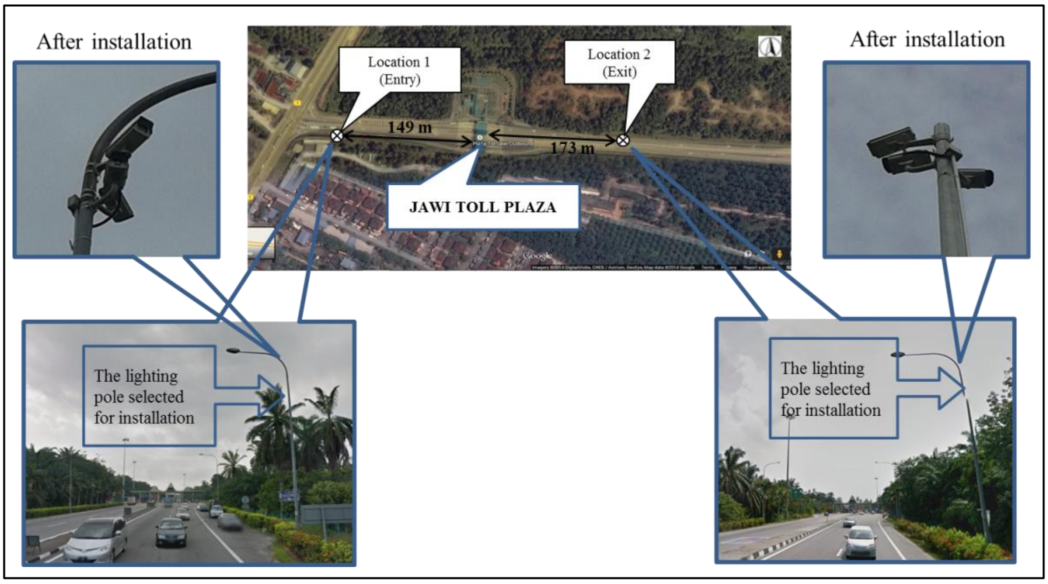
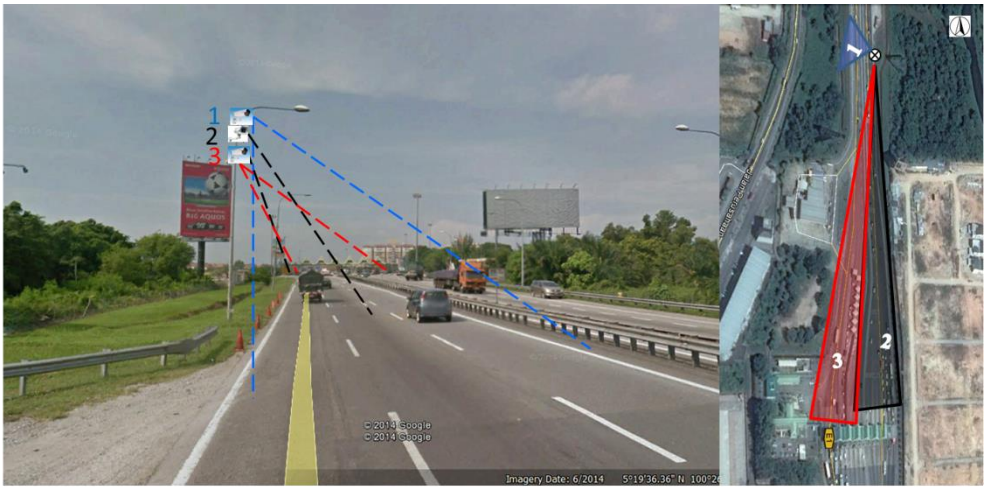


Figure 3.13 Entry and exit locations of the selected lighting poles at Jawi toll plaza.

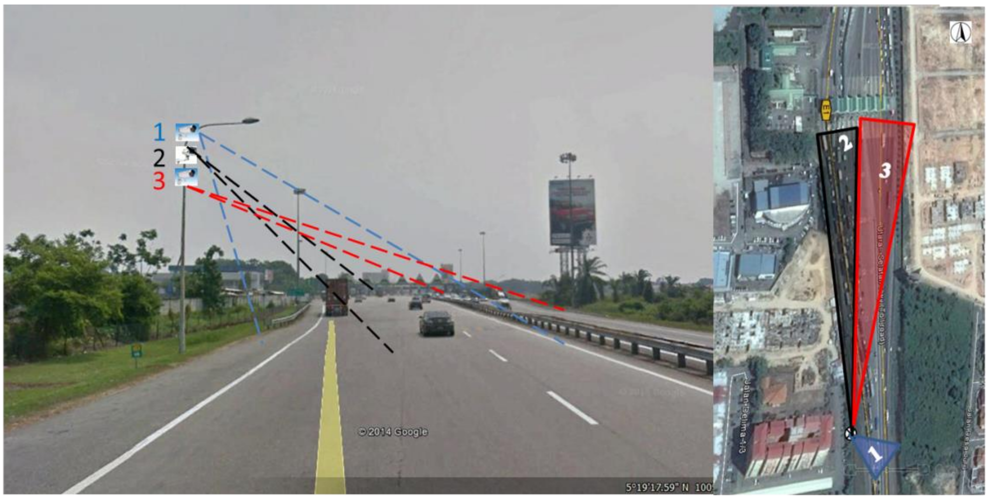
Each of the three CCTV cameras on the pole was setup to focus on a certain part of the toll plaza area to cover all the areas of the toll plaza within its traffic operations. Figure 3.14 shows the setup of the three CCTV cameras at the entry of the Juru toll plaza. Camera 1 focused on the upstream traffic lanes (traffic flow from Penang to Juru Toll Plaza); camera 2 focused on the behavior of the vehicles at the approaching zone and queue area of the toll plaza (entry toll lanes); and camera 3 focused on the behavior of the vehicle at the opposite direction after exiting the toll plaza to Penang (northbound).

For the exit direction of the Juru toll plaza, the setup of the cameras was the same way as the entry direction. Figure 3.15 shows that camera 1 focused on the upstream traffic lanes (traffic flow from Kuala Lumpur to the Juru toll plaza), camera 2 focused on the behavior of the vehicles at the approach zone and queue area of the toll plaza (exit toll lanes), and camera 3 focused on the behavior of the vehicles for the opposite direction after exiting the toll plaza to Kuala Lumpur (southbound).



- CCTV 1 : Focused on the upstream traffic lanes (from Penang to Juru toll plaza)
- CCTV 2 : Focused on the vehicles behaviour at the toll plaza area (entry toll lanes)
- CCTV 3 : Focused on the vehicles behaviour after exit the toll plaza to Penang (northbound)

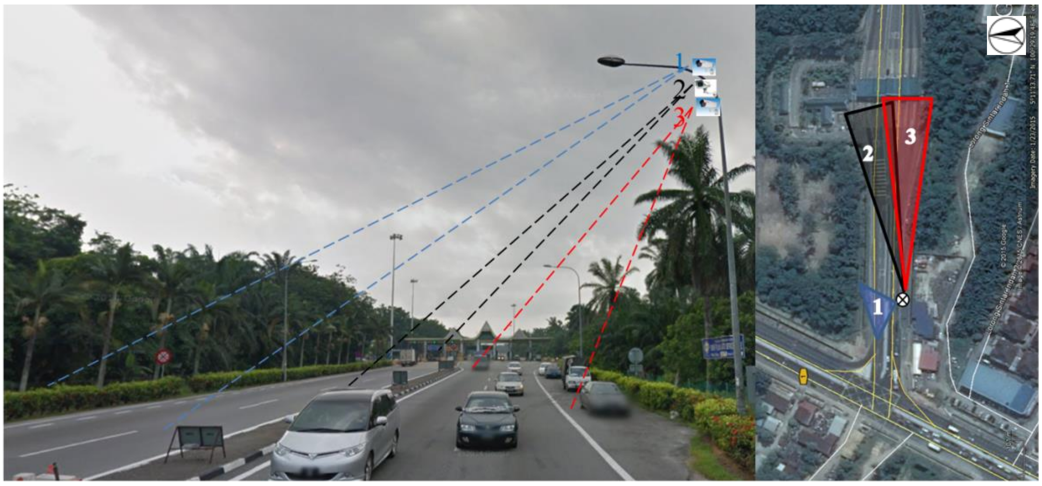
Figure 3.14 Cameras setup configuration at Juru toll plaza – Entry.



- CCTV 1 : Focused on the upstream traffic lanes (from KL to Juru toll plaza)
- CCTV 2 : Focused on the vehicles behaviour at the toll plaza area (exit toll lanes)
- CCTV 3 : Focused on the vehicles behaviour after exit the toll plaza to KL (southbound)

Figure 3.15 Cameras setup configuration at Juru toll plaza – Exit.

The same setup procedure of the cameras was applied to the Jawi toll plaza. Figure 3.16 and Figure 3.17 show the setup of the cameras for the entry and exit directions, respectively.



- CCTV 1 : Focused on the upstream traffic lanes (from local area to Jawi Toll Plaza)
- CCTV 2 : Focused on the vehicles behaviour at the toll plaza area (entry toll lanes)
- CCTV 3 : Focused on the vehicles behaviour after exit the tollbooths to local area

Figure 3.16 Cameras setup configuration at Jawi toll plaza – Entry.

- CCTV 1 : Focused on the upstream traffic lanes (from expressway to Jawi toll plaza)
- CCTV 2 : Focused on the vehicles behaviour at the toll plaza area (exit toll lanes)
- CCTV 3 : Focused on the vehicles behaviour after exit the toll plaza to expressway

Figure 3.17 Cameras setup configuration at Jawi toll plaza – Exit.

On the 27th and 28th of January 2015, CCTV cameras were installed at the Juru and Jawi toll plazas. A specialist company for CCTV systems did the installation, and a skylift truck was used during the installation process. During the installation process, one lane was closed for traffic management and safety purposes. Figure 3.18 shows some photos of the installation process for the CCTV system cameras at Juru and Jawi toll plazas.

Figure 3.18 Iinstallation process for the CCTV system cameras at Juru and Jawi toll plazas.

After completion of the installation, all the CCTV systems were tested and 24 hours recording were done for three days to ensure that all the systems are properly working. Figure 3.19 shows the recording screens of the CCTV cameras for the Juru and Jawi toll plazas.

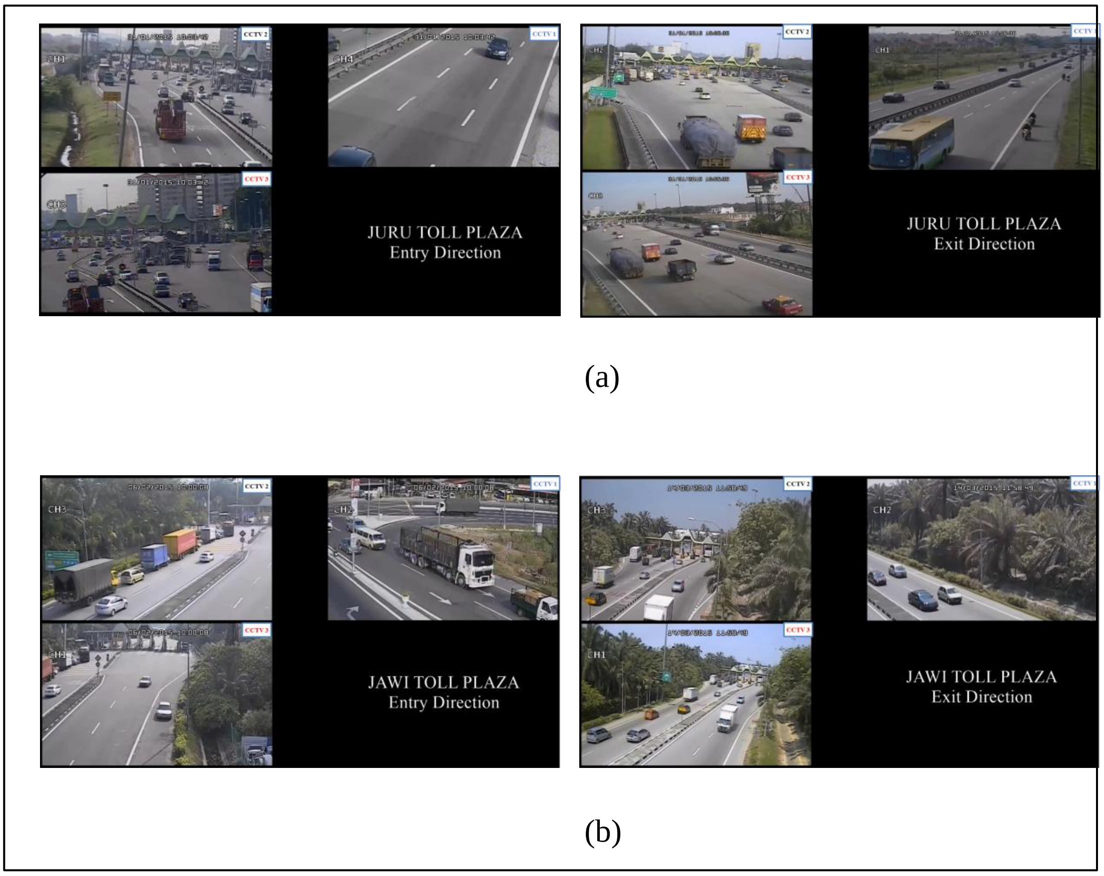


Figure 3.19 Recording screen of the cctv cameras; (a) Juru toll plaza, (b) Jawi toll plaza.

3.8 Video recording setup

Observing traffic flow components and behavior of vehicles at the tollbooths are very important to study the operation of toll plazas. The maximum performance for toll plaza operation is observed during peak hours. Field data observation was conducted with the use of video recordings during the morning (AM) and afternoon (PM) peak hours on April 2015.

Based on the traffic volume data obtained from PLUS for Juru and Jawi toll plazas from April 2014 to September 2014, two days which represent the highest average daily traffic were selected for the recording. One of the day selected was a Friday (a weekday), and the other day was a Saturday (a weekend). In addition, another day, which is Wednesday, was also selected to represent the normal traffic weekday. Each one of the selected days has different morning and evening peak hours for the entry and exit of toll plazas. Therefore, the cameras were needed to be setup to record according to the peak hours for the three days at each toll plaza. The recording time was extended one hour before and after the peak hour to ensure that the recording time is sufficient during the peak hours. Thus, the total recording time for each CCTV camera for each peak period was 3 hours.

3.9 VISSIM model development of toll plaza

As mentioned before, the microscopic simulation software, VISSIM, do not have a built-in toll plaza model. Therefore, the customized toll plaza model needs to be created and developed from the standard simulation software package. The processes of model creation consists of a series of programing steps and commands that must be addressed to simulate the actual situation of toll plaza traffic operations. This model, which accurately represents the actual operations at toll plazas, is known as the base model. The most important step of model creation and development is described in the following sections.

3.9.1 Toll plaza layout

The first step when creating the model was to import the satellite image of the toll plaza to be the background for the created model. Then, the satellite image background was scaled to match the real dimensions of the toll plaza network. The network was laid over the background by tracing the image with a series of links and connectors until all the roadways were covered with the correct dimensions and curvatures. Figure 3.20 shows the VISSIM model of the Juru and Jawi toll plazas.

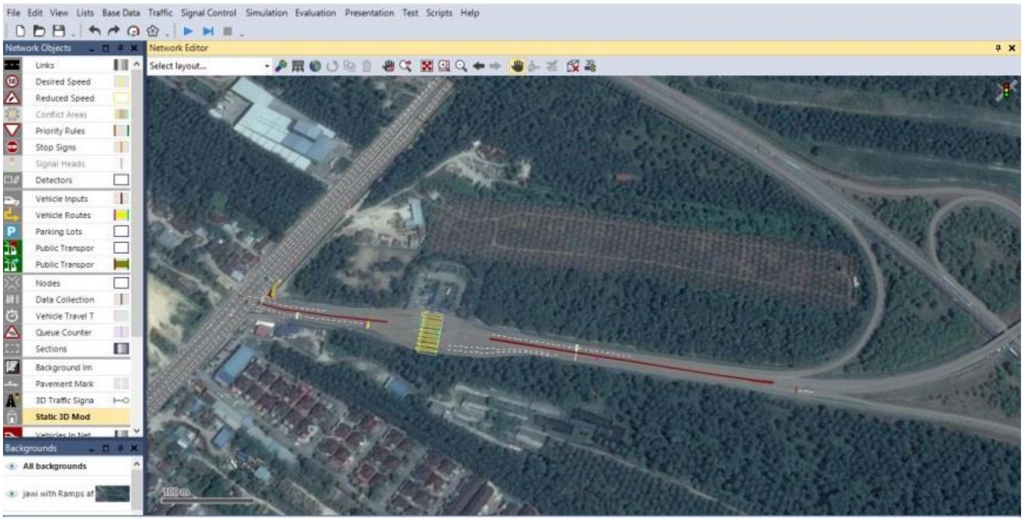
VISSIM links are single or multilane roadway segments, with a connector connecting every two links. Vehicles travelled from one link to the next through the connector. Each link and connector is defined by its name, length, location, number of lanes, lane width, and link type. Link type is identified whether it is a freeway, urban roadway, or footpath. Additionally, the link attribute contains details of the lanes that are used to specify which vehicles are allowed unto the lane and which vehicles are allowed or not to change lane. The connectors have the same details as the links. These details are very useful to simulate the traffic operations at the toll plaza roadways.

3.9.2 Defining the base model parameters

Once the toll plaza network and approaches are drawn correctly to match the toll plaza characteristics such as tollbooths location, number of toll lanes, and types of payment for each toll lane, the next step was to define the traffic and vehicle characteristics.

The VISSIM software stochastically simulates the traffic through the model. The stochastic nature of the traffic means the necessity to provide this type of variability in the VISSIM models. The VISSIM model accounts for this stochastic nature by implementing parameters based on stochastic distribution that represent the variance in vehicle behavior. The following steps are the important parameters needed to create the toll plaza model.

(a)



(b)

Figure 3.20 VISSIM models with satellite images; (a) Juru toll plaza, (b) Jawi toll plazas.

3.9.2(a) Acceleration and deceleration

To account for differences in the driving behavior of several drivers and different vehicle properties during acceleration and deceleration, VISSIM uses functions instead of individual acceleration or deceleration data.

Acceleration and deceleration are functions of the current speed. Thereby, combustion engines reaching their maximum acceleration at lower speeds are taken into account.

Four types of functions exist in VISSIM: two acceleration functions and two deceleration functions that are illustrated as curves:

1. Maximum acceleration is used to keep a certain speed on slopes, i.e., when stronger acceleration is required. The maximum acceleration is automatically adjusted for up and down gradients of links and connectors.
2. Desired acceleration is used in all situations in which maximum acceleration is not required.
3. Maximum deceleration shows that the maximum deceleration is the smallest acceleration value because deceleration values have a negative algebraic sign. The maximum deceleration is automatically adjusted for up and down gradients of links and connectors.
4. The desired deceleration is used in all situations, which needs to reduce speed or to stop at the stop signs. Thereby, maximum deceleration is not exceeded.

For this study, the distributions of the desired acceleration and deceleration are shown in Figure 3.21 and Figure 3.22, respectively, for traffic simulation model of the Juru and Jawi toll plazas.

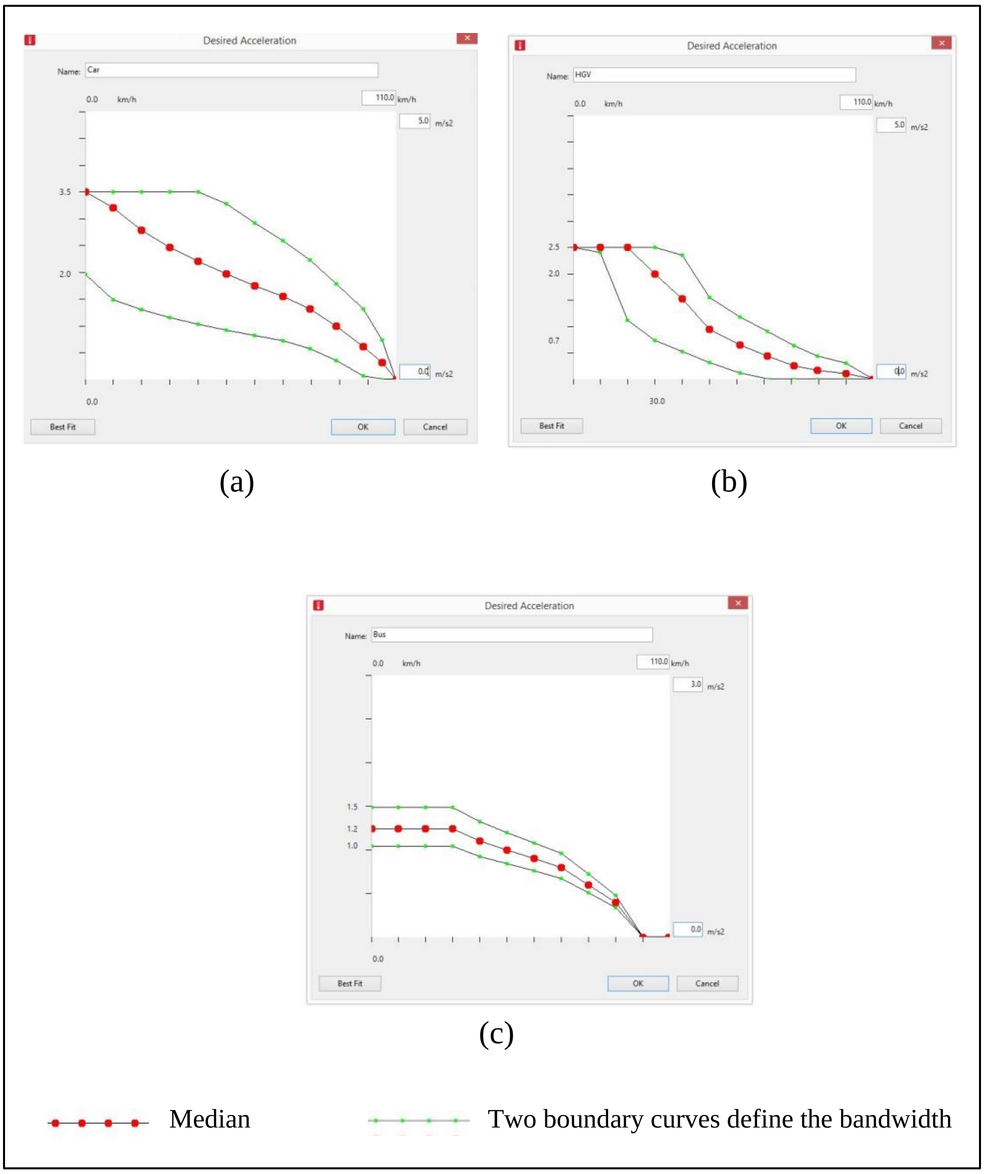


Figure 3.21 Distributions of the desired acceleration in VISSIM model for Juru and Jawi toll plazas; (a) Car, (b) HGV and (c) Bus.

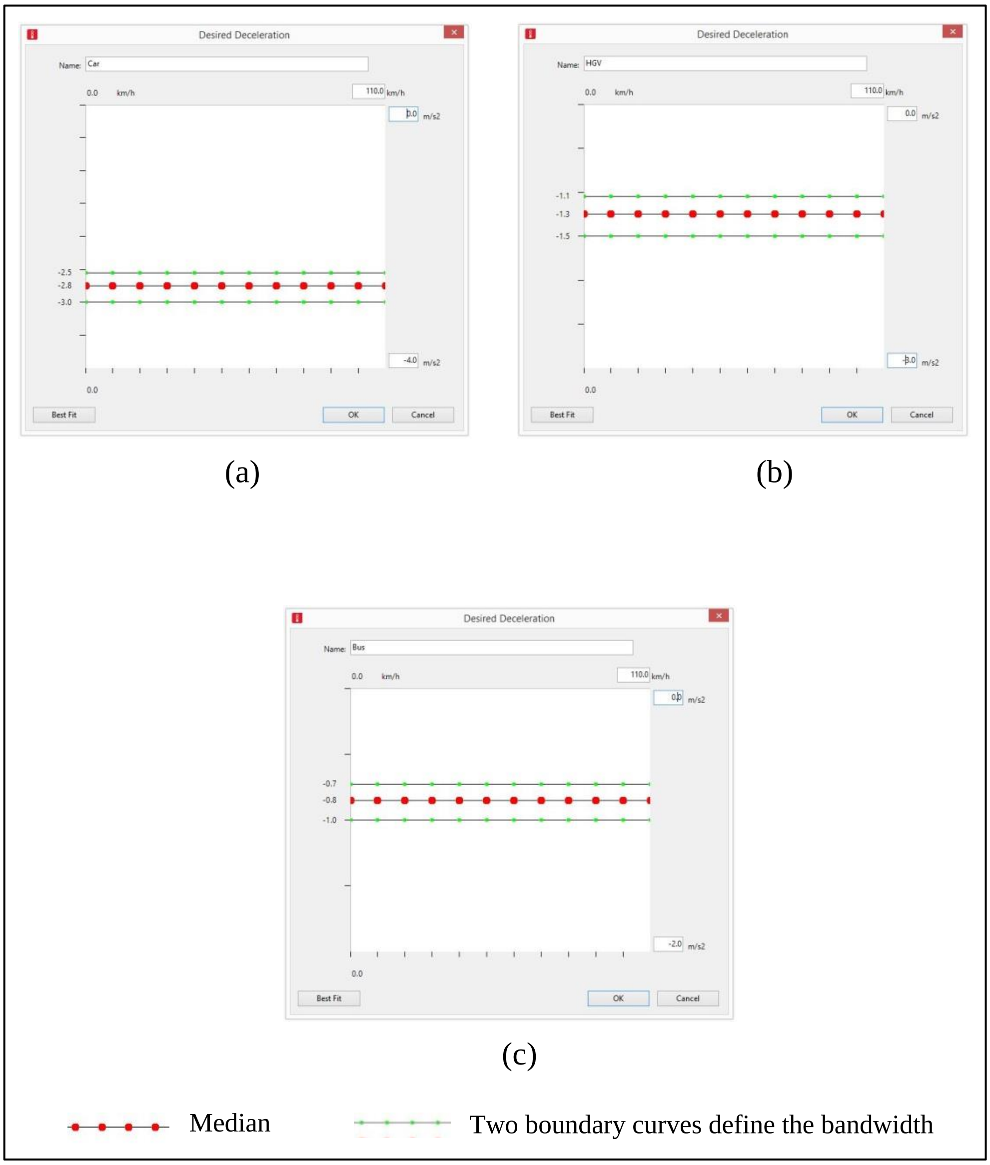


Figure 3.22 Distributions of the desired deceleration in VISSIM model for Juru and Jawi toll plaza; (a) Car, (b) HGV and (c) Bus.

3.9.2(b) Traffic composition and vehicle classes

In VISSIM, vehicles are assigned to certain types and combined with vehicle classes. However, vehicle types needed to be assigned to vehicle categories first. Vehicle categories, by default, contain categories of vehicles with similar traffic interaction.

A vehicle type allows the user to form a group of vehicles with the same technical driving characteristics.

In this step in developing the VISSIM toll plaza model, the traffic composition was created to differentiate different vehicle behaviors in the simulated model. The traffic composition in VISSIM allows the user to insert the relative flows of each link and the desired speed for each vehicle class. In this study, the traffic composition consists of five vehicle classes using three methods of payment.

The difficulty in this stage of the simulation of toll plaza operations was on how to simulate the real vehicle classes in the Juru and Jawi toll plazas. As previously mentioned, the vehicles at the toll plazas are classified into five classes: cars, small lorries, trucks, trailers, and busses. These classes used three types of payment, namely: mixed mode, Touch 'n Go, and Smart TAG. The mixed mode payment in the entry direction is different from the exit direction in terms of procedure, payment type, and service time. To solve this complexity, the vehicles are classified into two types at the toll plaza according to the toll lane selection: vehicles that select single-class lanes and vehicles that select multiclass lanes. The vehicles select single-class lanes were cars that used the Touch 'n Go payment and the cars that used Smart TAG payment. Both of these two classes were used in the entry and exit directions. The vehicles that selected the multiclass lanes were the vehicles that used the mixed mode payment. Table 3.1 shows the vehicle classes created for Juru and Jawi toll plazas.

As a result, twenty two classes of vehicles need to be created in the VISSIM model to represent the real traffic operation at the toll plazas.

Table 3.1 Vehicle classes created in VISSIM for Juru and Jawi toll plaza models

No	Class name		Payment type	Lane type
	Entry	Exit		
1	Car STAG	Car STAG	Smart TAG	Single class lanes
2	Car TNG	Car TNG	Touch 'n Go	Single class lanes
3	Entry Car Ticket	—	Ticket	Multi class lanes
4	Entry Car Tng	—	Touch 'n Go	Multi class lanes
5	—	Exit Car Cash	Cash	Multi class lanes
6	—	Exit Car Tng	Touch 'n Go	Multi class lanes
7	Entry Small lorry Ticket	—	Ticket	Multi class lanes
8	Entry Small lorry Tng	—	Touch 'n Go	Multi class lanes
9	—	Exit Small lorry Ticket	Cash	Multi class lanes
10	—	Exit Small lorry Tng	Touch 'n Go	Multi class lanes
11	Entry Truck Ticket	—	Ticket	Multi class lanes
12	Entry Truck Tng	—	Touch 'n Go	Multi class lanes
13	—	Exit Truck Cash	Cash	Multi class lanes
14	—	Exit Truck Tng	Touch 'n Go	Multi class lanes
15	Entry Trailer Ticket	—	Ticket	Multi class lanes
16	Entry Trailer Tng	—	Touch 'n Go	Multi class lanes
17	—	Exit Trailer Cash	Cash	Multi class lanes
18	—	Exit Trailer Tng	Touch 'n Go	Multi class lanes
19	Entry Bus Ticket	—	Ticket	Multi class lanes
20	Entry Bus Tng	—	Touch 'n Go	Multi class lanes
21	—	Exit Bus Cash	Cash	Multi class lanes
22	—	Exit Bus Tng	Touch 'n Go	Multi class lanes

3.9.2(c) Desired speed distribution

The desired speed distribution is an estimation of the upstream speed of the approaching vehicle toward the toll plaza. The distribution function of the desired speeds is a particularly important parameter because it impact the link capacity and the queuing at the tollbooths and, thereby, the operation of the toll plazas.

A driver will travel at his desired speed if not hindered by other vehicles or network objects. A driver, whose desired speed is higher than his current speed, will check whether he can overtake other vehicles without endangering anyone. The more the speed of the drivers differ, the more platoons are created.

In VISSIM, the desired speed distributions are defined depending on vehicle class, which are used for the command of vehicle compositions. The desired speeds at toll plazas varied according to the toll plaza type, toll plaza location, approach direction, and vehicle class. Thus, the observed speeds from Juru and Jawi toll plazas were classified into five categories for both entry and exit directions of each toll plaza to meet the needs of the VISSIM toll plaza models. The use of distributions of the values of the desired speeds rather than the average speeds makes the developed model more accurate in representing the real traffic operations of toll plazas.

The speed data observations were collected from the Juru and Jawi toll plazas using a laser speed gun on March 2015. Figure 3.23 shows the device used in measuring speed at the Juru and Jawi toll plazas. Figure 3.24 shows an example of the desired speed distribution for the vehicle type used in the VISSIM toll plaza model.

Figure 3.23 Stalker Lidar - laser speed gun.

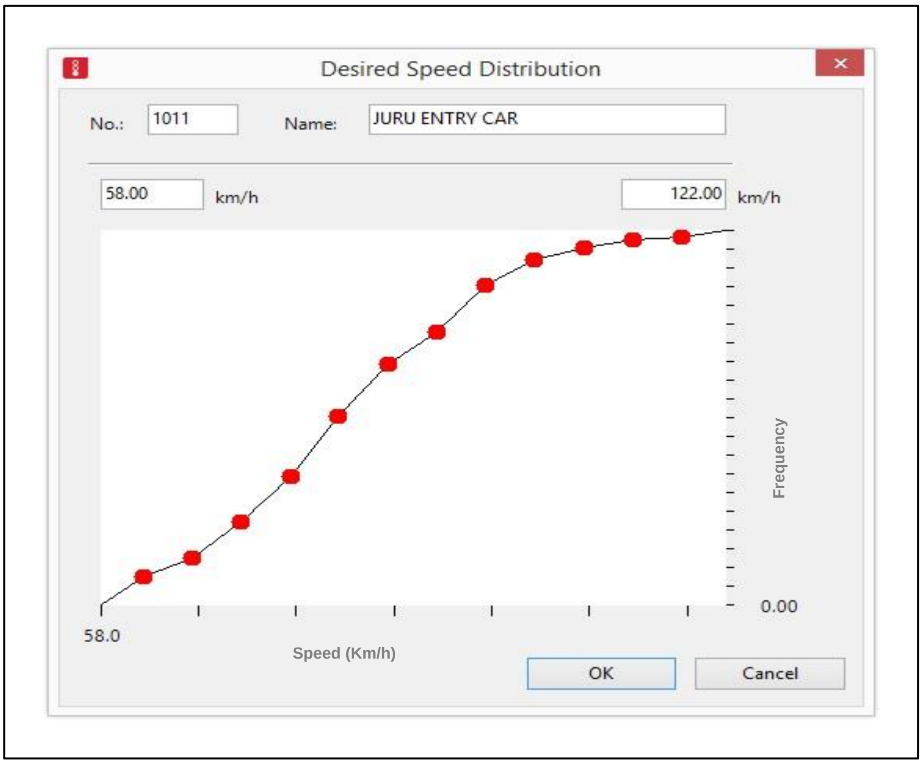


Figure 3.24 Desired speed distribution based on vehicle class in VISSIM toll plaza model - Example

3.9.2(d) Vehicle input

The observed vehicle volume per hour was inserted in the model by using the vehicle input command. These vehicle volumes were assigned to each group of traffic composition. Then, by means of Poisson distribution, the VISSIM software exactly generates the inserted number of vehicles and simulates these vehicles into the network.

The approaching vehicles in the real toll plazas travelled in their respective lanes to reach their desired toll lanes. Vehicles choose the toll lanes according to their classes and their methods of payment. In VISSIM, this behavior is simulated by using static vehicle routes. The static vehicle route allows users to split the approached vehicles into link classes to assign certain vehicle class to a particular route decision that represents the final toll lane decision. For the purposes of modelling the Juru and Jawi toll plazas, the static vehicle routing decision was sufficient to split the vehicle classes into three routes - mixed mode, Touch 'n Go, and Smart TAG - to ensure that each vehicle selects the correct toll collection lane. Thus, static routes were defined for each type of payment in both models of the Juru and Jawi toll plazas.

Figure 3.25 shows an example of the created static routing decision of a mixed mode toll lane in the Jawi toll plaza model.

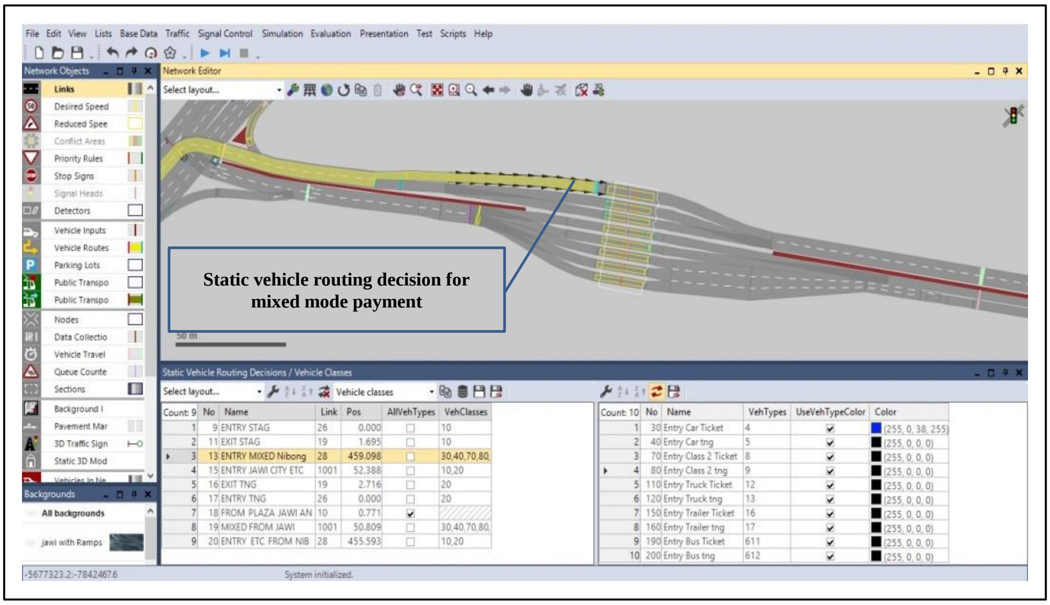


Figure 3.25 Static routing decision - mixed mode toll lane - Example.

3.9.2(e) Reduced speed area

The reduced speed areas allowed the user to emulate the Smart TAG lanes. This function provided the natural action of deceleration behavior of Smart TAG vehicles that decelerate at the lanes of the toll plaza. Cars that used the Smart TAG lanes do not need to stop and are assigned a speed distribution between 15 and 20 km/h within the toll plaza islands. Therefore, the reduced speed area are applied on the lanes specified for cars that used the Smart TAG lane in the Juru and Jawi toll plaza models. Figure 3.26 shows an example of the reduced speed area allocated at the Smart TAG lanes of the Juru model.

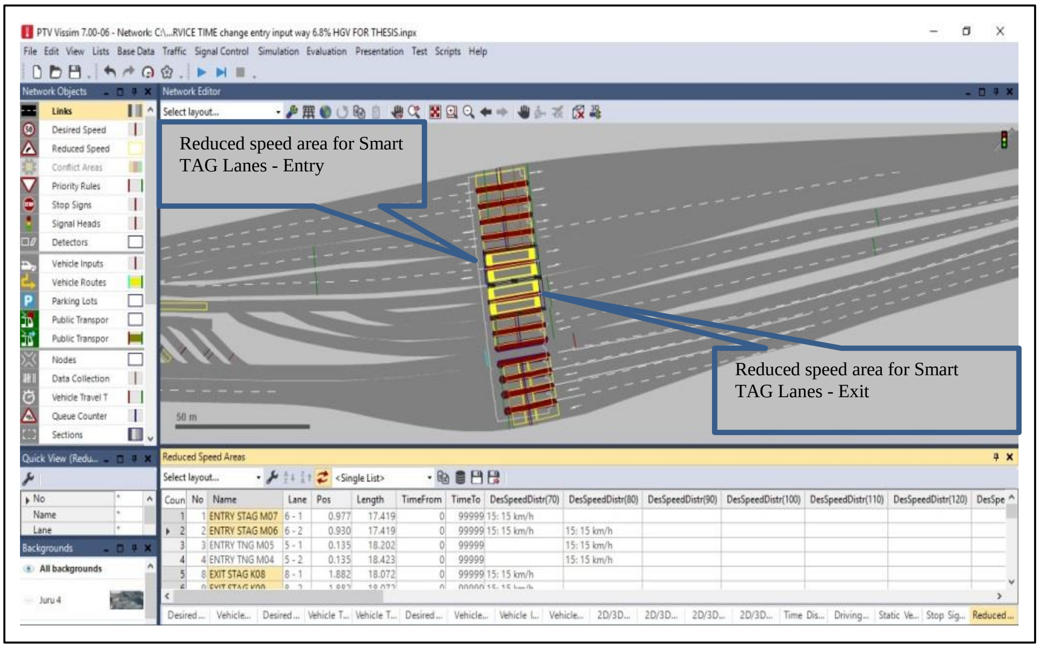


Figure 3.26 Reduced speed area for Smart TAG lanes at Juru toll plaza model – Example.

3.9.2(f) Stop signs and dwell time distributions

The VISSIM model simulates the service times at the toll lane by using the stop signs placed on a single-lane link that represents the location of the toll collection. Stop signs were used to simulate the toll service time for each vehicle needing to stop to make payments such as cash, ticket, and Touch 'n Go. This VISSIM parameter is suitable in modelling the conventional toll plazas because vehicles make a complete stop during either the manual or Touch 'n Go transactions. Furthermore, the vehicle dwell time at a stop sign is accurately set by the dwell time distribution. An option exists with each stop sign. This option enables the user to attach a unique dwell time distribution for each vehicle class and payment type.

Figure 3.27 shows an example of the stop sign window and assigned dwell time distribution.

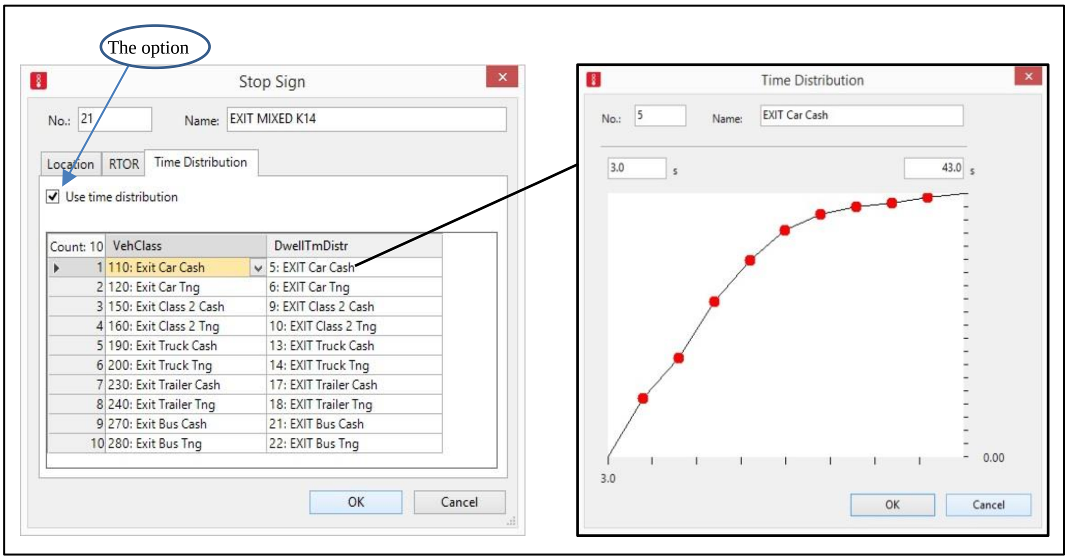


Figure 3.27 VISSIM windows for the stop sign and dwell time distribution – Example.

The dwell time distribution is important when the data of service times are available and thus a more realistic representation of the processing transaction operation is simulated (Ceballos and Curtis, 2004). Unlike the analytical models, service times do not need to be Poisson distributed. To define the dwell time distribution in the model, the service time frequencies from the data collection were plotted in a cumulative curve percentage. Then, the cumulative curve percentage was used to define dwell time distributions for each vehicle class in the model. One of the reason that there are twenty two vehicle classes created for each toll plaza model; therefore, twenty two dwell time distributions graphs were also created. Figure 3.28 shows an example of the dwell time distributions graph created in the toll plaza models.

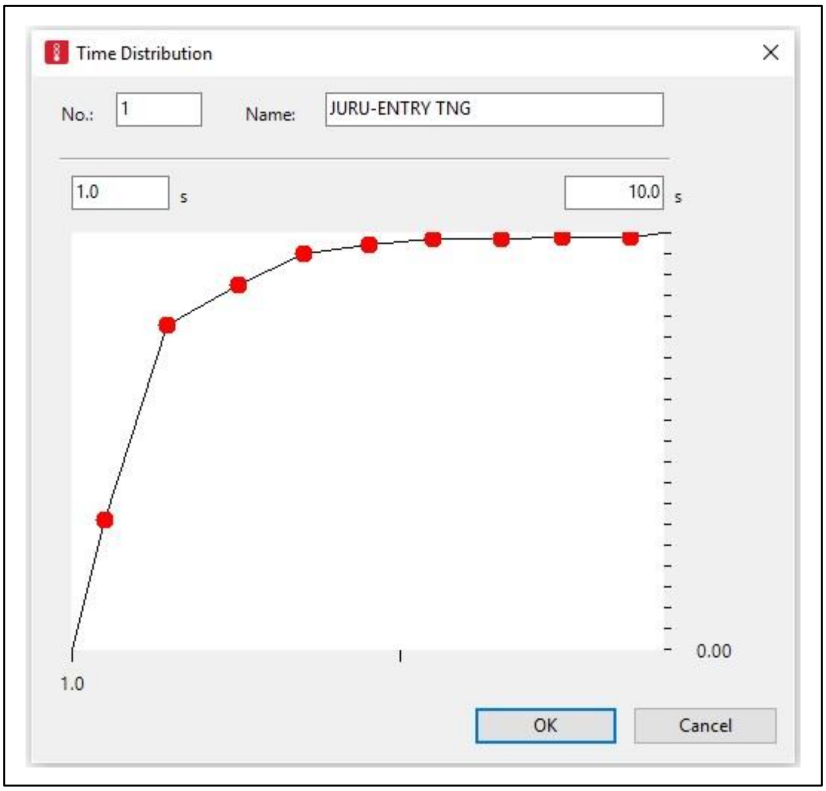


Figure 3.28 Dwell time distribution for car Touch ´n Go at Juru toll plaza model – Example.

3.9.3 Calibration of the models

Calibration is a process of adjusting the model’s parameters to improve the model’s ability to accurately reproduce traffic operation characteristics (Dowling et al., 2004). Calibration is performed on various components to replicate observed data to a sufficient level to satisfy the objectives of the model (Bains et al., 2012).

Calibration is necessary because no single model is equally accurate for all possible traffic conditions. Even the most detailed microsimulation model still contains only a portion of all of the variables that affect real-world traffic conditions. Therefore, every model must be adapted to local conditions (Hourdakis et al., 2003).

Before any calibration, it is important to determine which MOE is used for calibration and which parameters directly affect the MOE. The parameters in which the field data are available should be reviewed and adjusted to reach the optimum toll operation and match the field conditions (Chu et al., 2004).

To proceed with the calibration of the toll plaza models, the Guidelines for Applying Traffic Microsimulation Modeling Software (Dowling et al., 2004) was used as a reference for guidance in the toll plaza model calibration. In this study, the model calibration was based on the key parameters such as desired speed and service time (Al-Deek and Mohamed, 2000; Grigoroudis and Siskos, 2010). These two parameters are very useful for toll plaza calibration because they represent the behavior of traffic situations.

The procedure of the toll plaza model calibration was divided into several steps. The first step was to select the measure of effectiveness MOE (throughput) (Klodzinski et al., 2008) as the index of comparison between the simulated and observed values. Second, the simulation models for 10 simulation models repetitions with different input values were run and the outputs of the selected MOE were obtained (Bains et al., 2012; Dowling et al., 2004; Poon and Dia, 2005). Then, the statistical paired two samples t-test analysis with 95% level of confidence was use to compare the observed MOE values with the outputs from the simulation results (Dowling et al., 2004). The paired two samples t-test (t) value is calculated using Equation (3-6) (Montgomery and Runger, 2003):

$$t = \frac{\sum D}{\sqrt{\frac{n(\sum D^2)-(\sum D)^2}{n-1}}} \tag{3-6}$$

Where:

t = t-test value.

D = Difference between the observed and simulated MOE.

n = Number of simulation runs.

The p-value used to compare between the simulated and observed MOE to determine whether there is a significant difference between them. The p-value approach has two hypothesis; the first is the null hypothesis (H_0), which assumes that the mean of two paired samples are equal. The second hypothesis will be an alternative hypothesis (H_a), which assumes that the means of two paired samples are not equal. The level of significance was tested at the 95% confidence level. If the p-value is greater than 0.05, then there is no evidence to support rejecting the null hypothesis, that means the simulation outputs show a statistical significance of similarity to the observed MOE and, thus, the models of the Juru and Jawi toll plazas can be considered as well calibrated.

But if the p-value is smaller than 0.05, then there is enough evidence to support rejecting the null hypothesis, that means a significant difference is seen between the simulated and observed values of the MOE, thus the model's key parameters need more adjustments depending on the field observation and the rerun the ten simulation models repetitions.

A multiple of 10 simulation runs with different values of the key parameters were done until the calibration was completed. Figure 3.29 shows the flowchart of the calibration process.

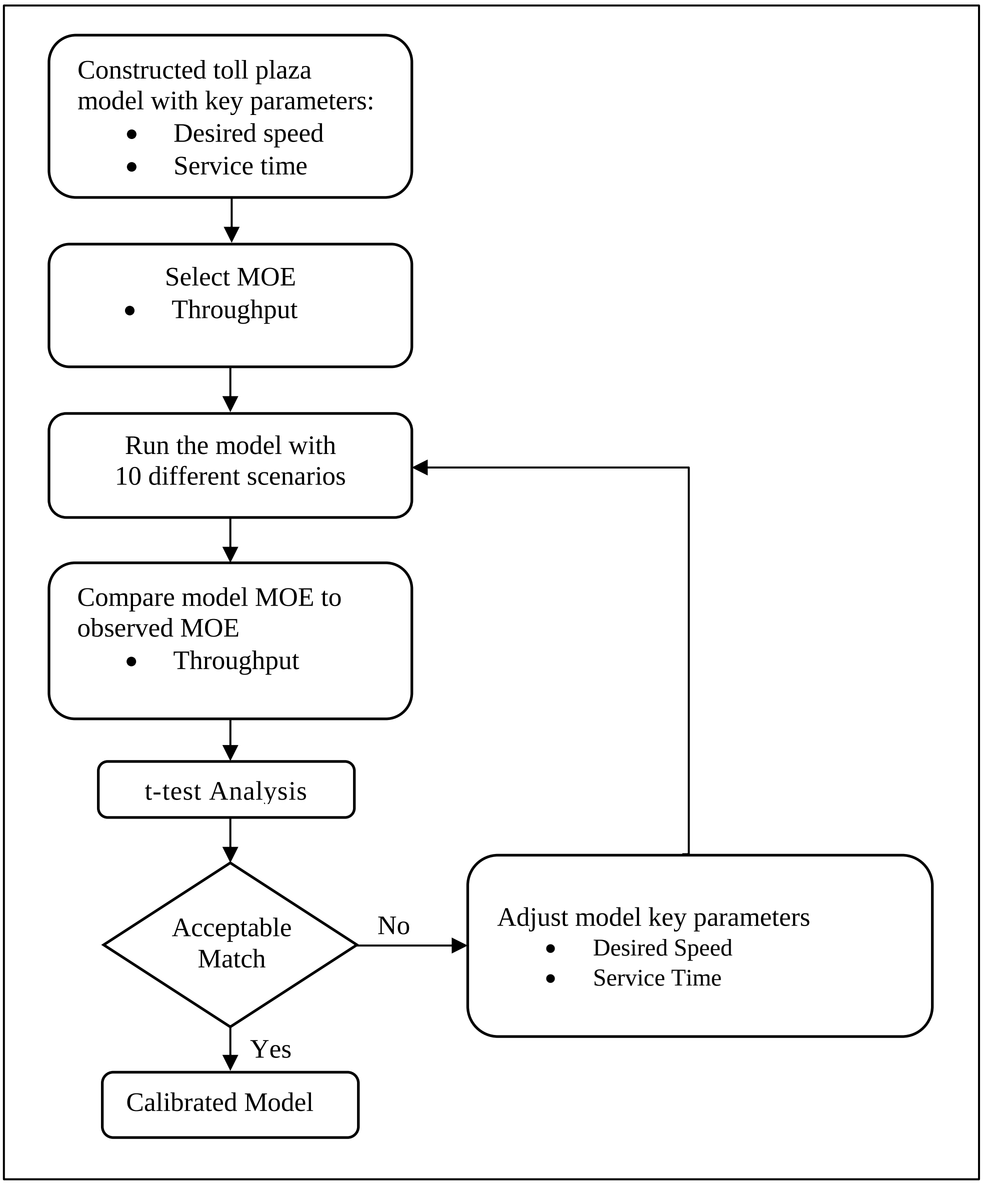


Figure 3.29 Flowchart of the calibration process of the simulation (Mckinnon, 2013).

3.9.4 Assessment of overall the toll operation of the toll plazas

After the models were calibrated, the next steps are to achieve the objectives of the following:

- To examine the effect of traffic composition on queue lengths at toll plazas.
- To develop equations to calculate the actual capacity of the conventional toll plazas.
- To predict the effectiveness of implementing a full electronic toll collection (ETC) system of the operation of conventional toll plazas in the future.

These objectives were achieved through the simulation of several scenarios of the calibrated models. Each objective has specific scenarios to replicate the objective conditions such as increasing the percentage of heavy vehicles at toll lanes to examine the effect of heavy vehicles on queue lengths at toll plaza; simulating the current traffic conditions to estimate the actual capacity of the toll plaza; and introducing a new traffic flow with full ETC toll conditions to examine the effectiveness of implementing the full ETC system of the operation on the toll plazas.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of experimental investigations carried out in this research including the analysis of observed data collections of the parameters that influence the operations and the capacities of the toll plaza lanes. In addition, the chapter presents the observation results needed to calculate the service time for each vehicle type for all types of payment.

4.2 Data collection

The field data input required for the Juru and Jawi toll plaza models were extracted from the video recordings and gathered from the database from the PLUS company for the months of April to September 2014. The collected data was then categorized into three major categories: toll plaza, traffic, and vehicle characteristics. These characteristics have major impact on the operation of the toll plazas and, hence, the capacity of the toll lanes.

4.2.1 Toll plaza characteristic

In this study, the toll plaza characteristics include the number of toll lanes for each direction, type of payment for each lane, and the toll collection procedure at the mixed mode lane.

4.2.1(a) **Toll lanes and payment types**

The previous chapter mentioned in detail the payment types for toll lanes of the Juru and Jawi toll plazas. Table 4.1 shows the summary of the toll lane numbers, lane types, and payment types at the Juru and Jawi toll plazas. The Juru toll plaza has twenty-three toll lanes, seven toll lanes at the entry and 16 toll lanes at the exit. In addition, the Juru toll plaza has eight staggered tollbooths at the exit. All the payment types are used in the Juru toll plaza which are mixed mode, Touch 'n Go, and Smart TAG.

The Jawi toll plaza has eight toll lanes, three toll lanes at the entry and five toll lanes at the exit with payment types of mixed mode, Touch 'n Go, and Smart TAG.

Table 4.1 Toll lanes and the payment types at the Juru and Jawi toll plazas

		Mixed mode			Touch 'n Go			Smart TAG			Staggered			Total Direction	Total Plaza
		Lane	Lane type	No.	Lane	Lane type	No.	Lane	Lane type	No.	Booth	Lane type	No.		
Juru	Entry	M01-M03	Multi-class	3	M04-M05	Single class	2	M06-M07	Single class	2	-	-	-	7	23
	Exit	K13-K16	Multi-class	4	K10-K11	Single class	2	K08-K09	Single class	2	K31-K38	Multi-class	8	16	
Jawi	Entry	M01	Multi-class	1	M02	Single class	1	M03	Single class	1	-	-	-	3	8
	Exit	K06-K08	Multi-class	3	K05	Single class	1	K04	Single class	1	-	-	-	5	

4.2.1(b) **Toll collection procedure at the mixed mode lane**

The conventional toll collection procedure is one of the major problems at toll plazas in Malaysia. These conventional toll collections are the mixed mode toll collections and multiclass lanes. The mixed mode lane payment methods included manual payment (cash/ticket) and electronic toll collection (Touch 'n Go) and all vehicles classes use these lanes.

In Malaysia, the procedures of toll collections in the mixed mode lanes vary depending on the payment method and vehicle class. The operator in the tollbooth must specify the class, provide tickets, receive cash, make changes, and issue receipt because the Malaysian toll lanes are not provided with automatic vehicle identification (AVI). In addition, the operator has to enter the plate number for trucks, small lorries, and trailers. Figure 4.1 shows the operator entering the plate and the class number for the truck.

Vehicles that use Touch 'n Go to make payment such as small lorries, trucks, trailers, and busses had to pass the card to the operator to complete the transaction because the drivers in these vehicles are unable to reach the Contactless Smart Card (CSC) reader.

As a result, the mixed mode toll lane collection procedures directly impact the service time and the throughput capacity, thus directly influencing the toll lane operation. Figure 4.2 shows that the location of the reader which is too low for drivers of heavy vehicles to reach and assistance is needed from the tollbooth operator to touch the card at the reader, translating into longer service time.

Figure 4.1   The operator inside the tollbooth typing the truck details.

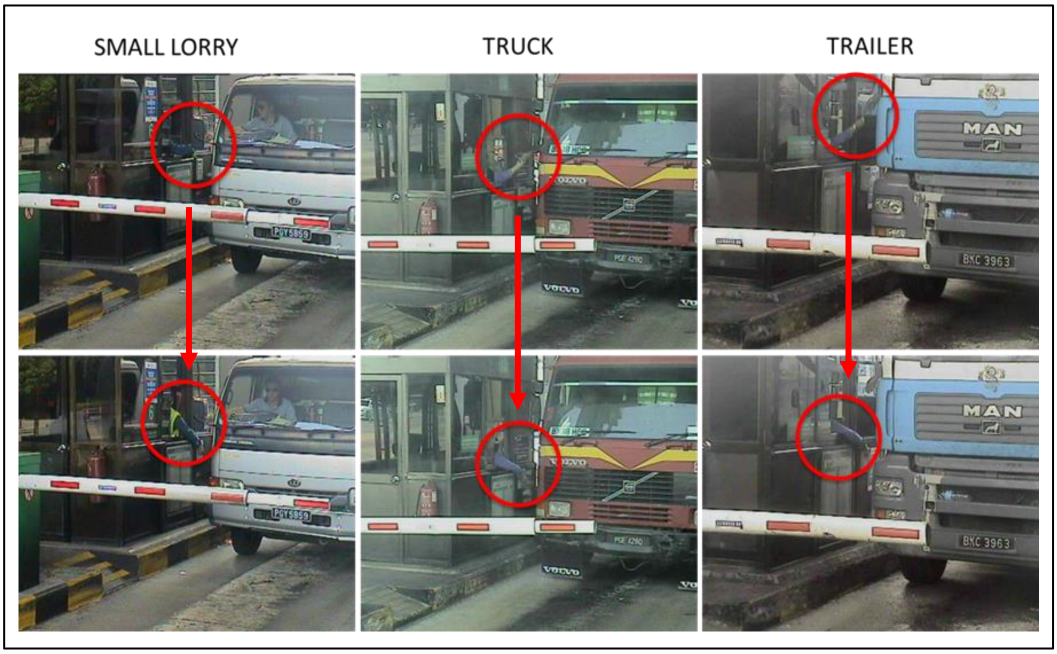


Figure 4.2 Location of CSC reader too low for heavy vehicles

4.2.2 Traffic characteristics

Traffic flow of Malaysian expressways is heterogeneous with different types of vehicles such as cars, small lorries, and heavy vehicles. Heterogeneous traffic has a multiple effect on the toll plaza operations depending on the traffic characteristics. The traffic characteristics are the proportion of vehicles arriving at the entire toll plaza belonging to different types of payments. Traffic characteristics are classified into traffic volume, throughput, traffic composition, desired speed, and queue length.

4.2.2(a) **Traffic volume and throughput**

Traffic volume and throughput are interrelated elements in the operation of toll plazas. A direct correlation exists between throughput and traffic volume. Therefore, these two characteristics are described as one element in this subsection.

Traffic volumes and throughput data collected for the months of April to September 2014 for Juru and Jawi toll plazas are categorized into:

i. direction of travel: entry and exit;
ii. traffic volume at the toll lanes for each direction;
iii. traffic volume by mode of payment;
iv. each day for 24 hours.

Generally, traffic volume in the exit direction of Juru and Jawi toll plazas are greater than the traffic volume at the entry direction for the months of April to September 2014 as shown in Figure 4.3.

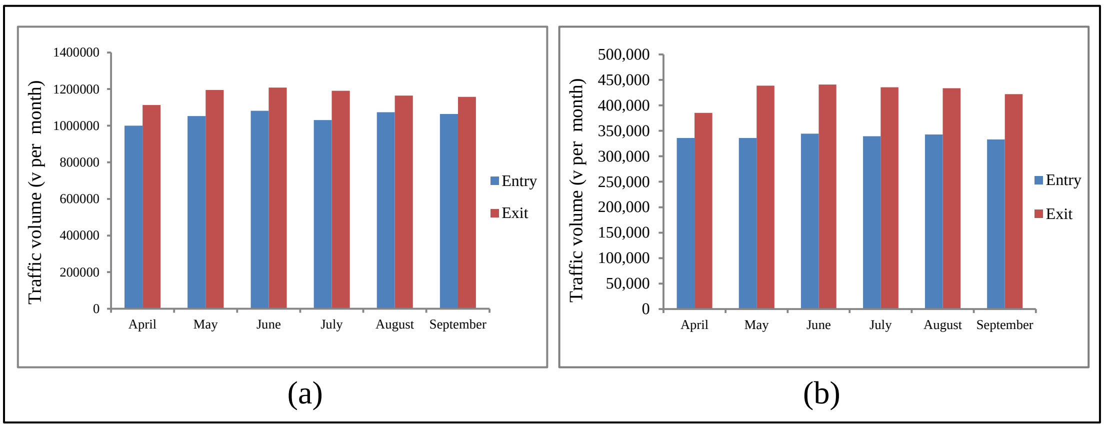


Figure 4.3 Monthly traffic volume for April to September 2014 at; (a) Juru toll plaza, (b) Jawi toll plaza.

Figure 4.4 shows the average monthly traffic volume for the same period at Juru toll plaza. The exit is higher than entry lane at about 208,000 vehicle per month, which represents 6% of the total average monthly traffic. For Jawi, the average monthly traffic volume is shown in Figure 4.5. The exit is higher than entry lane at about 87,000 vehicle per month, which represents 12% of the total.

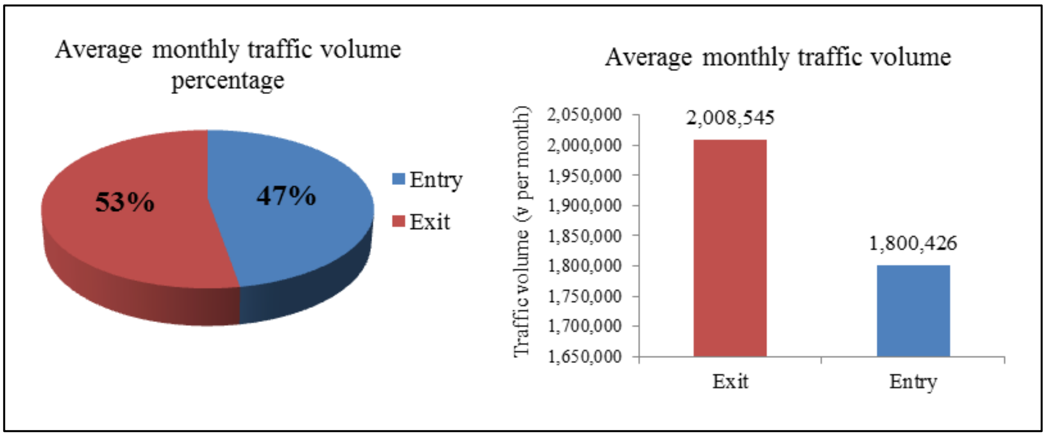


Figure 4.4 Average monthly traffic volume at Juru toll plaza for April to September 2014 for entry and exit.

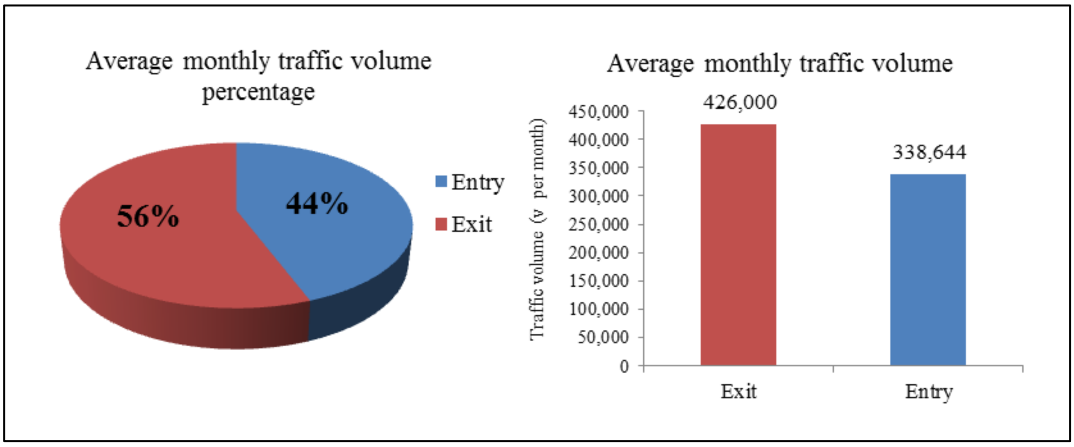


Figure 4.5 Average monthly traffic volume at Jawi toll plaza for April to September 2014 for entry and exit.

As previously mentioned, video recording was one of the sources for field data collections. Therefore, the study used video recordings for three days within a week for two reasons. First, the CCTV system recordings have limited storage and it is illogical to record every day. Second, the maximum toll operation presents with the highest traffic volume approaching the toll plaza, which means during the peak hours.

Therefore, the suggested three days were the following: the first day had the highest average daily traffic in weekdays, the second day had the highest average daily traffic in weekends, and the third day is a normal weekday. Thus, Figure 4.6 shows the average daily traffic at the Juru and Jawi toll plazas from April to September 2014 and shows that the first day was Friday, the second day was Saturday, and the third day was Wednesday for both toll plazas and for both directions.

After choosing the recording days, identifying the morning and evening peak hours on Wednesday, Friday, and Saturday was needed. The average hourly traffic volume data by toll lane based on the payment method and direction of travel is used to determine the peak hour.

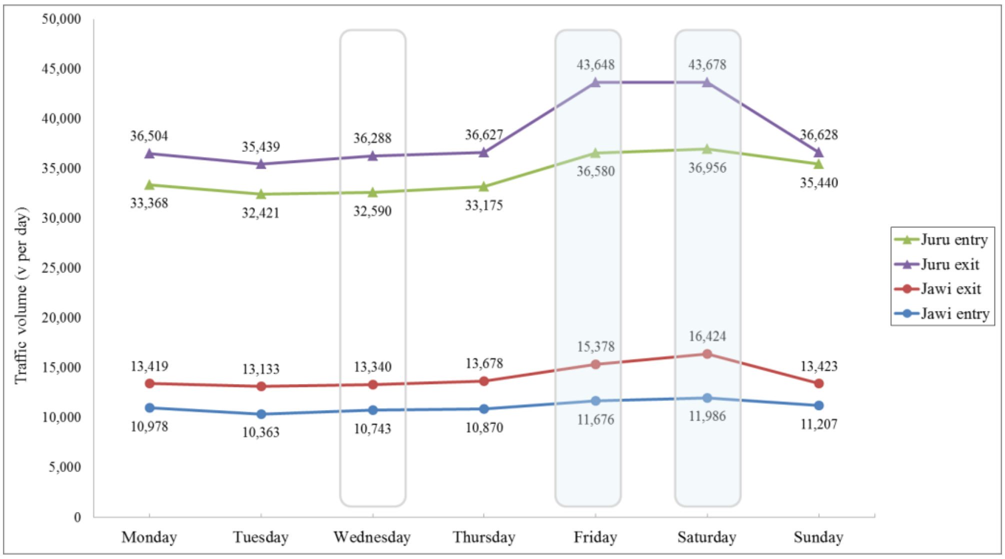


Figure 4.6 Average daily traffic at Juru and Jawi toll plaza for April to September 2014 for entry and exit

For the Juru toll plaza, Table 4.2 shows the average hourly traffic volume by lane for Wednesdays. At entry, the maximum hourly traffic volume is 1,751 vph from 6:00–7:00 AM in the morning and 2,375 vph from 5:00–6:00 PM in the evening. At exit, the maximum hourly traffic volume is 2,631 vph from 7:00–8:00 AM in the morning and 2,561 vph from 5:00–6:00 PM in the evening.

Table 4.3 shows the average hourly traffic volume by lane for Fridays. At entry, the maximum hourly traffic volume is 2,006 vph from 10:00–11:00 AM in the morning and 2,578 vph from 5:00–6:00 PM in the evening. At exit, the maximum hourly traffic volume is 2,536 vph from 7:00–8:00 AM in the morning and 2,999 vph from 5:00–6:00 PM in the evening. Table 4.4 shows the average hourly traffic volume by lane for Saturdays. At entry, the maximum hourly traffic volume is 2,100 vph at 11–12 in the morning and 2,306 vph from 2:00–3:00 PM in the evening. At exit, the maximum hourly traffic volume is 2,650 vph from 11:00 AM to12:00 PM in the evening and 2,883 vph from 5:00–6:00 PM in the evening. As a result, Table 4.5 shows the summary of the peak hours at the Juru toll plaza for the three chosen days for this study.

Table 4.2 Average hourly traffic volume for Juru toll plaza by lane for Wednesdays (April to September 2014)

Direction	No	Type	Hours / Lane	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Total
ENTRY	1	Mixed mode	M01	120	98	65	52	96	173	185	200	233	229	217	224	229	228	233	228	223	215	208	186	173	164	161	140	4,280
	2	Mixed mode	M02	133	68	55	50	58	124	264	268	264	257	256	251	251	263	259	243	270	269	259	219	204	190	164	151	4,789
	3	Mixed mode	M03	34	13	3	0	4	0	101	107	119	159	183	199	240	231	223	235	274	267	305	145	128	168	185	127	3,451
	4	Touch´n Go	M04	48	30	22	18	35	112	271	241	222	241	234	219	221	236	252	276	307	328	274	204	174	165	121	82	4,333
	5	Touch´n Go	M05	32	18	14	12	20	81	208	216	199	212	209	192	197	225	245	254	295	311	275	199	166	153	108	67	3,909
	6	Smart TAG	M06	103	69	49	40	52	155	427	413	350	350	355	359	369	394	413	424	503	535	447	347	327	318	241	170	7,208
	7	Smart TAG	M07	33	16	9	7	13	64	294	290	230	249	244	249	251	287	298	317	405	450	337	233	198	193	122	76	4,864
			Total	503	311	216	178	278	709	1,751	1,736	1,619	1,697	1,697	1,692	1,758	1,863	1,923	1,979	2,277	2,375	2,104	1,532	1,371	1,351	1,102	814	32,835
EXIT	1	Smart TAG	K08	58	43	34	33	55	236	565	545	417	375	372	380	394	404	405	416	526	546	429	347	260	217	151	95	7,303
	2	Smart TAG	K09	51	37	29	28	28	129	383	412	258	216	239	232	255	249	269	284	377	395	314	258	208	164	113	73	5,000
	3	Touch´n Go	K10	41	32	26	31	53	180	349	354	268	242	241	234	244	262	267	284	346	342	259	221	176	143	98	66	4,758
	4	Touch´n Go	K11	30	22	18	19	26	110	254	247	155	141	149	162	161	173	179	201	270	263	185	158	119	96	63	45	3,247
	5	Mixed mode	K13	68	52	52	57	86	137	147	147	139	146	148	150	156	154	157	158	153	157	143	141	132	146	118	88	3,031
	6	Mixed mode	K14	60	57	52	53	73	119	127	127	127	124	133	135	137	139	146	139	149	150	133	126	126	123	100	82	2,737
	7	Mixed mode	K15	57	51	57	56	70	102	106	111	112	112	120	121	119	119	121	125	135	136	120	114	106	107	91	73	2,440
	8	Mixed mode	K16	64	64	67	65	75	87	93	94	99	106	108	108	103	106	118	113	122	115	103	100	91	96	79	68	2,245
	9	Staggered	K31	0	0	0	0	0	0	0	0	0	0	0	0	0	9	16	13	8	11	3	0	0	0	0	0	59
	10		K32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	11		K33	0	0	0	0	0	0	10	29	38	54	33	8	0	18	24	27	17	19	17	2	2	0	0	0	296
	12		K34	0	0	0	0	0	5	60	103	82	75	59	58	53	55	65	66	67	67	46	31	18	1	0	0	910
	13		K35	0	0	0	0	0	5	58	102	80	76	63	53	48	57	59	56	73	63	48	31	17	14	6	1	908
	14		K36	1	0	0	0	0	7	61	91	37	70	32	47	46	49	55	54	55	55	49	31	22	18	6	1	785
	15		K37	4	0	0	0	0	18	104	121	112	110	96	90	93	98	94	103	108	104	80	65	53	55	42	9	1,560
	16		K38	9	1	0	0	0	29	132	149	130	124	116	121	124	131	127	130	144	138	110	104	81	79	62	17	2,058
			Total	443	359	335	341	466	1,165	2,449	2,631	2,054	1,971	1,909	1,897	1,933	2,021	2,102	2,169	2,548	2,561	2,039	1,731	1,411	1,257	929	617	37,338
Grand Total				946	670	551	519	743	1,874	4,199	4,367	3,673	3,668	3,606	3,590	3,691	3,884	4,025	4,147	4,825	4,936	4,143	3,263	2,782	2,609	2,031	1,431	70,172

Table 4.3 Average hourly traffic volume for Juru toll plaza by lane for Fridays (April to September 2014)

Direction	No	Type	Hours / Lane	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Total
ENTRY	1	Mixed mode	M01	133	104	74	55	103	185	206	225	247	243	234	235	231	233	251	257	249	247	235	212	195	179	171	161	4,664
	2	Mixed mode	M02	187	106	72	71	77	131	256	275	304	257	242	240	243	280	275	261	275	254	273	232	232	208	204	185	5,139
	3	Mixed mode	M03	26	27	17	0	0	0	131	130	134	174	194	199	188	225	235	209	230	258	264	113	105	160	181	136	3,334
	4	Touch´n Go	M04	65	46	34	30	51	109	273	267	250	286	296	279	265	263	314	343	369	377	333	243	211	204	169	112	5,189
	5	Touch´n Go	M05	54	32	22	21	38	90	250	254	246	281	294	284	256	263	312	341	382	386	347	261	219	204	164	107	5,110
	6	Smart TAG	M06	137	92	67	55	81	158	435	424	372	396	422	420	407	411	441	483	546	565	480	379	356	361	301	215	8,005
	7	Smart TAG	M07	51	30	15	13	22	64	304	303	258	289	324	312	305	316	363	388	474	491	393	293	257	259	187	113	5,824
			Total	652	437	302	246	372	738	1,855	1,878	1,811	1,925	2,006	1,969	1,895	1,989	2,192	2,284	2,524	2,578	2,325	1,733	1,575	1,574	1,377	1,028	37,266
EXIT	1	Smart TAG	K08	138	118	92	82	86	237	545	570	423	391	389	419	421	442	492	520	583	566	485	449	379	324	254	187	8,591
	2	Smart TAG	K09	120	100	88	76	70	128	380	390	273	247	274	282	295	313	353	384	459	452	386	378	325	266	203	156	6,398
	3	Touch´n Go	K10	90	78	66	64	79	178	331	336	267	258	269	275	283	293	335	362	396	393	329	298	260	219	160	121	5,738
	4	Touch´n Go	K11	70	58	54	43	51	117	242	237	165	158	174	198	200	214	266	299	358	363	274	246	210	169	123	97	4,386
	5	Mixed mode	K13	100	88	92	89	97	133	136	148	142	146	141	152	158	159	174	168	169	176	161	163	158	150	135	113	3,350
	6	Mixed mode	K14	94	81	84	81	90	117	122	128	125	127	137	137	141	137	147	153	147	152	145	145	147	133	120	107	2,995
	7	Mixed mode	K15	87	76	83	81	86	103	104	108	110	113	118	120	122	126	131	140	146	151	145	140	138	125	113	99	2,766
	8	Mixed mode	K16	81	80	78	85	85	90	92	98	97	106	104	105	106	115	118	124	126	130	118	115	115	104	93	84	2,447
	9	Staggered	K31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	3
	10		K32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	11		K33	0	0	0	0	0	1	10	7	27	16	12	11	9	14	29	66	44	47	36	52	28	0	0	0	410
	12		K34	0	0	0	0	0	7	51	87	74	73	66	63	66	60	94	103	103	104	79	63	40	3	0	0	1,135
	13		K35	0	0	0	0	0	8	53	88	72	62	68	60	63	55	88	88	100	94	78	66	43	13	7	3	1,107
	14		K36	9	5	4	13	6	8	54	83	58	58	54	55	61	54	75	74	80	85	62	51	51	46	26	15	1,086
	15		K37	15	10	13	28	29	17	95	112	102	102	104	106	106	100	114	121	127	130	111	100	93	101	61	34	1,929
	16		K38	20	16	13	40	40	27	126	144	126	129	125	128	136	135	148	155	158	156	141	128	119	129	88	54	2,480
			Total	824	710	668	681	718	1,169	2,341	2,536	2,062	1,986	2,035	2,111	2,165	2,218	2,566	2,757	2,996	2,999	2,551	2,392	2,106	1,781	1,380	1,070	44,822
Grand Total				1,476	1,147	970	927	1,089	1,907	4,196	4,414	3,873	3,911	4,042	4,080	4,060	4,208	4,757	5,041	5,520	5,577	4,876	4,125	3,681	3,355	2,757	2,099	82,088

Table 4.4 Average hourly traffic volume for Juru toll plaza by lane for Saturdays (April to September 2014)

Direction	No	Type	Hours / Lane	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Total
ENTRY	1	Mixed mode	M01	138	115	95	57	85	187	237	248	265	245	243	249	249	259	275	281	270	255	250	210	196	193	178	151	4,933
	2	Mixed mode	M02	187	110	74	70	56	131	311	288	295	280	276	272	258	306	286	244	268	279	282	216	234	248	221	196	5,386
	3	Mixed mode	M03	16	0	3	7	3	1	136	131	138	190	221	221	191	244	228	215	235	233	242	99	96	141	169	137	3,297
	4	Touch´n Go	M04	79	56	41	30	41	108	235	256	278	296	294	296	306	316	339	334	323	324	293	233	226	230	186	134	5,254
	5	Touch´n Go	M05	67	45	29	21	29	90	218	242	274	290	296	289	291	300	332	343	317	316	306	241	232	228	180	120	5,095
	6	Smart TAG	M06	158	115	85	57	68	151	310	333	341	377	409	431	455	453	469	460	457	456	418	350	375	393	325	247	7,693
	7	Smart TAG	M07	63	39	23	13	15	70	203	234	257	299	323	343	360	355	378	364	351	364	329	256	265	288	207	125	5,526
			Total	709	480	351	256	297	737	1,649	1,733	1,848	1,978	2,063	2,100	2,109	2,232	2,306	2,241	2,221	2,228	2,121	1,605	1,623	1,723	1,465	1,109	37,183
EXIT	1	Smart TAG	K08	98	68	53	50	67	159	304	416	440	457	478	514	530	515	506	502	511	547	497	438	389	329	239	149	8,257
	2	Smart TAG	K09	69	52	43	36	45	95	174	267	291	310	355	380	406	391	387	359	388	404	365	352	312	266	190	109	6,044
	3	Touch´n Go	K10	71	53	40	42	55	149	228	285	305	322	342	348	357	350	367	359	368	368	329	298	267	233	164	109	5,810
	4	Touch´n Go	K11	51	37	31	29	33	90	136	187	205	237	275	295	305	303	310	307	326	320	281	245	223	189	130	80	4,625
	5	Mixed mode	K13	87	69	65	57	63	134	126	139	139	150	154	159	169	172	174	169	176	174	167	163	169	165	144	112	3,294
	6	Mixed mode	K14	84	70	63	59	60	113	118	127	127	139	144	147	156	157	163	159	165	164	156	151	156	144	125	100	3,047
	7	Mixed mode	K15	72	59	57	54	53	109	109	111	117	129	130	135	138	147	151	152	154	152	138	133	132	130	114	91	2,765
	8	Mixed mode	K16	62	61	61	62	67	91	94	99	104	111	112	110	121	121	130	129	134	131	124	115	109	104	90	75	2,416
	9	Staggered	K31	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	20	0	0	0	0	0	0	26
	10		K32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	6	0	0	0	0	0	14
	11		K33	0	0	0	0	0	0	7	21	20	27	15	42	30	10	24	24	32	65	70	33	13	0	0	0	433
	12		K34	0	0	0	0	0	9	49	78	83	90	90	88	94	83	86	97	83	97	79	56	38	9	6	2	1,215
	13		K35	0	0	0	0	0	9	46	82	87	92	94	87	82	81	80	87	89	90	73	54	37	5	0	0	1,175
	14		K36	1	0	0	0	0	16	38	66	45	65	58	76	71	68	70	71	67	68	60	51	49	43	22	7	1,011
	15		K37	12	10	8	10	4	24	87	110	119	117	122	119	125	118	117	121	122	122	103	100	94	93	57	28	1,942
	16		K38	31	16	15	15	8	32	110	133	140	145	144	150	151	154	152	144	153	153	139	132	129	129	91	52	2,516
			Total	636	495	435	413	455	1,031	1,626	2,121	2,223	2,391	2,516	2,650	2,733	2,675	2,716	2,677	2,768	2,883	2,587	2,319	2,116	1,838	1,371	914	44,590
Grand Total				1,345	975	786	669	752	1,768	3,275	3,853	4,071	4,369	4,578	4,750	4,842	4,906	5,023	4,919	4,989	5,111	4,708	3,924	3,738	3,562	2,836	2,023	81,773

Table 4.5 Peak hours at the Juru toll plaza

Day	Peak hour			
	Entry		Exit	
	AM	PM	AM	PM
Wednesday	6 - 7	5 - 6	7 - 8	5 - 6
Friday	10 - 11	5 - 6	7 - 8	5 - 6
Saturday	11-12	2 - 3	11-12	5 - 6

For the Jawi toll plaza, Table 4.6, 4.7 and 4.8 show the average hourly traffic volume by lane for Wednesdays, Fridays, and Saturday, respectively.

Table 4.9 shows the summary of the peak hours at the Jawi toll plaza for the three chosen days in this study.

Table 4.6 Average hourly traffic volume for Jawi toll plaza by lane for Wednesdays (April to September 2014)

Direction	No	Type	Hour / Lane	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Total
ENTRY	1	Mixed mode	M01	50	36	33	46	120	167	174	170	179	165	152	133	191	186	175	205	198	158	142	87	127	150	115	81	3,240
	2	Touch´n Go	M02	14	8	7	12	30	129	322	252	175	164	171	157	164	192	184	191	217	191	134	119	91	71	44	25	3,063
	3	Smart TAG	M03	18	11	8	11	36	172	467	353	241	211	217	207	230	239	239	230	251	238	200	165	121	91	64	33	4,053
			Total	83	55	48	69	186	468	963	774	595	540	541	498	585	616	598	626	665	586	476	371	338	312	224	139	10,356
EXIT	1	Smart TAG	K04	53	30	18	13	12	38	151	160	159	171	182	184	191	208	225	244	354	427	340	238	201	186	144	93	4,024
	2	Touch´n Go	K05	30	18	13	9	14	29	140	133	125	137	150	146	147	150	166	189	259	290	261	188	144	127	95	63	3,020
	3	Mixed mode	K06	20	10	2	0	0	0	101	97	79	108	115	112	113	116	133	134	154	156	146	107	79	21	17	11	1,830
	4		K07	0	0	0	0	0	30	77	42	102	119	120	119	121	124	135	138	152	153	145	112	94	128	113	78	2,104
	5		K08	86	62	44	37	44	43	41	87	87	98	106	105	98	104	114	119	129	123	120	97	73	98	83	67	2,063
			Total	189	119	77	59	71	140	510	518	553	632	673	665	670	702	772	824	1,048	1,149	1,012	742	591	560	452	312	13,041
Grand Total				272	174	125	128	257	608	1,473	1,293	1,148	1,172	1,214	1,163	1,255	1,318	1,370	1,450	1,713	1,735	1,488	1,112	930	872	675	451	23,398

Table 4.7 Average hourly traffic volume for Jawi toll plaza by lane for Fridays (April to September 2014)

Direction	No	Type	Hour / Lane	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Total
ENTRY	1	Mixed mode	M01	71	45	40	51	123	173	164	163	192	182	175	148	198	187	188	180	195	160	117	96	172	171	157	105	3,452
	2	Touch´n Go	M02	21	13	11	15	37	129	318	259	176	180	184	194	192	212	250	259	267	249	185	172	140	106	62	37	3,668
	3	Smart TAG	M03	27	18	12	14	40	169	455	362	256	232	232	246	249	275	294	272	279	284	237	209	169	129	86	49	4,596
			Total	118	76	63	81	201	470	937	783	624	594	590	589	639	674	733	711	741	692	539	478	481	406	305	190	11,716
EXIT	1	Smart TAG	K04	81	52	37	28	24	40	157	169	166	182	210	232	230	224	259	283	397	476	397	298	256	251	204	139	4,792
	2	Touch´n Go	K05	51	33	25	18	25	30	144	140	136	159	175	183	173	174	218	232	321	369	333	248	196	184	150	93	3,809
	3	Mixed mode	K06	52	34	14	0	0	0	114	108	91	120	128	132	127	115	142	150	172	185	175	128	94	69	74	19	2,243
	4		K07	34	30	19	11	8	31	84	43	108	125	133	136	129	123	151	156	167	184	167	138	116	140	131	99	2,461
	5		K08	105	76	63	53	62	48	34	95	89	104	115	118	107	106	130	139	149	158	148	119	98	118	103	79	2,416
			Total	323	225	158	109	119	149	533	555	589	690	762	801	765	743	900	959	1,206	1,371	1,220	930	759	762	663	428	15,721
		Grand Total		441	301	221	190	320	619	1,471	1,338	1,213	1,284	1,353	1,390	1,404	1,417	1,633	1,670	1,947	2,063	1,759	1,408	1,240	1,169	968	619	27,437

Table 4.8 Average hourly traffic volume for Jawi toll plaza by lane for Saturdays (April to September 2014)

Direction	No	Type	Hour / Lane	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Total
ENTRY	1	Mixed mode	M01	66	43	36	33	88	152	166	145	156	179	160	159	196	149	153	158	191	174	150	76	201	187	167	105	3,292
	2	Touch´n Go	M02	24	14	10	14	31	85	170	206	204	237	269	277	309	308	315	275	258	256	202	180	171	143	85	48	4,093
	3	Smart TAG	M03	29	18	12	16	39	92	209	249	257	277	298	296	338	316	323	275	263	309	272	238	205	169	111	60	4,669
			Total	120	75	58	63	158	330	544	600	618	693	728	732	843	773	791	708	712	738	623	493	577	498	363	214	12,053
EXIT	1	Smart TAG	K04	86	65	43	28	22	50	154	186	184	198	232	263	289	289	303	311	328	350	326	273	265	281	233	151	4,911
	2	Touch´n Go	K05	59	41	31	18	18	53	189	217	195	201	208	224	249	245	265	261	284	288	288	237	208	197	163	102	4,244
	3	Mixed mode	K06	59	40	14	1	0	2	146	140	115	124	124	136	131	147	159	160	161	152	154	116	101	69	79	29	2,357
	4		K07	1	0	0	0	0	46	154	125	127	134	142	143	151	147	157	162	159	158	157	126	115	147	135	110	2,595
	5		K08	116	86	82	62	51	61	45	125	114	118	121	126	125	127	132	145	145	142	140	112	94	127	109	91	2,595
			Total	319	232	171	109	91	212	689	792	735	775	827	892	946	955	1,016	1,039	1,077	1,090	1,065	864	784	821	719	482	16,703
		Grand Total		440	307	229	172	249	542	1,233	1,392	1,353	1,469	1,555	1,624	1,789	1,728	1,807	1,747	1,789	1,828	1,688	1,357	1,361	1,319	1,082	696	28,756

Table 4.9 Peak hours at Jawi toll plaza

Day	Peak hour			
	Entry		Exit	
	AM	PM	AM	PM
Wednesday	6 - 7	4 - 5	10 - 11	5 - 6
Friday	6 - 7	4 - 5	11 - 12	5 - 6
Saturday	11- 12	12 - 1	11 - 12	5 - 6

During the peak hours of the three days, traffic volume during the morning peak hour is different than evening peak hour. Figure 4.7 shows the comparison of the traffic volumes between morning and evening peak hours at Juru toll plaza. At entry, traffic volume during evening peak hour is higher than traffic volume during morning peak hour for all the three days. At exit, traffic volume during evening peak hour is also higher than the traffic volume during morning peak hour on Friday and Saturday. However, on Wednesday, the traffic volume during morning peak hour is higher than the traffic volume during evening peak hour.

As a result, the performance of traffic operation at Juru toll plaza is at the maximum based on evening peak hours at the entry and at exit on Friday and Saturday except on Wednesday.

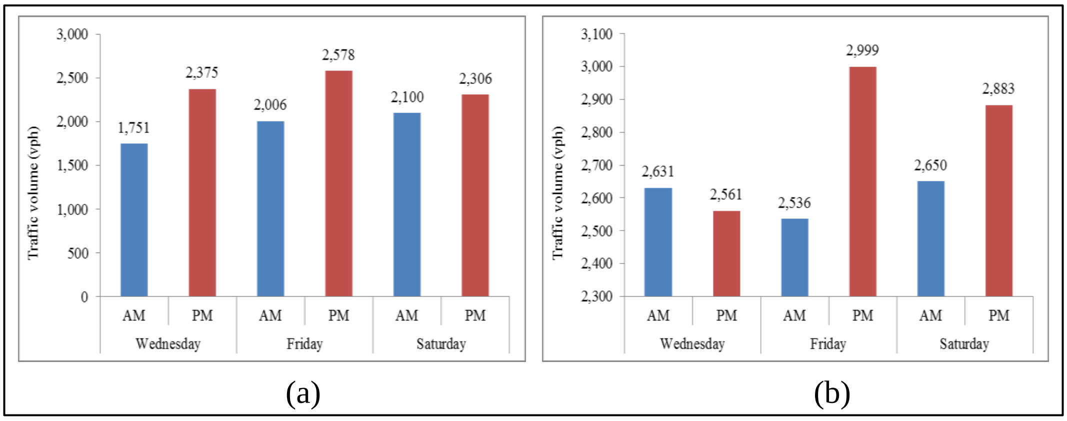


Figure 4.7 Traffic volume of morning and evening peak hours at Juru toll plaza: (a) entry, (b) exit.

For the Jawi toll plaza, Figure 4.8 shows the comparison of the traffic volumes between morning and evening. At entry, the traffic volume at morning is higher than the traffic volume at evening on Wednesday and Friday. However, on Saturday, the traffic volume at evening is higher than the traffic volume at morning. At exit, traffic volume at evening is higher than the traffic volume at morning for all the three days.

As a result, for entry, the performance of traffic operation at Jawi toll plaza is at the maximum during morning peak hours on Wednesday and Friday; however, Saturday has the maximum performance was during evening peak hours. For exit, the maximum performance of traffic operation at Jawi toll plaza was during evening peak hours for all the three days.

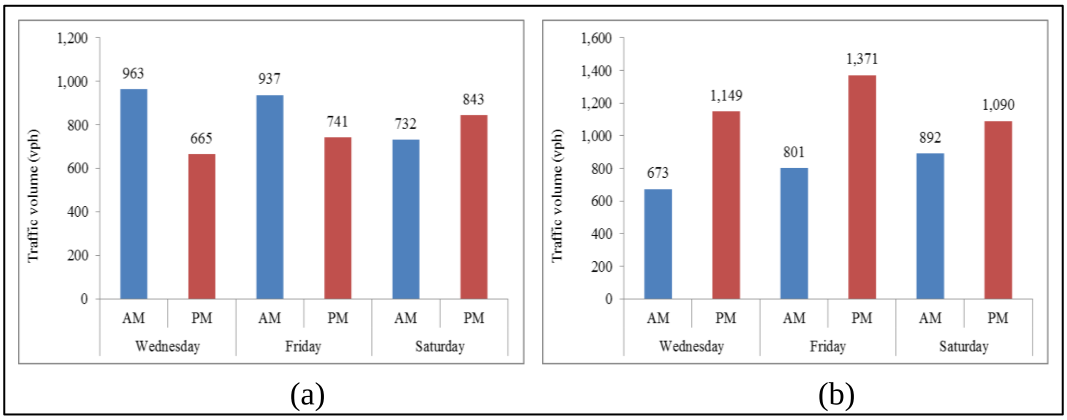


Figure 4.8 Traffic volume of morning and evening peak hours at Jawi toll plaza: (a) entry, (b) exit.

To have a better understanding of the average hourly traffic volume behavior in a day at toll plazas and to also determine the preferred mode of payment type at toll plazas further analyses were conducted. Figure 4.9, 4.10 and 4.11 show the trend of the average hourly traffic volume by payment type in the Juru toll plaza for entry and exit on Wednesdays, Fridays, and Saturdays, respectively. For entry of the three days, Figure 4.9a, 4.10a and 4.11a show that the preferred payment type in this direction was between mixed mode and Smart TAG during most of the day. However, in the morning and evening peak hours, Smart TAG has the highest traffic volume. For exit of the three days, Figure 4.9b, 4.10b and 4.11b show that the mixed mode was the preferred payment type during a day and during morning and evening peak hours.

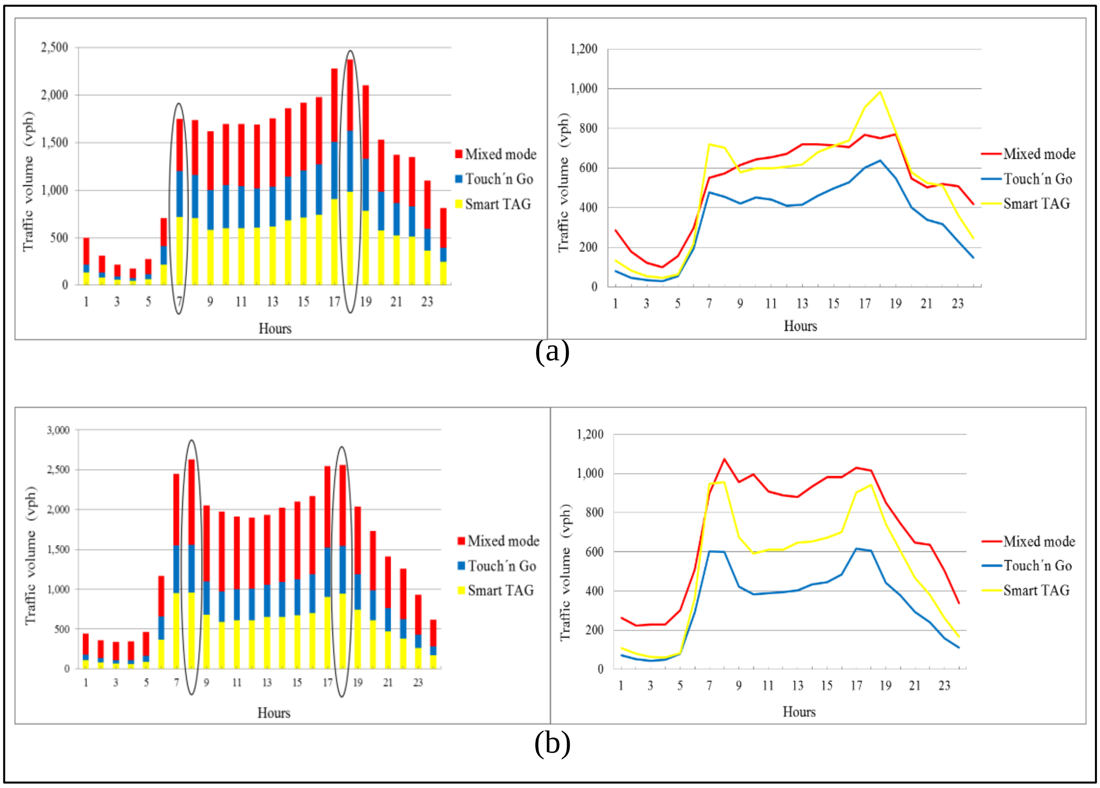


Figure 4.9 Average hourly traffic volume at Juru toll plaza by payment type on Wednesdays: (a) entry, (b) exit.

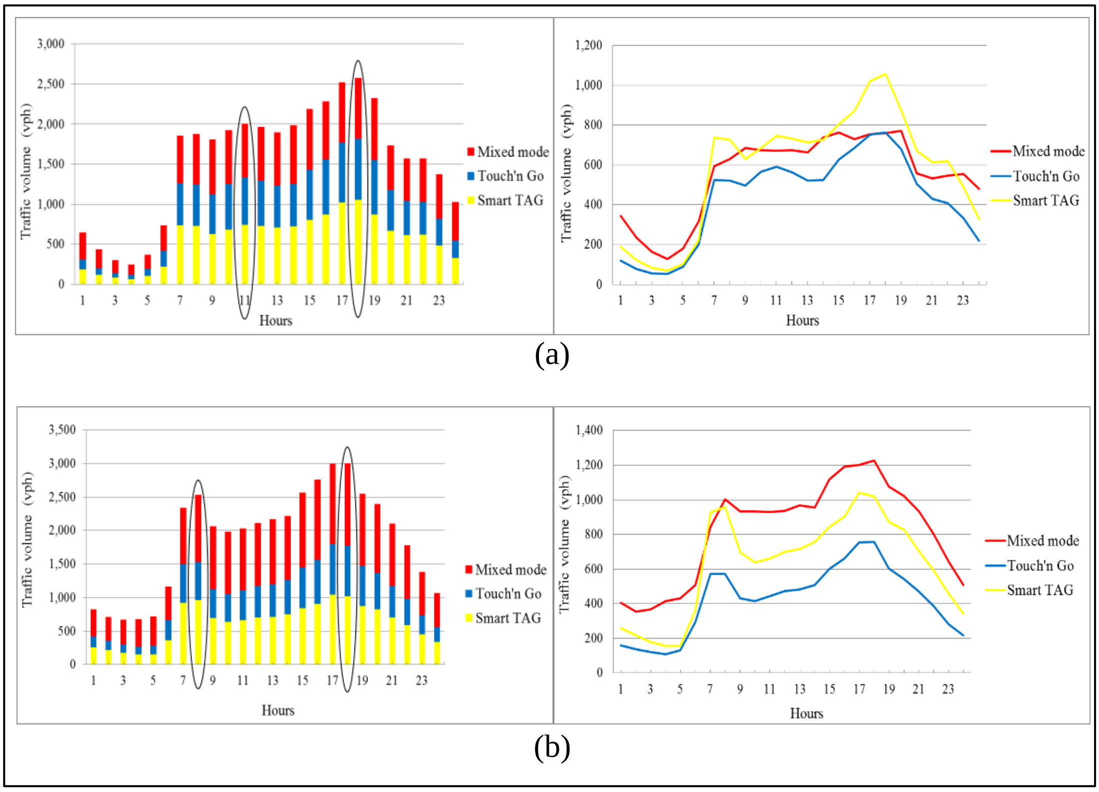


Figure 4.10 Average hourly traffic volume at Juru toll plaza by payment type on Fridays: (a) entry, (b) exit.

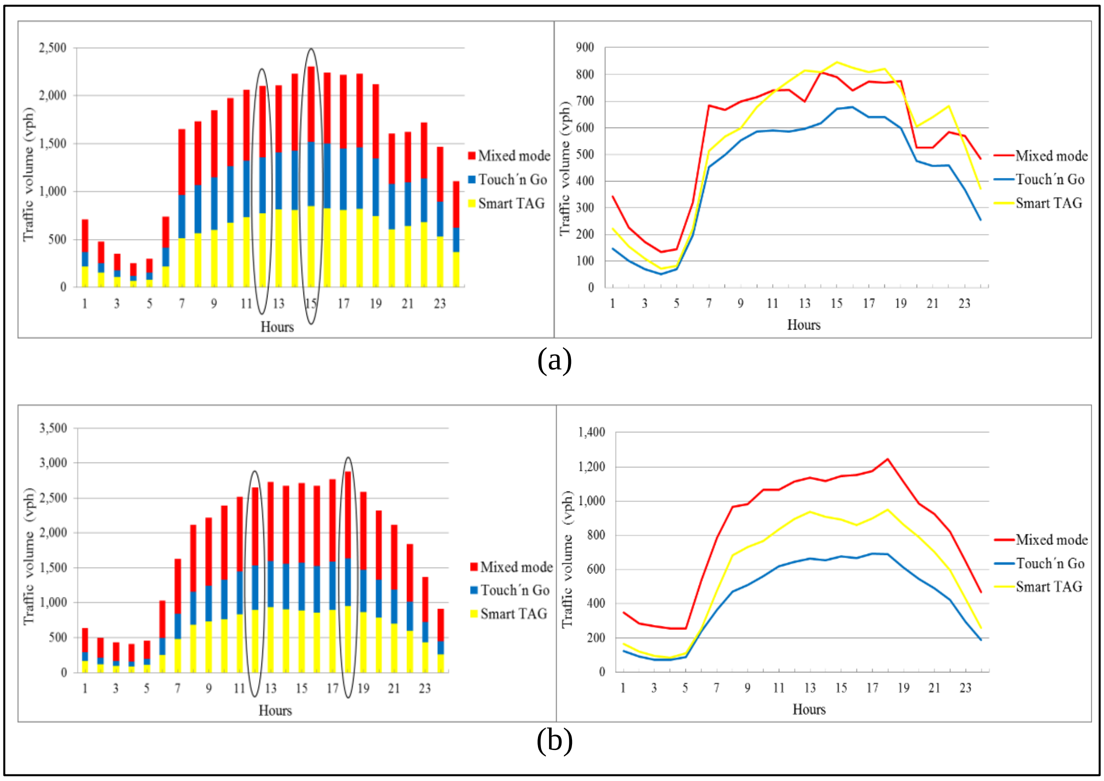


Figure 4.11 Average hourly traffic volume at Juru toll plaza by payment type on Saturdays: (a) entry, (b) exit

For the Jawi toll plaza, Figure 4.12, 4.13 and 4.14 show the trend of the average hourly traffic volume by payment type for entry and exit on Wednesdays, Fridays, and Saturdays. For entry of the three days, Figure 4.12a, 4.13a and 4.14a show that the Smart TAG was the preferred payment type during a day and during morning and evening peak hours. Furthermore, the increment of the hourly traffic volumes at entry during morning and evening peak hours comes from the Smart TAG and Touch 'n Go payment, unlike the mixed mode payment that shows a limited hourly traffic volume because of the influence of the signalized intersection near the Jawi toll plaza.

For exit, Figure 4.12b, 4.13b and 4.14b show that mixed mode was the preferred mode of payment for the whole three days.

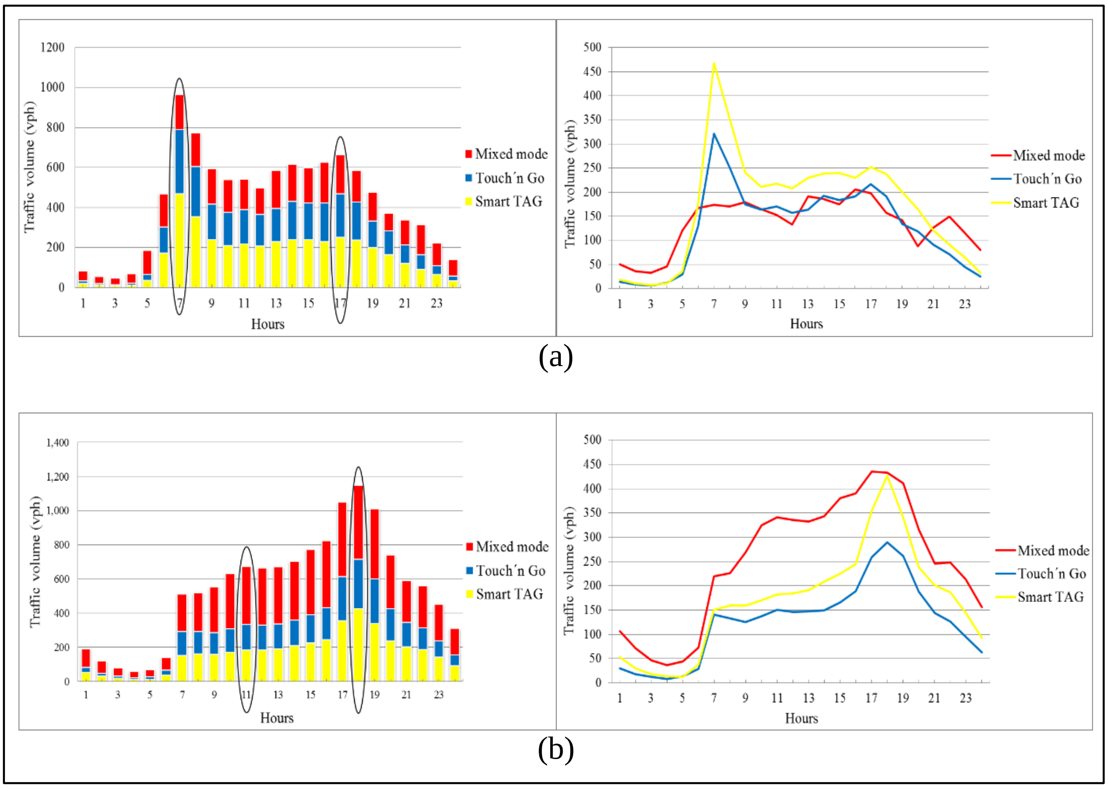


Figure 4.12 Average hourly traffic volume at Jawi toll plaza by payment type on Wednesdays: (a) entry, (b) exit.

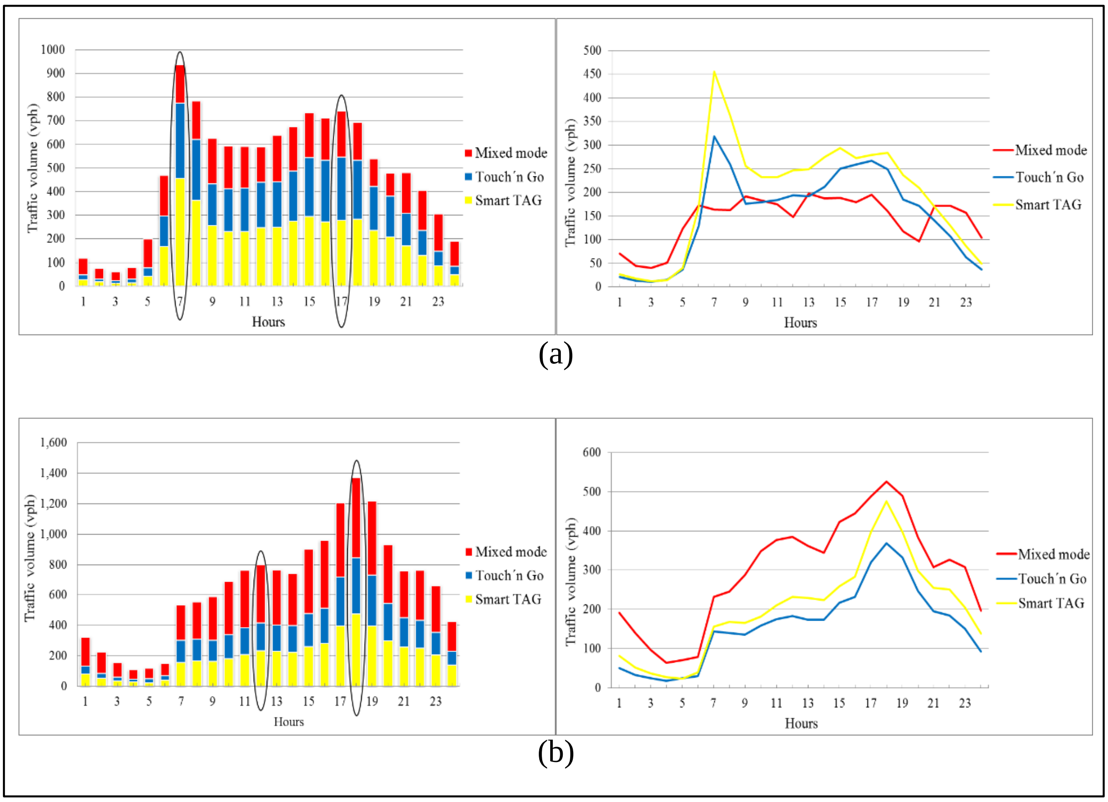


Figure 4.13 Average hourly traffic volume at Jawi toll plaza by payment type on Fridays: (a) entry, (b) exit.

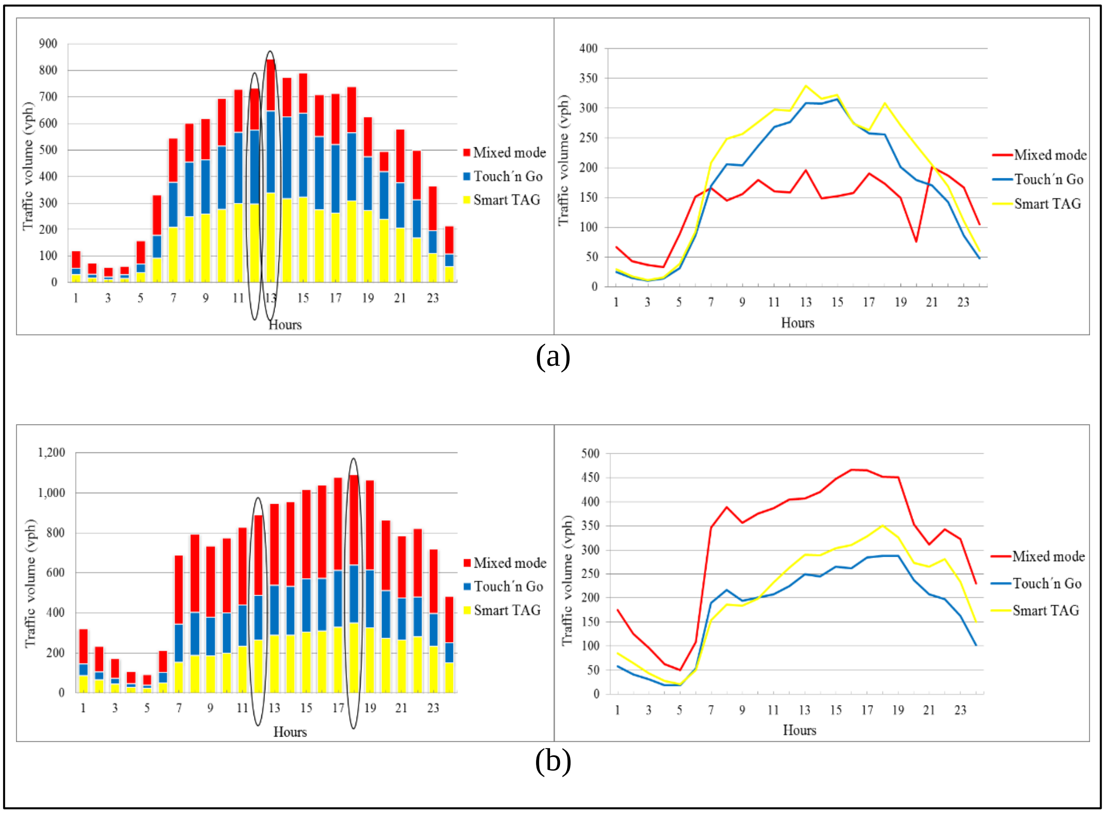


Figure 4.14 Average hourly traffic volume at Jawi toll plaza by payment type on Saturdays: (a) entry, (b) exit.

As a result of the trend of the average hourly traffic volume by payment type in the Juru and Jawi toll plazas for entry and exit on Wednesdays, Fridays, and Saturdays, the Juru toll plaza experiences maximum toll operation performance at entry from the mixed mode and Smart TAG payments and at exit from mixed mode payment.

The Jawi toll plaza experiences maximum toll operation performance at entry from the Smart TAG and Touch 'n Go payments and at exit from mixed mode payment.

To finalize this subsection, the traffic volumes differently influence the operations of the toll plazas depending on the volumes and payment methods. The throughput reflects the toll operations performance in relation with traffic volumes and payment methods with the limitation of the toll operation capacity.

4.2.2(b) **Desired speed**

Each vehicle traveling on the roadway lanes approaching the toll plaza has its own desired speed. This desired speed is assigned in VISSIM using a cumulative distribution with certain parameters specified by the user as inputs. The cumulative distribution of desired speeds was taken from the field observations using laser speed gun at the Juru and Jawi toll plazas for each vehicle type. Figure 4.15 to 4.19 show the frequency and cumulative curve of the speed data collections for the Juru toll plaza. The average speeds and the cumulative curves for vehicle types at the entry are almost the same as at the exit. Figure 4.20 to 4.24 shows the frequency and cumulative curve of the speed data collections for the Jawi toll plaza. The average speeds at the entry are lower than the exit for all vehicle types of the Jawi toll plaza due to location of the plaza which is near to a signalised intersection.

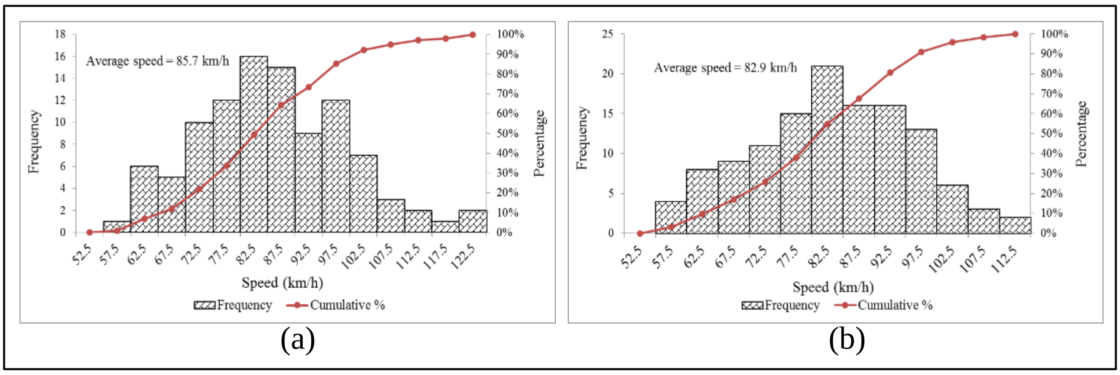


Figure 4.15 Speed data collection (average speed, frequency and cumulative curve) for car at Juru toll plaza: (a) entry, (b) exit.

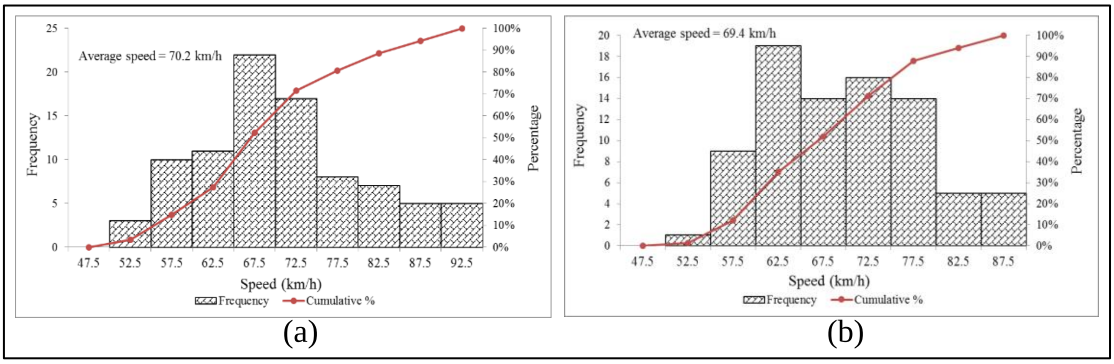


Figure 4.16 Speed data collection (average speed, frequency and cumulative curve) for small lorry at Juru toll plaza: (a) entry, (b) exit.

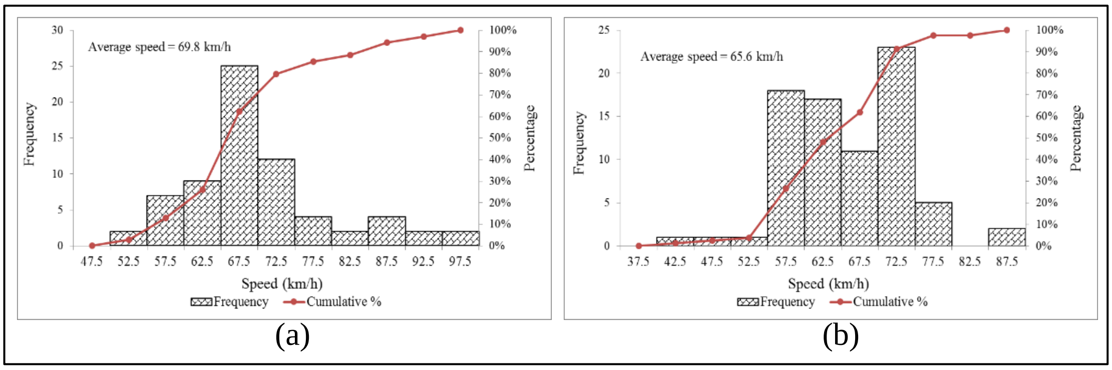


Figure 4.17 Speed data collection (average speed, frequency and cumulative curve) for truck at Juru toll plaza: (a) entry, (b) exit.

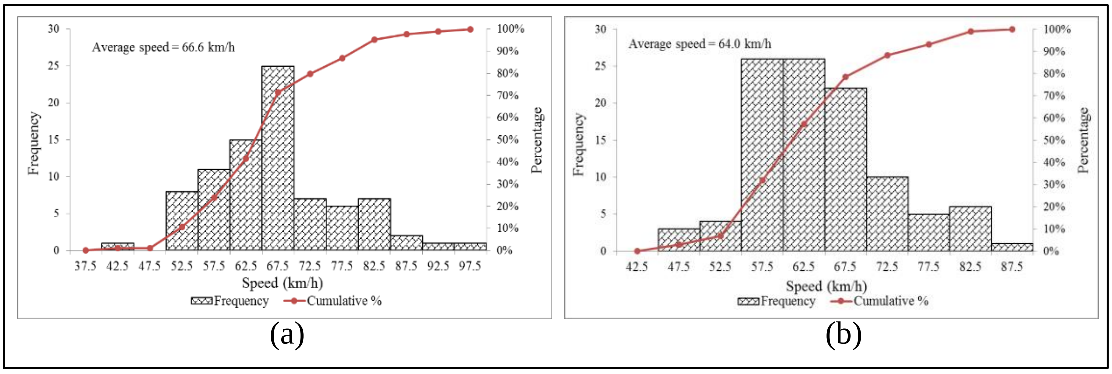


Figure 4.18 Speed data collection (average speed, frequency and cumulative curve) for trailer at Juru toll plaza: (a) entry, (b) exit.

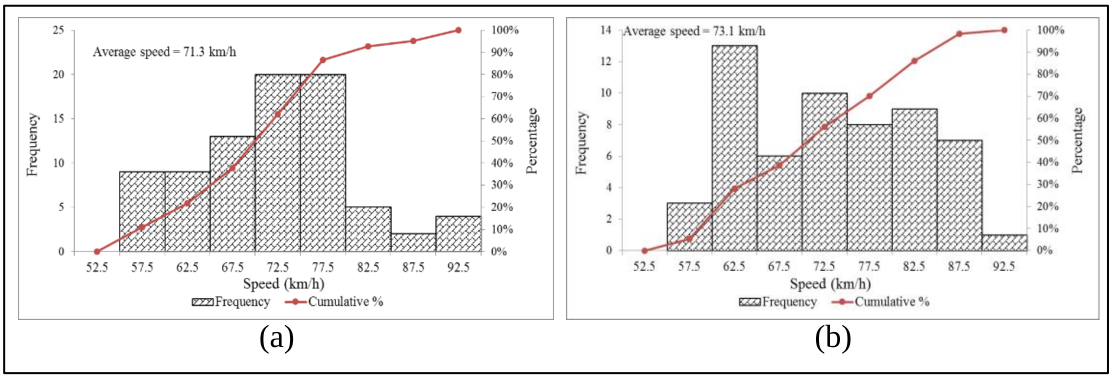


Figure 4.19 Speed data collection (average speed, frequency and cumulative curve) for bus at Juru toll plaza: (a) entry, (b) exit.

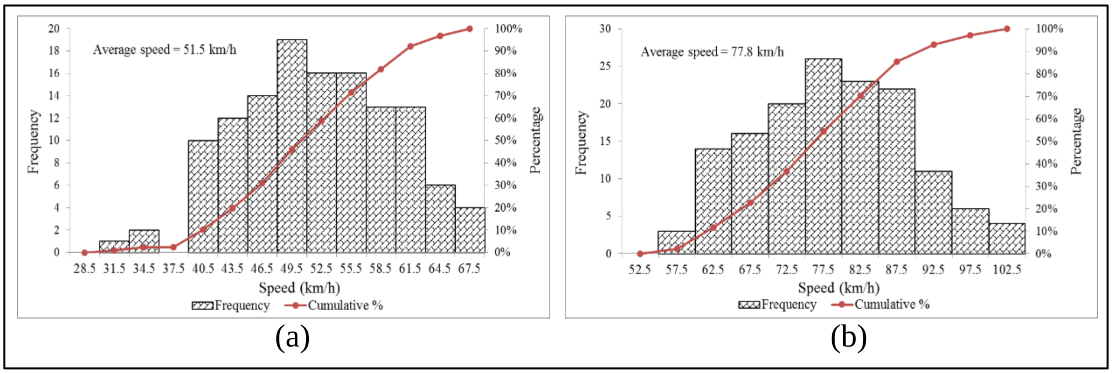


Figure 4.20 Speed data collection (average speed, frequency and cumulative curve) for car at Jawi toll plaza: (a) entry, (b) exit.

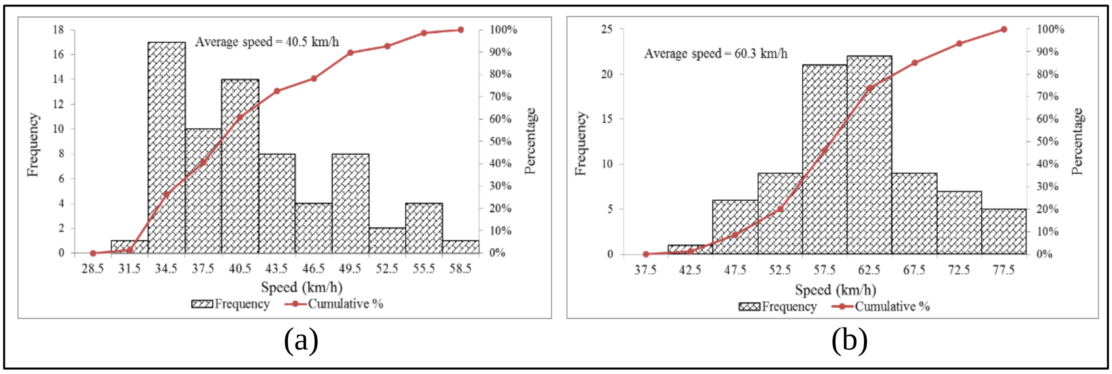


Figure 4.21 Speed data collection (average speed, frequency and cumulative curve) for small lorry at Jawi toll plaza: (a) entry, (b) exit.

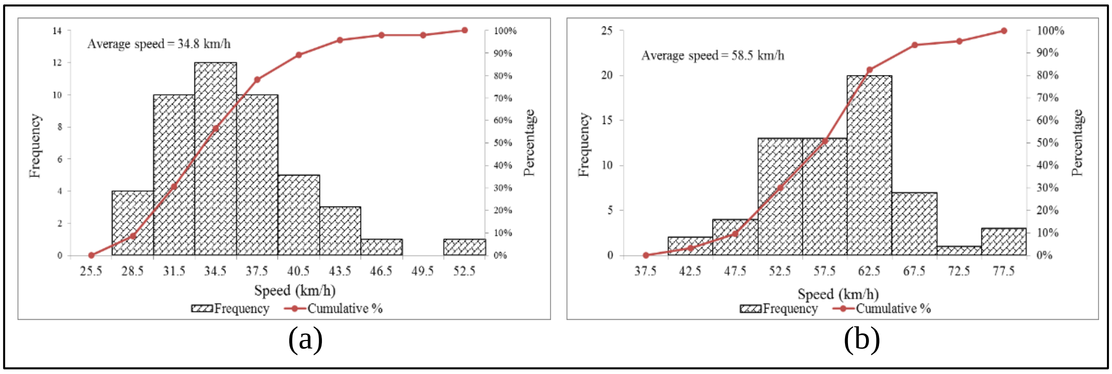
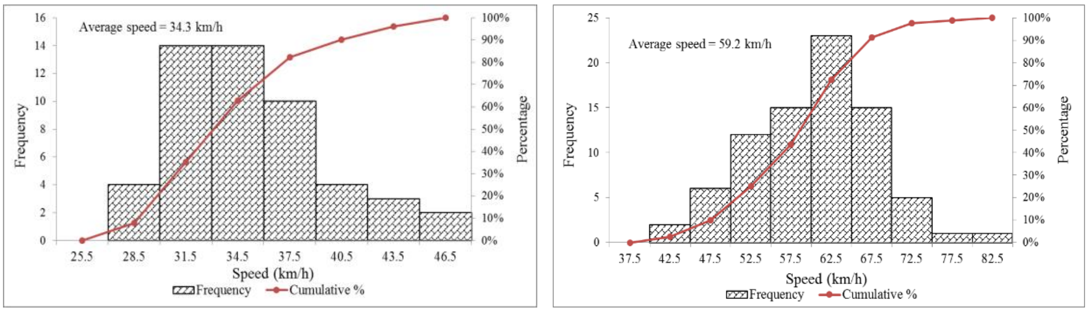
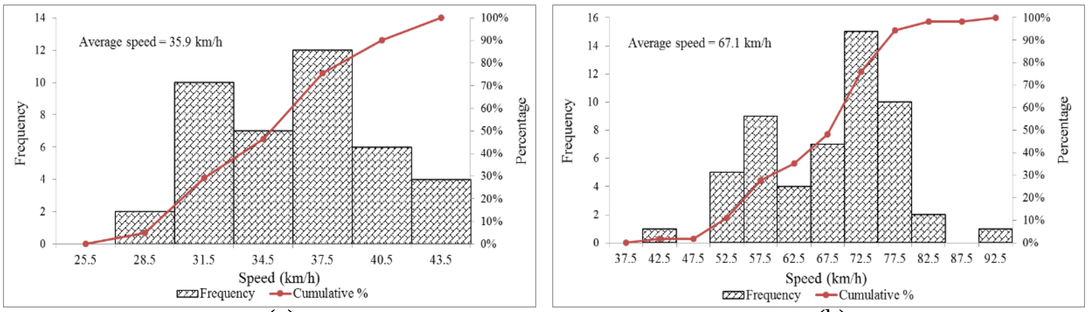


Figure 4.22 Speed data collection (average speed, frequency and cumulative curve) for truck at Jawi toll plaza: (a) entry, (b) exit.



(a) (b)

Figure 4.23 Speed data collection (average speed, frequency and cumulative curve) for trailer at Jawi toll plaza: (a) entry, (b) exit.



(a) (b)

Figure 4.24 Speed data collection (average speed, frequency and cumulative curve) for bus at Jawi toll plaza: (a) entry, (b) exit.

4.2.2(c) **Queue length**

Queue length is the number of vehicles queuing in a toll lane, waiting to be served, to pass through the toll plaza. It is an indicator of the operational effectiveness of a toll lane. Queue length directly depends upon traffic volume, service time, and the arrival pattern of vehicles. This is where the difference between vehicle categories becomes important. A high percentage of heavy vehicles cause longer queue lengths at the mixed mode toll lanes, while a high number of cars that are expected to exceed the toll lane capacity cause longer queue lengths especially at the ETC lanes.

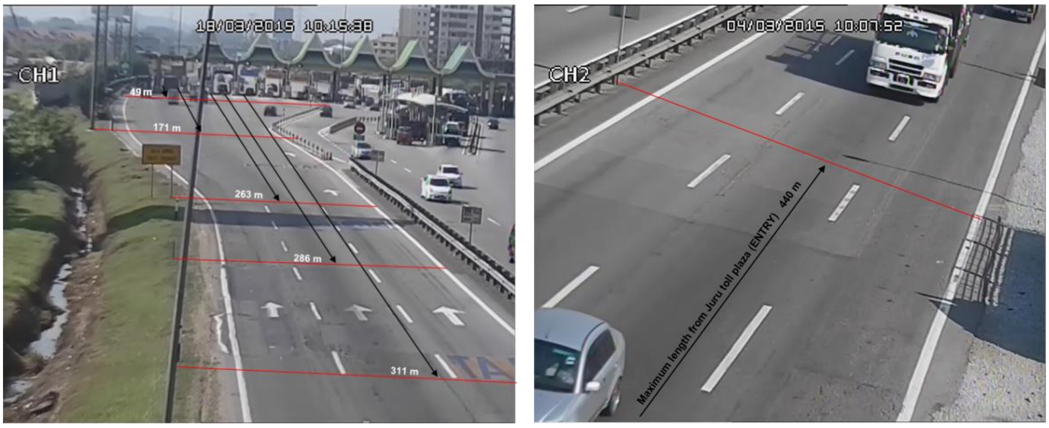
The queue lengths were measured in terms of maximum queue lengths at the toll plazas from the video recordings. Some photos were also taken to see the queuing conditions at the toll lanes to understand the queuing conditions at the Juru and Jawi toll plazas. The selected video recordings for the measurements were for each Wednesday, Friday, and Saturday of the month of March 2015.

The measuring wheel instrument was used to measure the field distances at the sites from the toll plaza (where vehicles stop to pay the tolls) to the marks that are clearly seen in the videos. These marks could be a lighting pole, a signboard, or pavement marks. It was easy to estimate the queue length when the last queuing vehicle stopped at or near these marks.

Figure 4.25 shows the measurement distances for the selected marks at the Juru toll plaza for the entry direction. Figure 4.25a and Figure 4.25b shows the screen capture of the video recording of the camera toward the toll plaza and toward the upstream lanes with the maximum queue length, respectively, measured for the entry direction which is equal to 440 m. If the queue length of the vehicles is more than the maximum measured length, it exits the range of the camera and the queue length in this case is symbolized as ∞.

Figure 4.26 shows the measurement distances for the selected marks at the Juru toll plaza for the exit direction, where Figure 4.26a and Figure 4.26b show the screen capture of the camera toward the toll plaza and upstream lanes, respectively, with the maximum queue length measuring 403 m.

The same details for the entry and exit of the Jawi toll plaza are shown in Figure 4.27 and 4.28.

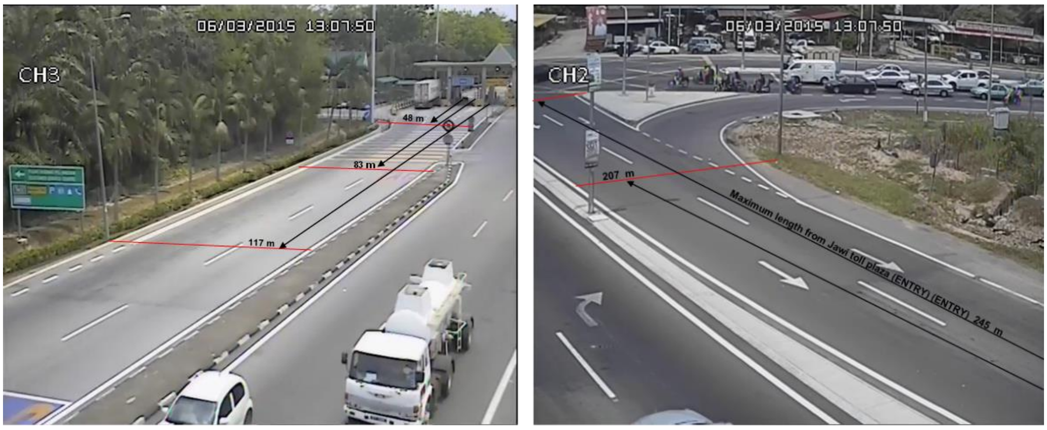


(a) (b)

Figure 4.25 Field distance measurements at the entry of Juru toll plaza; (a) Video recording of camera toward toll plaza, (b) Video recording of camera toward upstream lanes with maximum length of 440m.

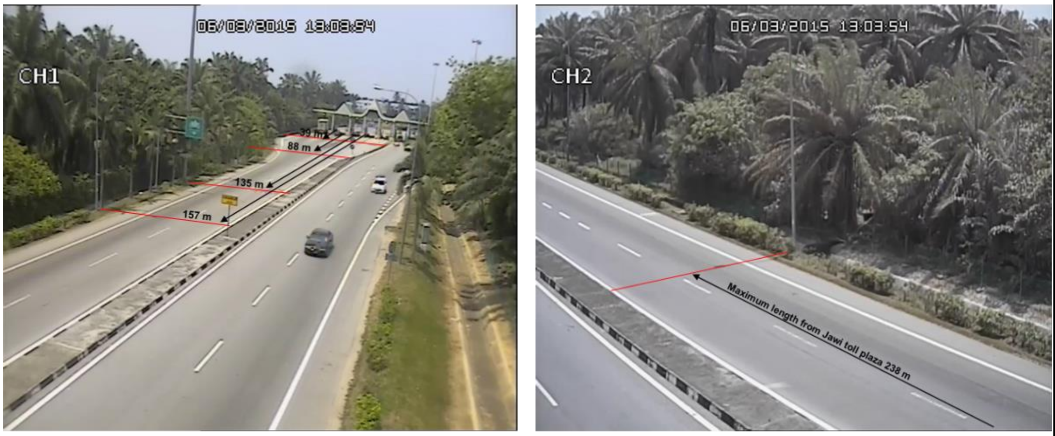
(a) (b)

Figure 4.26 Field distance measurements at the exit of Juru toll plaza; (a) Video recording of camera toward toll plaza, (b) Video recording of camera toward upstream lanes with maximum length of 403m.



(a) (b)

Figure 4.27 Field distance measurements at the entry of Jawi toll plaza; (a) Video recording of camera toward toll plaza, (b) Video recording of camera toward upstream lanes with maximum length of 245m.



(a) (b)

Figure 4.28 Field distance measurements at the exit of Jawi toll plaza; (a) Video recording of camera toward toll plaza, (b) Video recording of camera toward upstream lanes with maximum length of 238m.

Table 4.10 shows the summary of results obtained from the videos from March 2015 for Wednesdays, Fridays, and Saturdays at the Juru toll plaza. For entry to the toll lanes, the results show that majority of the maximum queue lengths for the three days occur between 10:00 AM and 12:00 PM and between 4:00 and 6:00 PM. For exit, the majority of the maximum queue lengths occur between 8:00 and 11:00 AM and between 5:00 and 6:00 PM. Most of the maximum queue lengths are too long and exceed the camera view range especially in the morning for entry and exit to the toll lanes. Figure 4.29 shows the maximum queue length condition at entry exceeding the camera view range, while Figure 4.30 shows the maximum queue length condition at exit.

Table 4.10 Maximum queue length summary of Juru toll plaza for March 2015.

			AM				PM			
			Time	Maximum queue length (m)			Time	Maximum queue length (m)		
Direction	Day	Date		Mixed mode	Touch 'n Go	Smart TAG		Mixed mode	Touch 'n Go	Smart TAG
Entry	Wednesdays	4/3/2015	10 - 11	86	10	5	5 - 6	175	15	10
		11/3/2015	11 - 12	310	15	0	5 - 6	210	15	0
		18/3/2015	11 - 12	More than 440 m (∞)	10	0	5 - 6	78	10	25
		25/3/2015	11 - 12	325	15	5	5 - 6	85	40	15
		Average		290.3	12.5	2.5		137.0	20.0	12.5
	Fridays	6/3/2015	11 - 12	295	10	10	4 - 5	281	24	30
		13/3/2015	10 - 11	More than 440 m (∞)	63	5	5 - 6	75	35	50
		20/3/2015	10 - 11	More than 440 m (∞)	10	5	5 - 6	40	30	25
		27/3/2015	11 - 12	More than 440 m (∞)	15	10	5- 6	280	70	30
		Average		404	98.0	30.0		169.0	39.8	33.8
	Saturdays	7/3/2015	10 - 11	196	5	0	5 - 6	110	55	30
		14/3/2015	11 - 12	More than 440 m (∞)	154	0	5 - 6	68	40	15
		21/3/2015	11 - 12	315	161	20	5 - 6	30	35	0
		28/3/2015	11 - 12	190	10	0	5 - 6	55	80	20
		Average		285.3	82.5	5.0		65.8	52.5	16.3
Exit	Wednesdays	4/3/2015	10 - 11	260	10	0	5 - 6	85	55	120
		11/3/2015	10 - 11	More than 403 m (∞)	15	0	5 - 6	93	20	60
		18/3/2015	8 - 9	142	38	10	5 - 6	80	65	90
		25/3/2015	10 - 11	220	15	0	5 - 6	115	40	70
		Average		294.3	19.5	2.5		93.3	45.0	85.0
	Fridays	6/3/2015	8 - 9	More than 403 m (∞)	15	10	5 - 6	155	80	120
		13/3/2015	8 - 9	127	20	65	5 - 6	75	105	50
		20/3/2015	8 - 9	115	10	0	5 - 6	120	95	15
		27/3/2015	8 - 9	195	15	30	5 - 6	205	150	65
		Average		210.0	60.0	26.3		138.8	107.5	62.5
	Saturdays	7/3/2015	9 - 10	215	10	80	5 - 6	110	65	15
		14/3/2015	10 - 11	More than 403 m (∞)	10	15	5 - 6	80	20	105
		21/3/2015	9 -10	305	15	15	5 - 6	70	110	120
		28/3/2015	9 - 10	310	20	10	5 - 6	75	155	130
		Average		308.3	13.8	30.0		83.8	87.5	92.5

(a) (b)

Figure 4.29 Screen capture for the maximum queue length condition when exceeding the camera view range at the entry of Juru toll plaza; (a) Video recording of camera toward toll plaza, (b) Video recording of camera toward upstream lanes.

(a) (b)

Figure 4.30 Screen capture for the maximum queue length condition when exceeding the camera view range at the exit of Juru toll plaza; (a) Video recording of camera toward toll plaza, (b) Video recording of camera toward upstream lanes.

Figure 4.31 shows a comparison for the average maximum queue length at the Juru toll plaza between the morning and evening. At entry, the average maximum queue lengths of the mixed mode and Touch 'n Go lanes in the morning were longer than in the evening. However, the average maximum queue length for Smart TAG in the evening was slightly longer than in the morning. Furthermore, Fridays show the longest average maximum queue length for all payment types in the morning and evening except for the Touch 'n Go lane in the evening.

At the exit for the mixed mode payment, the average maximum queue length in the morning is longer than in the evening; the longest length was on Wednesdays and Saturdays in the morning, while Fridays show the longest length in the evening. For Touch 'n Go and Smart TAG lanes, the average maximum queue lengths in the evening are longer than in the morning. Moreover, Fridays show the longest length for the Touch 'n Go lane in the morning and evening, while Saturdays show the longest length for the Smart TAG lane in the morning and evening.

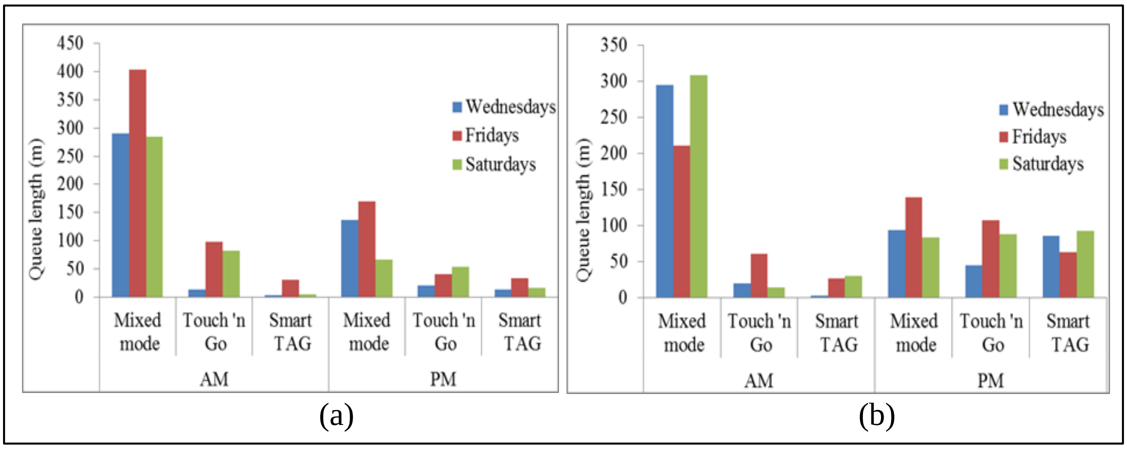


Figure 4.31 Average maximum queue length at Juru toll plaza: (a) entry, (b) exit.

Table 4.11 shows the summary of results obtained from the video recordings for Wednesdays, Fridays, and Saturdays of March 2015 for Jawi toll plaza. For entry, the results show that the majority of the maximum queue lengths of entry to the lane for Wednesdays and Fridays occur between 7:00 and 8:00 AM and between 4:00 and 5:00 PM. However, majority of the maximum queue lengths for entry for Saturdays occur between 11:00 and 12:00 AM and between 12:00 and 1:00 PM. The majority of the maximum queue lengths for exit for Wednesdays occur between 10:00 and 11:00 AM and between 5:00 and 6:00 PM. However, the majority of the maximum queue lengths for exit for Fridays and Saturdays occur between 11:00 and 12:00 AM and between 4:00 and 5:00 PM.

Figure 4.32 and Figure 4.33 show the maximum queue length condition at entry exceeding the camera view range and the maximum queue length condition at exit, respectively.

Figure 4.34 shows a comparison for the average maximum queue length at the Jawi toll plaza between the morning and evening. At the entry to the mixed mode lane, the average maximum queue length in the morning was longer than in the evening for Wednesdays and Saturdays; in the morning of Fridays, it was shorter than in the evening. For the Touch 'n Go and Smart TAG lanes, the average maximum queue length for Fridays and Saturdays did not show a significant difference between the morning and evening while the average maximum queue length for the Touch 'n Go and Smart TAG lanes in the morning was longer than in the evening for Wednesdays.

At exit for the mixed mode, Fridays show the longest average queue length in the evening and longer than the average maximum queue length in the morning for the three days. For Wednesdays and Saturdays, the average maximum queue length in the morning was slightly longer than in the evening. For Touch 'n Go and Smart TAG, the average maximum queue length in the evening was longer than in the morning for all the three days.

Finally, the results of the maximum queue length for the Juru and Jawi toll plazas show that the majority of the long queue length occurs at the mixed mode lanes for both toll plazas. Furthermore, the maximum queue lengths did not always occur during the peak hours and, thus, the causes of the queue length did not depend only on the traffic volume. Sometimes, when the mixed mode queue length is very long and exceeds the range of the camera view, a high percentage of heavy vehicles was noticed in the queue lengths. On the other hand, most of the maximum queue length for the Touch 'n Go lane occurs because of the high traffic rate, while the maximum queue length for the Smart TAG lane causes the vehicle to stop in the toll lane due to detection failure of the Smart TAG device or insufficient balance in the card.

At the Juru toll plaza, the queue length in the morning is longer than in the evening in both directions for all the three days. However, the situation is different at the Jawi toll plaza depending on the day and the direction of the travel.

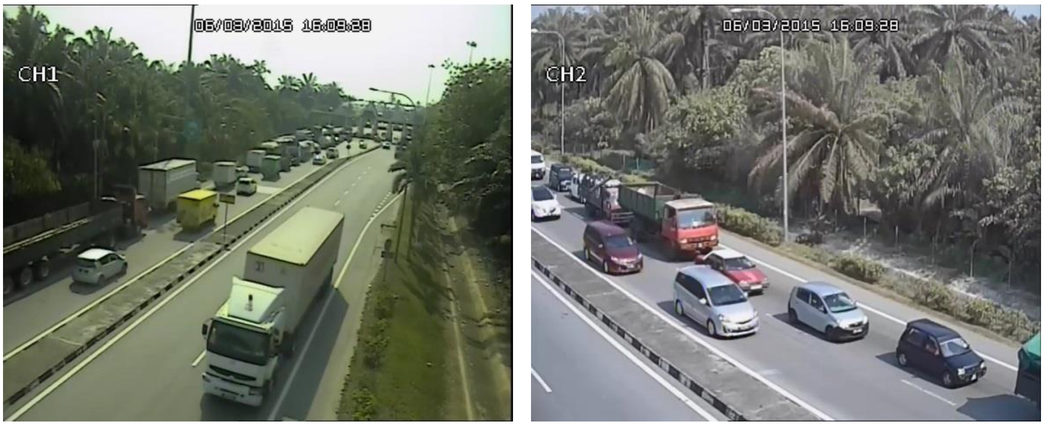
All these information are useful to understand toll plaza operations and to give guidelines for the objective of this study to examine the effect of heavy vehicles on queues at toll plaza.

Table 4.11 Maximum queue length summary of Jawi toll plaza for March 2015.

Direction	Day	Date	AM Time	AM Maximum queue length (m) Mixed mode	AM Touch 'n Go	AM Smart TAG	PM Time	PM Maximum queue length (m) Mixed mode	PM Touch 'n Go	PM Smart TAG
Entry	Wednesdays	4/3/2015	7 - 8	maximum 245	95	130	4 - 5	150	80	15
		11/3/2015	7 - 8	200	80	105	4 - 5	145	34	25
		18/3/2015	7 - 8	178	90	97	4 - 5	maximum 245	60	35
		25/3/2015	7 - 8	maximum 245	100	90	4 - 5	205	40	25
		Average		209.5	91.3	105.5		166.7	53.5	25.0
	Fridays	6/3/2015	7 - 8	145	87	114	4 - 5	210	85	120
		13/3/2015	7 - 8	maximum 245	83	125	4 - 5	maximum 245	117	80
		20/3/2015	7 - 8	190	60	100	4 - 5	210	85	60
		27/3/2015	7 - 8	maximum 245	110	85	4 - 5	maximum 245	60	40
		Average		140.8	85.0	106.0		210.0	86.8	75.0
	Saturdays	7/3/2015	11 - 12	The maximum 245	80	85	12 - 1	140	50	35
		14/3/2015	11 - 12	The maximum 245	70	60	12 - 1	210	83	75
		21/3/2015	11 - 12	maximum 245	82	96	12 - 1	150	105	80
		28/3/2015	11 - 12	maximum 245	95	95	12 - 1	140	85	110
		Average		maximum 245	81.8	84.0		160.0	80.8	75.0
Exit	Wednesdays	4/3/2015	10 - 11	70	40	0	5 - 6	60	45	60
		11/3/2015	10 - 11	145	20	15	5 - 6	70	80	45
		18/3/2015	10 - 11	50	15	10	5 - 6	140	50	35
		25/3/2015	10 - 11	90	20	15	5 - 6	50	105	50
		Average		88.8	23.8	10.0		80.0	70.0	47.5
	Fridays	6/3/2015	11 - 12	50	15	20	4 - 5	More than 238 m (∞)	40	15
		13/3/2015	11 - 12	90	30	25	4 - 5	More than 238 m (∞)	20	15
		20/3/2015	11 - 12	65	45	50	5 - 6	More than 238 m (∞)	60	15
		27/3/2015	11 - 12	50	25	10	5 - 6	70	60	80
		Average		63.8	28.8	26.3		196.0	45.0	31.3
	Saturdays	7/3/2015	11 - 12	60	45	40	5 - 6	70	40	15
		14/3/2015	11 - 12	165	45	45	5 - 6	60	90	20
		21/3/2015	11 - 12	40	45	10	5 - 6	60	40	60
		28/3/2015	11 - 12	55	20	35	5 - 6	120	80	60
		Average		80.0	38.8	32.5		77.5	62.5	38.8

(a) (b)

Figure 4.32 Screen capture for the maximum queue length condition when exceeding the camera view range at the entry of Jawi toll plaza; (a) Video recording of camera toward toll plaza, (b) Video recording of camera toward upstream lanes.



(a) (b)

Figure 4.33 Screen capture for the maximum queue length condition when exceeding the camera view range at the exit of Jawi toll plaza; (a) Video recording of camera toward toll plaza, (b) Video recording of camera toward upstream lanes.

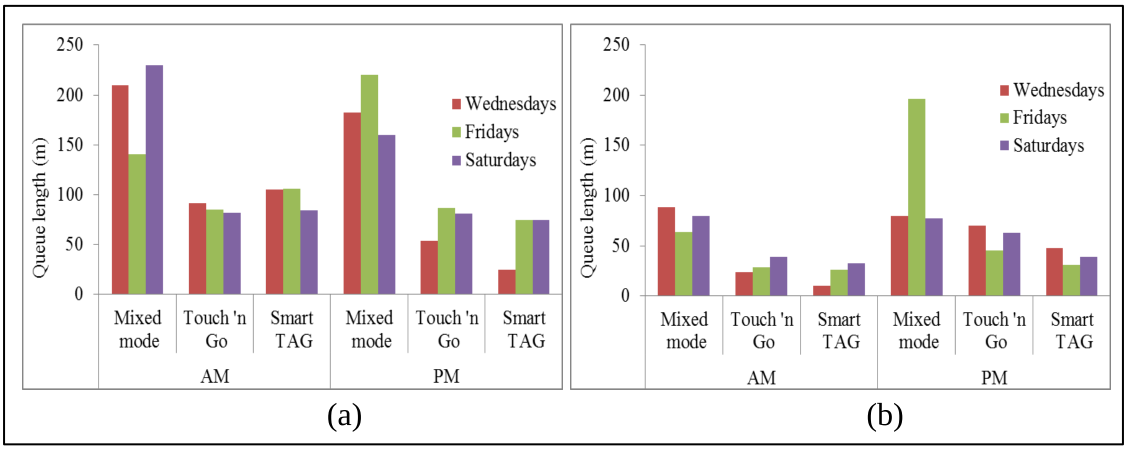


Figure 4.34 Average maximum queue length at Jawi toll plaza: (a) entry, (b) exit.

4.2.2(d) **Traffic composition**

Traffic composition represents the proportions of different vehicle types in the traffic flow. This is useful to control the way vehicles behave and react in the toll plaza and to incorporate the differences in terms of their operational performance in the simulation model. Traffic compositions are important because vehicle travel routes are assigned for specific vehicle types (Transportation Research Board, 2000). In addition, the service time of the mixed mode lane depends upon the arrival pattern of vehicles. Moreover, the traffic composition in the toll plaza modelling concepts is not only focused on the proportions of different vehicle types in the traffic flow but also on the proportion of the traffic flow based on the toll lane types (payment methods).

At the Juru toll plaza, Figure 4.35 shows the traffic composition for the entry to the lanes with a traffic volume of 2,501 vph, which consists of 85.5% cars, 7.7% small lorries, 1.8% trucks, 3.5% trailers, and 1.6% busses. On the other hand, Figure 4.36 shows the traffic volume based on the payment method and the number of vehicles using ticket or Touch 'n Go at the mixed mode lanes and the number of cars using Touch 'n Go or Smart TAG at the ETC lanes.

Figure 4.37 shows the traffic composition at the exit lane with a traffic volume of 2,920 vph, which consists of 83.9% cars, 8.5% small lorries, 2.6% trucks, 4.2% trailers, and 0.8% busses. Figure 4.38, on the other hand, shows the traffic volume based on the payment method and the number of vehicles using cash or Touch 'n Go payments at the mixed mode and staggered lanes and the number of cars using the Touch 'n Go or Smart TAG payments at the ETC lanes.

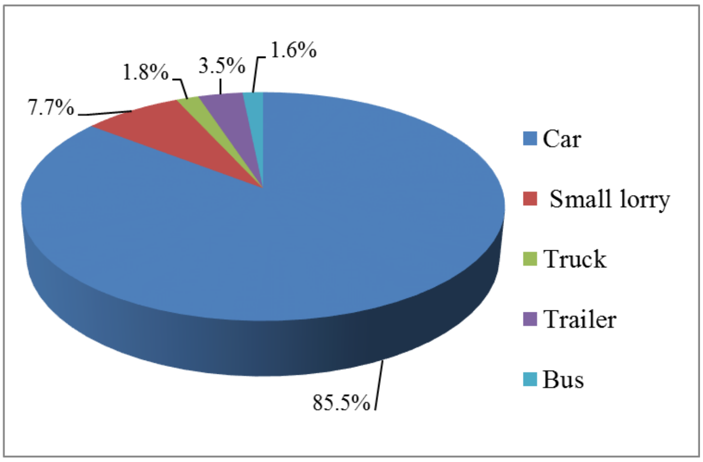


Figure 4.35 Traffic composition percentages by vehicle category at Juru toll plaza – Entry.

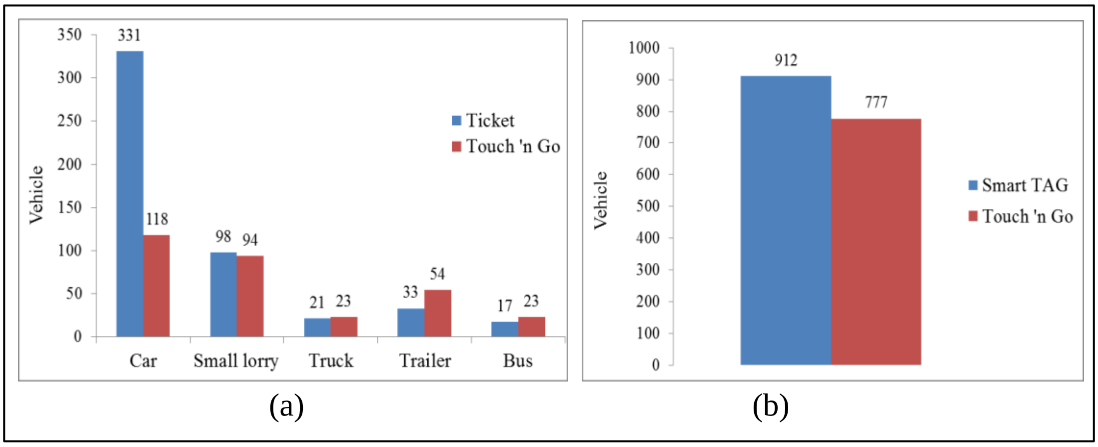


Figure 4.36 Entry traffic volume at Juru toll plaza based on payment method; (a) Mixed mode lanes (3 booths), (b) Smart TAG and Touch 'n Go lanes (2 lanes).

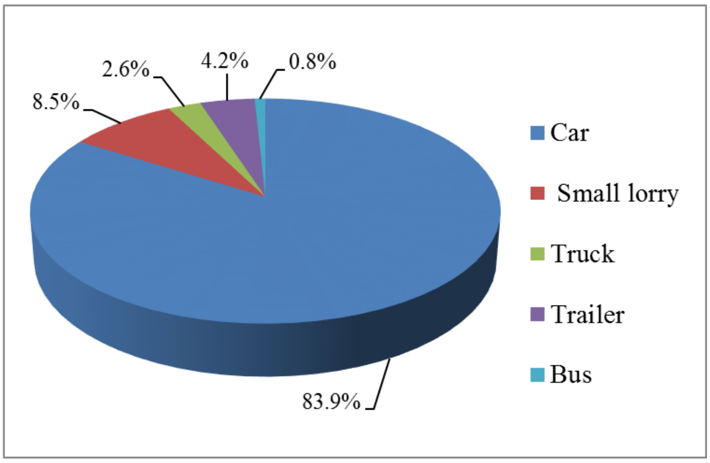


Figure 4.37 Traffic composition percentages by vehicle category at Juru toll plaza – Exit.

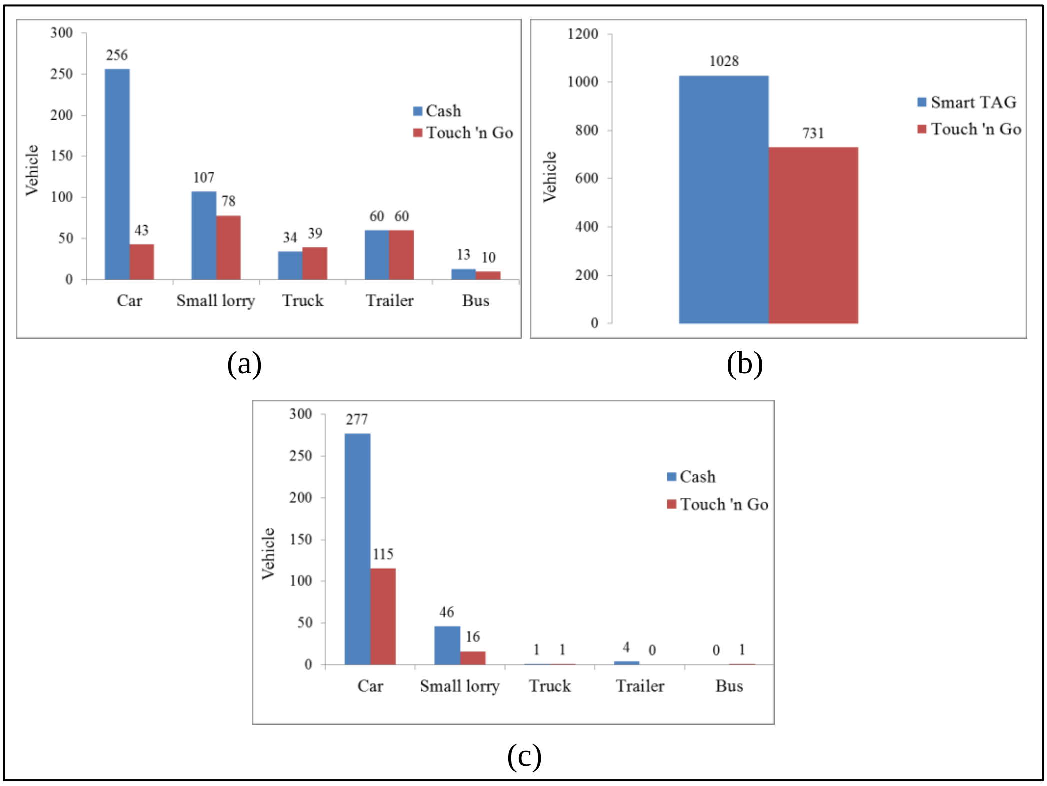


Figure 4.38 Exit traffic volume at Juru toll plaza based on payment method; (a) Mixed mode lanes (4 booths), (b) Smart TAG and Touch 'n Go lanes, (c) Staggered lanes (8 booths).

At the Jawi toll plaza, Figure 4.39 shows the traffic composition for entry into the toll lane with a traffic volume of 790 vph, which consists of 75.1% cars, 14.9% small lorries, 2.0% trucks, 7.2% trailers, and 0.8% busses. Moreover, Figure 4.40 shows the traffic volume based on the payment method and the number of vehicles using ticket or Touch 'n Go at the mixed mode lanes and the number of cars using Touch 'n Go or Smart TAG at the ETC lanes.

Figure 4.41 shows the traffic composition for the exit with a traffic volume of 1,282 vph, which consists of 92.4% cars, 3.8% small lorries, 0.6% trucks, 2.0% trailers, and 1.2% busses. On the other hand, Figure 4.42 shows the traffic volume based on the payment method and the number of vehicles using cash or Touch 'n Go at the mixed mode lanes and the number of cars using Touch 'n Go or Smart TAG at the ETC lanes.

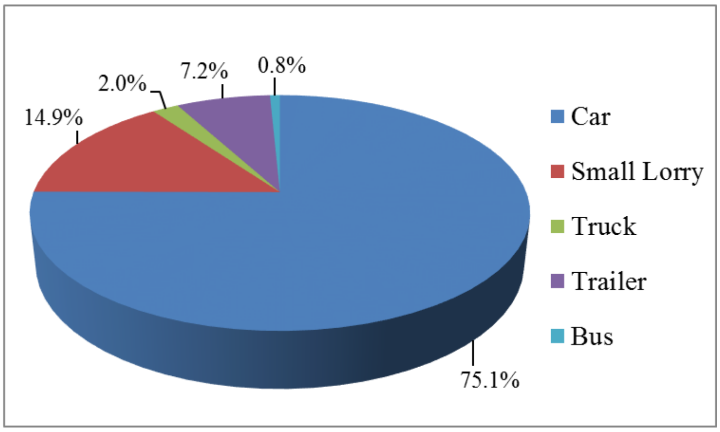


Figure 4.39 Traffic composition percentages by vehicle category at Jawi toll plaza – Entry.

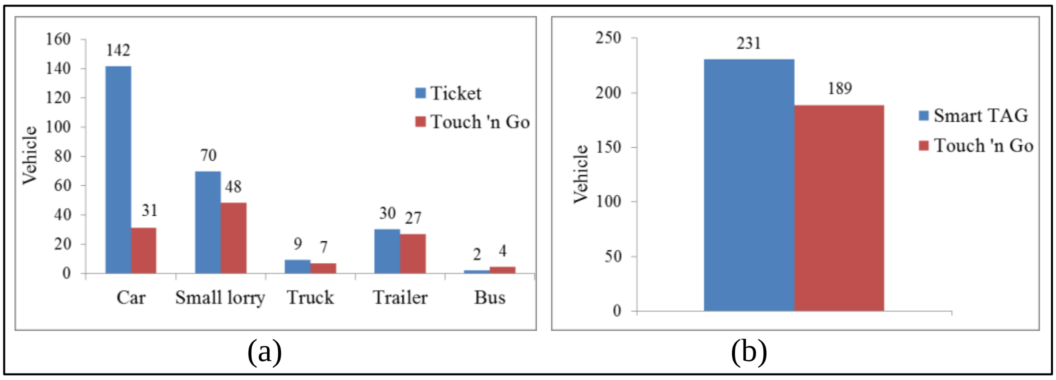


Figure 4.40 Entry traffic volume at Jawi toll plaza based on payment method; (a) Mixed mode lanes (1 booth), (b) Smart TAG and Touch 'n Go lanes (1 lane).

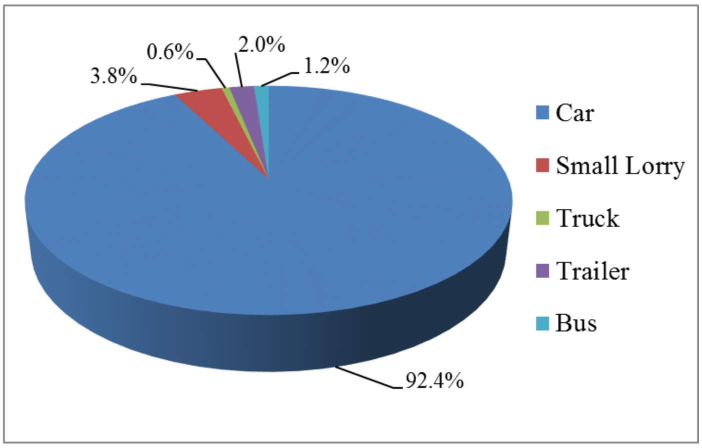


Figure 4.41 Traffic composition percentages by vehicle category at Jawi toll plaza – Exit.

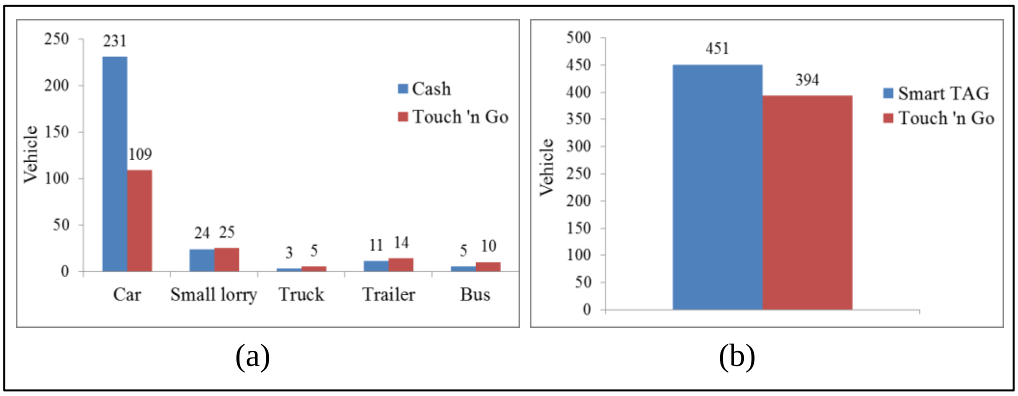


Figure 4.42 Exit traffic volume at Jawi toll plaza based on payment method; (a) Mixed mode lanes (3 booths), (b) ETC lanes.

4.2.3 Vehicle characteristics

The individual vehicle data collected was on payment type, vehicle type, drivers' delay upon payment, and vehicle service time.

4.2.3(a) **Payment type**

As mentioned previously, the methods of toll payment are divided into three types: the mixed mode, Touch 'n Go, and Smart TAG. These types are available in the Juru and Jawi toll plazas which are named and classified, according to the vehicle types, into:

1. Mixed mode/multiclass: payment types are cash/ticket and Touch 'n Go and accepts all vehicle classes.
2. Touch 'n Go/single class: payment type is Touch 'n Go and accepts only class 1.
3. Smart TAG/single class: payment type is Smart TAG and accepts only class 1.

Figure 4.43, 4.44 and 4.45 show a general trend of the payment type percentages in the Juru toll plaza for the entry and exit lanes and also compares the total daily throughput for Wednesdays, Fridays, and Saturdays, respectively, between the morning and evening.

For entry, the mixed mode and Smart TAG payments recorded almost the same total percentages for the three days (Wednesday, Friday, and Saturday). However, in the morning and evening peak hours, the Smart TAG obtains the highest percentage of the payment for the three days. For exit, the situation is different in which the majority of the payment is done at the mixed mode toll lanes, including the staggered booths for all the three days at the total and at peak hours.

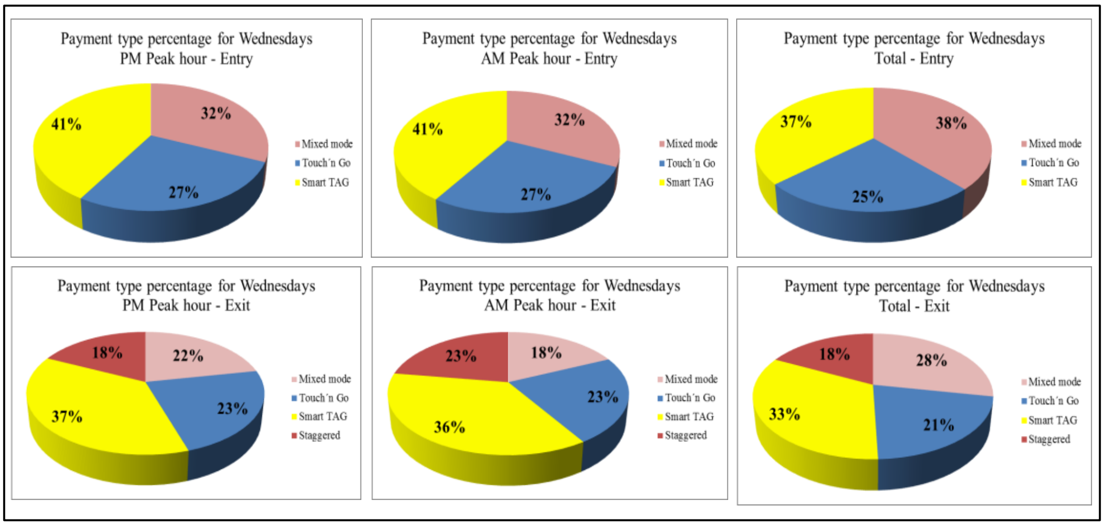


Figure 4.43 Payment type percentages in Juru toll plaza for entry and exit on Wednesdays.

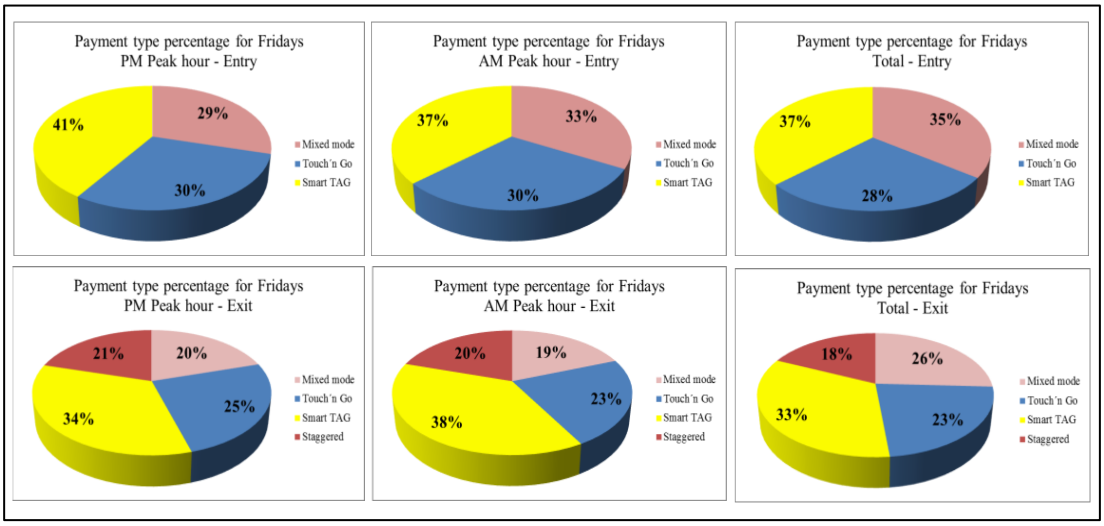


Figure 4.44 Payment type percentages in Juru toll plaza for entry and exit on Fridays.

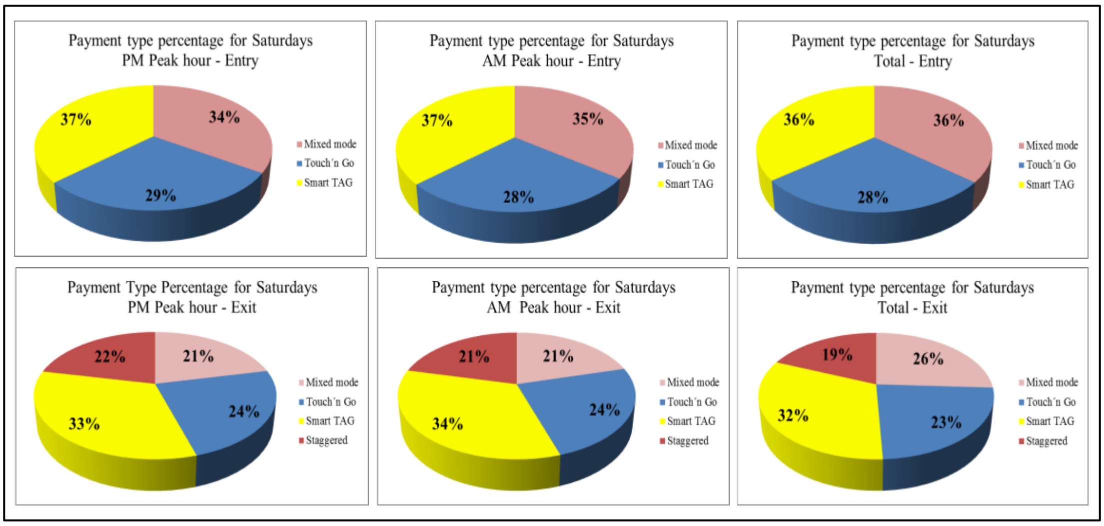


Figure 4.45 Payment type percentages in Juru toll plaza for entry and exit on Saturdays.

For the Jawi toll plaza, Figure 4.46, 4.47 and 4.48 show a general trend of the percentages of the payment type for entry and exit, and also compares between the morning and evening with the total daily throughput for Wednesdays, Fridays, and Saturdays, respectively. For entry, Smart TAG has the major percentage of the total payment type in the morning and evening peak hours for all the three days. For exit, the percentages are different in which the majority of the total payment was done by the mixed mode in the morning and evening peak hours for all the three days.

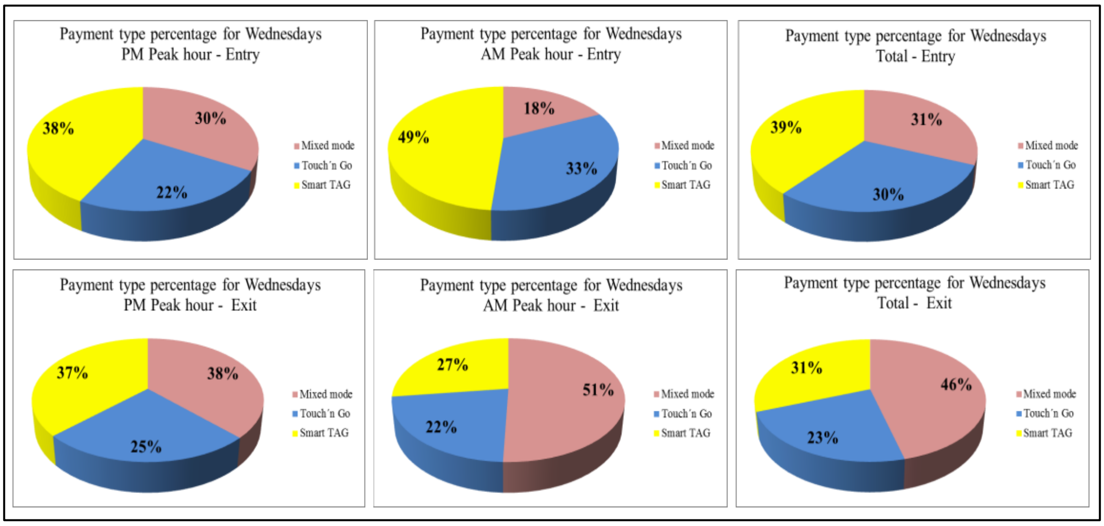


Figure 4.46 Payment type percentages in Jawi toll plaza for entry and exit on Wednesdays.

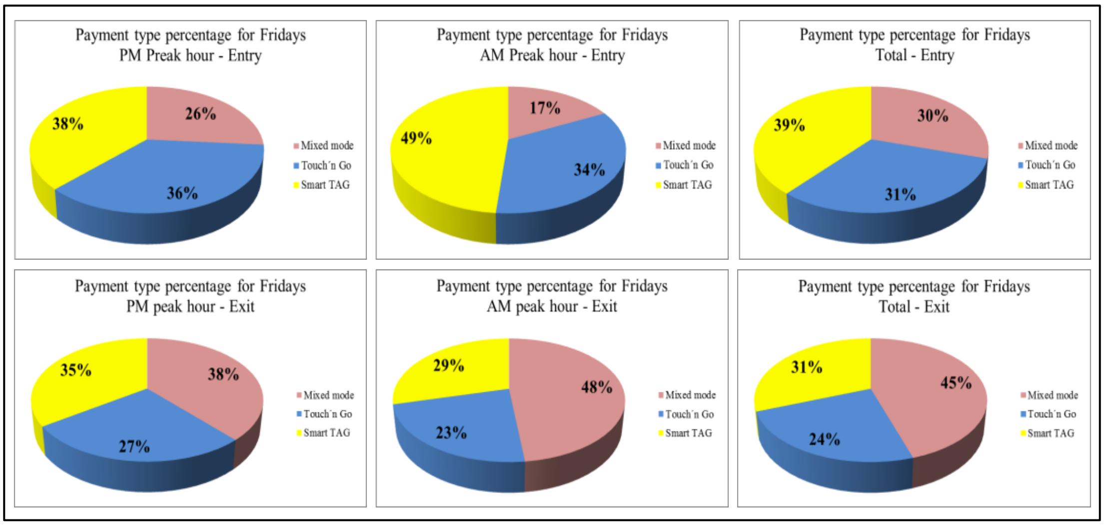


Figure 4.47 Payment type percentages in Jawi toll plaza for entry and exit on Fridays.

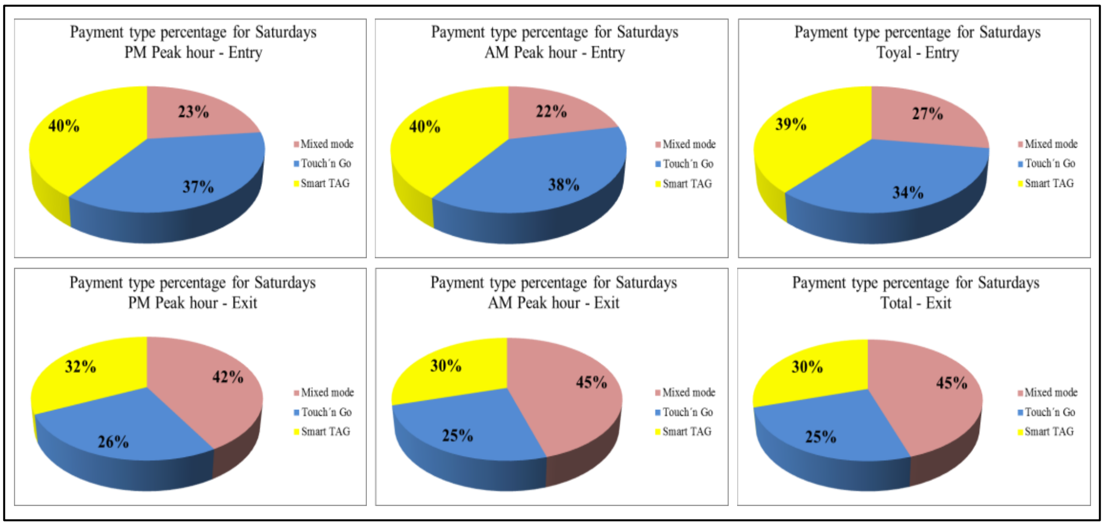


Figure 4.48 Payment type percentages in Jawi toll plaza for entry and exit on Saturdays.

4.2.3(b) **Vehicle type**

Vehicles in the Malaysian expressways (closed system) are divided into five classes according to the vehicle classification adopted by PLUS based on the toll fare and the number of axles and wheels. However, due to reason of passenger cars and taxis having the same vehicle characteristics and thus behaving in the same manner, they were grouped in the same vehicle type in the simulation model. Also, based on field data, huge variations were observed in terms of vehicle length for trailer even though they are classified as vehicles having three or more axles.

The variation in vehicle length for trailers impacts the toll operation. Therefore, vehicles in this class are divided into trucks (heavy vehicles having three or more axles with a vehicle length of between 8.5 m and 13.0 m) and trailers (having three or more axles with a vehicle length of more than 13.0 m).

Figure 4.49a shows the vehicle classification adopted by PLUS, while Figure 4.49b shows the vehicle type used in the simulation model. Figure 4.50 to 4.54 show the photos extracted from video recordings to illustrate the vehicles type and class.

Vehicle Classification - PLUS			
No	Vehicle class	Icon	Description
1	Class 1		Vehicles with 2 axles and 3 or 4 wheels excluding taxis
2	Class 2		Vehicles with 2 axles and 5 or 6 wheels excluding buses.
3	Class 3		Vehicles with 3 or more axles.
4	Class 4		Taxis
5	Class 5		Buses

(a)

Vehicle type - Simulation model			
No	Vehicle type	Icon	Description
1	Type 1	+	Car and Taxi
2	Type 2		Small lorry (2 axles and 6 wheels)
3	Type 3		Truck (3 or more axles. With length 8.5-13.0 m)
4	Type 4		Trailer (3 or more axles. With length more than 13.0 m)
5	Type 5		Bus

(b)

Figure 4.49 Vehicle classifications; (a) Vehicle classification adopted by PLUS, (b) Vehicle type used in the simulation model.

Figure 4.50 Vehicle type 1, Class 1 and Class 4 (Car and Taxi).

Figure 4.51 Vehicle type 2, Class 2 (Small lorry).

Figure 4.52 Vehicle type 3, Class 3 (Truck).

Figure 4.53 Vehicle type 4, Class 3 (Trailer).

Figure 4.54 Vehicle type 5, Class 5 (Bus).

4.2.3(c) **Service time**

Service time is one of the main input parameters in the toll plaza model, which most significantly influences the performance of toll operation and, thus, the overall toll plaza capacity.

The service time in the mixed mode and Touch 'n Go lanes is the time in seconds that a vehicle spends at a tollbooth to pay a toll until it starts moving. However, the service time is the time for the headway for the Smart TAG lanes. This principle gave the procedure for the observation and extraction of data of the vehicle service time from video recordings for each individual vehicle when it stopped at the tollbooth to make payment.

In order to achieve the first objective of this study, the operation and service time for each gate are investigated. In particular, it aims to determine the service times of vehicles at the Juru and Jawi toll plazas for both entry and exit directions. In this regard, the determination of the service time at this type of toll plaza (conventional toll plaza) becomes too complex, especially at the multiclass mixed mode toll lane. The complexity comes from the fact that the multiclass mixed mode toll lanes have five types of vehicles, with each type having its own service time. Furthermore, the service time is different, whether at entry or exit, for a particular vehicle type.

Finally, the total number of vehicle service time at multiclass mixed mode and single-class for Touch 'n Go toll lanes at both entry and exit is:

Service times = [(five vehicle types) X (two payment types (ticket/cash or Touch 'n Go)) + (one Touch 'n Go)] X (two directions)

= 22 (4-1)

During the observations of the vehicle service time from the videos, it was noticed that the service time of vehicles using mixed mode and Touch 'n Go lanes consists of two components:

i. Transaction time: this is the measurement time from the time the vehicle stops at the tollbooth until the time of taking a ticket or completing the Touch 'n Go transaction for entry. For exit, this is until the time of taking a receipt for cash and Touch 'n Go transaction at the mixed mode or completing the transaction of the Touch 'n Go lanes.
ii. Start-up delay time: this is the measurement time from the end of the transaction until the time the vehicle starts moving.

The service time of vehicles was measured by playing back the videos and recording the time of each vehicle stops, completing the transaction, and starting to move. This procedure was repeated for each vehicle at the mixed mode and Touch 'n Go toll lanes of the Juru and Jawi toll plazas.

Table 4.12 shows a sample of the time recordings for the transaction and start-up delay time for cars at the entry direction of the Juru toll plaza from the video recordings.

Table 4.12 Time recording for the transaction and start-up delay time for car at the entry direction of Juru toll plaza – Sample.

CAR Type (Class 1&4) Ticket						CAR Type (Class 1&4) Touch 'n Go					
Stop time	End transaction time	Start moving time	Transaction time (s)	Start-up delay time (s)	Service Time (s)	Stop time	End transaction time	Start moving time	Transaction time (s)	Start-up delay time (s)	Service Time (s)
10:30:03	10:30:05	10:30:05	2	0	2						
10:30:10	10:30:11	10:30:11	1	0	1						
10:30:17	10:30:18	10:30:18	1	0	1						
10:30:25	10:30:27	10:30:28	2	1	3						
10:30:50	10:30:52	10:30:53	2	1	3						
						10:31:55	10:31:56	10:31:57	1	1	2
10:32:16	10:32:17	10:32:18	1	1	2						
10:32:23	10:32:25	10:32:26	2	1	3						
10:33:35	10:33:37	10:33:38	2	1	3						
						10:34:29	10:34:32	10:34:33	3	1	4
10:34:48	10:34:50	10:34:51	2	1	3						
10:34:55	10:34:56	10:34:57	1	1	2						
10:35:01	10:35:02	10:35:03	1	1	2						
10:35:08	10:35:09	10:35:10	1	1	2						
10:35:47	10:35:49	10:35:50	2	1	3						
						10:35:56	10:35:57	10:35:58	1	1	2
10:36:20	10:36:23	10:36:24	3	1	4						
10:37:11	10:37:13	10:37:13	2	0	2						
10:37:33	10:37:39	10:37:42	6	3	9						
10:37:46	10:37:48	10:37:48	2	0	2						
						10:37:56	10:37:57	10:37:58	1	1	2
10:38:03	10:38:05	10:38:06	2	1	3						
10:38:12	10:38:14	10:38:15	2	1	3						

As a result of the observations of the vehicle service time, a total of 3,312 vehicles were measured at the Juru toll plaza: 1,544 vehicles for entry and 1,768 vehicles for exit. On the other hand, the total number of vehicles measured at the Jawi toll plaza was 3,124 vehicles: 1,518 vehicles for entry and 1,506 vehicles for exit. All the measurements for the service time of the vehicles were randomly recorded during the peak hours for Wednesdays, Fridays, and Saturdays.

According to the VISSIM model requirements, service times need to be represented as cumulative curves. At the Juru toll plaza, Figure 4.55 shows the frequencies and cumulative curves of the measured service times for cars at the multiclass toll lanes. While the Figures of the frequencies and cumulative curves of the measured service times for small lorries, trucks, trailers, and busses at the multiclass toll lanes showed in Appendix A. Figure 4.56 shows the frequency and cumulative curve of the measured service times for Touch 'n Go for the single-class lane.

All the figures of the service time at the Juru toll plaza showed that the service times for ticket is lower than the service times for cash for all vehicle types due to long procedure for cash payment. Additionally, the service times for Touch 'n Go at entry is lower than the service times at exit because most drivers ask for receipts at the exit. Moreover, the service time for Touch 'n Go at single-class lanes at entry is also lower than the exit because the drivers at the exit spend longer time in the transaction and therefore wait longer before starting to move. For more details, figures in Appendix A show the transaction, start-up delay and service times at Juru toll plaza.

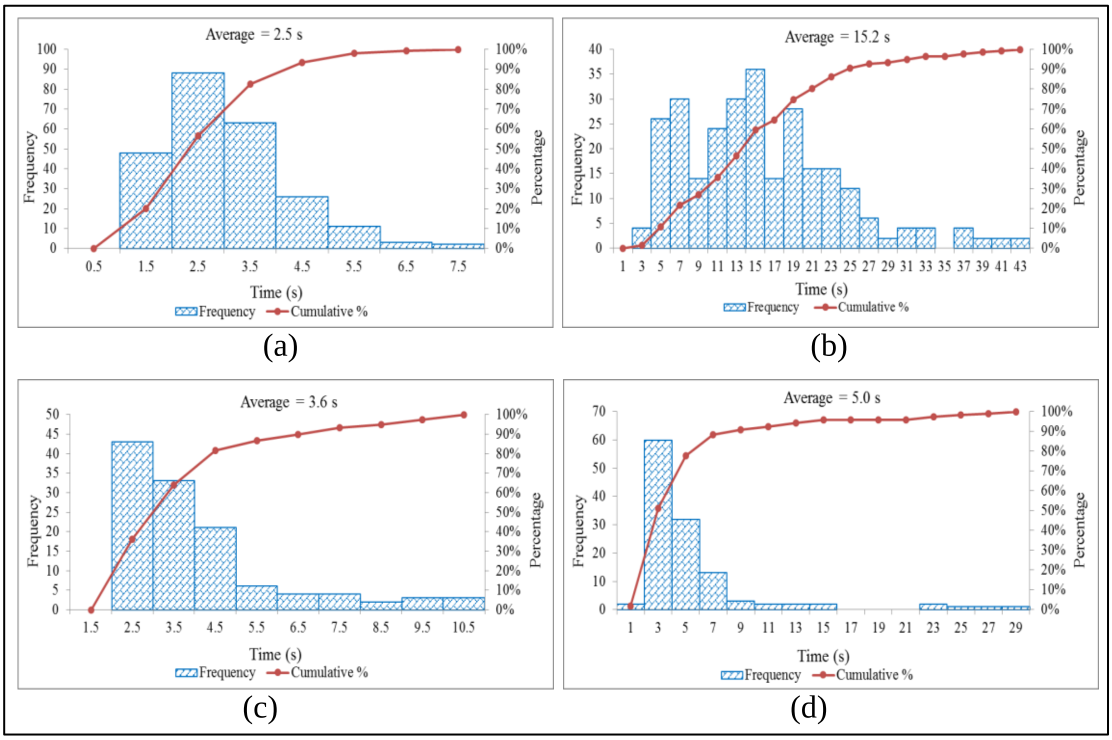


Figure 4.55 Frequencies and cumulative curves of service time for car at Juru toll plaza; (a) entry - ticket, (b) exit - cash, (c) entry - Touch 'n Go, (d) exit - Touch 'n Go.

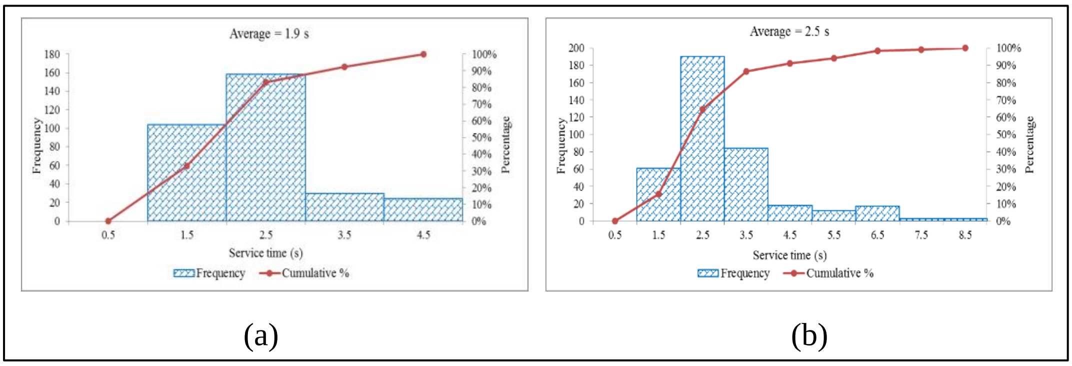


Figure 4.56 Frequencies and cumulative curves of service time for Touch 'n Go – Single class lanes at Juru toll plaza; (a) Entry, (b) Exit.

For the Jawi toll plaza, Figure 4.57 shows the frequencies and cumulative curves of the measured service times for cars at the multiclass toll lanes. While the Figures of the frequencies and cumulative curves of the measured service times for small lorries, trucks, trailers, and busses at the multiclass toll lanes showed in Appendix B. Figure 4.58 shows the frequency and cumulative curve of the measured service times for Touch 'n Go for the single - class lane at the Jawi toll plaza.

All the figures of the service time at Jawi toll plaza showed the same behavior as the service times at the Juru toll plaza for ticket, cash, and Touch 'n Go. For more details, figures in Appendix B show the transaction, start-up delay and service times at Jawi toll plaza.

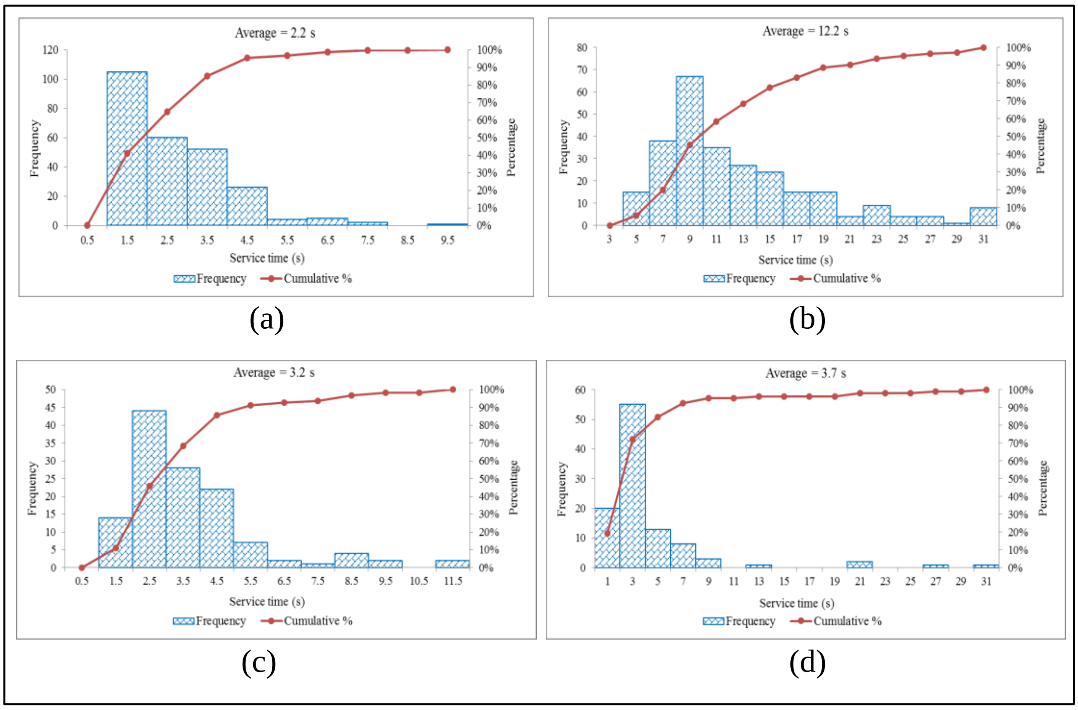
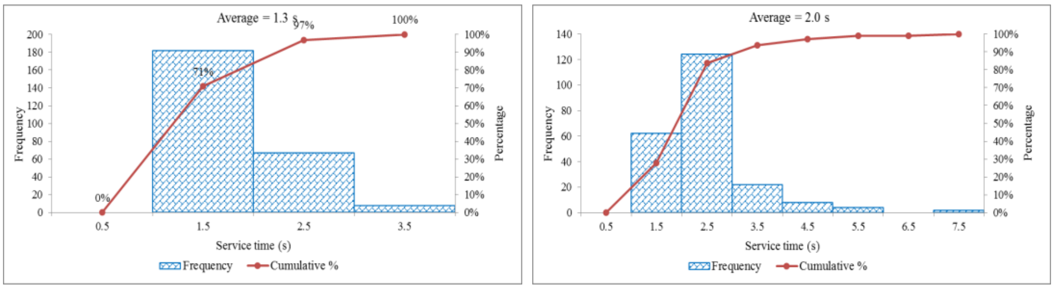


Figure 4.57 Frequencies and cumulative curves of service time for car at Jawi toll plaza; (a) entry - ticket, (b) exit - cash, (c) entry - Touch 'n Go, (d) exit - Touch 'n Go.



(a) (b)

Figure 4.58 Frequencies and cumulative curves of service time for Touch 'n Go – Single class lanes at Jawi toll plaza; (a) Entry, (b) Exit.

Finally, based on the results shown in figures in Appendix A for the Juru toll plaza, Figure 4.59 shows the summary of the transaction, start-up delay, and service times at entry mixed mode lanes for ticket and Touch 'n Go based on vehicle type. The same charts were plotted for the exit as shown in Figure 4.60.

Based on the results shown in Figure 4.59 and Figure 4.60, it is concluded that:

a) For entry:

- The transaction time for ticket is longer than the Touch 'n Go for small lorries, trucks, and trailers. However, for cars and busses, the transaction time for Touch 'n Go is longer than the ticket. Because, for ticket, the operator provides ticket for the approaching vehicles before reaching the tollbooth. While for Touch 'n Go, the operator waits for the driver to stop and touch the card on the Contactless Smart Card (CSC) reader to make the transaction and that take longer time than ticket.
- The start-up delay time is almost equal between the ticket and Touch 'n Go.

- The service time (which is the sum of the transaction time and start-up delay time) for the ticket is longer than Touch 'n Go for small lorries, trucks, and trailers. However, the service time for Touch 'n Go is longer than ticket for cars and busses. For ticket, the longest service time was for trucks (7.8 s) and trailers (7.9 s), and the shortest service time was for cars (2.5 s). Moreover, for Touch 'n Go, the longest service time was for trucks (5.6 s), and the shortest service time was for cars (2.5 s).

b) For exit:

- The transaction time for cash is much longer than the Touch 'n Go for all vehicle types, because of the long procedure of the cash payment.
- The start-up delay time for cash is slightly longer than Touch 'n Go for all vehicle types except for small lorries.
- The service time is the longest for small lorries, trucks, and trailers for cash with a close value between 22.4 s and 23.0 s. For Touch 'n Go, the same vehicles also have the longest service time with a close value between 11.9 s and 13.0 s. The reason of the long service time for these vehicles is because the operator needs to enter vehicle class and plate number.

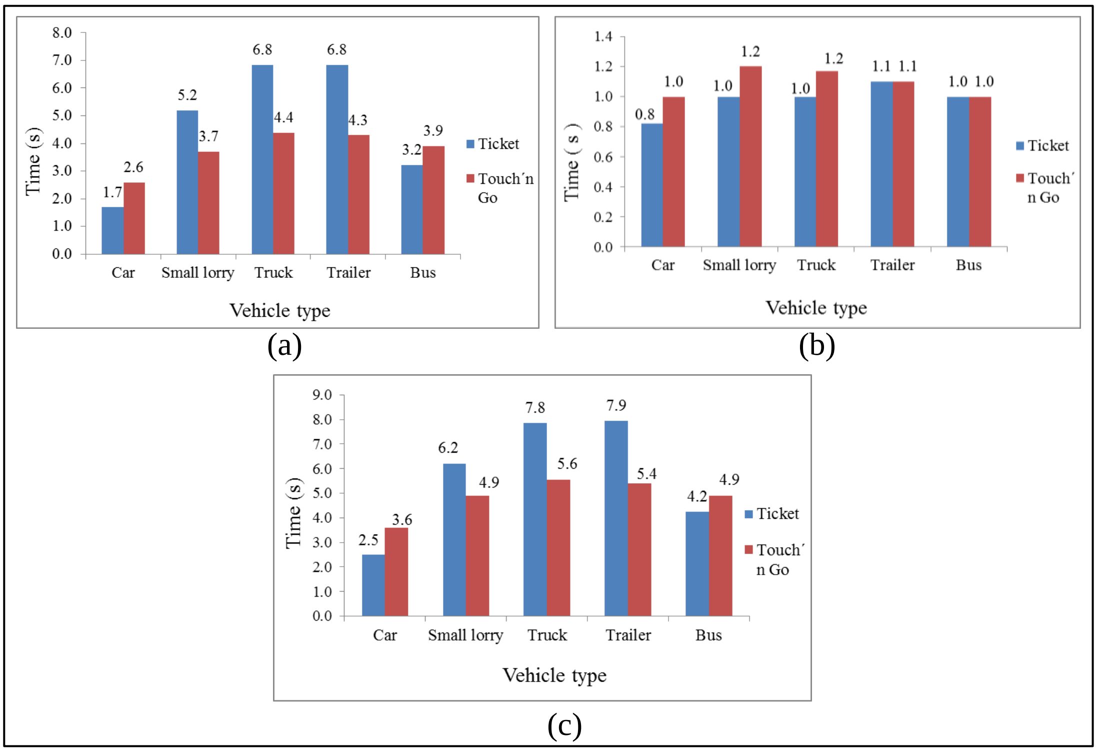


Figure 4.59 Entry Juru toll plaza – (mixed mode): (a) Transaction time, (b) Start-up delay time, (c) Service time.

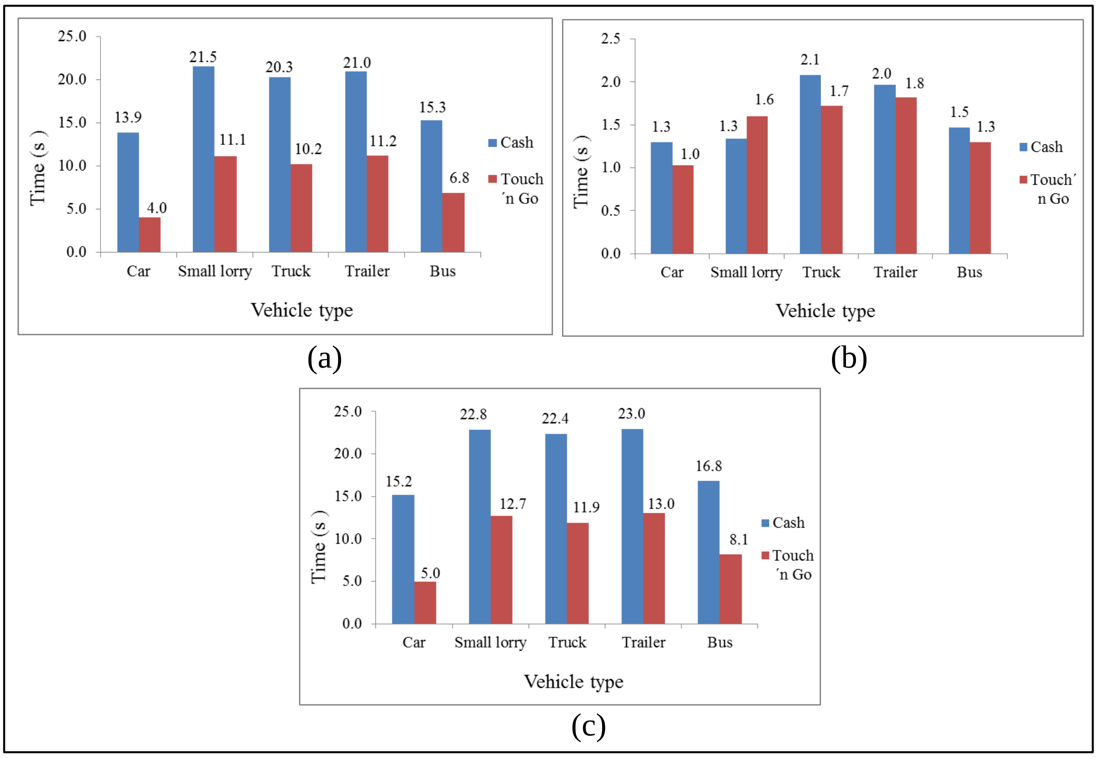


Figure 4.60 Exit Juru toll plaza – (mixed mode): (a) Transaction time, (b) Start-up delay time, (c) Service time.

Figure 4.61 shows the comparison of service time (transaction time + start-up delay time) between entry and exit at mixed mode lanes. Based on the results shown in the charts, the following conclusions are made:

- The service time for entry is much lower than the service time for exit.
- The service time for entry using Touch 'n Go is longer than the ticket for cars and busses. Because, for Touch 'n Go, the operator waits for the driver to stop at tollbooth and touch the card on the Contactless Smart Card (CSC) reader to make the transaction. While for ticket, the operator provides ticket for the approaching vehicle before reaching the tollbooth and most of the time, vehicles do not make a complete stop at tollbooths.
- The service time for exit using Touch 'n Go is longer than entry, most probably due to printing of receipt.

Figure 4.62 shows the comparison of transaction, start-up delay, and service times for Touch 'n Go single-class lanes between entry and exit. The figure shows that transaction, start-up delay, and service times for Touch 'n Go lanes at exit are slightly higher than the values for entry. The drivers at the exit spend longer time at Touch 'n Go toll lanes for checking the remaining balance in the Touch 'n Go cards.

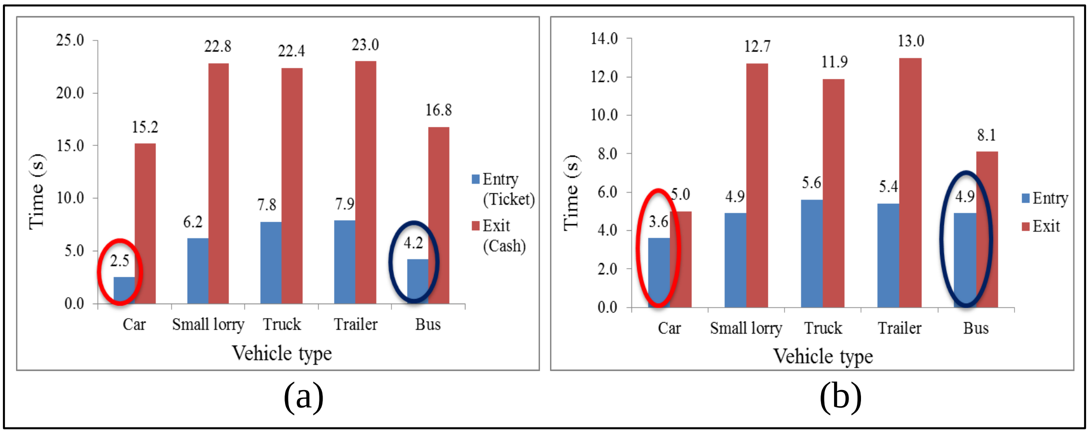


Figure 4.61 Comparison of service time at Juru toll plaza between entry & exit at mixed mode lane: (a) Ticket vs Cash, (b) Touch 'n Go.

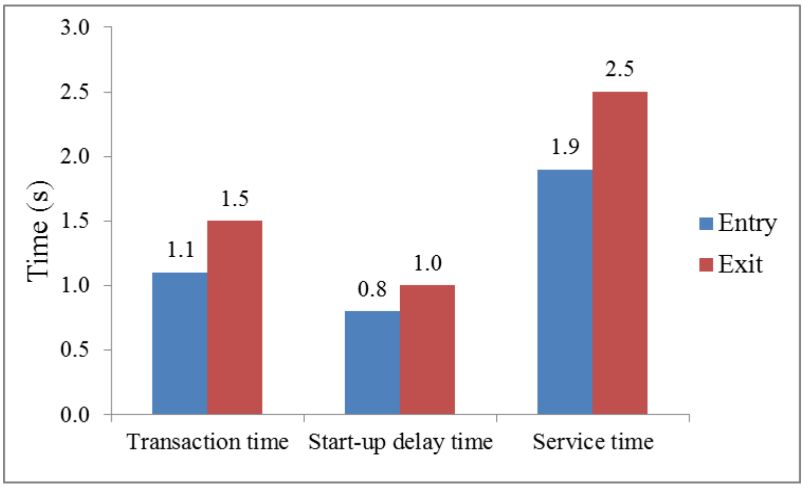


Figure 4.62 Comparison of transaction time, start-up delay and service time at Juru toll plaza between entry & exit for Touch 'n Go lane.

Similar methods that applied to the Juru toll plaza were adopted for the Jawi toll plaza. Figure 4.63 shows the summary of the transaction, start-up delay, and service times at the entry of the mixed mode lanes for ticket and Touch 'n Go based on vehicle type. The same charts were plotted for exit as shown in Figure 4.64.

Based on the results shown in Figure 4.63 and Figure 4.64, it can be concluded that:

a) For entry:

- The transaction and service times for ticket is longer the Touch 'n Go for all vehicle types except for cars and busses.
- The start-up delay time is between 1.0 s and 1.6 s for all vehicle types for ticket and Touch 'n Go except for car, which was 0.8 s for ticket.
- The maximum service time for ticket and Touch 'n Go was for trucks 6.8s and 6.4 s, respectively, while the minimum service time for ticket and Touch 'n Go was for cars was 2.2 s and 3.2 s.

b) For exit:

- The transaction and service times for cash are longer with a significant difference in the Touch 'n Go for all vehicle types.
- The start-up delay time for cash is slightly longer than Touch 'n Go for all vehicle types except for the trailers.
- The maximum service time for cash was for trailers 25.4 s and for Touch 'n Go was for trucks 12.4 s. The minimum service time for cash and Touch 'n Go was for cars 12.2 and 3.7 s, respectively.

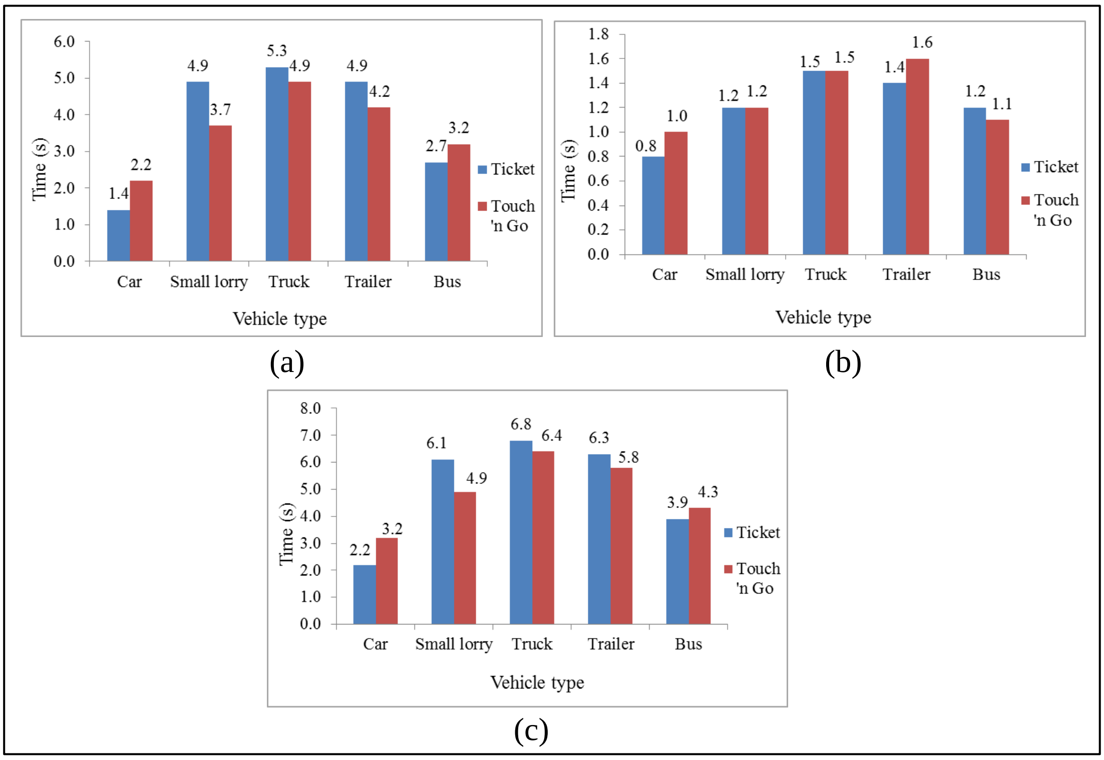


Figure 4.63 Entry Jawi toll plaza – (mixed mode): (a) Transaction time, (b) Start-up delay time, (c) Service time.

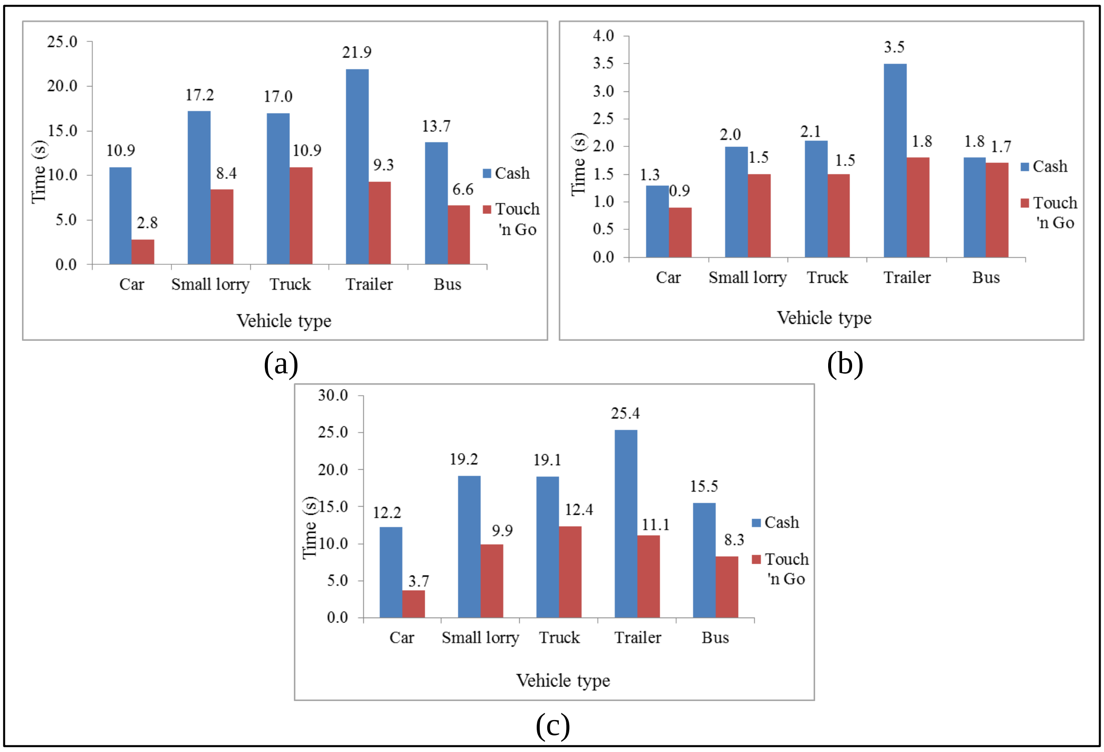


Figure 4.64 Exit Juru toll plaza – (mixed mode): (a) Transaction time, (b) Start-up delay time, (c) Service time.

A comparison of service time between entry and exit at the mixed mode lanes shown in Figure 4.65. Based on the results, it can be concluded that:

- The service time for exit is much longer than the service time for entry.
- For entry, the service time using ticket is lower than the Touch 'n Go for cars and busses.
- The service time for Touch 'n Go at exit is longer than entry, due to printing of receipt.

Figure 4.66 shows transaction, start-up delay, and service times for Touch 'n Go lanes at entry which are slightly lower than the values for exit. The drivers at the exit spend longer time to check the balance.

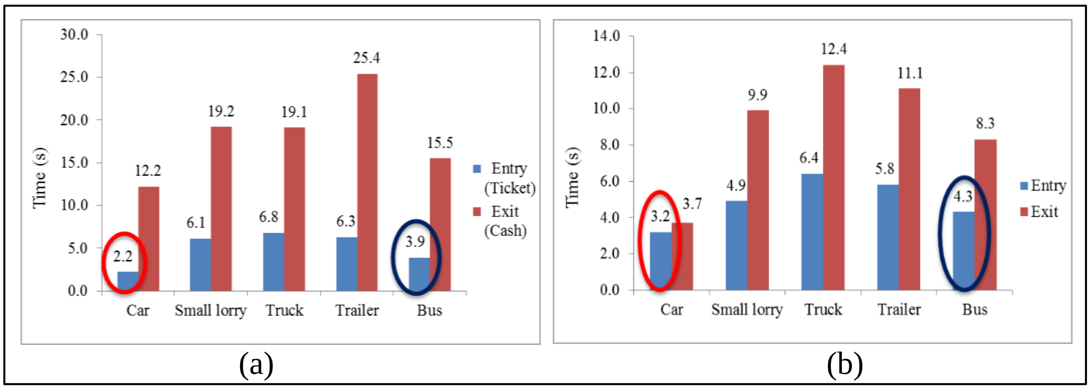


Figure 4.65 Comparison of service time at Jawi toll plaza between entry & exit at mixed mode lane: (a) Ticket vs Cash, (b) Touch 'n Go.

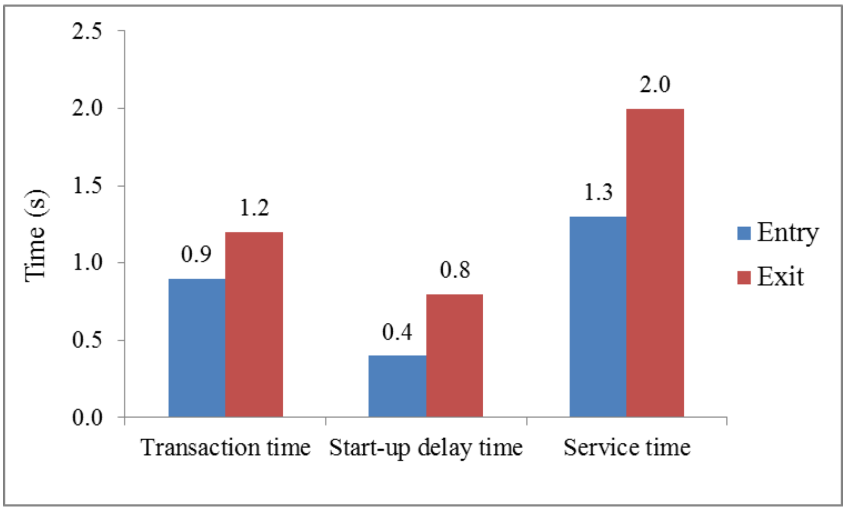


Figure 4.66 Comparison of transaction time, start-up delay and service time at Jawi toll plaza between entry & exit for Touch 'n Go lane.

CHAPTER FIVE
DEVELOPMENT OF TOLL PLAZA MODELS

5.1 Introduction

This chapter presents the creation and calibration of the base models for Juru and Jawi toll plazas, also presents the findings of the simulation models which represent the objectives of this study.

5.2 Base models creation

Once the requirements of the basic features used to build the toll plaza models were completed, the base models of the Juru and Jawi toll plazas were created with the necessary inputs related to the real toll plazas. The necessary inputs are:

1. The satellite image is used to match the information on the number of lanes in the toll plazas and the geometry of each toll plaza area. Additionally, the configurations of the toll plaza are represented by the number of the toll lanes dedicated for each type of payment.
2. The desired speed distribution, which is a particularly important parameter, impacts the link capacity and the queuing at the tollbooths and thereby the operation of the toll plaza. Figure 5.1 shows the desired speed distribution inputs of vehicle types in the Juru toll plaza model for entry. In this figure, the minimum speeds for cars, small lorries, trucks, trailers, and busses were 58, 51, 50, 43, and 55 km/h, respectively. The maximum speeds for the same vehicles were 122, 93, 96, 99, and 93 km/h, respectively. Figure 5.2 shows the desired speed distribution inputs of vehicle types in the Juru toll plaza model for exit. In this figure, the minimum speeds for cars, small lorries, trucks, trailers, and

busses were 56, 53, 44, 47, and 58 km/h, respectively. The maximum speeds for the same vehicles were 112, 88, 87, 86, and 92 km/h, respectively.

Figure 5.3 shows the desired speed distribution inputs of vehicle types in the Jawi toll plaza model for entry. In this figure, the minimum speeds for cars, small lorries, trucks, trailers, and busses were 32, 29, 26, 28, and 28 km/h, respectively. The maximum speeds for the same vehicles were 67, 57, 51, 46, and 44 km/h, respectively. Figure 5.4 shows the desired speed distribution inputs of vehicle types in the Jawi toll plaza model for exit. In this figure, the minimum speeds for cars, small lorries, trucks, trailers, and busses were 55, 41, 44, 41, and 44 km/h, respectively. The maximum speeds for the same vehicles were 104, 78, 76, 81, and 90 km/h, respectively.

3. The service time is the distribution for each vehicle type needing to stop to make a payment in the toll lane of the toll plaza. For each toll plaza model in this study, there are twenty two service time distributions: eleven service time distributions for entry and eleven service time distributions for exit. Figure 5.5 shows sample of the service time distributions input for vehicle types at multiclass lane for entry at the Juru toll plaza model. For all service time distribution inputs of Juru and Jawi toll plaza models are showed in the Appendix C.

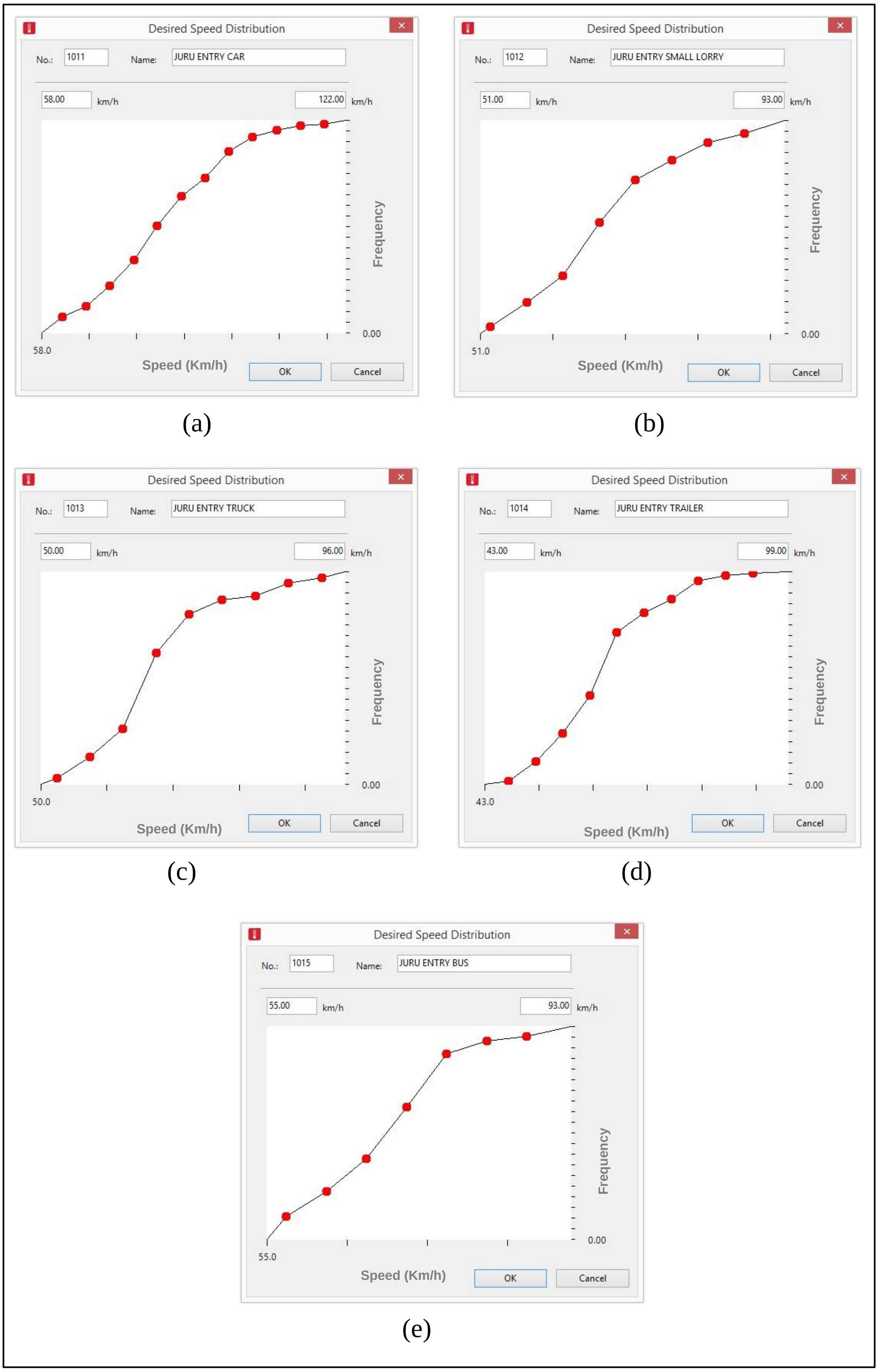


Figure 5.1 Desired speed distribution for vehicle types for Juru toll plaza model- Entry; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

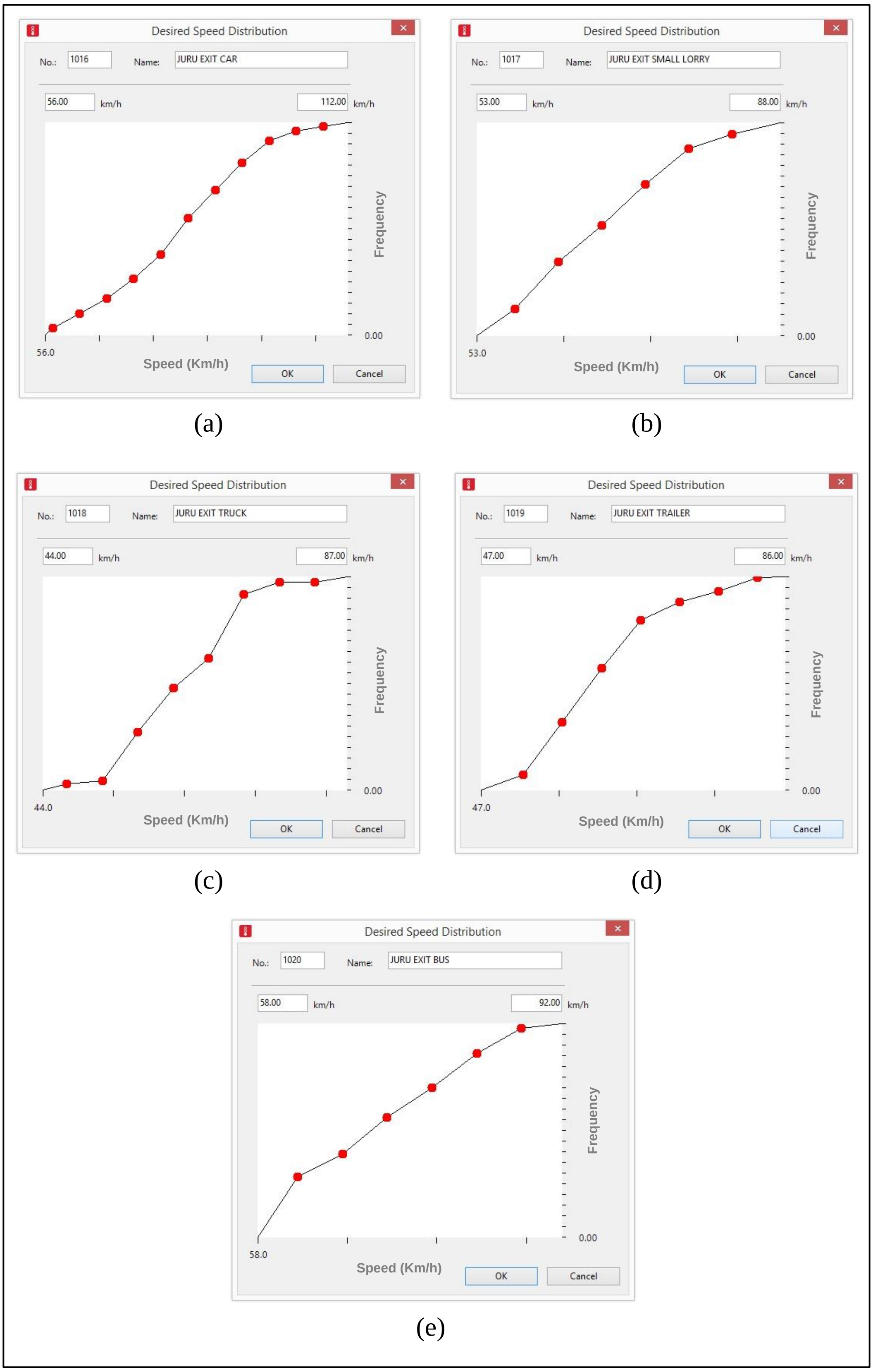


Figure 5.2 Desired speed distribution for vehicle types for Juru toll plaza model- Exit; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

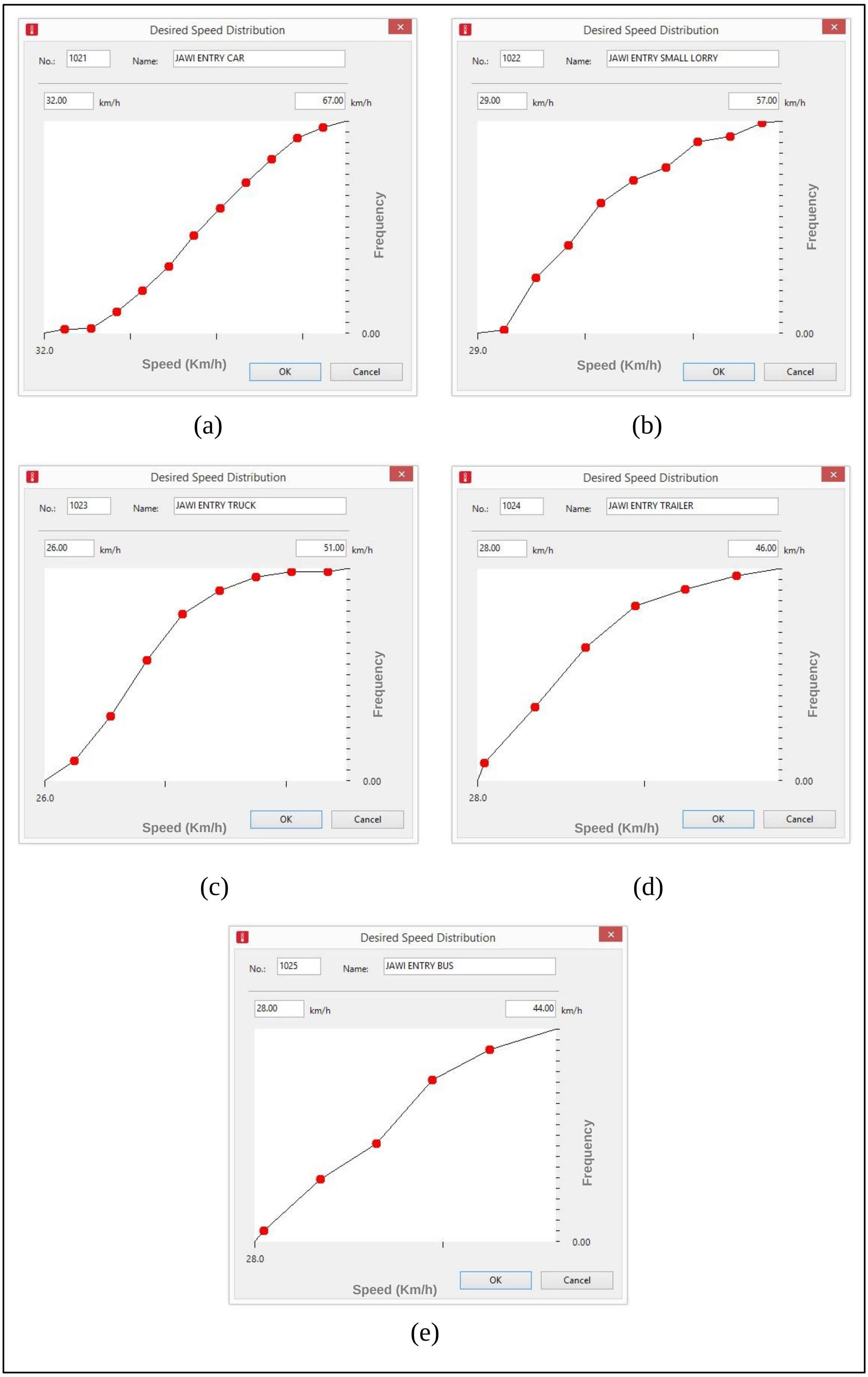


Figure 5.3 Desired speed distribution for vehicle types for Jawi toll plaza model- Entry; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

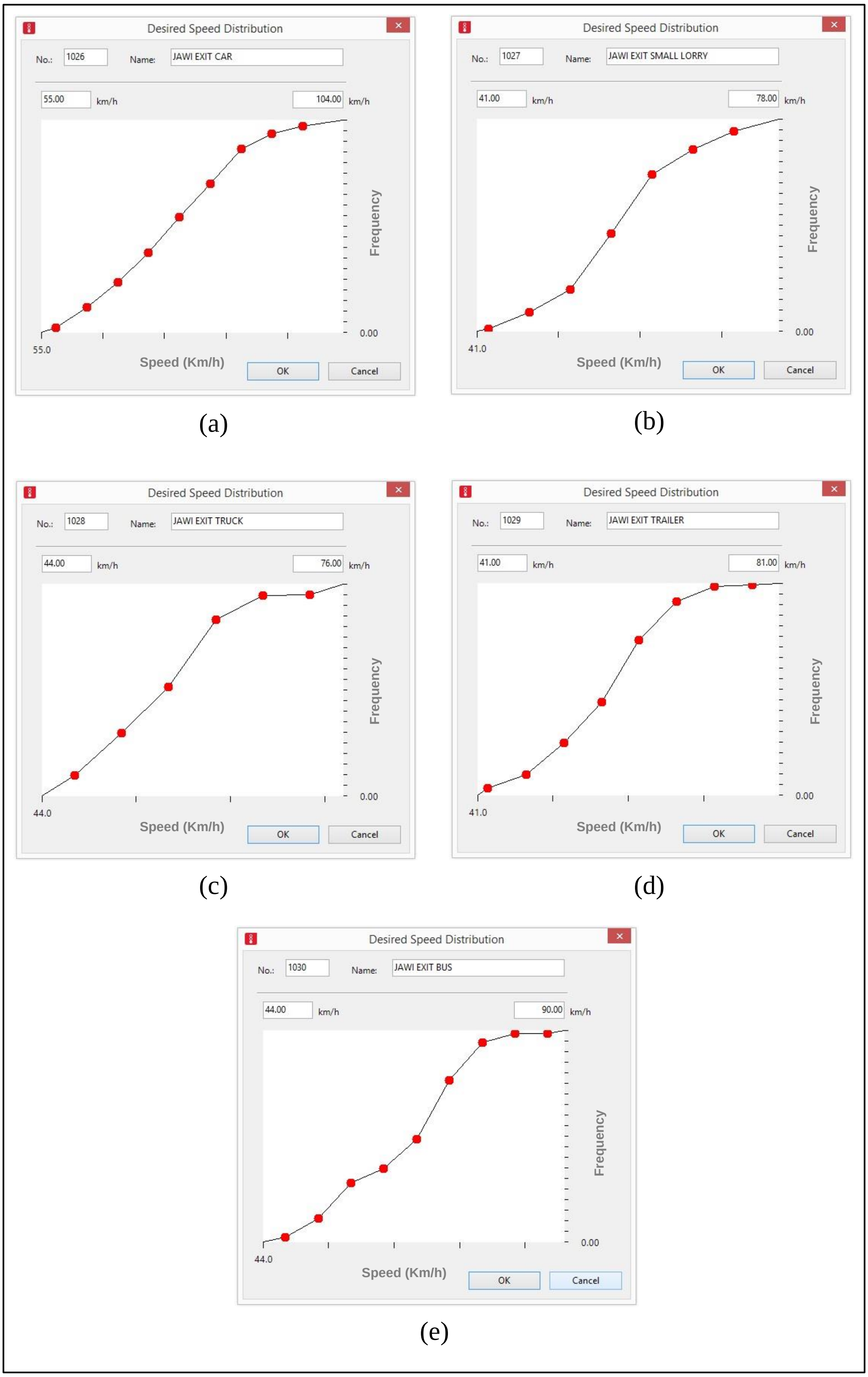


Figure 5.4 Desired speed distribution for vehicle types for Jawi toll plaza model- Exit; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

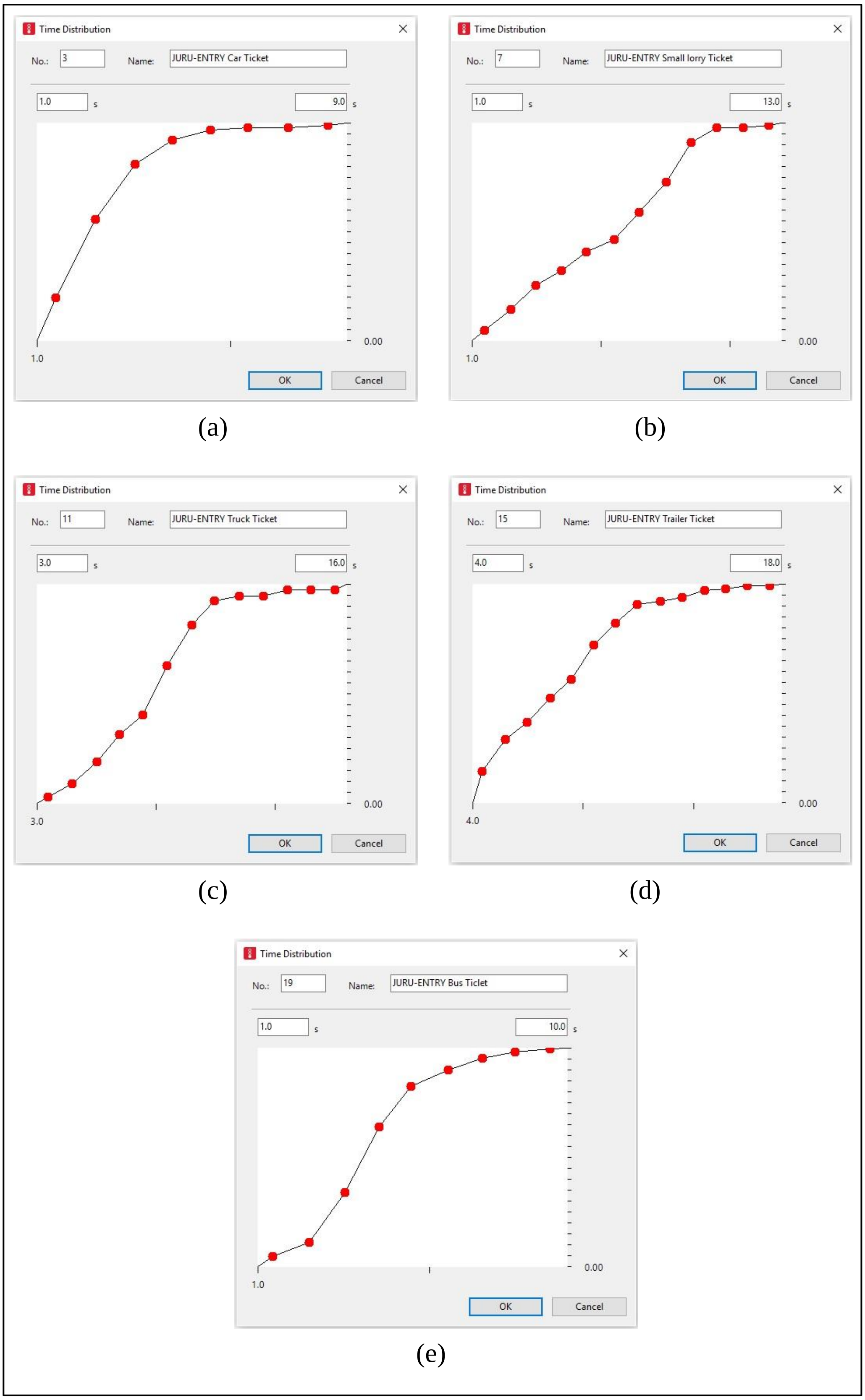


Figure 5.5 Service time distribution for vehicle types at multiclass lane – Juru toll plaza - Entry - Ticket; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

The service time and desired speed distribution parameters are very useful for a toll plaza operation because they represent the behavior of traffic situations. Therefore, these parameters are used in the toll plaza model calibration in the next step.

5.3 Calibration of Toll plaza models

All the model parameters must be modified from their default values to the observed values allowing the models to accurately reflect the performance of the toll operations under study after the base models of the Juru and Jawi toll plazas were created.

As mentioned in the previous chapter for the calibration steps, the throughput was selected as the MOE; the desired speed and the service time were the key parameters that are adjusted every 10 runs until the observed and the simulated values of the throughputs show no significant difference. To achieve that mission, the paired two samples t-test statistical analysis was used with the p-value to compare the observed throughput from the video recordings on March 2015 with the simulated values for the 10 runs.

Two hypothesis exist in the p-value approach. The first is the null hypothesis, which assumes that the observed and simulated throughput values are equal if the p-value is greater than 0.05. The second hypothesis is an alternative hypothesis, which assumes that the observed and simulated throughput values are not equal, when the p-value is less than 0.05, which means more adjustment is needed for the models until they are calibrated.

Table 5.1 shows the final throughputs results of the 10 runs for the models of the Juru and Jawi toll plazas. The calculated p-value of the throughput at the entry and exit were 0.070 and 0.585, respectively, for the Juru toll plaza model. For the Jawi toll plaza model, the calculated p-vale of the throughput at the entry and exit were 0.167 and 0.095, respectively. All the calculated p-values were within the significance level of 95%.

Figure 5.6 and 5.7 shows the calibrated model for the Juru and Jawi toll plazas, respectively.

Table 5.1 Statistical comparison for throughput of the calibrated Juru and Jawi models.

No. of runs	Juru toll plaza				Jawi toll plaza			
	Entry		Exit		Entry		Exit	
	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
1	3187	3165	3032	3021	783	786	591	579
2	3104	3023	2916	2931	662	647	870	858
3	2515	2583	2733	2711	734	743	944	929
4	2152	2114	2354	2357	559	563	1021	992
5	2224	2201	2561	2567	791	783	1282	1283
6	2281	2210	2662	2659	838	857	1275	1217
7	2236	2167	2533	2543	723	735	1349	1358
8	2301	2289	2514	2522	819	824	1525	1478
9	2372	2379	2826	2830	710	724	1462	1483
10	2190	2144	2498	2508	804	809	1474	1472
Calculated t-test value	2.0572		0.5659		1.5049		1.8624	
P-value	0.070		0.585		0.167		0.095	

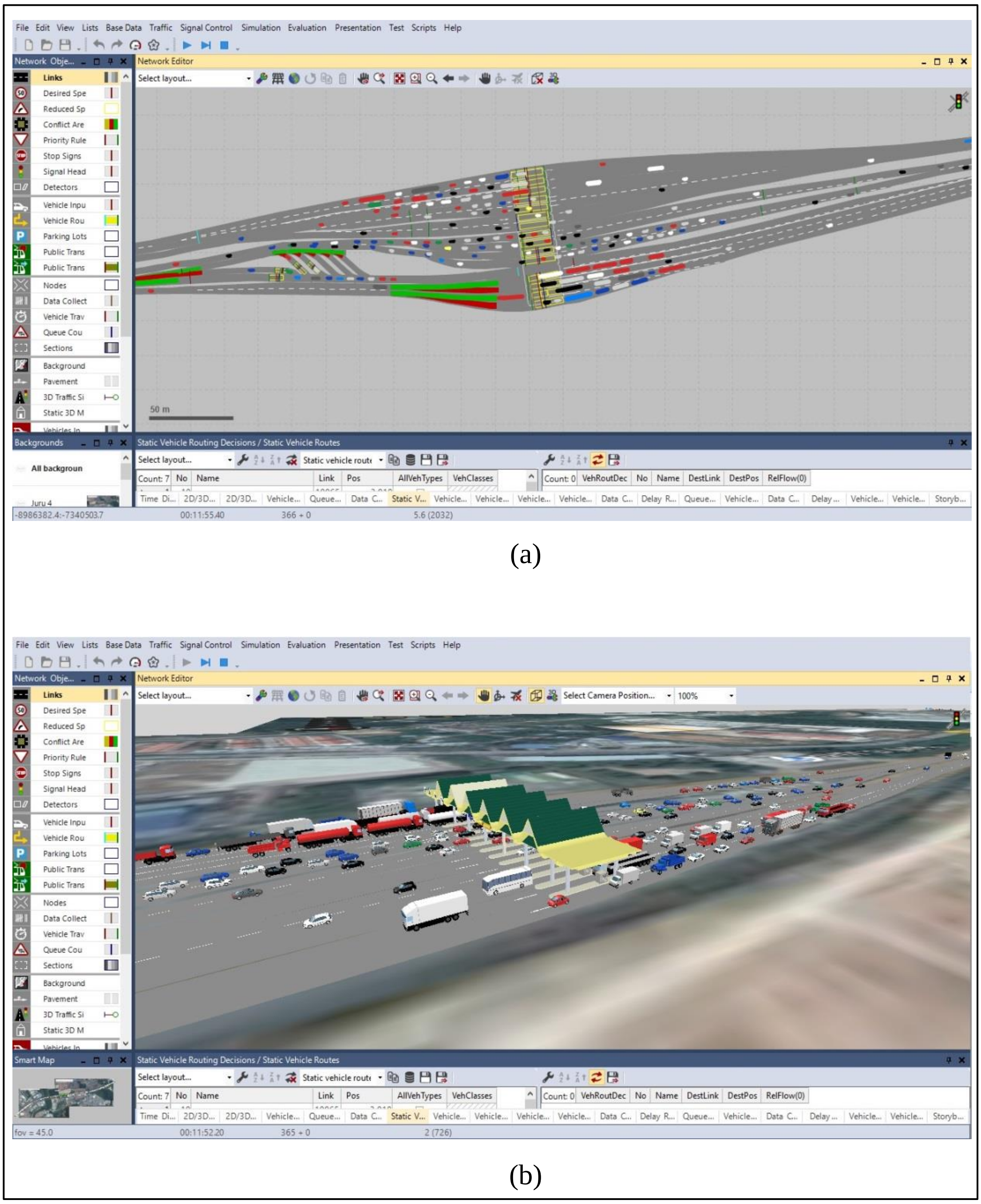
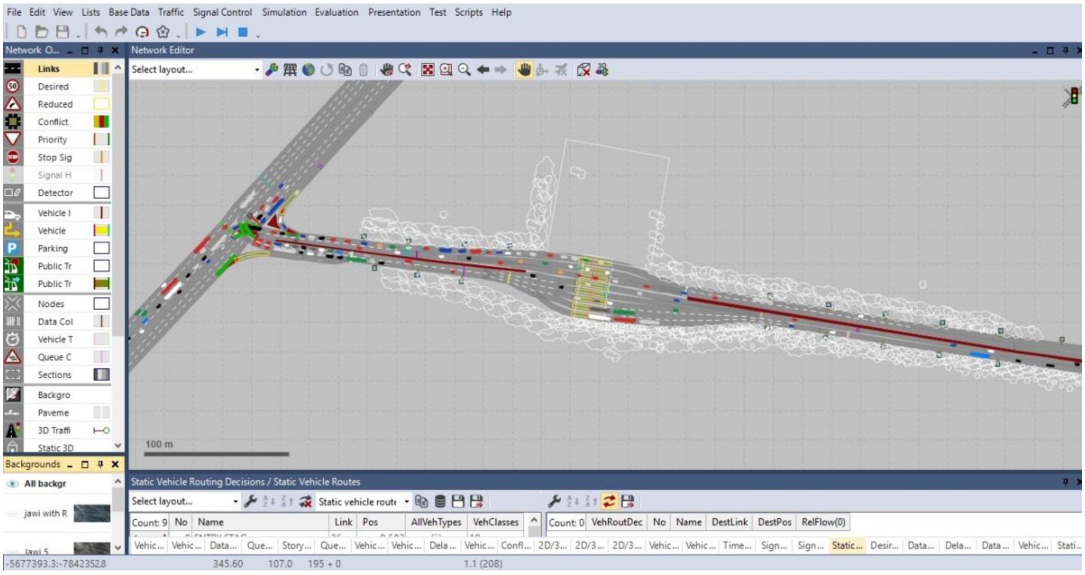
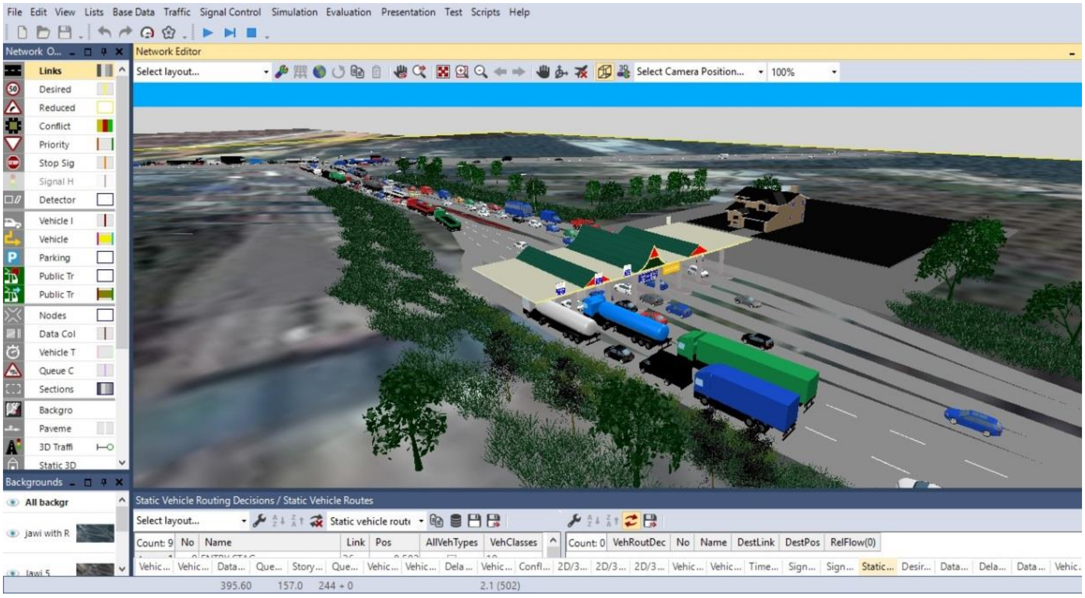


Figure 5.6 Calibrated model for Juru toll plaza; (a) 2D Model, (b) 3D Model.



(a)



(b)

Figure 5.7 Calibrated model for Jawi toll plaza; (a) 2D Model, (b) 3D Model.

5.4 Assessment the overall toll operations of toll plaza

The models accurately replicate and predict the real traffic operations at the toll plazas through the scenarios once the base models are calibrated.

The scenarios include simulating the current model under increased flows, such as increasing the percentage of heavy vehicles at the toll lanes to examine the effect of heavy vehicles on queue lengths at toll plaza; simulating the current traffic conditions to estimate the actual capacity of the toll plaza; and introducing a new traffic flow with full ETC toll conditions to examine the effectiveness of implementing the full ETC system at the toll plaza performance. These represented the thesis objectives that are achieved by the calibrated models of the toll plazas.

5.4.1 Effect of heavy vehicles on queue lengths at the toll plaza

New models are constructed and used as scenarios representing different traffic conditions at toll plazas to test the impact of the percentage of heavy vehicles on the queue lengths at the mixed mode toll lanes and to also test whether an influence exist on the heavy vehicle percentages on the queue lengths of other toll lane types.

For the Juru toll plaza, six scenarios were identified and simulated to study the traffic operations of the toll lanes:

1. Scenario 1: base scenario (normal traffic flow).
    - Entry: 2,501 vph with 6.8% heavy vehicles
    - Exit: 2,920 vph with 7.6% heavy vehicles
2. Scenario 2: same traffic volume as in scenario 1 but percentage of heavy vehicles increased to 10%, 12%, 14%, 16%, and 18%.

Results obtained in Scenarios 1 and 2 were used to investigate the impact of heavy vehicles on the operation of the toll plaza in terms of queue and maximum queue lengths.

Figure 5.8 shows the impact of heavy vehicles on queue and maximum queue lengths. Queue length is measured at the end of the 1 hour simulation period, while maximum queue length is the highest queue length recorded during the simulation period. Based on the graphs plotted in Figure 5.8, for entry, the results indicated that queue length gradually increased with the increment of heavy vehicles percentage until the percentage of heavy vehicles is 16% upon which the queue length then rapidly increased from 98.6 m to 258.2m for 16% and 18% of heavy vehicles, respectively.

However, for exit, the opposite situation was observed in which the queue length rapidly increased from 71.8 m to 227.7 with 7.6% and 12% of heavy vehicles, respectively, and then gradually increase to 287.4 m for 18% of heavy vehicles. As for the graph plotted for maximum queue length, a similar trend was observed for both entry and exit but with more drastic changes for exit and less drastic changes for entry.

For the influence of the heavy vehicle percentages on the queue lengths of other toll lane types, Figure 5.9 shows the queue lengths of mixed mode, Touch 'n Go, and Smart TAG lanes at the entry and exit. On the other hand, Figure 5.10 shows the maximum queue lengths of mixed mode, Touch 'n Go, and Smart TAG at the entry and exit.

Based on the graphs plotted in Figure 5.9 and 5.10, no significant influence exists on the percentages of heavy vehicles on other toll lane types for both entry and exit.

Figure 5.11 shows the screen capture of the 2D and 3D of the Juru toll plaza simulation model (for scenario with 18% of heavy vehicles).

The results of Scenarios 1 and 2 proved the percentage impacts of heavy vehicle on the toll plaza operation of the mixed mode toll lanes represented by the increase in queue lengths according to the percentage increments of the heavy vehicles. The significant impact of the heavy vehicle percentages starts from 16% and 7.6% for entry and exit, respectively. On the other hand, the results showed that the percentage of heavy vehicles had no influence on ETC lanes for both entry and exit.

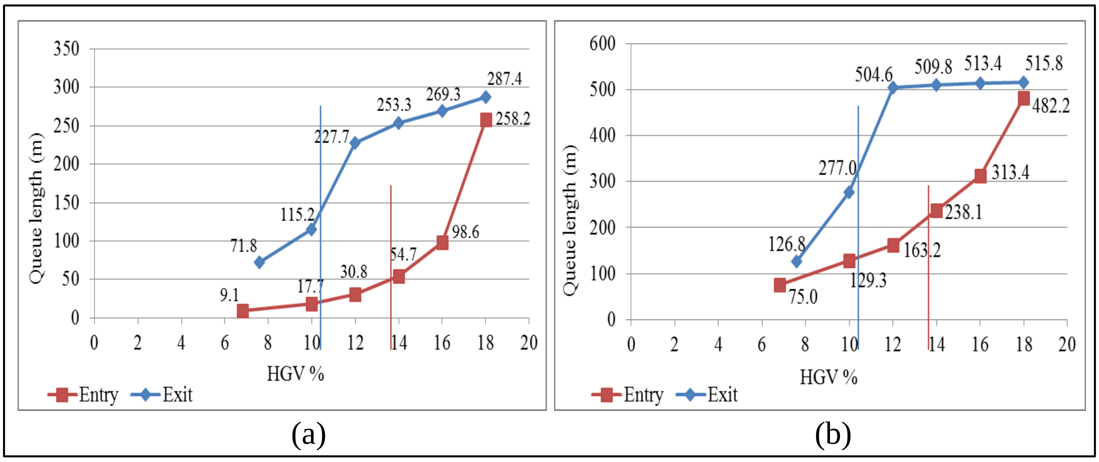


Figure 5.8 Impact of heavy vehicle at Juru toll plaza on: (a) queue length, (b) maximum queue length

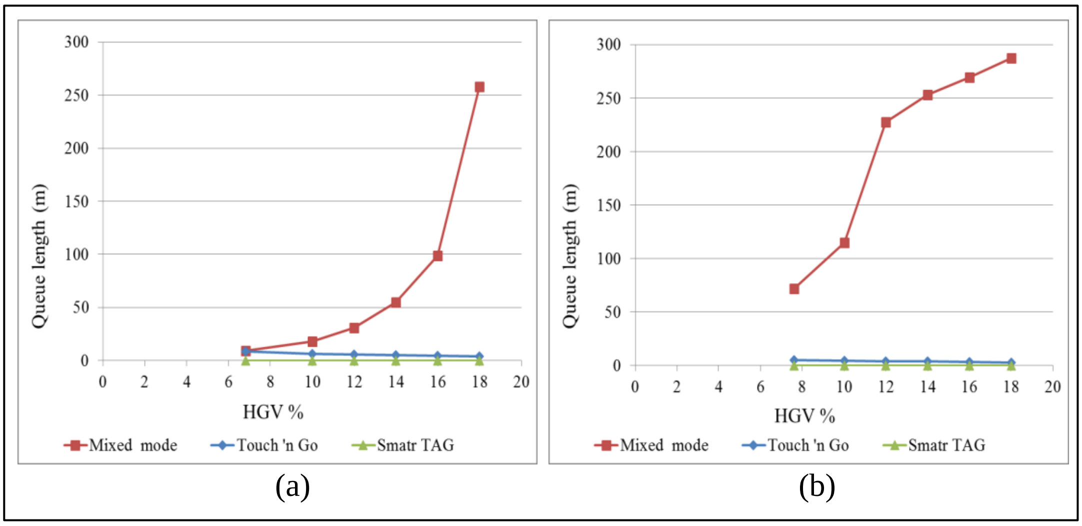


Figure 5.9 Queue length results of Juru toll plaza model at: (a) entry, (b) exit.

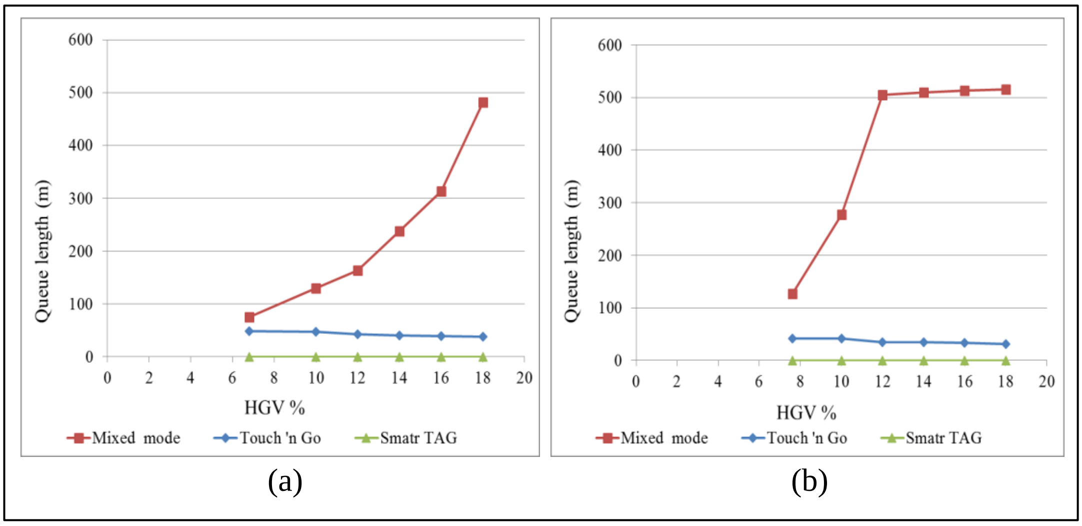
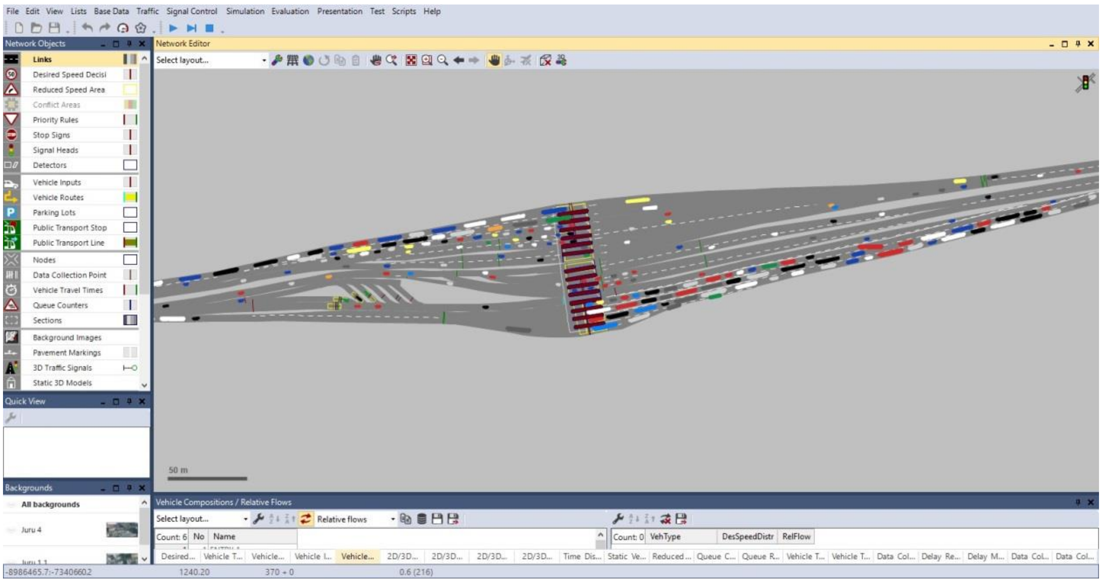


Figure 5.10 Maximum queue length results of Juru toll plaza model at: (a) entry, (b) exit.



2D View

3D View

Figure 5.11 Screen capture of the 2D and 3D of Juru toll plaza simulation model.

The traffic operations of the Jawi toll plaza behaves differently than the Juru toll plaza. The Jawi toll plaza is a ramp toll plaza that is usually located in the urban areas and close to the signalized intersection. This type of toll plaza influenced the queue lengths at the signalized intersection and also the location of the intersection affecting the toll plaza operation. The mutual influence between the toll plaza and the signalized intersection are explained by six scenarios identified and simulated to test the impact of percentages of heavy vehicles on the queue lengths at the Jawi toll lanes and around the traffic light intersection. The six scenarios also test whether an influence exist on the heavy vehicle percentages on the queue lengths of other toll lane types. The six scenarios are as follows:

1. Scenario 1: base scenario (normal traffic flow).
    - Entry: 790 vph with 8.3% heavy vehicles.
    - Exit: 1,282 vph with 7.1% heavy vehicles.
2. Scenario 2: the same traffic volume as in scenario 1 but percentage of heavy vehicles increased to 10%, 12%, 14%, 16%, and 18%.

The queue and maximum queue lengths are calculated at the toll plaza for entry and exit as well as for the signalized intersection. Figure 5.12 shows the positions of the queuing at the intersection and at the Jawi toll plaza for the six model scenarios.

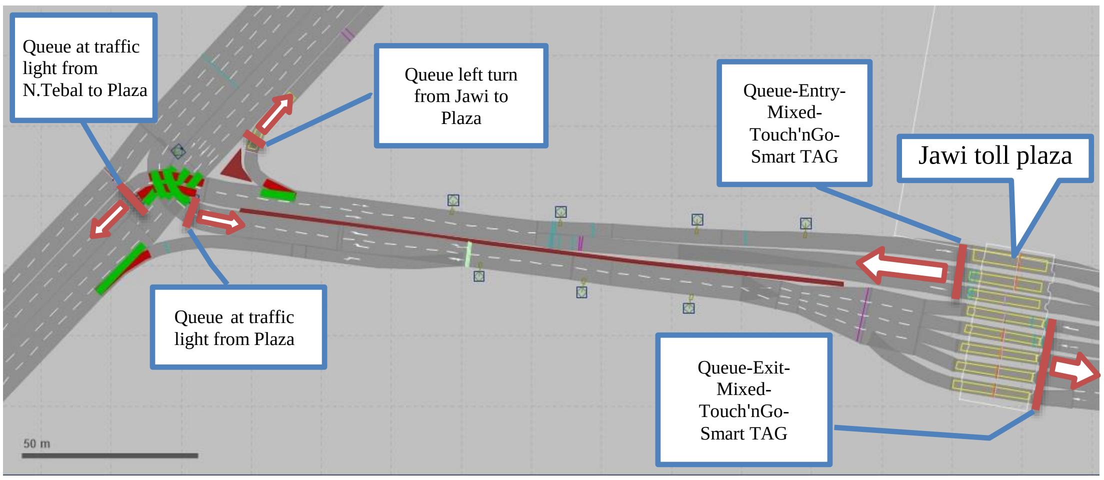


Figure 5.12 Queue positions at the traffic light intersection and Jawi toll plaza.

Figure 5.13 shows the impact of heavy vehicle on the queue length at the Jawi toll plaza and at the signalized intersection. For entry, the results indicated that queue length gradually increased with the increment of the percentage of heavy vehicles for the mixed mode and did not show a rapid increase from 181.7 m to 219.1 m for 8.3% and 18% of heavy vehicles, respectively, due to cycle time of the traffic light. For the queue length at the traffic light from Nibong Tebal to the toll plaza, the graph shows a significant continuing increase with the increment of the percentage of heavy vehicles from 129.3 m to 350.1 m for 8.3% and 18% of heavy vehicles, respectively. For the queue length at the left turn from Jawi to the toll plaza, the graph shows a slight increase in the queue length from 7.9 m and 18.2 m for 8.3% and 18% of heavy vehicles, respectively. For Touch 'n Go and Smart TAG queue lengths, the results did not show any changes in their queue lengths with the increments of the percentage of heavy vehicles.

For exit, the mixed mode queue length gradually increased with the increment of the percentage of heavy vehicles from 12.6 m to 31.7 m for 7.1% and 18% of heavy vehicles, respectively. The queue length at the traffic light from plaza toll gradually increased with the increment of the percentage of heavy vehicles until the percentage of heavy vehicles is 16%, upon which the queue length then increases rapidly from 68.6 m to 126.5 m for 16% and 18% of heavy vehicles. However, the queue length for Touch 'n Go and Smart TAG did not change with the increment of the percentage of heavy vehicles until the percentage of heavy vehicles is 16%, upon which the queue lengths for Touch 'n Go and Smart TAG increased from 10.8 m and 0.0 m for 16% of heavy vehicles to 13.2 m and 6.2 m for 18% of heavy vehicles, respectively.

Figure 5.14 shows the impact of the percentage of heavy vehicle on the maximum queue length at the Jawi toll plaza and at the signalized intersection. For entry, the maximum queue lengths of Smart TAG, Touch 'n Go, and at the left turn from Jawi to the toll plaza shows a similar trend as plotted for the queue lengths in Figure 5.13. The maximum queue length at the traffic light from Nibong Tebal to the toll plaza rapidly increased with the increment of the percentage of heavy vehicles until the percentage of heavy vehicles is more than 14%, upon which the maximum queue length then increases gently. For mixed mode, the maximum queue length almost reaches the maximum distance between the traffic light intersection and the Jawi toll plaza, which is 245 m with all percentages of the heavy vehicles.

A similar trend was plotted for the mixed mode maximum queue length but with more drastic changes for exit. However, the maximum queue length at the traffic light from the toll plaza shows a significant impact on the maximum queue lengths for both Smart TAG and Touch 'n Go when the percentage of heavy vehicles exceeds 12% and becomes a drastic influence at the percentage of heavy vehicles of 16%. This is due to queuing oversaturation of heavy vehicles during the red phase reaching the plaza toll area and thus causing breakdown of the flow of the toll lanes.

Figure 5.15 shows the 2D and 3D screen capture of the Jawi toll plaza simulation model (for scenario with 18% of heavy vehicles).

Finally, the results indicated that the percentage of the heavy vehicles in the traffic flow has a significant impact on the queue lengths at the Juru and Jawi toll plazas.

However, the percentage of the heavy vehicles does not have an influence on the queue lengths of ETC lanes such as Touch 'n Go and Smart TAG at the mainline toll plaza like Juru. However, in the ramp toll plaza such as the Jawi toll, the percentage of heavy vehicles influences the ETC lanes just for the exit direction.

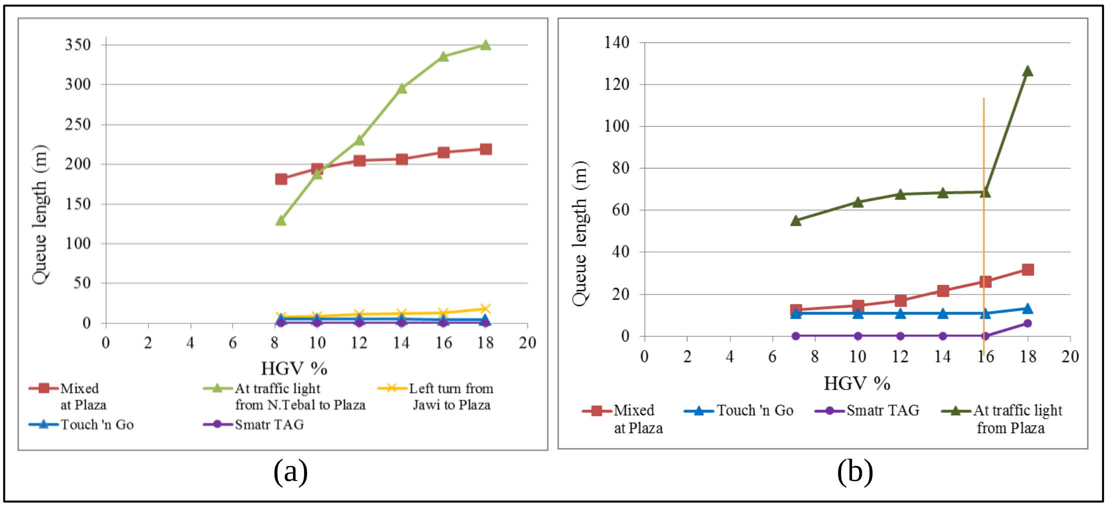


Figure 5.13 Impact of heavy vehicle on the queue length at Jawi toll plaza and at the signalized intersection: (a) entry, (b) exit.

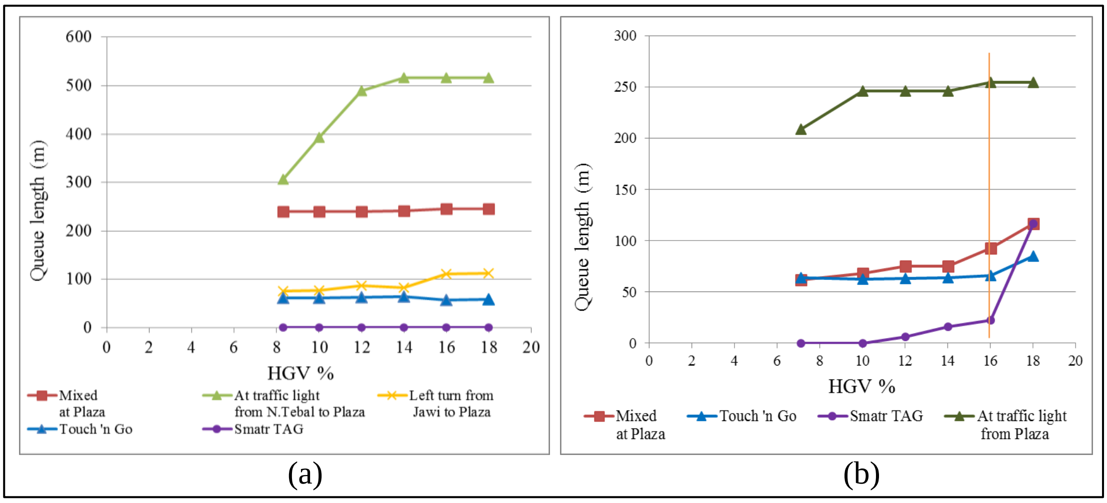


Figure 5.14 Impact of heavy vehicle on the maximum queue length at Jawi toll plaza and at the signalized intersection: (a) entry, (b) exit.

Figure 5.15 Screen capture of the 2D and 3D of Jawi toll plaza simulation model.

5.4.2 Estimation on the actual capacity of the toll plaza.

The inter-vehicle time value for each vehicle type with different payment type needs to be determined to calculate the actual capacity of the toll plaza. This is achieved by means of the VISSIM simulation model.

In this objective, the calibrated model of the Juru toll plaza was used to create several scenarios. These scenarios were used to replicate the continued queue conditions with high traffic volume to obtain the maximum throughput for each toll lane. Inter-vehicle time is the time difference between two consecutive vehicles as they stop to pay the toll at the toll lane; it is the sum of the service time and headway. Therefore, inter-vehicle times are used to calculate the capacity of each lane type. The service time is assumed to be zero and the inter-vehicle time, therefore, is equal to the vehicle headway for the Smart TAG lane.

In order to determine the inter-vehicle time for a particular vehicle type, one scenario with only one type of vehicle must be created and simulated. Therefore, as there are twenty-two vehicle types created in the study, twenty-two scenarios must be constructed to get the inter-vehicle time for the twenty-two vehicle types.

The results of throughput form the scenarios for each vehicle type are used to calculate the value of inter-vehicle time as follows:

$$\text{Inter-vehicle time for vehicle}_{(x,\,y)} = \frac{3600}{\text{Throughput for vehicle}_{(x,\,y)}} \quad (5\text{-}1)$$

$$\text{Capacity of toll lane with vehicle}_{(x,\,y)} = \frac{3600}{\text{Inter-vehicle time for vehicle}_{(x,\,y)}} \quad (5\text{-}2)$$

where;

x = vehicle type and y = payment mode.

Table 5.2 and Table 5.3 show the toll lane capacity for the entry and exit for each vehicle type, respectively.

Table 5.2 Toll lane capacity for entry according to vehicle type and its payment mode.

Lane type	Vehicle type (X)	Payment mode (Y)	Inter-vehicle time Ti (s)	Capacity for vehicle $_{(x, y)}$ (vph)
Mixed mode lanes	Car	Ticket	7.12	506
		Touch 'n Go	8.59	419
	Small lorry	Ticket	13.84	260
		Touch 'n Go	12.37	291
	Truck	Ticket	17.34	208
		Touch 'n Go	15.11	238
	Trailer	Ticket	19.16	188
		Touch 'n Go	16.41	219
	Bus	Ticket	15.3	235
		Touch 'n Go	15.89	227
ETC lanes	Touch 'n Go		7.25	497
	Smart TAG		3.58	1005

Table 5.3 Toll lane capacity for exit according to vehicle type and its payment mode.

Lane type	Vehicle type (X)	Payment mode (Y)	Inter-vehicle time Ti (s)	Capacity for vehicle $_{(x, y)}$ (vph)
Mixed mode lane	Car	Cash	23.24	155
	Car	Touch 'n Go	11.69	308
	Small lorry	Cash	30.5	118
	Small lorry	Touch 'n Go	20.26	178
	Truck	Cash	34.88	103
	Truck	Touch 'n Go	24.22	149
	Trailer	Cash	35.6	101
	Trailer	Touch 'n Go	26.03	138
	Bus	Cash	27.86	129
	Bus	Touch 'n Go	19.17	188
ETC lanes	Touch 'n Go		7.82	460
	Smart TAG		4.49	802

At the mixed mode lanes, for entry, as shown in Figure 5.16, the lane capacity of vehicles using the Touch 'n Go is higher than the capacity of the same lane with vehicles using the ticket for all vehicle types except for cars and busses. The service time for taking a ticket is less than using the Touch 'n Go for cars and busses. For exit, Figure 5.17 shows that the lane capacity of vehicles using the Touch 'n Go is much higher than the capacity of the same lane with vehicles using cash payment for all vehicle types because of the long service time for cash payment.

Figure 5.18 shows a comparison between the entry and exit for the lane capacity of vehicles using the Touch 'n Go in the mixed mode lanes and for the lane capacity of vehicles using the Touch 'n Go and Smart TAG in the ETC lanes. At the mixed mode lane, the lane capacity of vehicles using the Touch 'n Go at entry is higher than the lane capacity of vehicles using the Touch 'n Go at exit due to higher service time at exit caused by receipt collection.

At the ETC lane, the lane capacity of the Touch 'n Go at entry is higher than the lane capacity of the Touch 'n Go at exit because the drivers at the exit spend more time during the transaction to check the toll fee and the remaining balance in his or her card.

Comparing the capacity values calculated for Smart TAG lanes for entry and exit for the lane capacity of Smart TAG, a lower capacity value was obtained for exit at the Juru toll plaza. The lower capacity value is due to merging effect of the Smart TAG lanes in which the two toll lanes merge to become one lane upon leaving the toll plaza. This value is only applicable for this toll plaza and any toll plaza which has the same toll lane configuration. For other types of configuration that does not have a merging problem, the estimated capacity for Smart TAG lane for entry is used for exit as well.

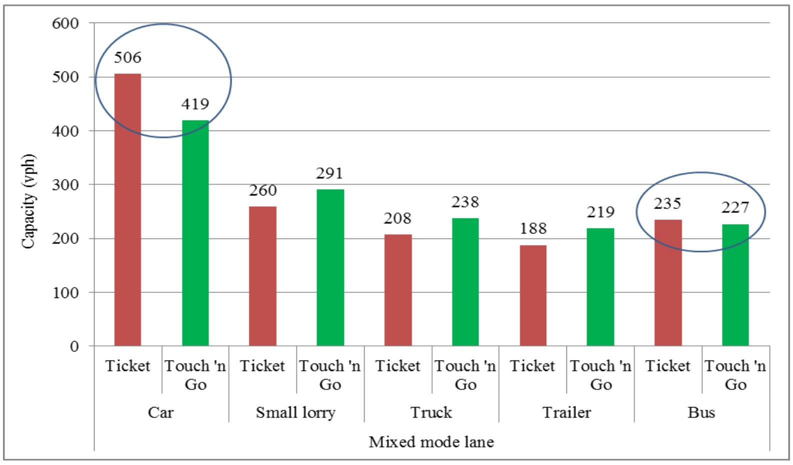


Figure 5.16 Mixed mode toll lane capacity for entry according to vehicle type and its mode of payment.

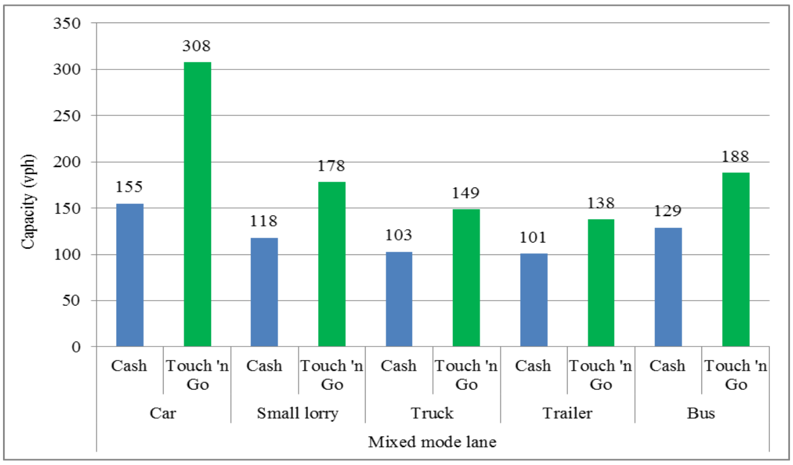


Figure 5.17 Mixed mode toll lane capacity for exit according to vehicle type and its mode of payment.

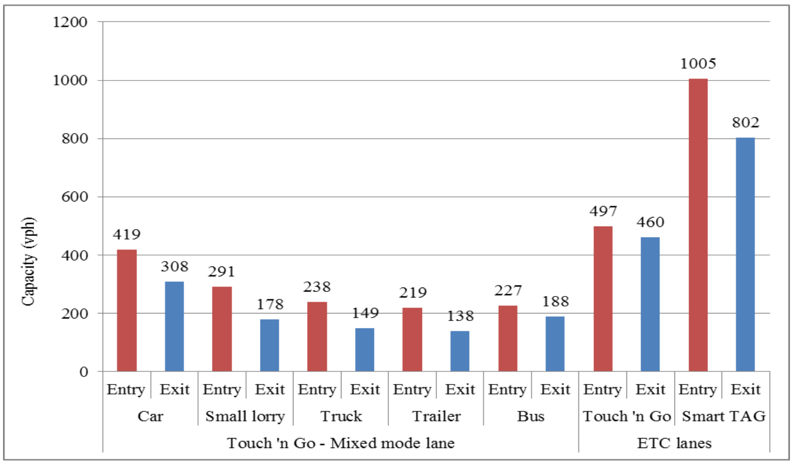


Figure 5.18 Toll lane capacity comparison between entry and exit- Touch 'n Go in Mixed mode lane- Smart TAG and Touch 'n Go in ETC lane.

Finally, the form of the equation for the calculated actual capacities for closed - system toll plaza are shown in following equations for entry and exit, according to Table 5.2 and Table 5.3.

$$\text{Capacity of toll plaza } (C_{Plaza}) = [\text{capacities of Mixed mode lanes} + \text{capacities of Touch 'n Go lanes} + \text{capacities of Smart TAG lanes}] \quad (5\text{-}3)$$

$$C_{Plaza} \text{ for entry} = [(N_{Mix\text{-}Entry} \times C_{Mix\text{-}Entry}) + (N_{TNG\text{-}Entry} \times C_{TNG\text{-}Entry}) + (N_{STAG\text{-}Entry} \times C_{STAG\text{-}Entry})] \quad (5\text{-}4)$$

$$C_{Plaza} \text{ for exit} = [(N_{Mix\text{-}Exit} \times C_{Mix\text{-}Exit}) + (N_{TNG\text{-}Exit} \times C_{TNG\text{-}Exit}) + (N_{STAG\text{-}Exit} \times C_{STAG\text{-}Exit})] \quad (5\text{-}5)$$

$$C_{Mix\text{-}Entry} = 3600 / [(P_{car,ticket} \times 7.12) + (P_{car,TNG} \times 8.59) + (P_{s.lorry,ticket} \times 13.84) + (P_{s.lorry,TNG} \times 12.37) + (P_{truck,ticket} \times 17.34) + (P_{truck,TNG} \times 15.11) + (P_{trailer,ticket} \times 19.16) + (P_{trailer,TNG} \times 16.41) + (P_{bus,ticket} \times 15.30) + (P_{bus,TNG} \times 15.89)] \quad (5\text{-}6)$$

$$C_{Mix\text{-}Exit} = 3600 / [(P_{car,cash} \times 23.24) + (P_{car,TNG} \times 11.69) + (P_{s.lorry,cash} \times 30.50) + (P_{s.lorry,TNG} \times 20.26) + (P_{truck,cash} \times 34.88) + (P_{truck,TNG} \times 24.22) + (P_{trailer,cash} \times 35.60) + (P_{trailer,TNG} \times 26.03) + (P_{bus,cash} \times 27.86) + (P_{bus,TNG} \times 19.17)] \quad (5\text{-}7)$$

Where;

C_{Plaza} = Toll plaza total capacity.

$P_{x,y}$ = Proportion of vehicle type (x) with payment mode (y).

$N_{Mix\text{-}Entry}$ = Number of Mixed mode toll lane for entry.

$N_{Mix\text{-}Exit}$ = Number of Mixed mode toll lane for exit.

$N_{TNG\text{-}Entry}$ = Number of Touch 'n Go toll lane for entry.

$N_{TNG\text{-}Exit}$ = Number of Touch 'n Go toll lane for exit.

$N_{STAG\text{-}Entry}$ = Number of Smart TAG toll lane for entry.

$N_{STAG\text{-}Exit}$ = Number of Smart TAG toll lane for exit.

$C_{Mix\text{-}Entry}$ = Capacity of Mixed mode toll lane for entry.

$C_{Mix\text{-}Exit}$ = Capacity of Mixed mode toll lane for exit.

$C_{TNG\text{-}Entry}$ = Capacity of Touch 'n Go toll lane for entry.

$C_{TNG\text{-}Exit}$ = Capacity of Touch 'n Go toll lane for exit.

$C_{STAG\text{-}Entry}$ = Capacity of Smart TAG toll lane for entry.

$C_{STAG\text{-}Exit}$ = Capacity of Smart TAG toll lane for exit.

5.4.2(a) **Verification of the toll plaza capacity**

Model verification is the process of reviewing the implementation of the simulation model and making sure that it is functioning as expected. The quality of simulation models plays a very important role to apply them to actual data. To verify the toll plaza models which have been developed for the actual capacity in this study, several comparison were conducted between the collected data and the simulated data for the throughput. The data collection were extracted from the video recordings on September 2015 for Juru toll plaza. The verification for the actual capacity was performed for mixed mode, Touch 'n Go and Smart TAG lanes, then for the whole toll plaza.

i. Mixed mode toll lane capacity verification:

To insure that the selected peak hour for observing the real capacity has the optimal condition of maximum throughput, the selected peak hour is under the saturation flow rate and there is no unreasonable delay of drivers, vehicles, toll operators, and accidents.

Therefore, the observed value of the real capacity was extracted from videos recorded at the Juru toll plaza on Wednesday (23 September 2015 from 12:00 to 1:00 PM) at lane M02 for entry and on Saturday (19 September 2015 from 12:20 to 1:20 PM) at lane K13 for exit.

The results are shown in Table 5.4 and Table 5.5 for entry and exit, respectively. The calculated level of confidence, which is more than 95% for both entry and exit, indicated that the actual capacity values estimated from the developed equations fit well with the observed values.

Table 5.4 Verification of estimated capacity for mixed mode lane - Entry

Vehicle type (X)	Payment mode (Y)	Traffic volume composition by vehicle type and payment type (vph)	Proportion $P_{(x, y)}$	Inter-vehicle time Ti (s)	Ti x $P_{(x, y)}$
Car	Ticket	198	0.54	7.12	3.84
	Touch 'n Go	21	0.06	8.59	0.52
Small lorry	Ticket	38	0.10	13.84	1.38
	Touch 'n Go	35	0.10	12.37	1.24
Truck	Ticket	4	0.01	17.34	0.17
	Touch 'n Go	16	0.04	15.11	0.60
Trailer	Ticket	13	0.04	19.16	0.77
	Touch 'n Go	14	0.04	16.41	0.66
Bus	Ticket	9	0.02	15.3	0.31
	Touch 'n Go	17	0.05	15.89	0.79
Observed capacity		365			
Total			1.00		10.28
* Calculated capacity					350
Difference = Total - Capacity			15		
Level of confidence			95.92%		

* Calculated capacity = 3600/10.28 = 350

Table 5.5 Verification of estimated capacity for mixed mode lane – Exit.

Vehicle type (X)	Payment mode (Y)	Traffic volume composition by vehicle type and payment type (vph)	Proportion $P_{(x,y)}$	Inter-vehicle time Ti (s)	Ti x $P_{(x,y)}$
Car	Cash	94	0.59	23.24	13.83
	Touch 'n Go	26	0.16	11.69	1.92
Small lorry	Cash	11	0.07	30.5	2.12
	Touch 'n Go	13	0.08	20.26	1.67
Truck	Cash	2	0.01	34.88	0.44
	Touch 'n Go	3	0.02	24.22	0.46
Trailer	Cash	3	0.02	35.6	0.68
	Touch 'n Go	0	0.00	26.03	0.00
Bus	Cash	0	0.00	27.86	0.00
	Touch 'n Go	6	0.04	19.17	0.73
Observed capacity		158			
Total			1.00		21.85
* Calculated capacity					165
Difference = Total - Capacity			-7		
Level of confidence			95.70%		

* Calculated capacity = 3600/21.85 = 156

Where; $P_{(x,y)}$ = Proportion of vehicle type (x) with payment mode (y).

ii. Touch 'n Go toll lane capacity verification:

The maximum throughput was extracted for the Touch 'n Go lane from videos recorded with the same conditions as observed in the maximum throughput for the mixed mode lane. However, for this case, the full peak hour with the optimum condition was not obtained. The value of the real capacity of the Touch 'n Go lane was observed from half hour, which matches the optimum condition and was extracted from videos recorded at the Juru toll plaza on Wednesday (23 September 2015 from 11:55 AM to 12:25 PM) at lane M05 for entry and on Wednesday (23 September 2015 from 10:35 AM to 11:05 AM) at lane K11 for exit.

The extracted lane capacity of the Touch 'n Go lane was multiplied by two to get the throughput for one hour which equals to 516 vph for entry; the calculated level of confidence was 96.32%. For exit, same procedure was used to extracted lane capacity of the Touch 'n Go lane for one hour which equals to 442 vph for entry; the calculated level of confidence was 95.63%.

iii. Smart TAG toll lane capacity verification:

According to observations from videos recorded, the optimum condition for the maximum throughput of Smart TAG toll lanes was not obtained even when the toll lane is queuing. The stopping of vehicles, most of the time, at the Smart TAG lane is because of the detection failure of the Smart TAG device and sometimes due to insufficient balance in the card. Nevertheless, based on the observation from recorded videos on 23 September 2015, it is concluded that the average time taken for a stopped vehicle to resolve the problem at a Smart TAG lane is 40 s. This was the average of 90 stopped vehicles at the toll lane with an estimated headway of 3.58 s. The capacity of Smart TAG lane is calculated using Equation (5-8).

$$\text{Smart TAG lane capacity } (C_{STAG}) = \frac{3600 - (40 \times N)}{3.58} \tag{5-8}$$

where

N = Number of stopped vehicles.

Figure 5.19 shows the effect of stopped vehicles on the capacity of a Smart TAG lane. Based on the observation from recorded videos, 22 vehicles is the maximum number of stopped vehicles at a Smart TAG lane; this happened mostly during the peak hours.

Figure 5.19 shows that if 20 vehicles stopped during any hour, the capacity of the Smart TAG lane drop from 1,004 vph to only 778 vph based on the value plotted in the graph.

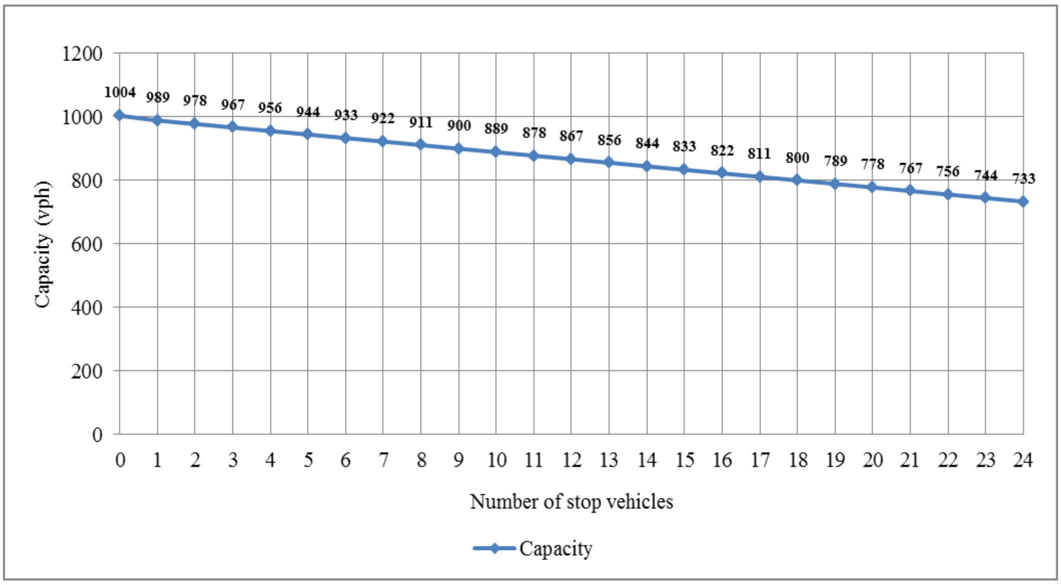


Figure 5.19 Effect of stopped vehicles on capacity for Smart TAG lane.

iv. Toll plaza capacity verification:

Once the lane capacity of each payment type of the toll plaza was verified, the next step was to verify the whole toll plaza model to ensure that the created equations from the calibrated toll plaza model, are accurately represent the actual capacity for the toll plaza.

Therefore, the toll plaza model was run for several rimes. Each time represents one hour from the video recordings, which extracted from September 2015. Table 5.6 shows the verification of the observed and simulated throughput for entry and exit at Juru toll plaza. Figure 5.20 and Figure 5.21 show the results of the regression analysis (R^2) between the observed and simulated throughput for the toll plaza model at entry and exit, respectively. The R^2 values for the entry and exit throughput were 0.967 and 0.972, respectively. That means the results from the toll plaza model were accurately represent the observed actual capacity in the real with a level of confidence about 96.7% and 97.2% for entry and exit respectively.

Table 5.6 Verification of observed and simulated throughput for Juru toll plaza at entry and exit.

		Entry			Exit		
Day	Date	Time	Observed	Simulated	Time	Observed	Simulated
Saturday	19/09/2015	10:00-11:00 AM	2339	2413	9:00-10:00 AM	1870	1786
Saturday	19/09/2016	5:00-6:00 PM	2634	2584	5:00-6:00 PM	2991	2874
Wednesday	23/09/2015	10:00-11:00 AM	2463	2481	9:00-10:00 AM	2090	1984
Wednesday	23/09/2016	5:00-6:00 PM	2574	2503	5:00-6:00 PM	2821	2963
Sunday	27/09/2015	10:00-11:00 AM	2478	2397	9:00-10:00 AM	2113	2152
Sunday	27/09/2016	5:00-6:00 PM	2675	2688	5:00-6:00 PM	3254	3159
Monday	28/09/2015	10:00-11:00 AM	1778	1741	9:00-10:00 AM	1830	1852
Monday	28/09/2016	5:00-6:00 PM	2158	2179	5:00-6:00 PM	1949	1984

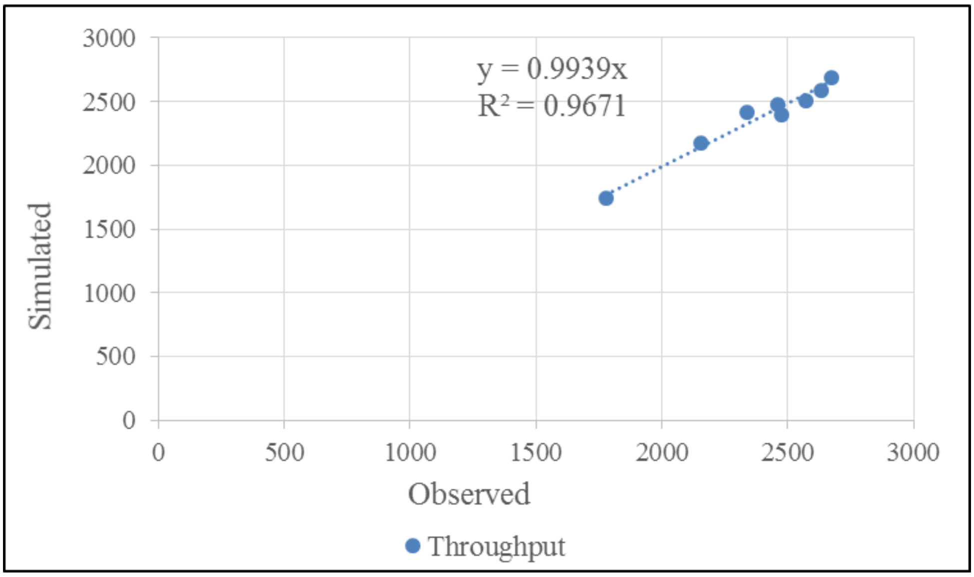


Figure 5.20 Regression analysis between observed and simulated throughput at entry Juru toll plaza.

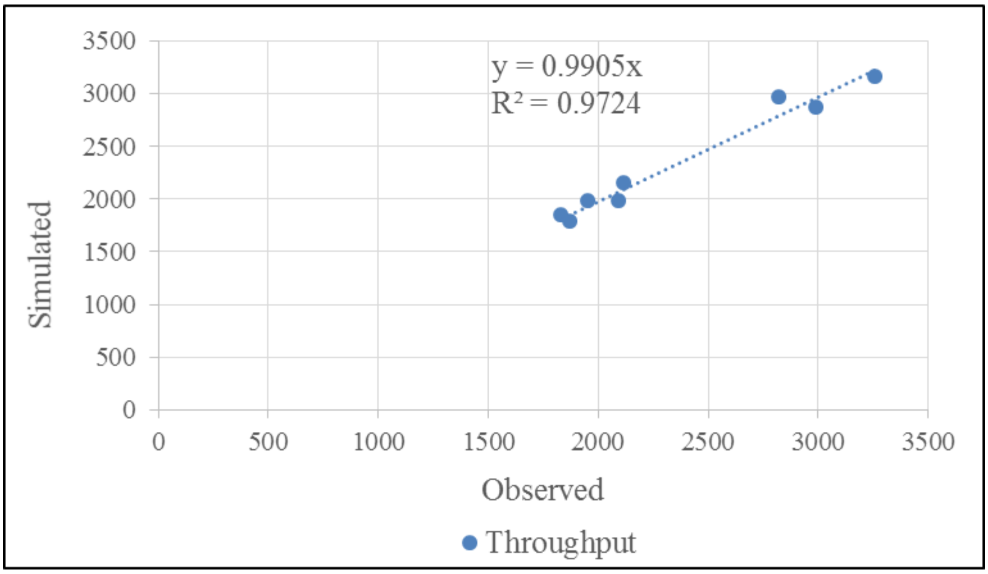


Figure 5.21 Regression analysis between observed and simulated throughput at exit Juru toll plaza.

5.4.3 Effectiveness of full ETC system at the toll plaza operation

This section represents the prediction of the toll plaza operation in the future when implementing only the ETC method in the closed system, which means the elimination of the ticket/cash payment methods in the multiclass lanes (mixed mode lanes previously). Therefore, several scenarios were used to simulate and study the influence of implementing the ETC on toll plaza operations in terms of queue length and maximum queue length in both the Juru and Jawi toll plazas.

5.4.3(a) Juru toll plaza

Three scenarios were identified and simulated to examine the effectiveness of implementing the full ETC in the Juru toll plaza:

1. Scenario 1: base scenario (normal traffic flow)
   - Entry: 2,501 vph with 6.8% heavy vehicles
   - Exit: 2,920 vph with 7.6% heavy vehicles
2. Scenario 2: proposed traffic volume for the future as high traffic volume with percentage of heavy vehicles of 12% (average percentage between 6% and 18%).
   - Entry: 2,900 vph.
   - Exit: 3,500 vph
3. Scenario 3: same as in scenario 2 but with full ETC.

The graphs plotted in Figure 5.22 and Figure 5.23 are for queue length and maximum queue length, respectively, based on the results obtained from Scenarios 1, 2, and 3. Figure 5.22 shows that queue length rapidly increased with the increment of the percentage of heavy vehicles and traffic volume from 9.1 m and 216.7 m for Scenarios 1 and 2, respectively. Then, in Scenario 3, when the toll system is switched to full ETC, the queue length becomes 213.2 m with a slight improvement of about 1.6%. That means that the implementation of full ETC at entry does not improve the operation of the toll plaza because of the procedure of the toll operation for Touch 'n Go is longer than ticket.

For exit, in Figure 5.22, the queue length also rapidly increased with the increment of the percentage of heavy vehicles and traffic volume from 71.8 m to 273.1 m for Scenarios 1 and 2, respectively. Then, in Scenario 3, with implementation of full ETC, the queue length reduced to 72.2 m with high improvement of about 73.6%. That means the implementation of full ETC at exit improved the operation of the toll plaza.

Figure 5.23 shows the results of the maximum queue length from the three scenarios for the Juru toll plaza at the entry and exit. In this figure, the maximum queue length has a similar trend observed in the queue length figure. For the entry, the maximum queue length almost did not change after the implementation of full ETC with no improvement at all. For exit, the maximum queue length significantly reduced after the implementation of full ETC with a high improvement percentage of 72.9%.

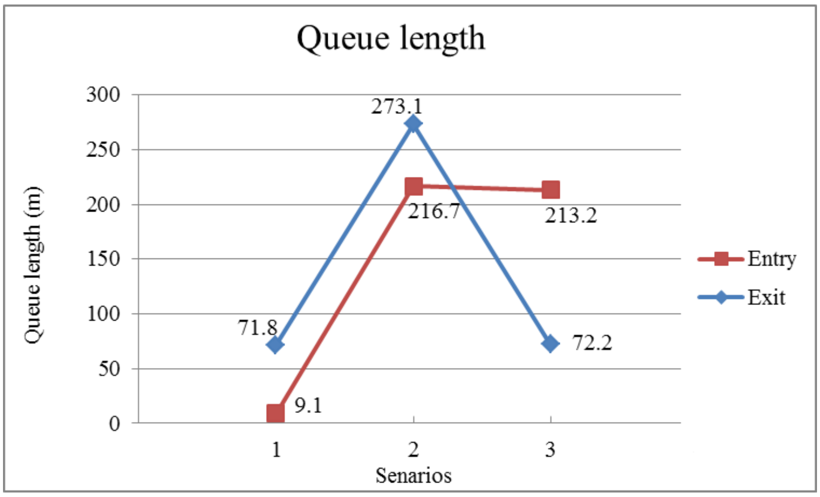


Figure 5.22 Simulation results for Juru toll plaza at entry and exit – Queue length.

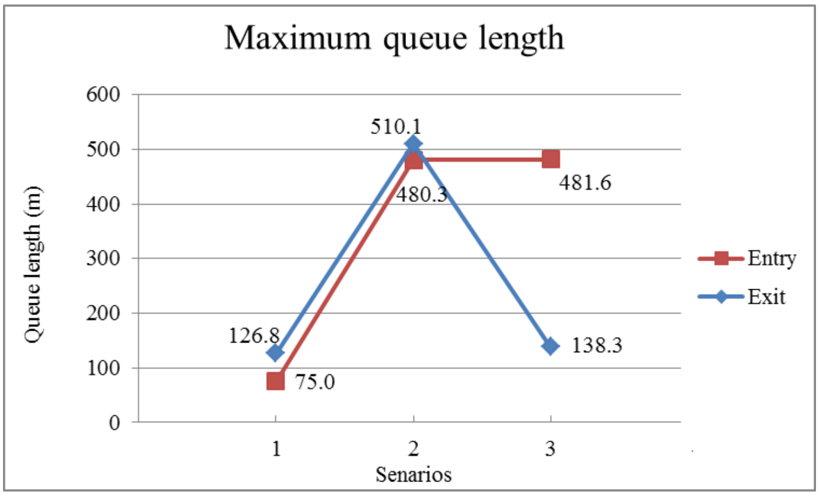


Figure 5.23 Simulation results for Juru toll plaza at entry and exit – Maximum Queue length.

5.4.3(b) Jawi toll plaza

Three scenarios were identified and simulated to examine the effectiveness of the implementation of full ETC in the Jawi toll plaza:

1. Scenario 1: base scenario (normal traffic flow)
    - Entry: 790 vph with 8.3% heavy vehicles
    - Exit: 1,282 vph with 7.1% heavy vehicles
2. Scenario 2: proposed traffic volume for the future as high traffic volume with percentage of heavy vehicles of 12%.
    - Entry: 1,290 vph.
    - Exit: 1,782 vph.
3. Scenario 3: the same as in scenario 2 but with full ETC.

Figure 5.24 shows the queue length at the entry of the Jawi toll plaza based on the results obtained from Scenarios 1, 2, and 3. The queue length for mixed mode gradually increased for Scenarios 1 to 2 and gradually decreased in scenario 3 after the implementation of full ETC with a slight improvement of about 5.8%. No significant changes are seen for the queue lengths for Touch 'n Go and Smart TAG lanes. However, the queue length at the traffic light from Nibong Tebal to the plaza rapidly increased with the increment of traffic volume in Scenario 2 from 129.3 m to 436.6 m for Scenarios 1 and 2, respectively. Then, when the toll system becomes a full ETC, the queue length becomes 428.4 m with a slight improvement of about 1.9% in Scenario 3. Also, for the queue length at the left turn from Jawi to the toll plaza, queue length rapidly increased with the increment of traffic volume in Scenario 2 from 8.9 m to 191.1 m for Scenarios 1 and 2. However, no significant improvement in queue length is seen after implementing the full ETC in Scenario 3.

Figure 5.25 shows the queue lengths at exit. For mixed mode, after the significant increase in the queue length from Scenarios 1 to 2, the queue length decreased rapidly from 293.8 m to 132.5 m for Scenarios 2 and 3 with a good improvement percentage of 55.9%. For Touch 'n Go and Smart TAG lanes, the queue lengths increased rapidly in Scenario 2 due to increment of total volumes and greatly influence the queued vehicles at the traffic light when vehicles exit the toll plaza and stopped at the traffic light. Moreover, the increase of the queue length for Touch 'n Go and Smart TAG lanes are higher after the implementation of full ETC in Scenario 3 as the throughput of multiclass lane increased. It is shown clearly at the graph of the queue length at the traffic light from the plaza that the queue length becomes 181.6 m and 192.8 m in Scenarios 2 and 3, respectively; this queue length is close to the toll plaza lanes.

In this case, the improvement percentage after full ETC implementation for Touch 'n Go and Smart TAG are −26.0 % and −59.8%, respectively.

For maximum queue length, Figure 5.26 shows the maximum queue lengths for entry, at the mixed mode and Smart TAG lanes; the lengths of the queue did not change from Scenarios 2 to 3. For Touch 'n Go, the maximum queue length increased after implementing the full ETC system, from 67.0 m to 93.8 m in Scenarios 2 and 3, respectively. This is probably because of the tendency for cars to shift to the Touch 'n Go lane instead of using the multiclass lanes and hence increasing the volume at the Touch 'n Go lane. However, for the maximum queue length at the traffic light from Nibong Tebal to the plaza and the maximum queue length for the left turn from the Jawi to plaza, both have similar trend as observed in Figure 5.24 for queue length at entry.

Figure 5.27 shows the maximum queue lengths for exit. In this case, the maximum queue lengths for Touch 'n Go, Smart TAG, and the queue at the traffic light from the plaza did not change in Scenarios 2 to 3 which means that the implementation of full ETC did not improve the maximum queue lengths for these lanes. However, for mixed mode, the maximum queue length reduced from 461.9 m to 412.6 m in Scenarios 2 and 3 with a percentage improvement of 10.7%.

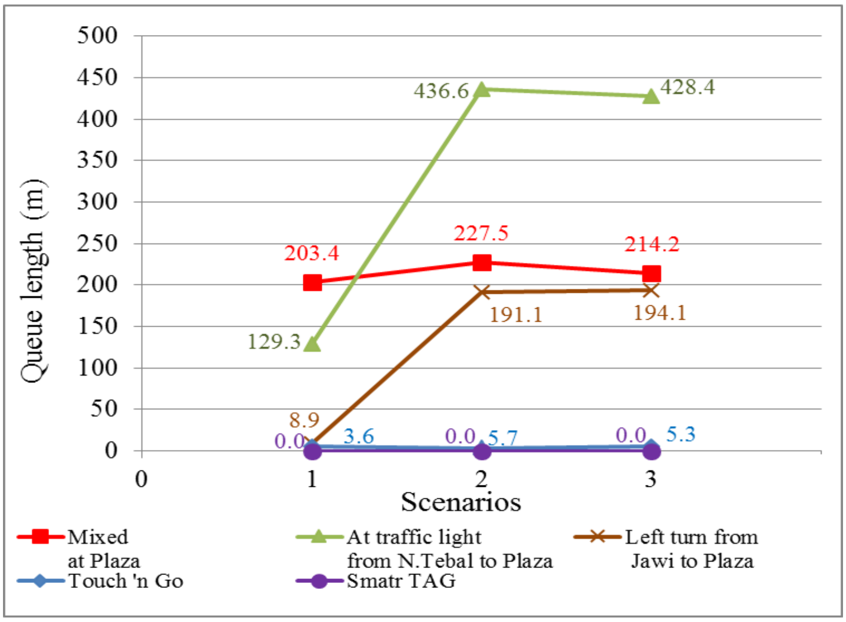


Figure 5.24 Simulation results for Jawi toll plaza at entry – Queue length.

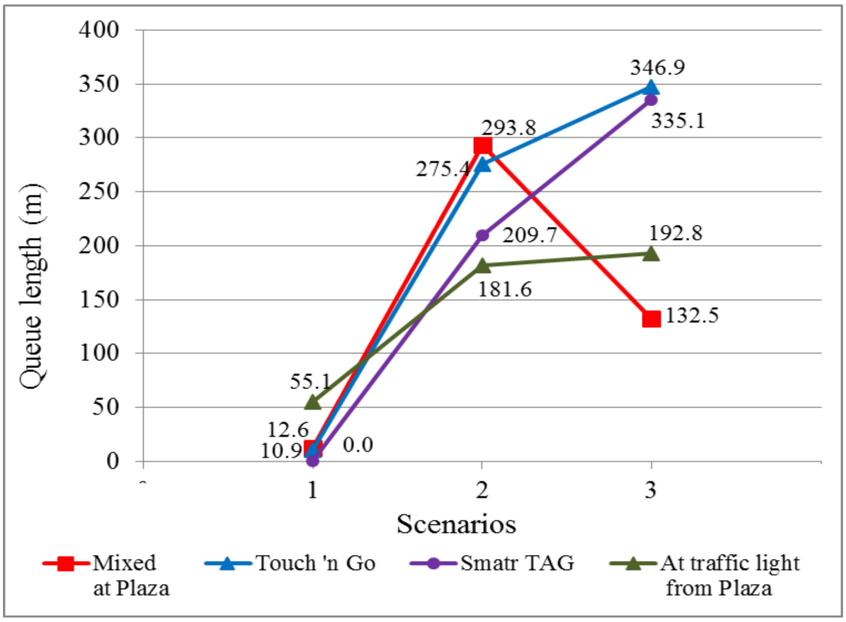


Figure 5.25 Simulation results for Jawi toll plaza at exit – Queue length.

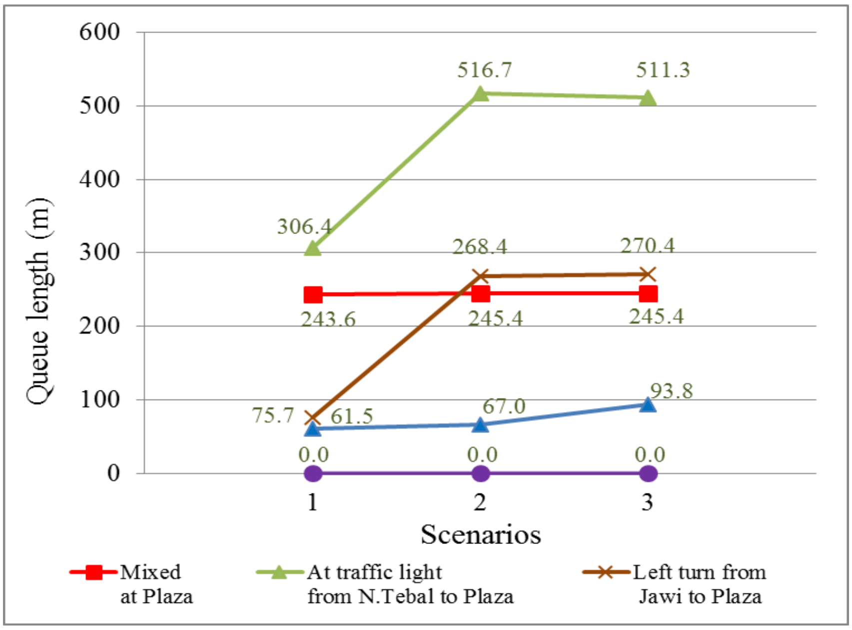


Figure 5.26 Simulation results for Jawi toll plaza at entry – Maximum queue length.

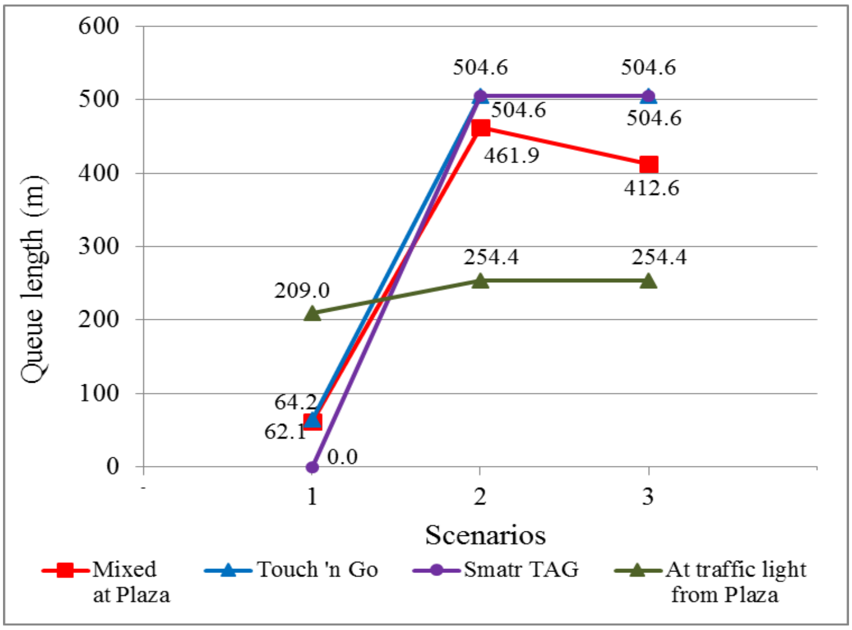


Figure 5.27 Simulation results for Jawi toll plaza at exit – Maximum queue length.

5.4.3(c) Optimum distance between Jawi toll plaza and the junction

The previous section presents the results of the scenarios of the implementation of full ETC in the Jawi ramp toll plaza. Moreover, the results show that the use of the full ETC in the ramp toll plazas does not improve the traffic operation at the toll plaza due to the length of the queuing vehicles at the traffic light junction that reaches to the toll lanes at the toll plaza.

This section tries to improve the toll operation at Jawi toll plaza after the implementation of full ETC, through examine and specifying the optimum distance between the toll plaza and the junction by using the same Scenario 3 of Jawi toll plaza in the previous section. But the different in the Scenario 3 of this section is to extend the distance between the toll plaza and the junction with the several steps. Each step represent new scenario of Scenario 3 with extending distance of 25m.

After running several scenarios, starting with Scenario 1 with distance about 250m between the toll plaza and the junction. Then continue with new scenarios by adding 250m to the previous scenario, until get a scenario with adjusted distance that made the queue length of the Smart TAG equals to zero, because the total input of the Smart TAG traffic volume at the exit was less than the Smart TAG lane capacity.

As a result, Figure 5.28 shows the trend of the Smart TAG queue lengths according to increments of the distances from toll plaza to the junction. Also the figure illustrates the optimum distance which is 397m, that prevents the influence the junction queue length on the operation of the toll plaza.

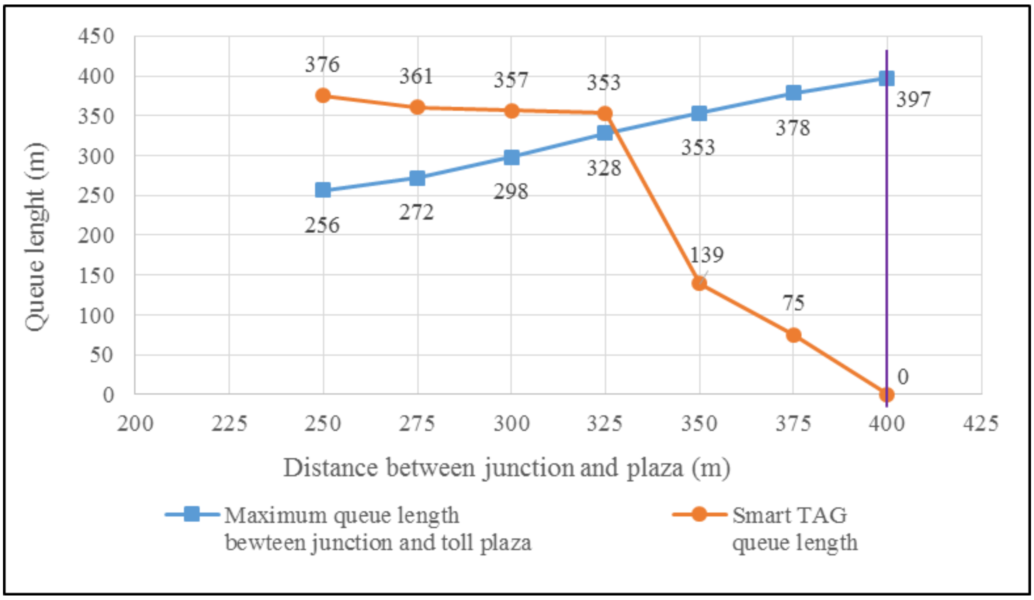


Figure 5.28 Scenarios of the maximum queue length between the junction and Jawi toll plaza to obtain the optimum distance.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The main goal of this study is to assess the overall toll operations of the two types of closed system toll plaza in the Malaysian expressway system, which provides a better understanding of the variables affecting the toll operations and thus the actual capacity of the toll plaza in terms of average and maximum queue lengths. A microscopic simulation software called VISSIM was used to build the toll plaza models for Juru and Jawi toll plazas to study their toll operations and actual capacities.

To simulate the toll operations at the toll plazas, microscopic data were needed for each individual vehicle arriving and departing the toll plaza. The approach used to collect the data was through video recordings. One of the most challenging tasks in this study was the installation of the CCTV cameras at the toll plazas as was needed to choose the most suitable system that is within the budget of this study. Another challenging task was to determine the locations and number of CCTV cameras needed to clearly record the movement of individual vehicle arriving and departing the toll plaza. The field data collection of the Juru and Jawi toll plazas were different in terms of number of lanes, lane configuration, toll base fee, expressway location, traffic demand, and the characteristics of traffic composition.

Finally, the toll plaza models were calibrated according to MOE and key parameters to match the real -world toll operations at toll plazas.

This chapter contains the general conclusions and recommendations for future research directions as presented in the succeeding sections.

6.2 Conclusions

A summary of the results of this thesis is presented in the following conclusions: The traffic volumes at the exit are greater than at the entry during peak hours for both toll plazas.At the Juru and Jawi toll plazas, the majority of the long queue lengths occurred at the mixed mode toll lanes. Furthermore, the maximum queue lengths did not always occur during the peak hours and, thus, the causes of the queue length were not dependent only on the traffic volume but also on the compositions of the traffic flow.

Service time, which is the total time a vehicle spent at the tollbooth to pay the toll until departure from the toll gate, is the most important parameter to evaluate the toll operation of toll plaza.

i. The service time is the summation of transaction and start-up delay times.
ii. Generally, service time for entry is much lower than the service time for exit.
iii. For entry, service time using the Touch 'n Go is longer than ticket for cars and busses.
iv. The service time for exit using the Touch 'n Go is longer than entry due to printing of receipt.
v. The location of the contactless smart card reader at each mixed mode lane is approximately 1 m from the road level, which is too low for the drivers of heavy vehicles to reach. They need the assistance of tollbooth operators to touch the card at the reader and, hence, longer service time.

The results of the calibration proved that the VISSIM microscopic simulation software was a suitable tool for simulating heterogeneous traffic flow to replicate accurately the real -world toll operation in toll plazas. Moreover, the results indicated that the percentage of the heavy vehicles in traffic flow significant impact the queue lengths at the Juru and Jawi toll plazas.

i. For the Juru toll plaza, the significant impact of the heavy vehicle percentages starts from 16% and 7.6% for the entry and exit, respectively. On the other hand, the results showed that the percentage of heavy vehicles had no influence on ETC lanes for both entry and exit.

ii. For the Jawi toll plaza, traffic operations behave differently from the Juru toll plaza. The Jawi toll plaza is a ramp toll plaza usually located in the urban areas and close to the signalized intersection. This type of toll plaza influenced the queue lengths at the signalized intersection and also on the location of the intersection effecting the toll plaza operation. Furthermore, the approached traffic volume at entry is dependent on the signal timing of the signalized intersection while the queue length boundary at the entry toll lanes is limited to the distance between the toll plaza and the signalized intersection. Therefore, the maximum queue length is no longer than 245 m, which is the distance between the Jawi toll plaza and the traffic light intersection.

iii. For entry, the results indicated that queue length gradually increased with the increment of heavy vehicles percentage for the mixed mode lane and did not show a rapid increase due to signal timing of the traffic light. However, a significant increase of the queue length continued to occur at the traffic light from Nibong Tebal to the Jawi toll plaza. However, the percentage of the heavy vehicles does not have an influence on the queue lengths of ETC lanes such as Touch 'n Go and Smart TAG at entry.

iv. For exit, the significant impact of the heavy vehicle percentages on the mixed mode lanes starts from 16%. Moreover, this percentage impacts the queue lengths at the Touch 'n Go and Smart TAG lanes.

The actual capacities for mainline toll plaza are:

i. For mixed mode lanes at entry and exit:

$$C_{Mix\text{-}Entry} = 3600 / [(P_{car,ticket} \times 7.12) + (P_{car,TNG} \times 8.59) + (P_{s.lorry,ticket} \times 13.84) + (P_{s.lorry,TNG} \times 12.37) + (P_{truck,ticket} \times 17.34) + (P_{truck,TNG} \times 15.11) + (P_{trailer,ticket} \times 19.16) + (P_{trailer,TNG} \times 16.41) + (P_{bus,ticket} \times 15.30) + (P_{bus,TNG} \times 15.89)] \quad (6\text{-}1)$$

$$C_{Mix\text{-}Exit} = 3600 / [(P_{car,cash} \times 23.24) + (P_{car,TNG} \times 11.69) + (P_{s.lorry,cash} \times 30.50) + (P_{s.lorry,TNG} \times 20.26) + (P_{truck,cash} \times 34.88) + (P_{truck,TNG} \times 24.22) + (P_{trailer,cash} \times 35.60) + (P_{trailer,TNG} \times 26.03) + (P_{bus,cash} \times 27.86) + (P_{bus,TNG} \times 19.17)] \quad (6\text{-}2)$$

ii. For Touch 'n Go lanes at entry = 497 vph and for exit = 460 vph.

iii. For Smart TAG lane:

$$\text{Smart TAG lane capacity } (C_{STAG}) = \frac{3600 - (40 \times N)}{3.58} \quad (6\text{-}3)$$

The calibrated models are used to predict the toll plaza operation in the future when implementing full ETC in the closed system and examining the effectiveness of implementation of full ETC system at the toll plaza operation in terms of queue lengths. The implementation of full ETC at the entry of the Juru and Jawi toll plazas did not improve the operations at the toll plazas. However, for exit, the implementation of full ETC significantly improves the toll operations. The queue lengths at mixed mode lanes for the Juru toll plaza reduced at a percentage of 73.6% after implementation of full ETC. However, for the exit at the Jawi toll plaza, the queue lengths at mixed mode lanes reduced at a percentage of 55.9% after the implementation of full ETC. Moreover, due to location of the traffic light intersection at a distance of 245 m, the throughput increased after the implementation of full ETC. The implementation of full ETC negatively influenced the queue lengths of the Touch 'n Go and Smart TAG lanes. After full ETC, the queue length of the Touch 'n Go and Smart TAG lanes increased at percentages of 26.0% and 59.8%, respectively.

6.3 Recommendations for future research

Some recommendations for future work associated with this study are listed below:

The improvement in service times should be investigated with the implementation of the AVI system in Malaysia. Furthermore, the new service time is depend on the procedures that adopted by Malaysian highway authority and the type of equipments that used in the toll plazas, and all these information are unavailable in this study.

The impact of heavy vehicles on the delay and travel time at the toll plazas should be investigated. The data collections of delay and travel time need special type of camera that can capture the vehicle category and the vehicle plate number which is not used in this study.

The capacity improvement of toll plazas with implementation of open road tolling (ORT) system, should be investigated in Malaysia. This work need special methodology to study; what type of ORT is suitable to the Malaysia expressway, what is the maximum speed for the approaching vehicles, what type of vehicles are allowable to use the ORT lanes and what type of the devices should mounted on the vehicles.

Furthermore, the created toll plaza model in this study is a useful instrument for Malaysian transportation agencies and toll authorities to redesign or retrofit toll plazas.

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APPENDECES

Appendix A Service time at Juru toll plaza;

Transaction time, start-up delay time and service time

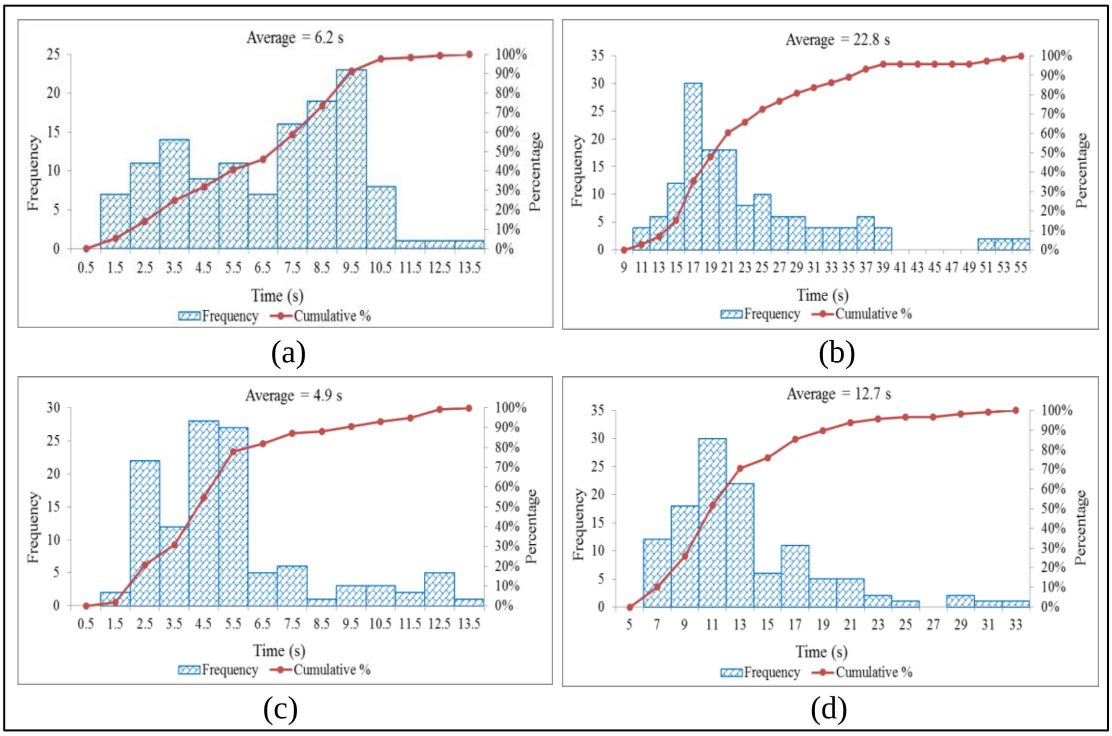


Figure A.1 Frequencies and cumulative curves of service time for small lorry at Juru toll plaza; (a) entry – ticket, (b) exit – cash, (c) entry - Touch 'n Go, (d) exit - Touch 'n Go.

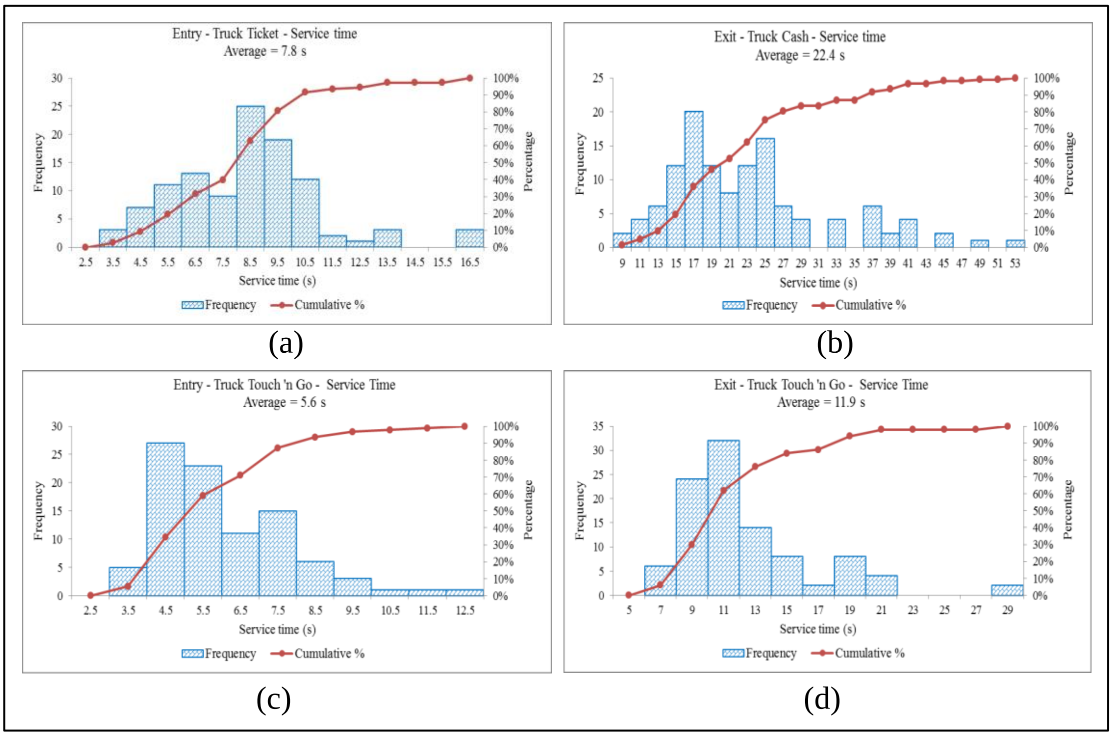


Figure A.2 Frequencies and cumulative curves of service time for Truck at Juru toll plaza; (a) entry – ticket, (b) entry - Touch 'n Go, (c) exit – cash, (d) exit - Touch 'n Go.

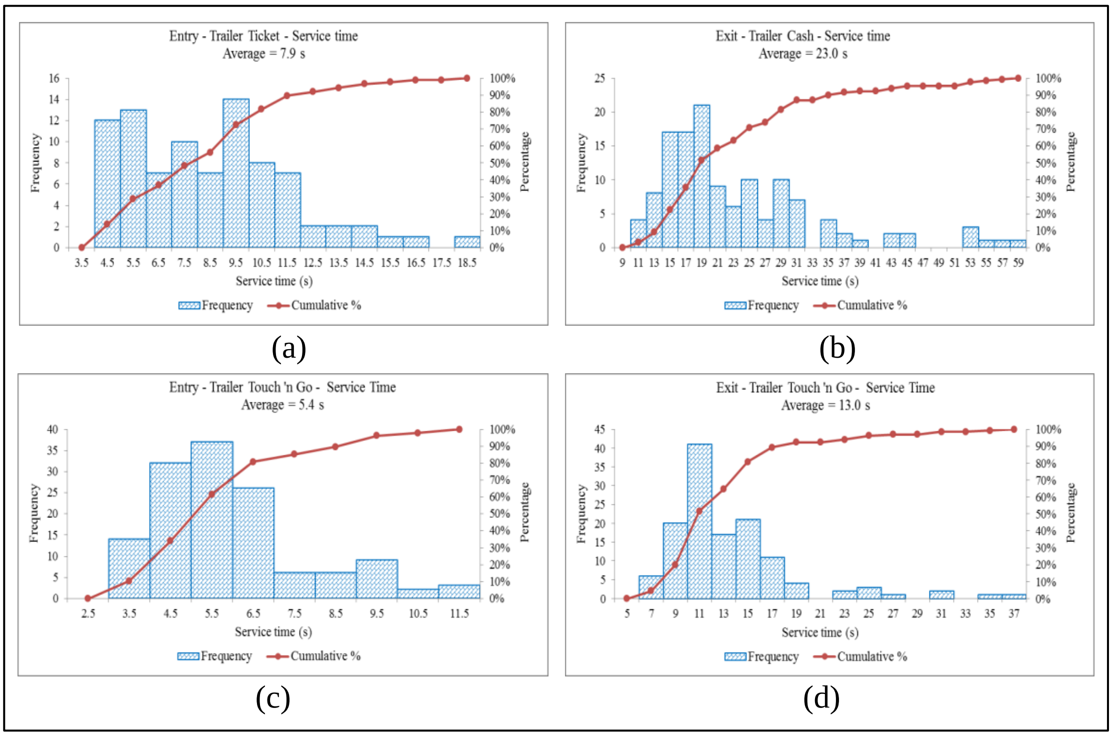


Figure A.3 Frequencies and cumulative curves of service time for Trailer at Juru toll plaza; (a) entry – ticket, (b) entry - Touch 'n Go, (c) exit – Cash, (d) exit - Touch 'n Go.

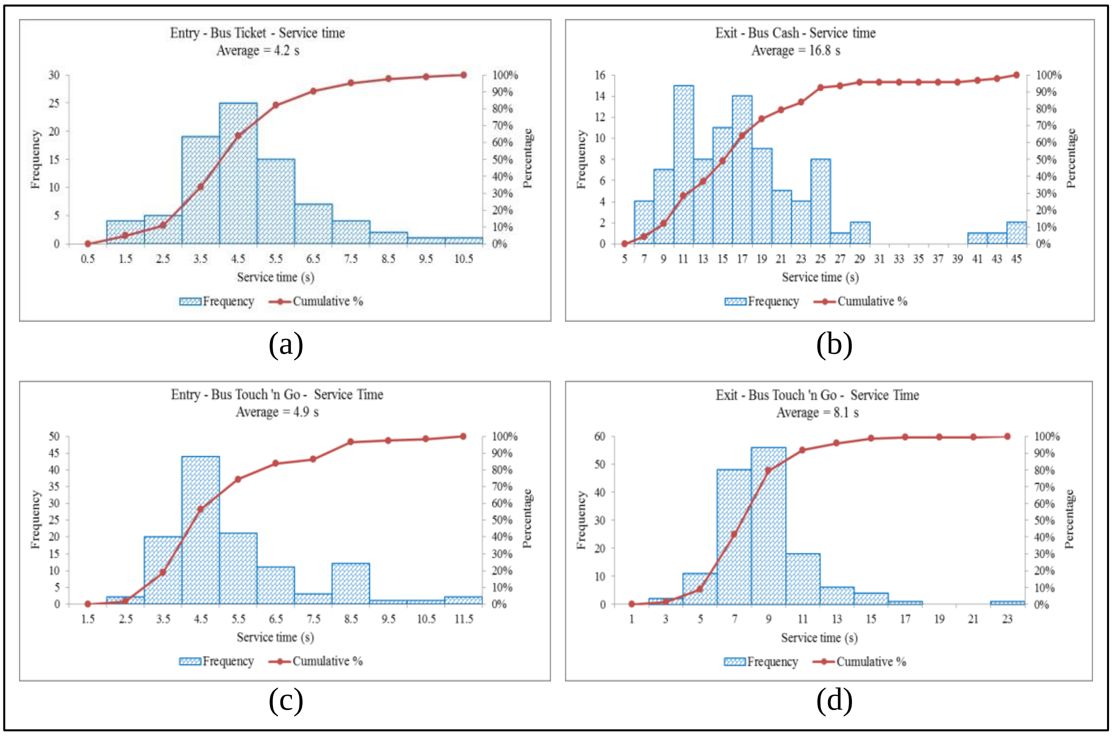
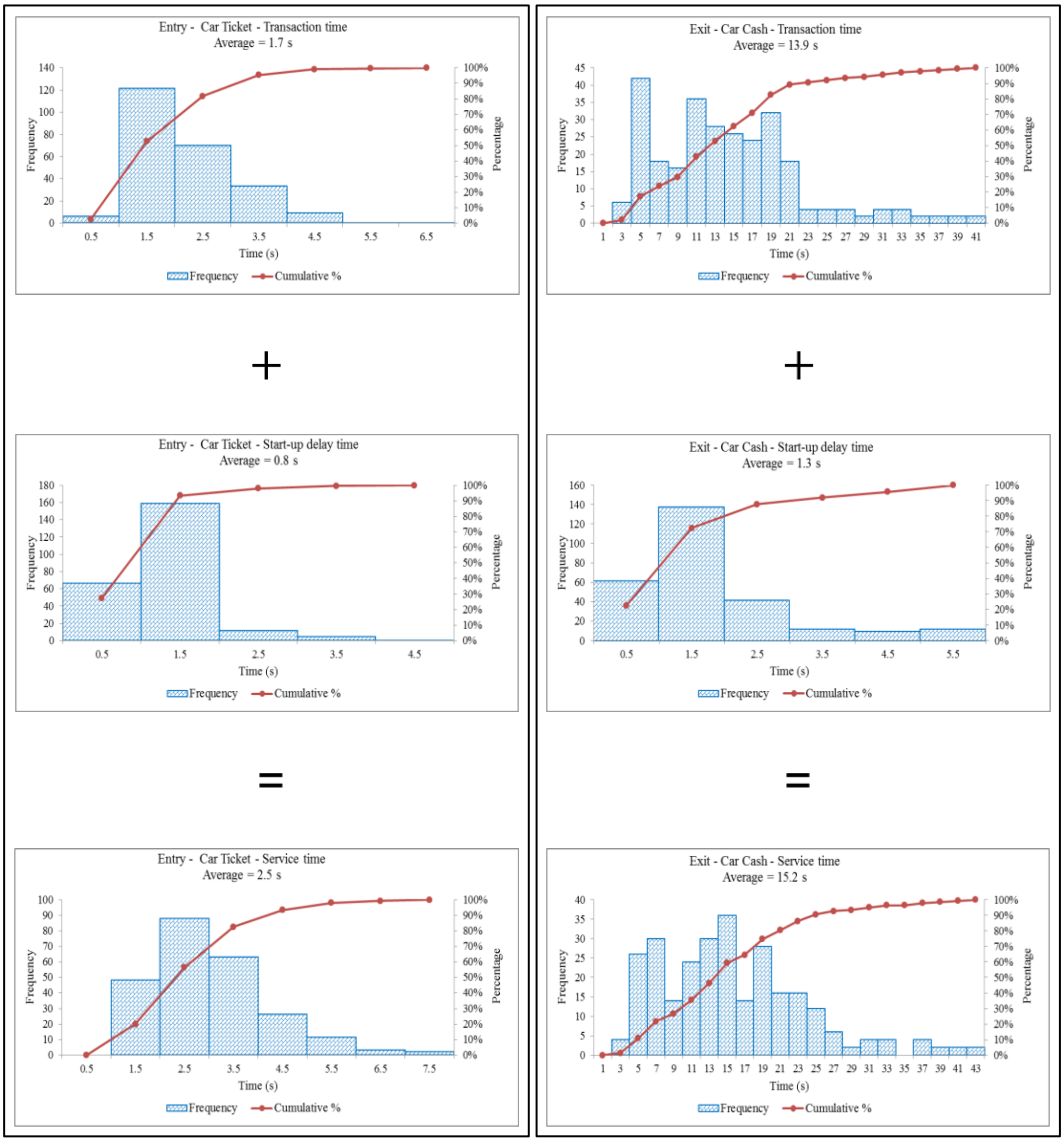
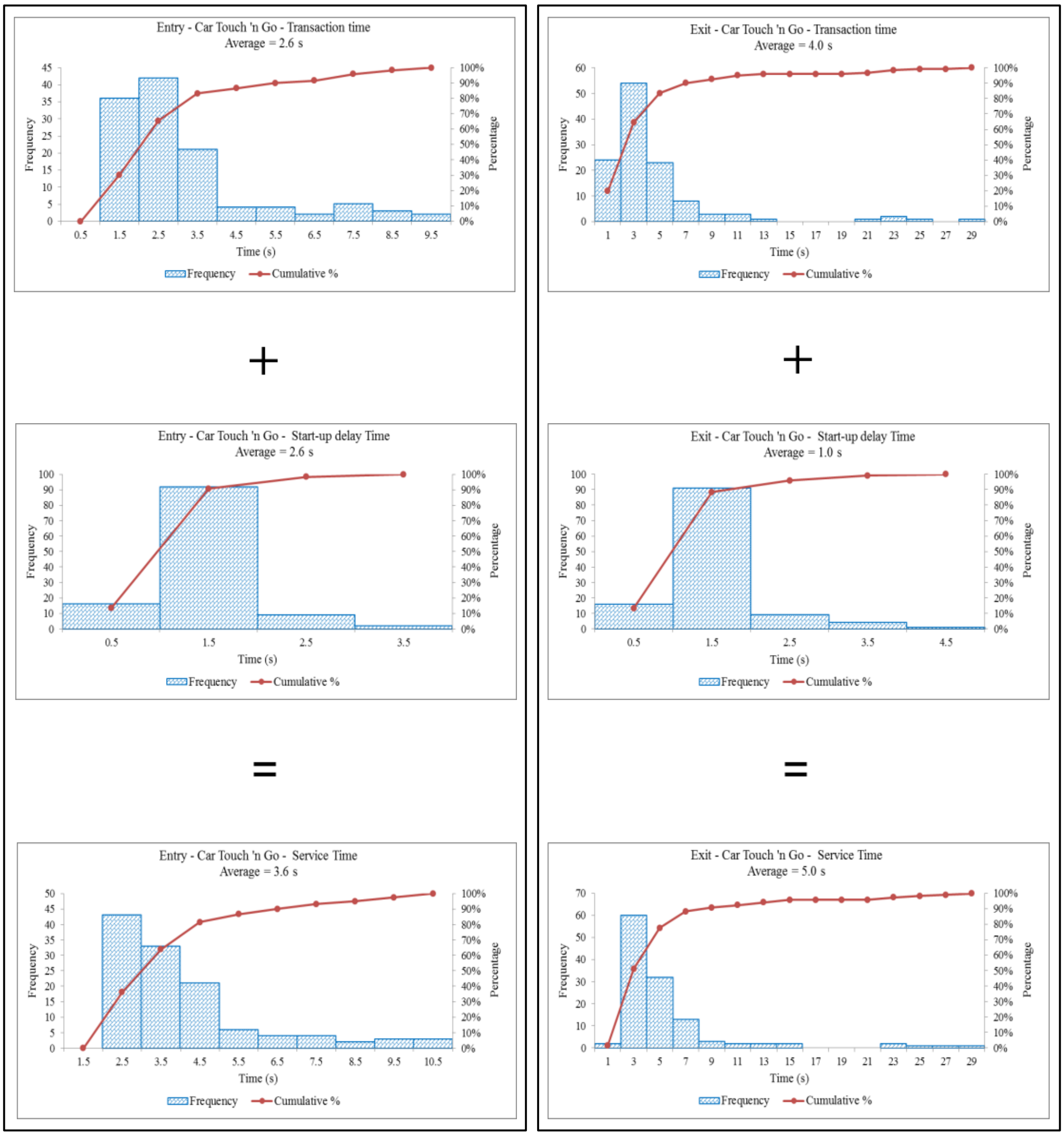


Figure A.4 Frequencies and cumulative curves of service time for Bus at Juru toll plaza; (a) entry – ticket, (b) entry - Touch ´n Go, (b) exit – cash, (c) exit - Touch 'n Go.



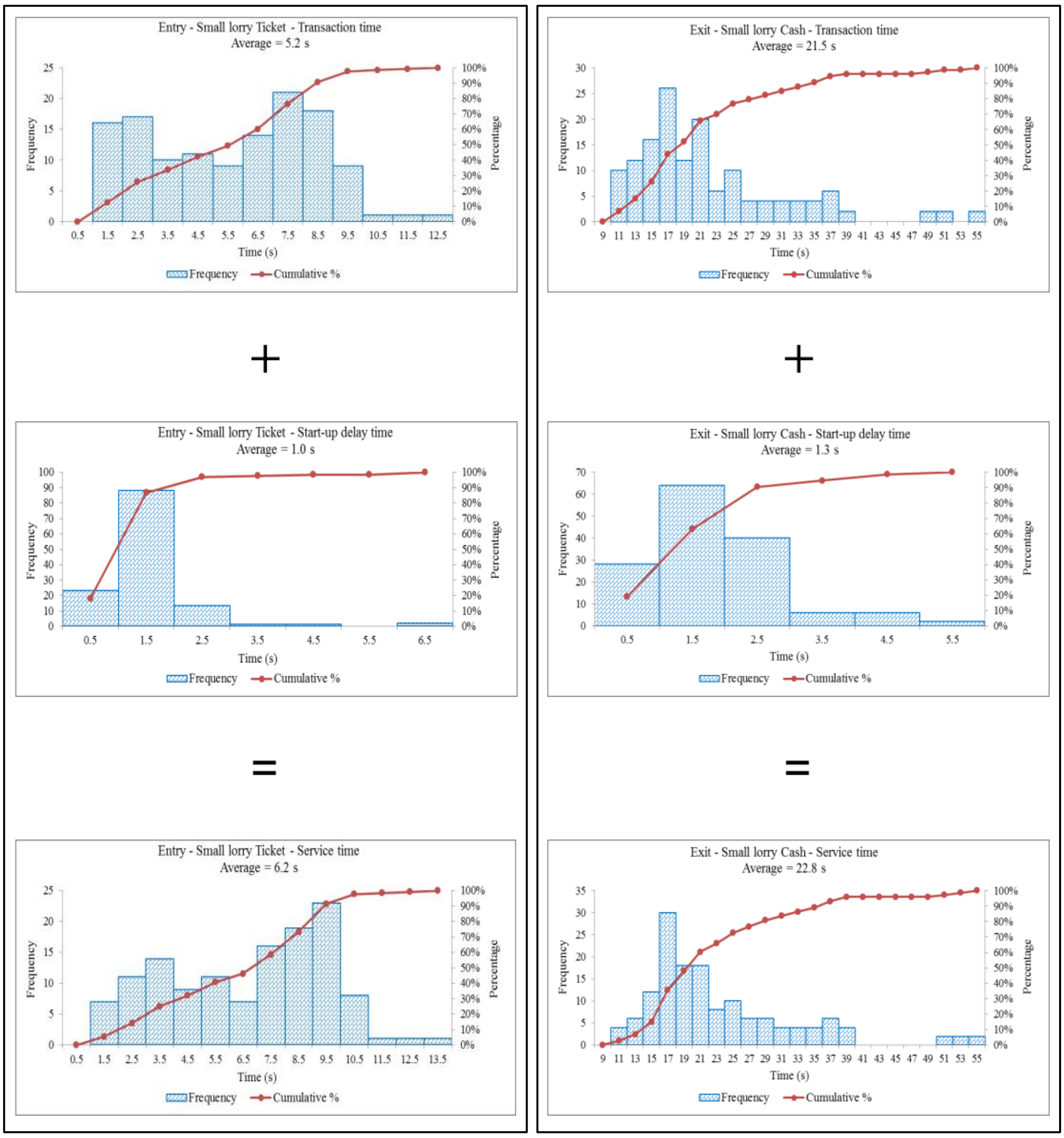
(a) (b)

Figure A.5 Frequencies and cumulative curves of transaction, start-up delay and service time for car at Juru toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



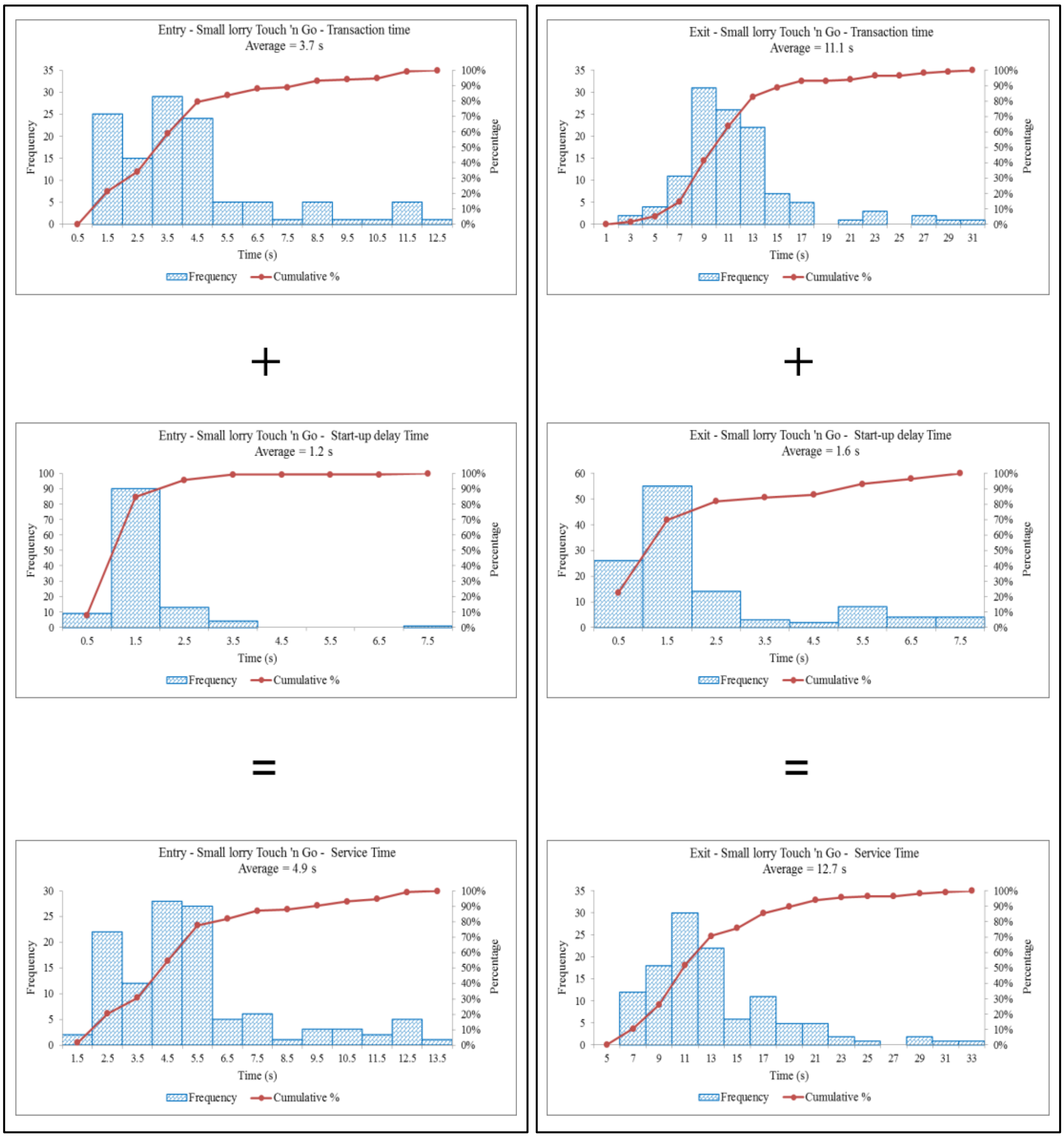
(a) (b)

Figure A.6 Frequencies and cumulative curves of transaction, start-up delay and service time for car – Touch 'n Go (mixed mode lanes) at Juru toll plaza; (a) Entry, (b) Exit.



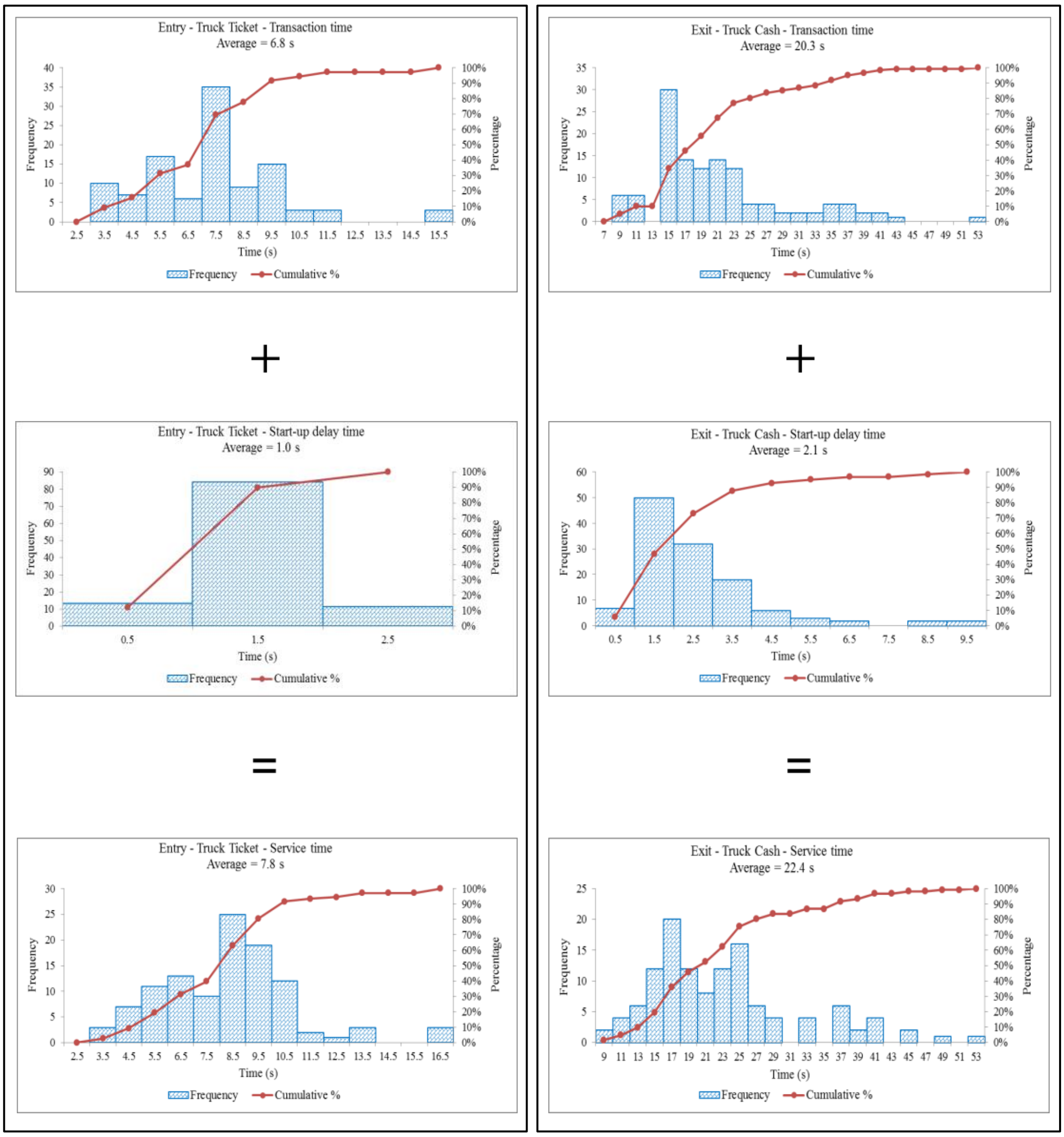
(a) (b)

Figure A.7 Frequencies and cumulative curves of transaction, start-up delay and service time for small lorry at Juru toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



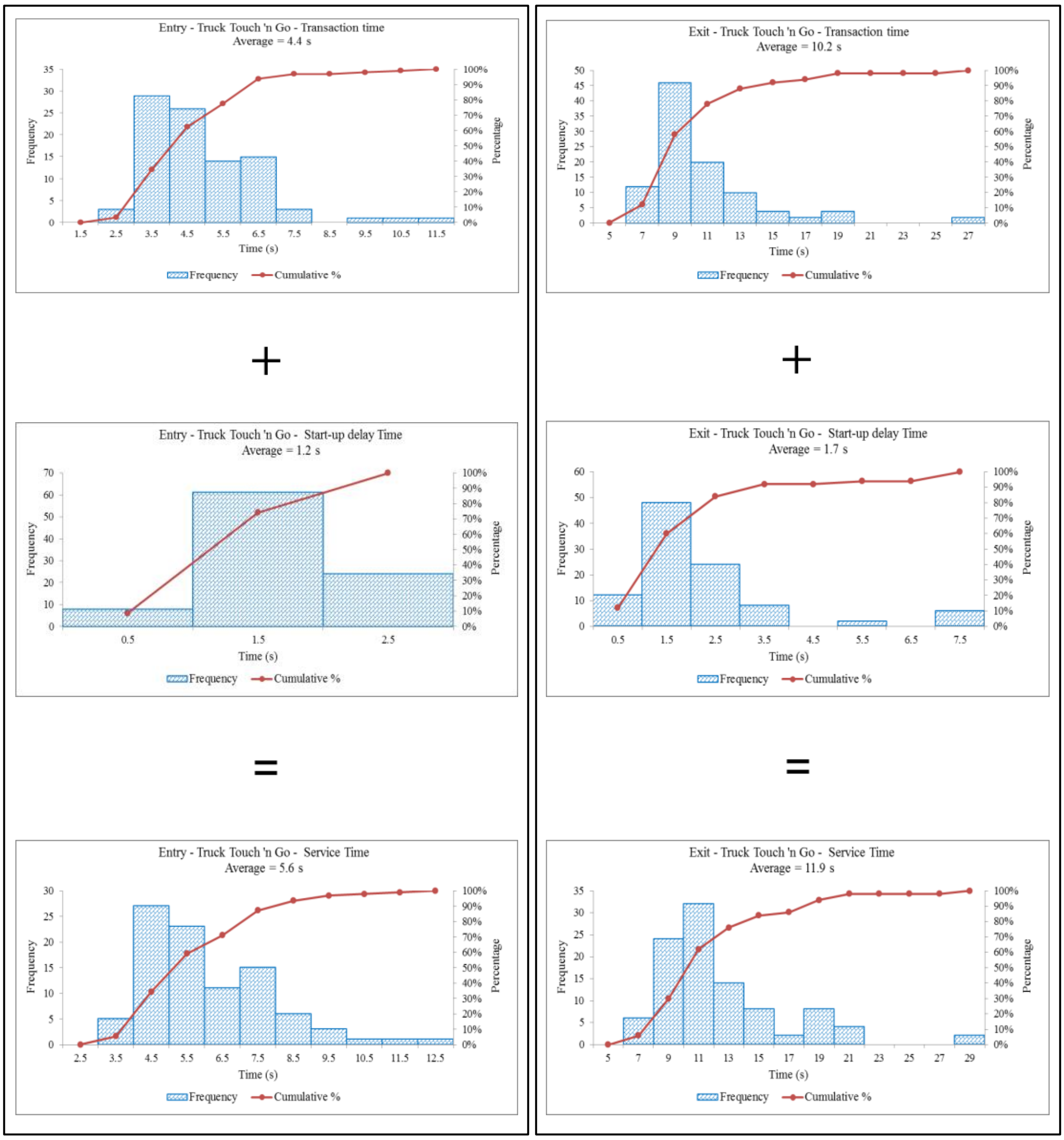
(a) (b)

Figure A.8 Frequencies and cumulative curves of transaction, start-up delay and service time for small lorry – Touch 'n Go (mixed mode lanes) at Juru toll plaza; (a) Entry, (b) Exit.



(a) (b)

Figure A.9 Frequencies and cumulative curves of transaction, start-up delay and service time for truck at Juru toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



(a) (b)

Figure A.10 Frequencies and cumulative curves of transaction, start-up delay and service time for truck – Touch 'n Go (mixed mode lanes) at Juru toll plaza; (a) Entry, (b) Exit.

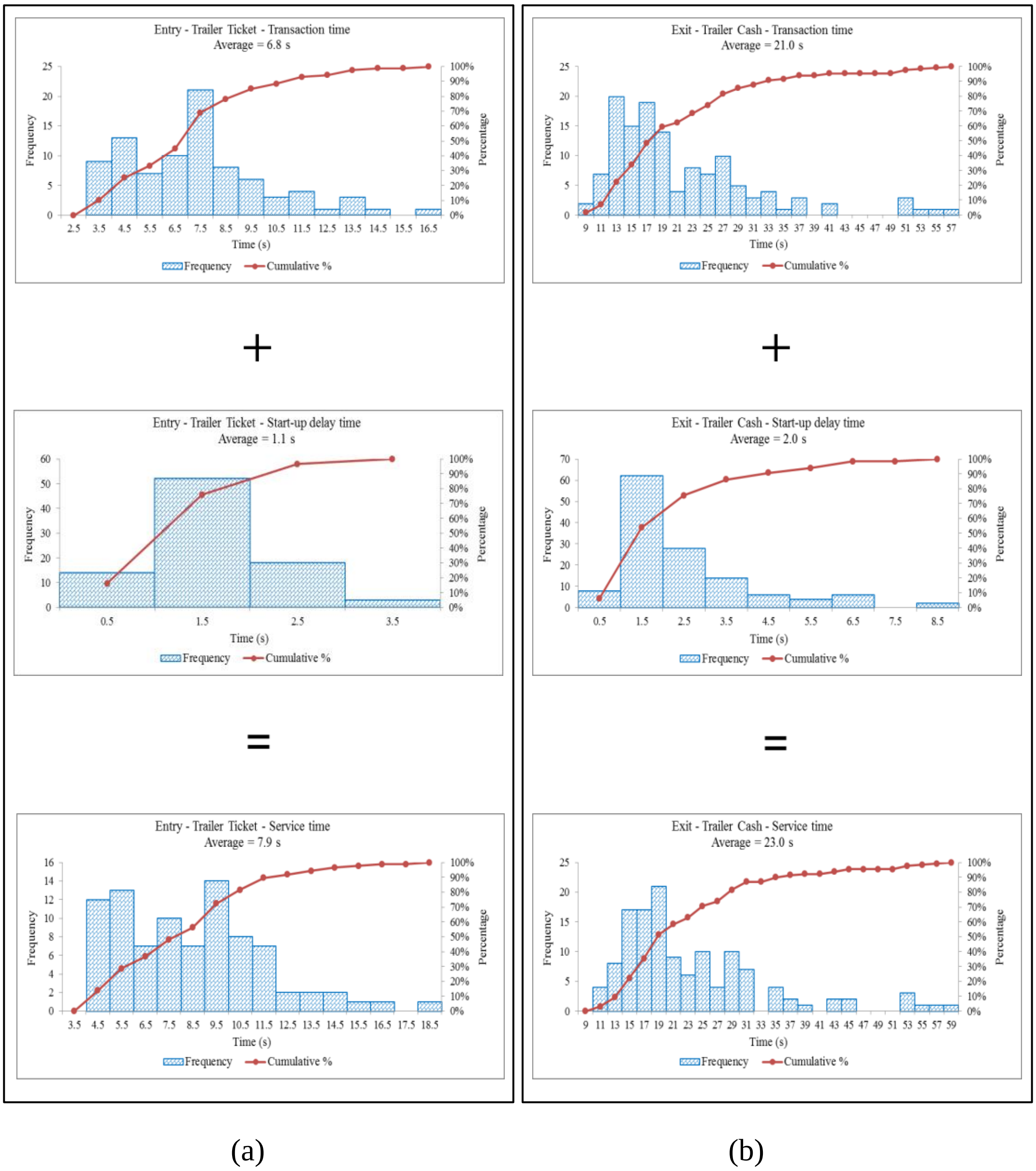
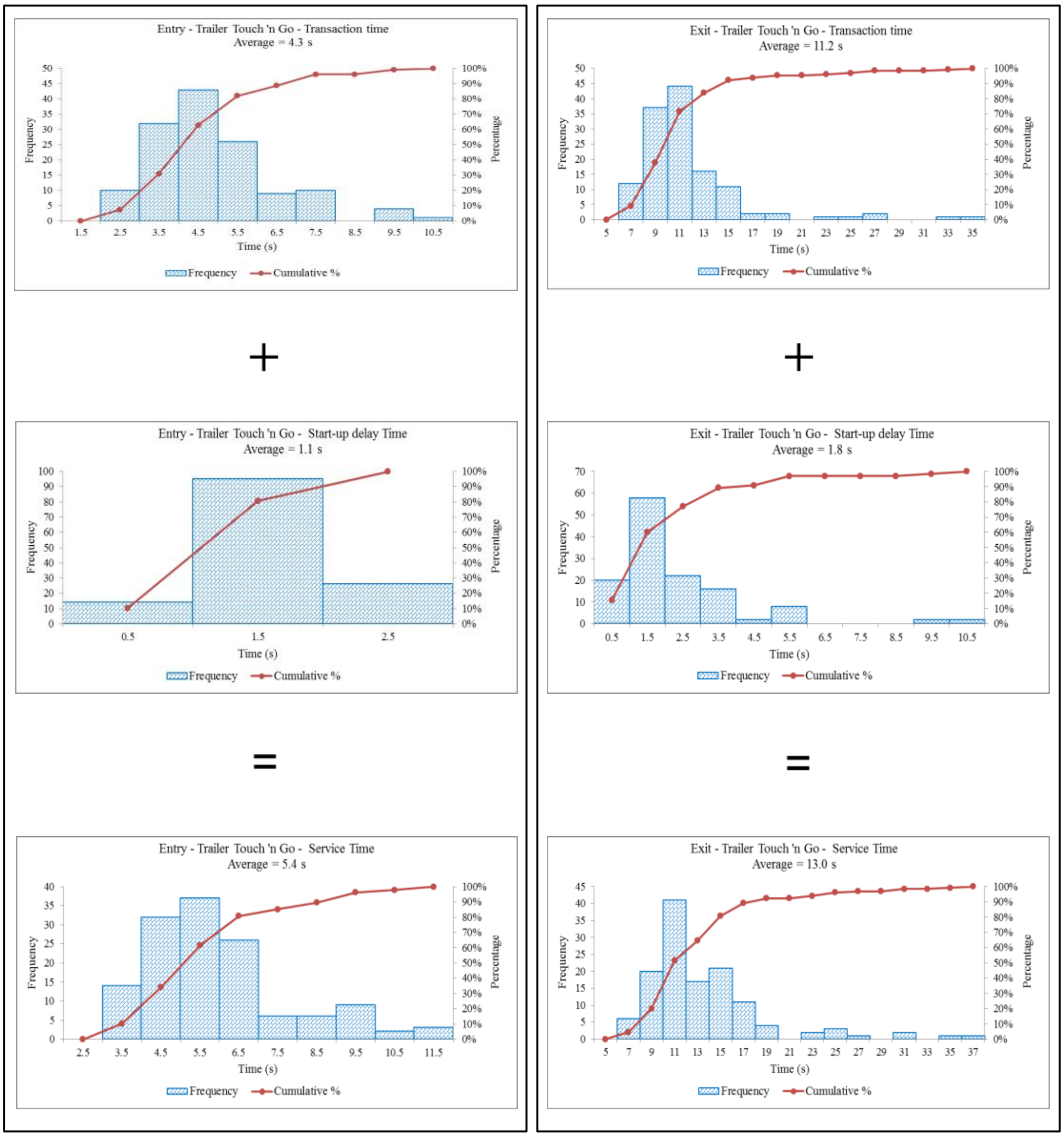
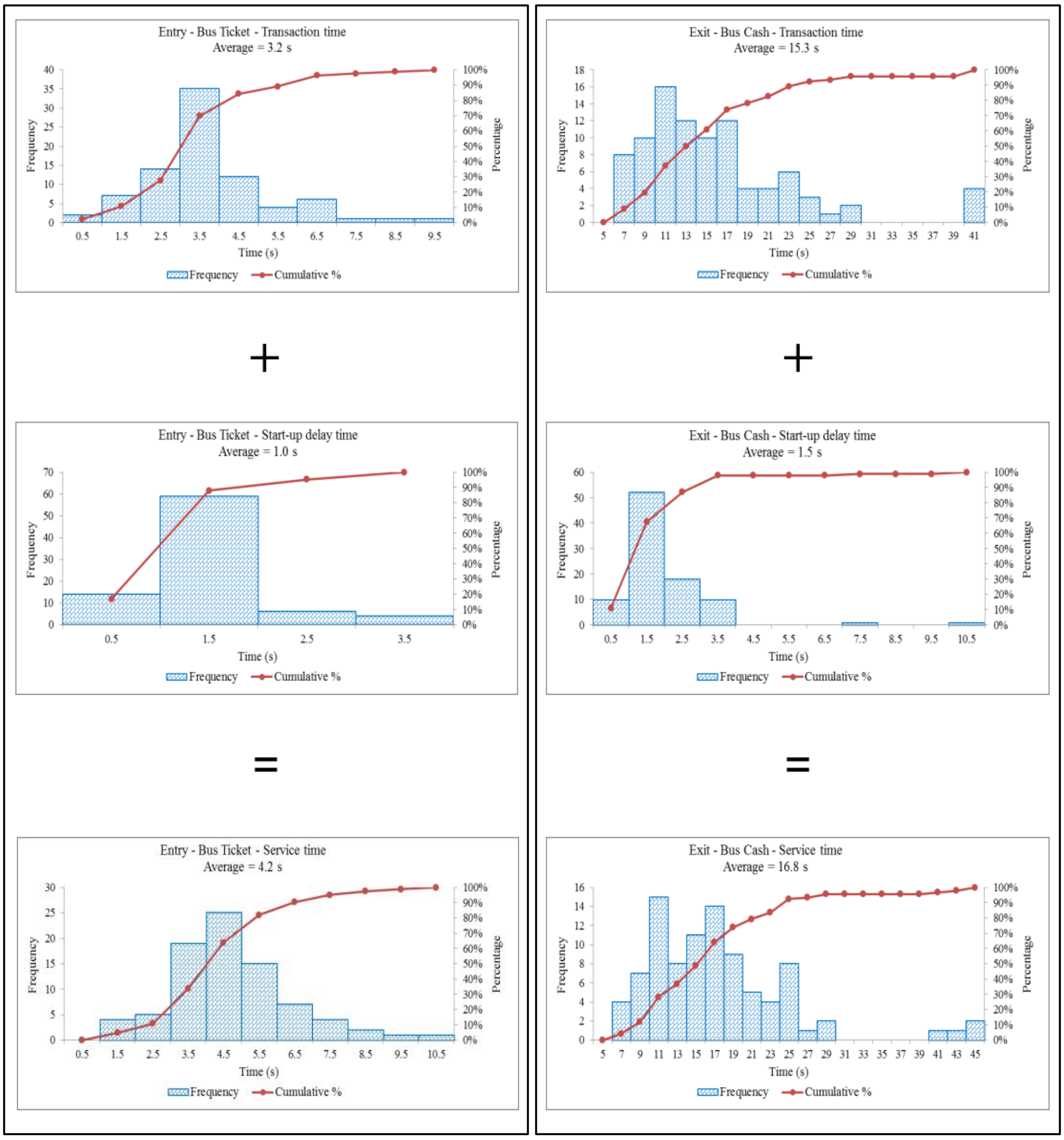


Figure A.11 Frequencies and cumulative curves of transaction, start-up delay and service time for trailer at Juru toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



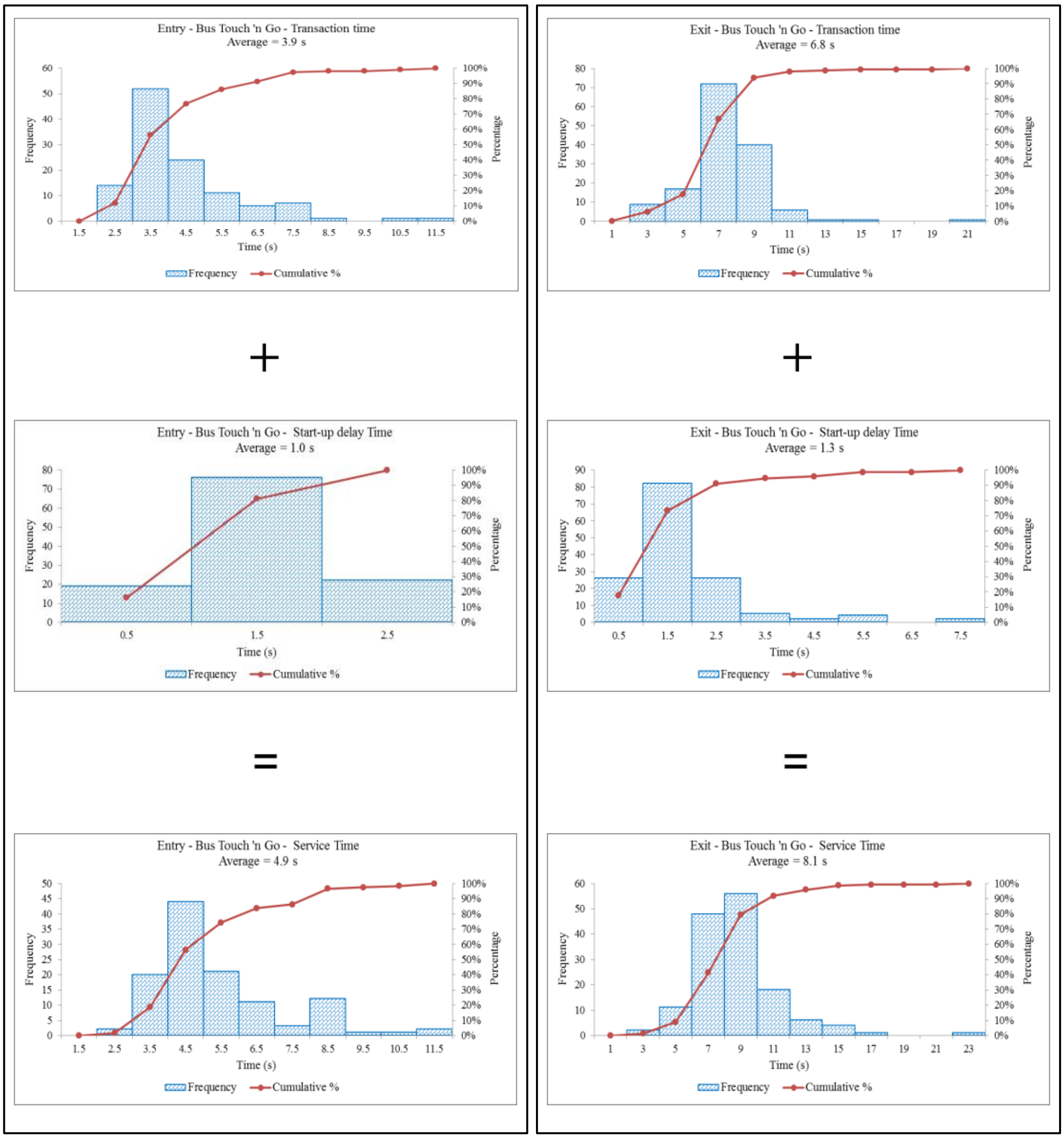
(a) (b)

Figure A.12 Frequencies and cumulative curves of transaction, start-up delay and service time for trailer – Touch 'n Go (mixed mode lanes) at Juru toll plaza; (a) Entry, (b) Exit.



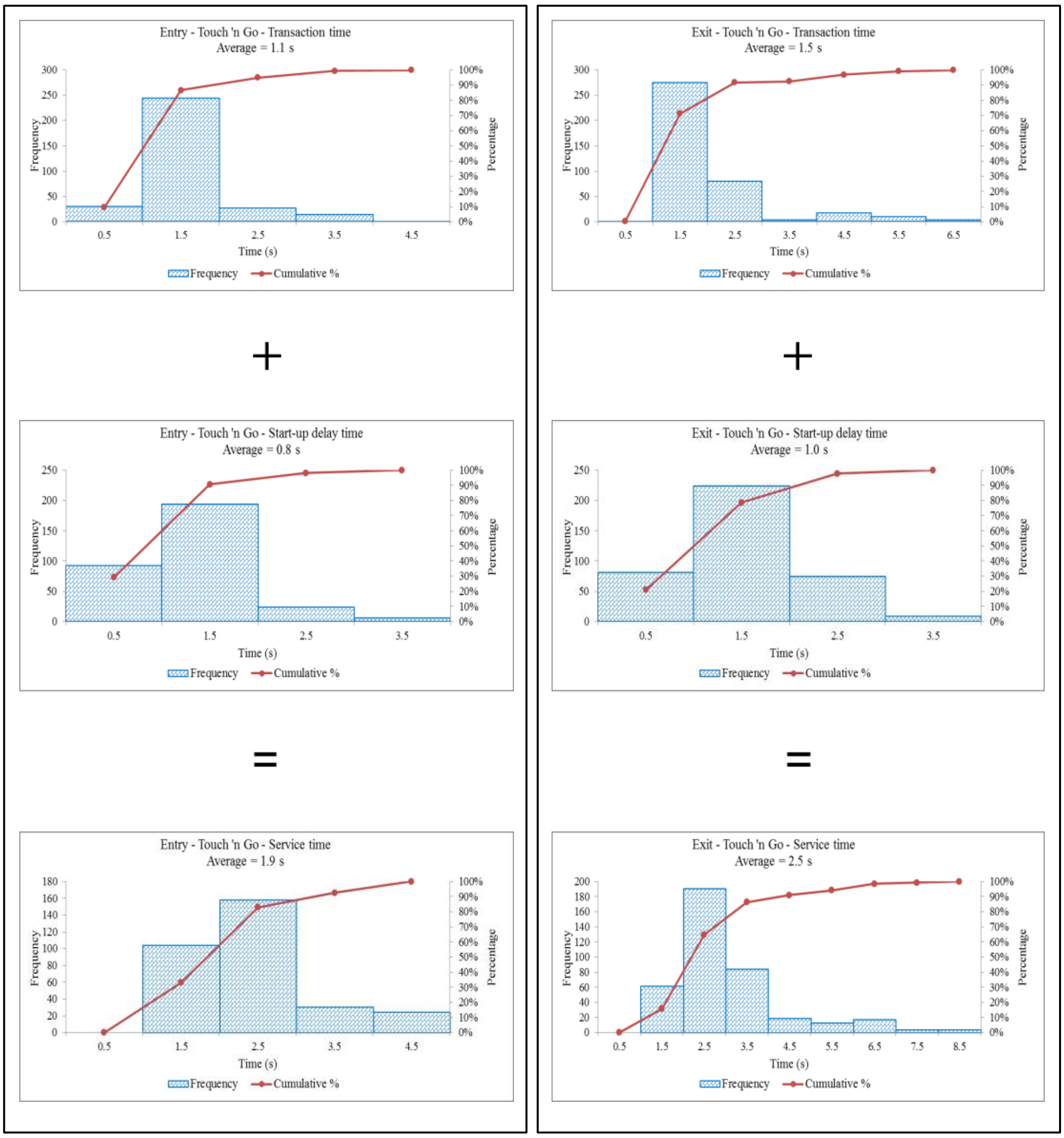
(a) (b)

Figure A.13 Frequencies and cumulative curves of transaction, start-up delay and service time for bus at Juru toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



(a) (b)

Figure A.14 Frequencies and cumulative curves of transaction, start-up delay and service time for bus – Touch 'n Go (multiclass lanes) at Juru toll plaza; (a) Entry, (b) Exit.



(a) (b)

Figure A.15 Frequencies and cumulative curves of service time for Touch 'n Go – Single class lanes at Juru toll plaza; (a) Entry, (b) Exit.

Appendix B Service time at Jawi toll plaza;

Transaction time, start-up delay time and service time

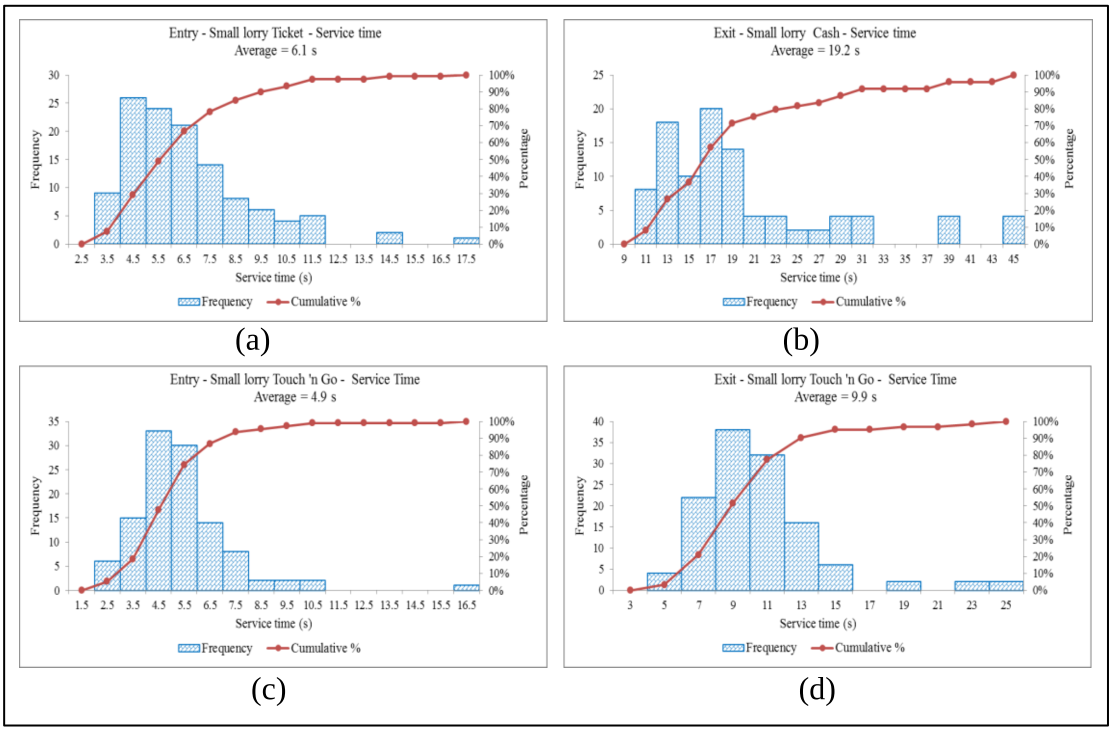


Figure B.1 Frequencies and cumulative curves of service time for Small lorry at Jawi toll plaza; (a) entry – ticket, (b) entry - Touch ´n Go, (c) exit – cash, (d) exit - Touch 'n Go.

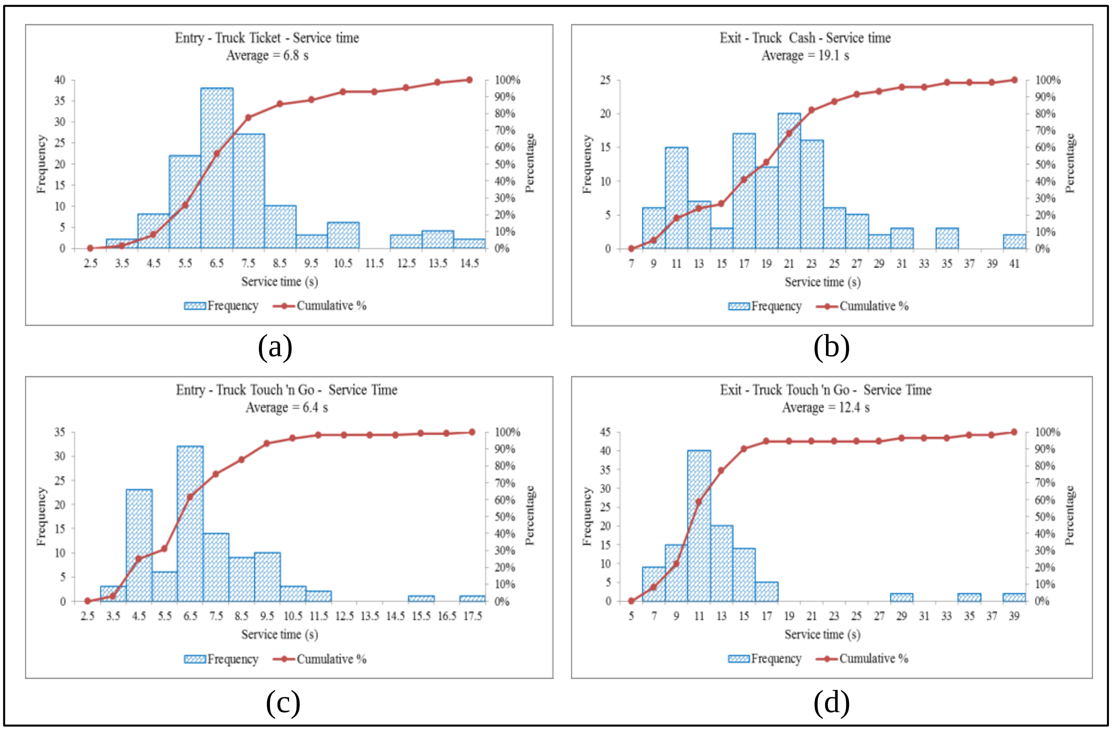


Figure B.2 Frequencies and cumulative curves of service time for Truck at Jawi toll plaza; (a) entry – ticket, (b)entry - Touch ´n Go, (c) exit – cash, (c) exit - Touch 'n Go.

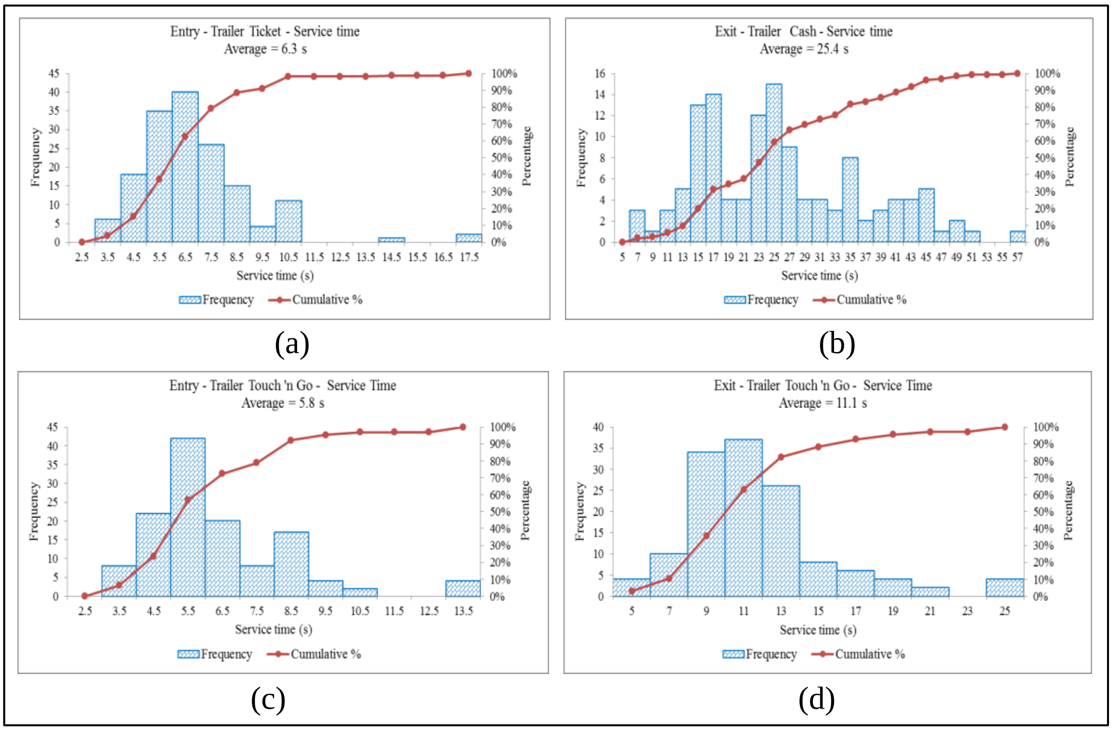


Figure B.3 Frequencies and cumulative curves of service time for Trailer at Jawi toll plaza; (a) entry – ticket, (b) entry - Touch ´n Go, (c) exit – cash, (d) exit - Touch 'n Go.

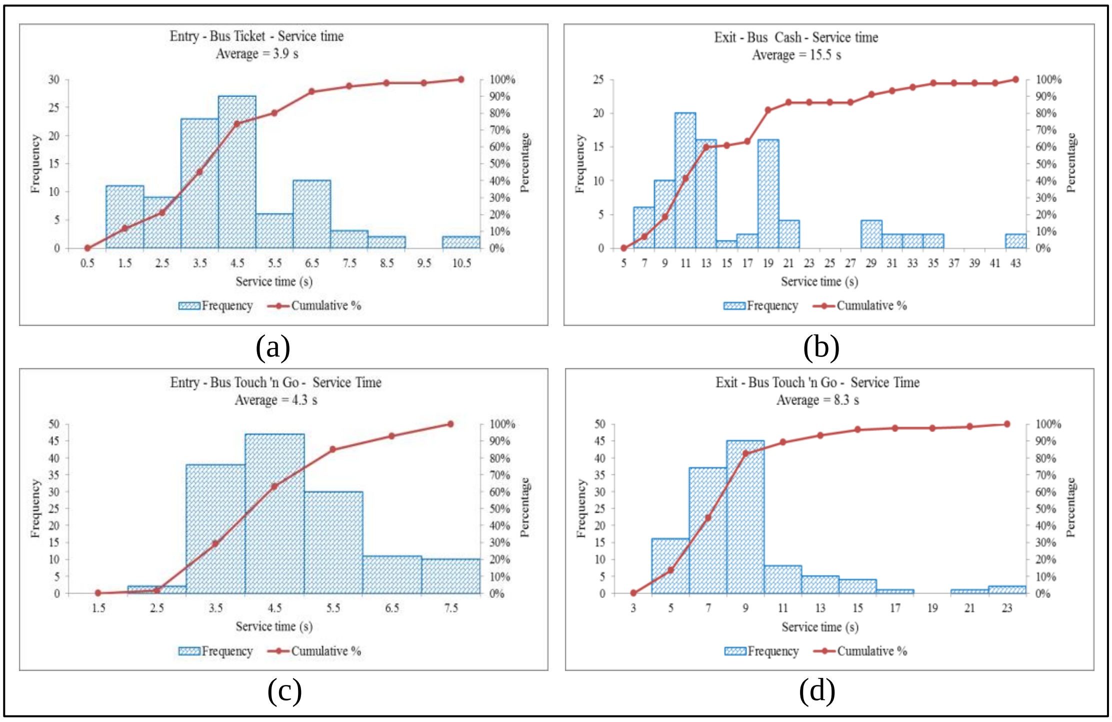
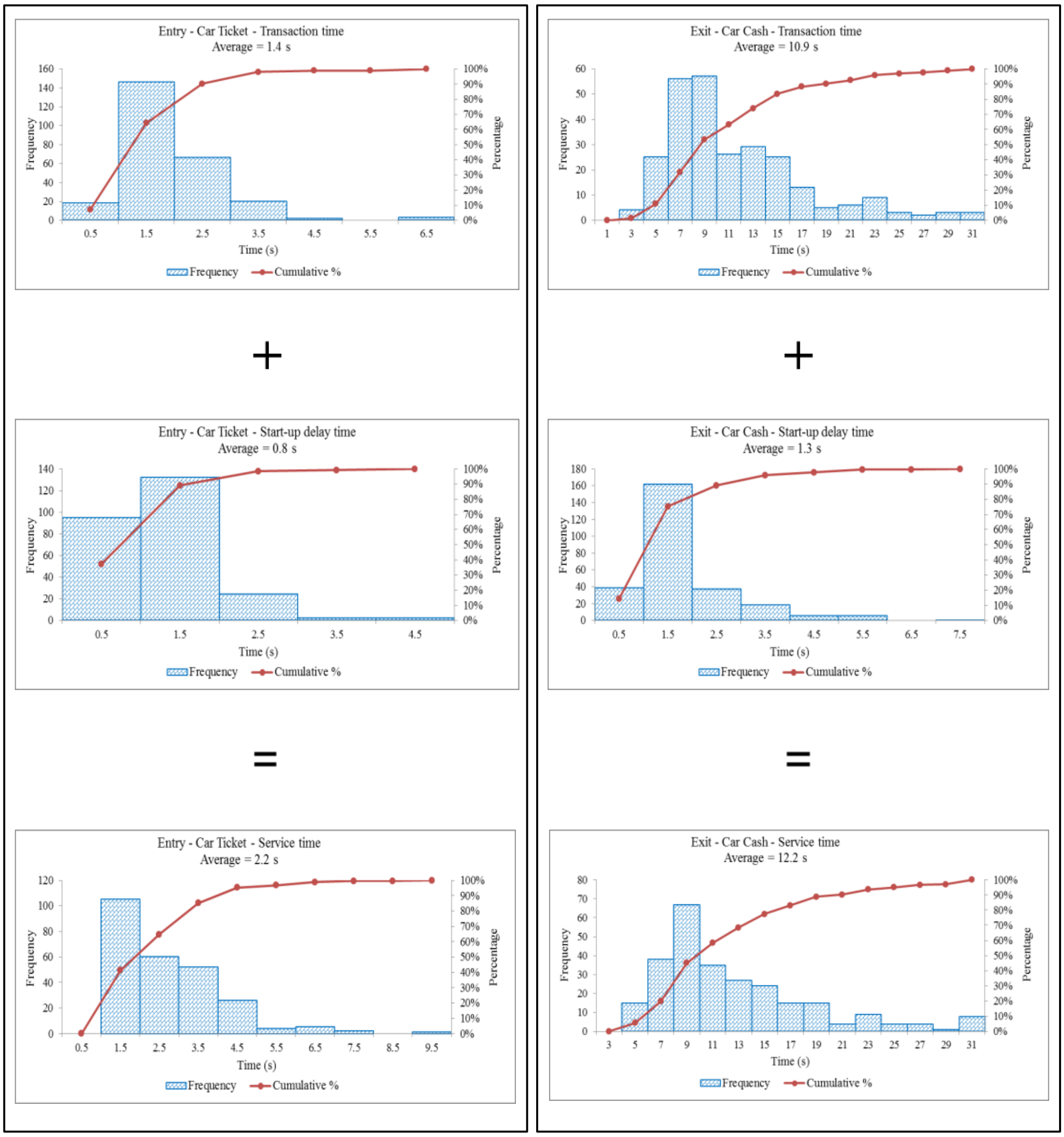
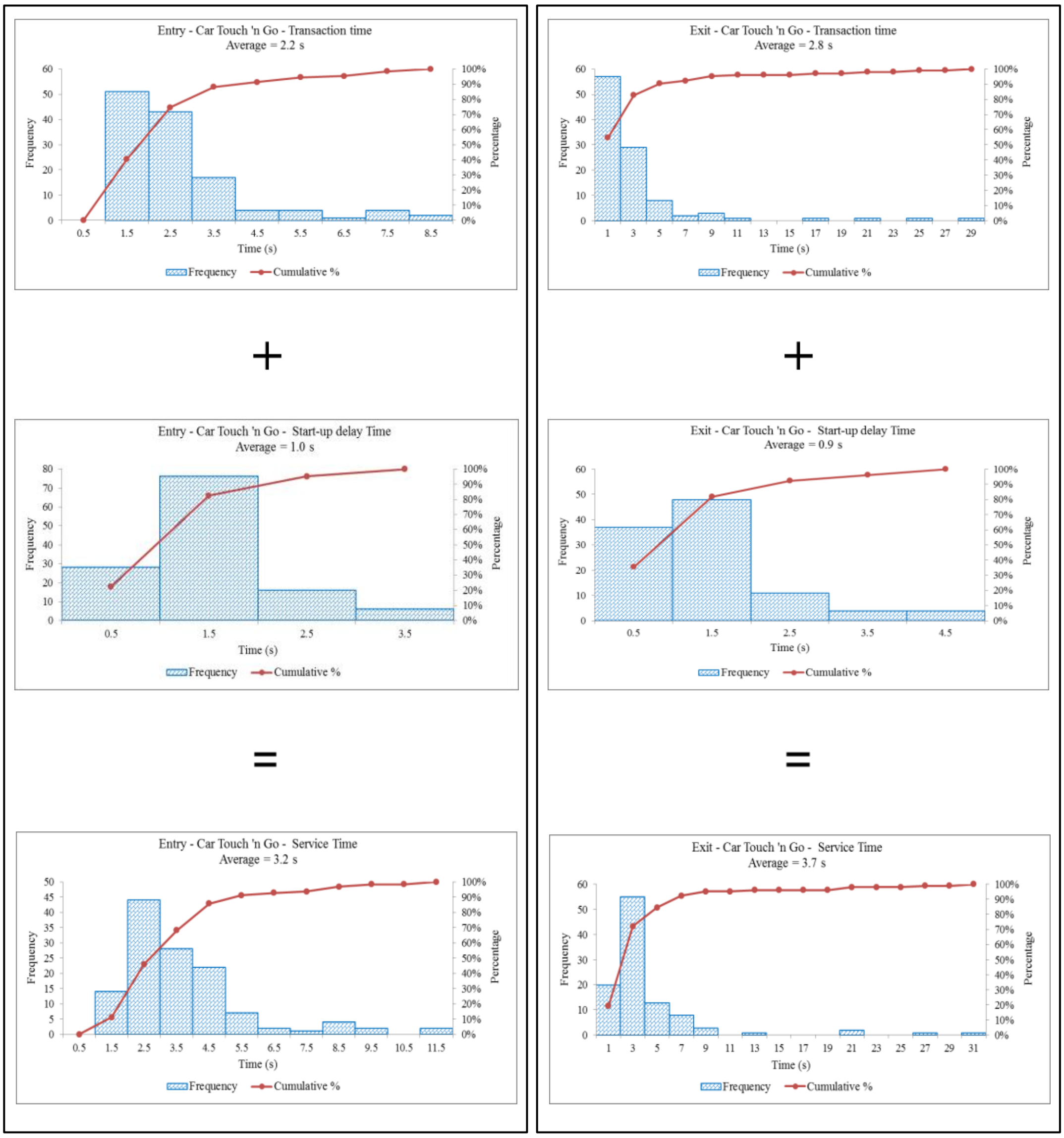


Figure B.4 Frequencies and cumulative curves of service time for Bus at Jawi toll plaza; (a) entry – ticket, (b) entry - Touch ´n Go, (c) exit – cash, (c) exit - Touch 'n Go.



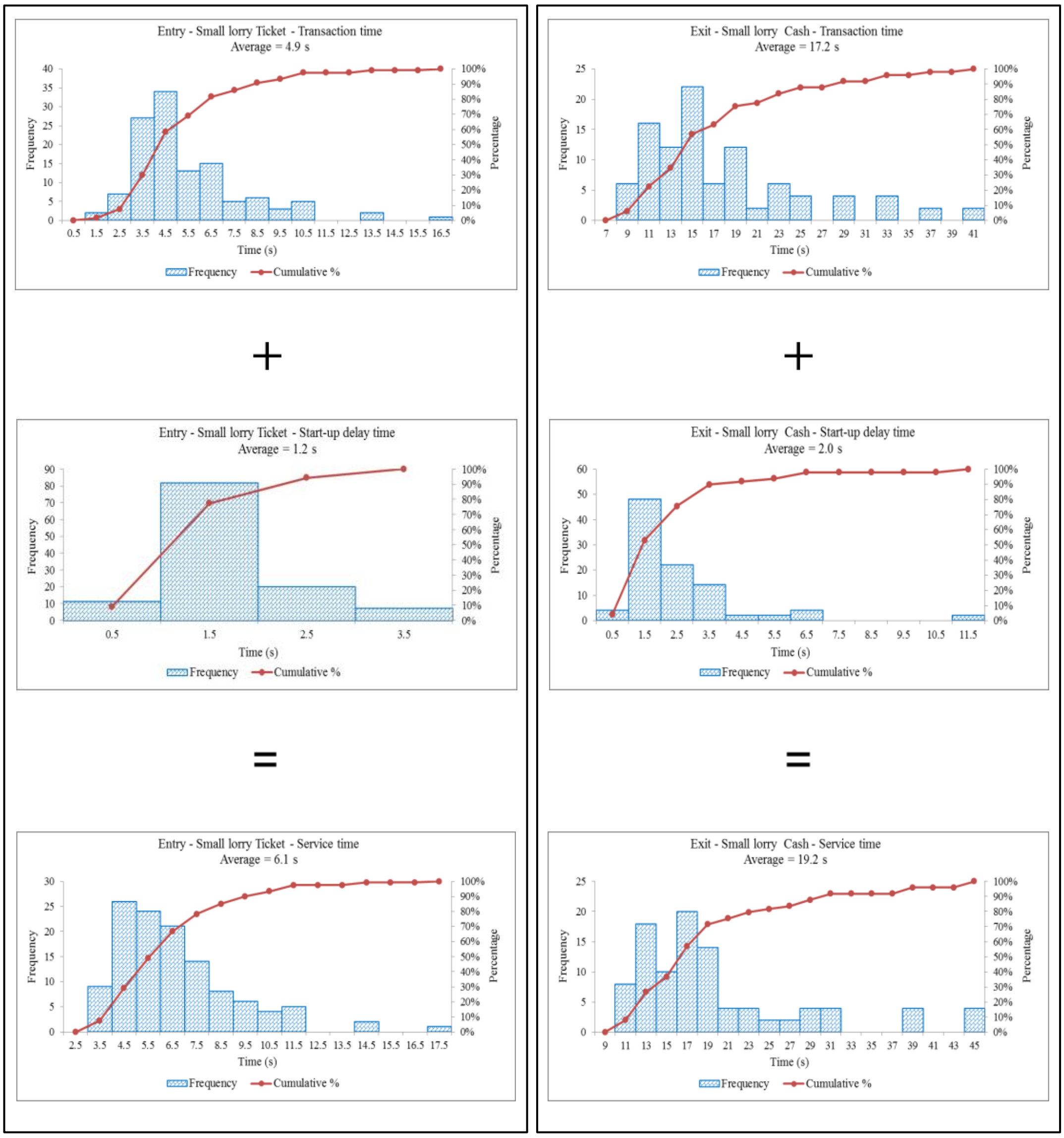
(a) (b)

Figure B.5 Frequencies and cumulative curves of transaction, start-up delay and service time for car at Jawi toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



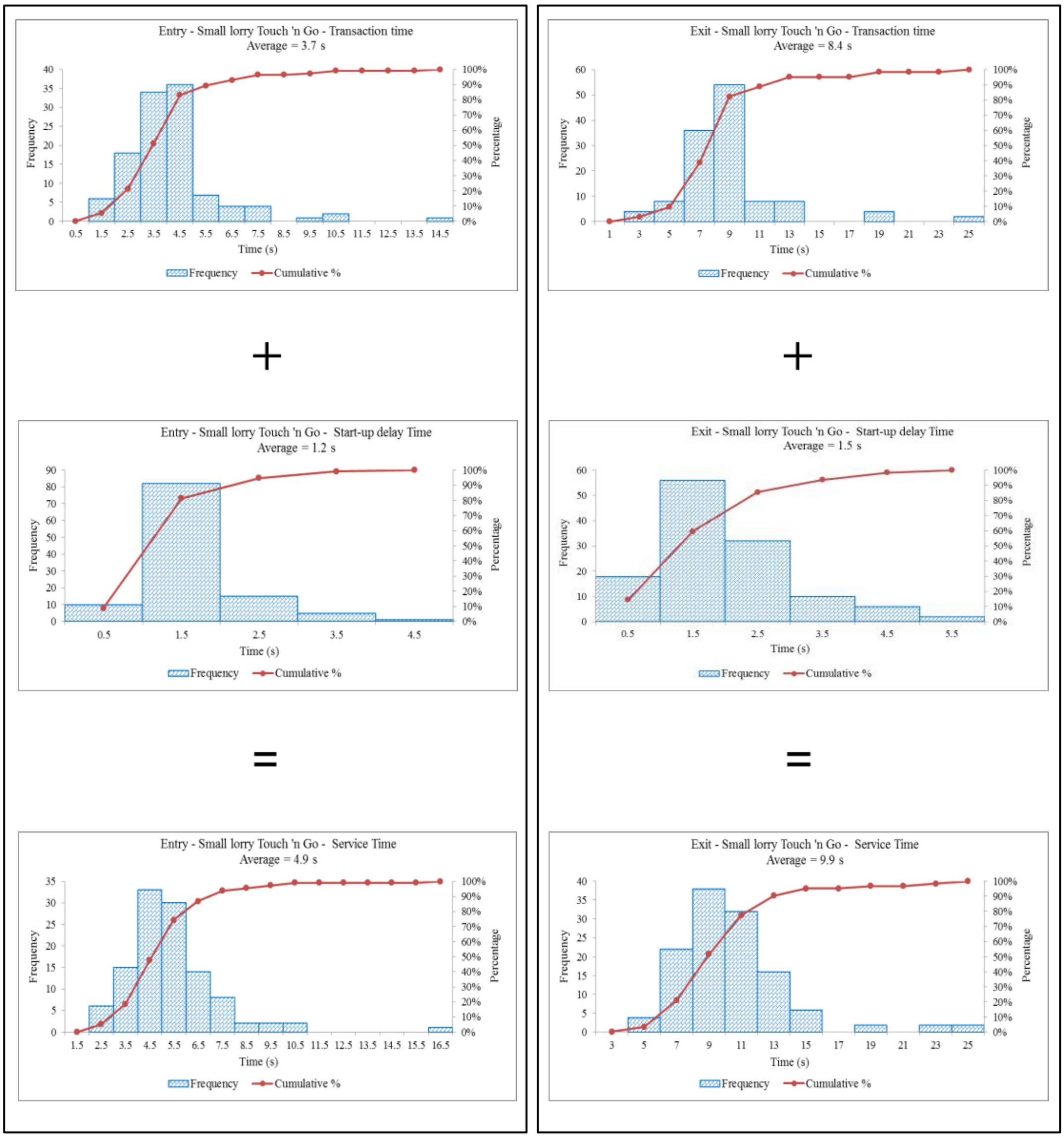
(a) (b)

Figure B.6 Frequencies and cumulative curves of transaction, start-up delay and service time for car – Touch 'n Go (multiclass lanes) at Jawi toll plaza; (a) Entry, (b) Exit.



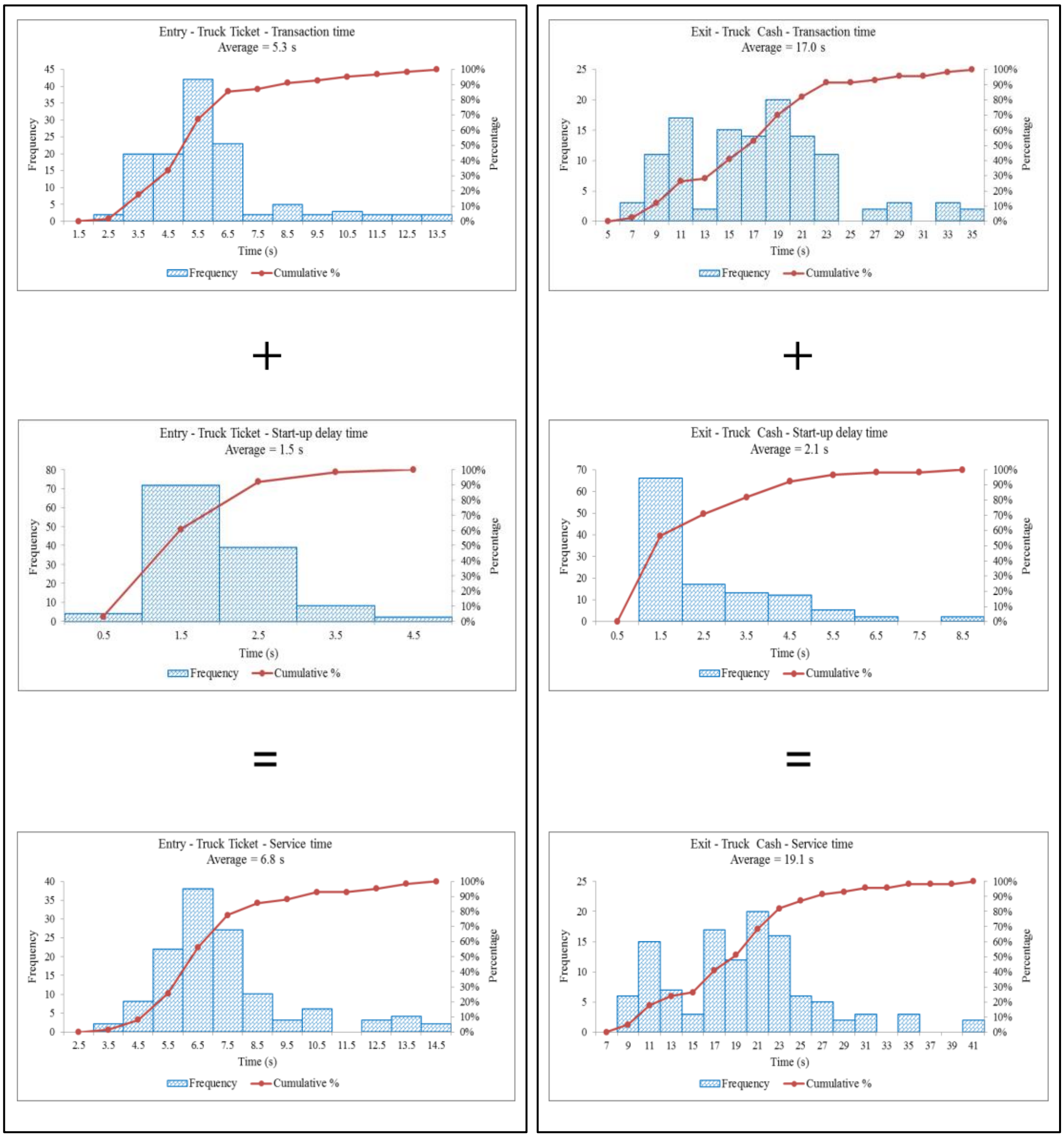
(a) (b)

Figure B.7 Frequencies and cumulative curves of transaction, start-up delay and service time for small lorry at Jawi toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



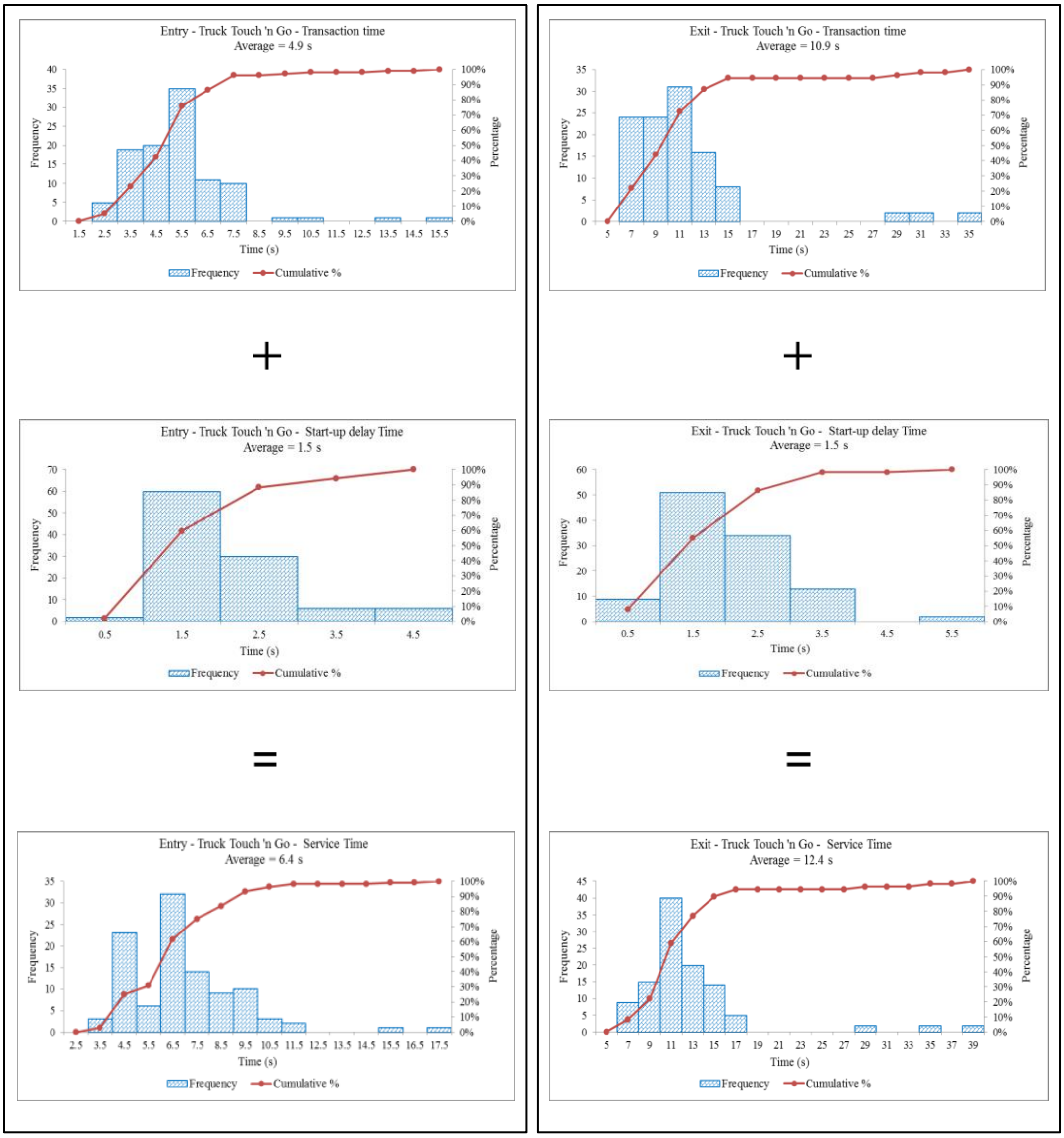
(a) (b)

Figure B.8 Frequencies and cumulative curves of transaction, start-up delay and service time for small lorry – Touch 'n Go (multiclass lanes) at Jawi toll plaza; (a) Entry, (b) Exit.



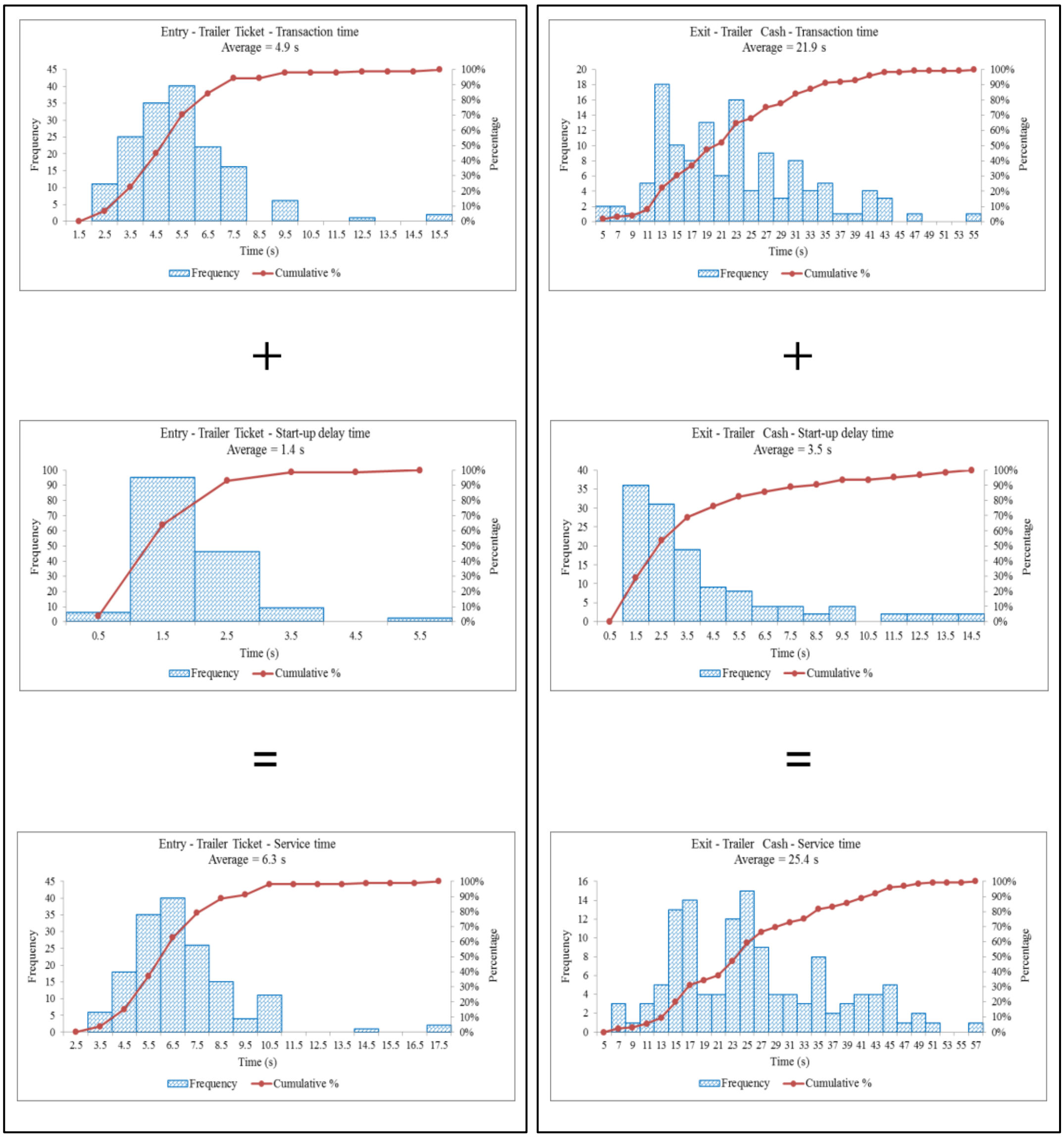
(a) (b)

Figure B.9 Frequencies and cumulative curves of transaction, start-up delay and service time for truck at Jawi toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



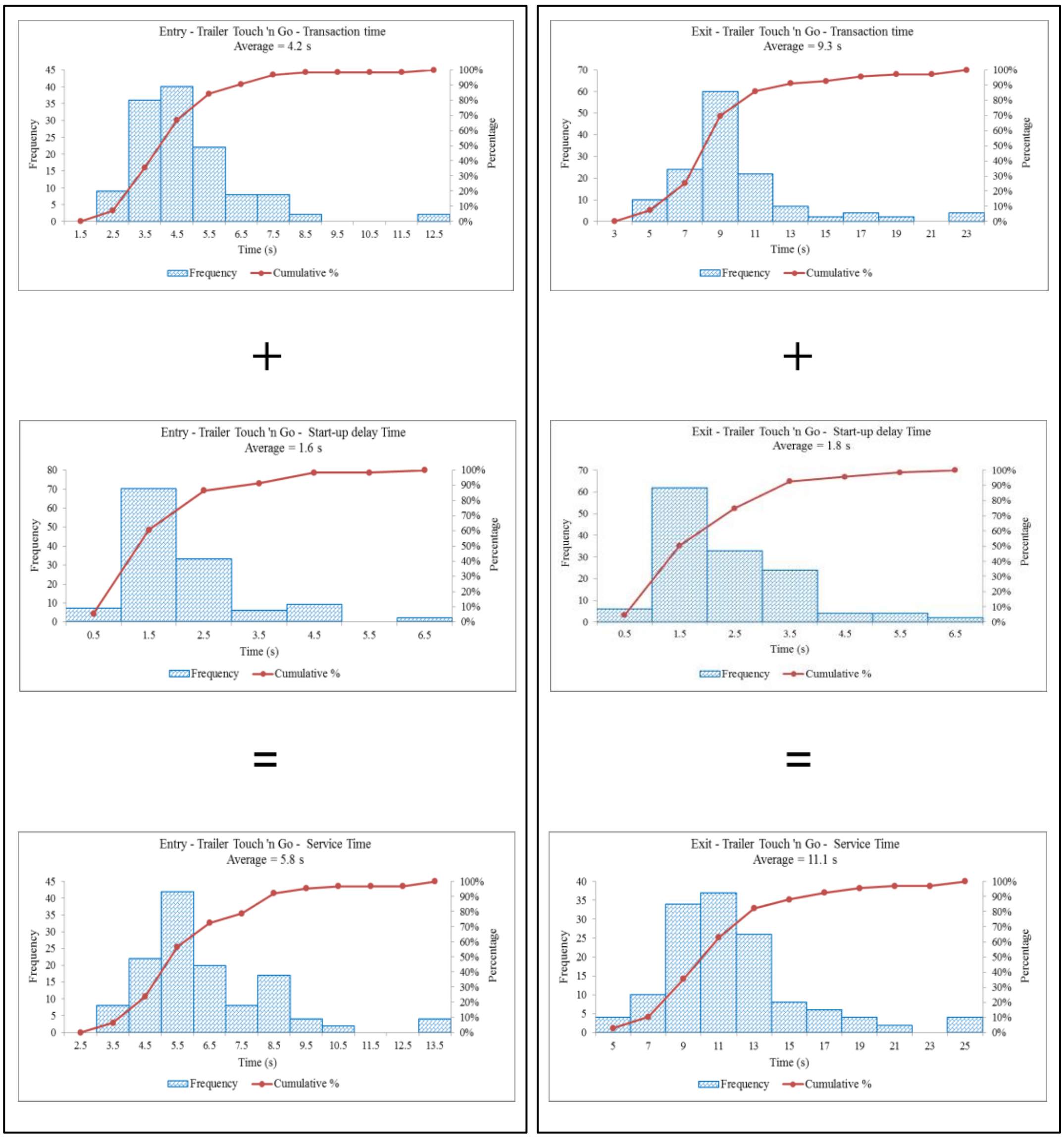
(a) (b)

Figure B.10 Frequencies and cumulative curves of transaction, start-up delay and service time for truck – Touch 'n Go (multiclass lanes) at Jawi toll plaza; (a) Entry, (b) Exit.



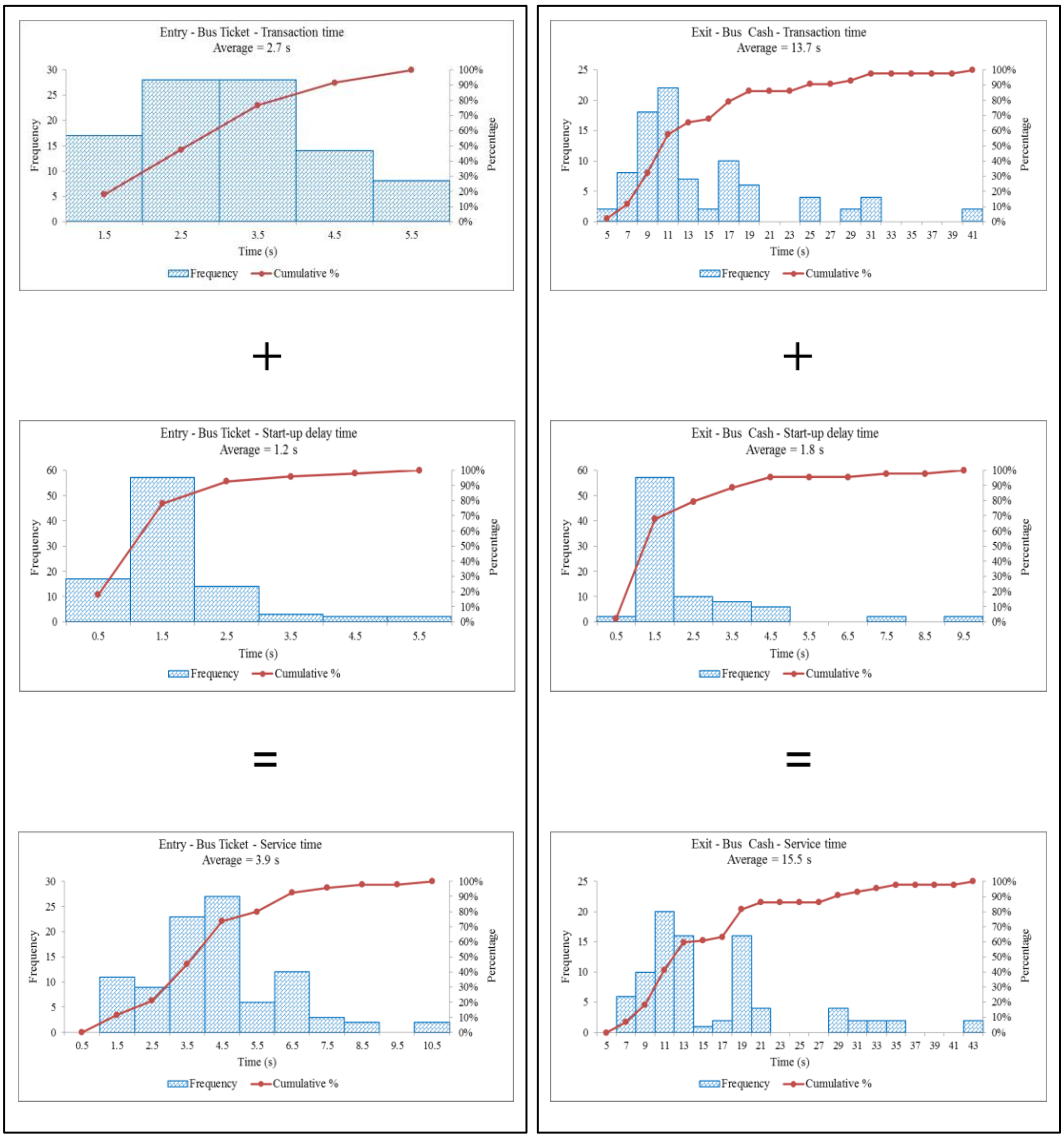
(a) (b)

Figure B.11 Frequencies and cumulative curves of transaction, start-up delay and service time for trailer at Jawi toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



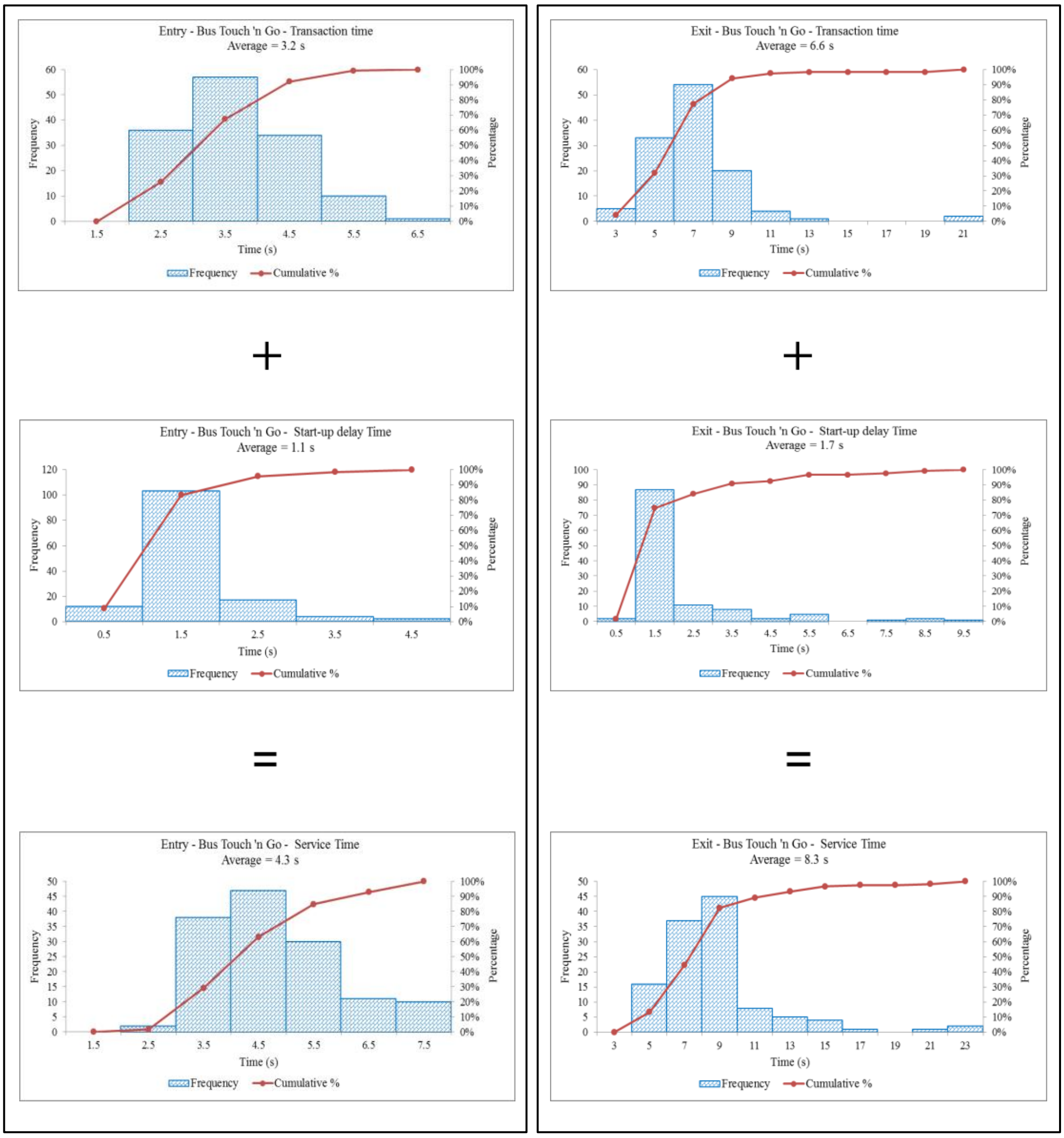
(a) (b)

Figure B.12 Frequencies and cumulative curves of transaction, start-up delay and service time for trailer – Touch 'n Go (multiclass lanes) at Jawi toll plaza; (a) Entry, (b) Exit.



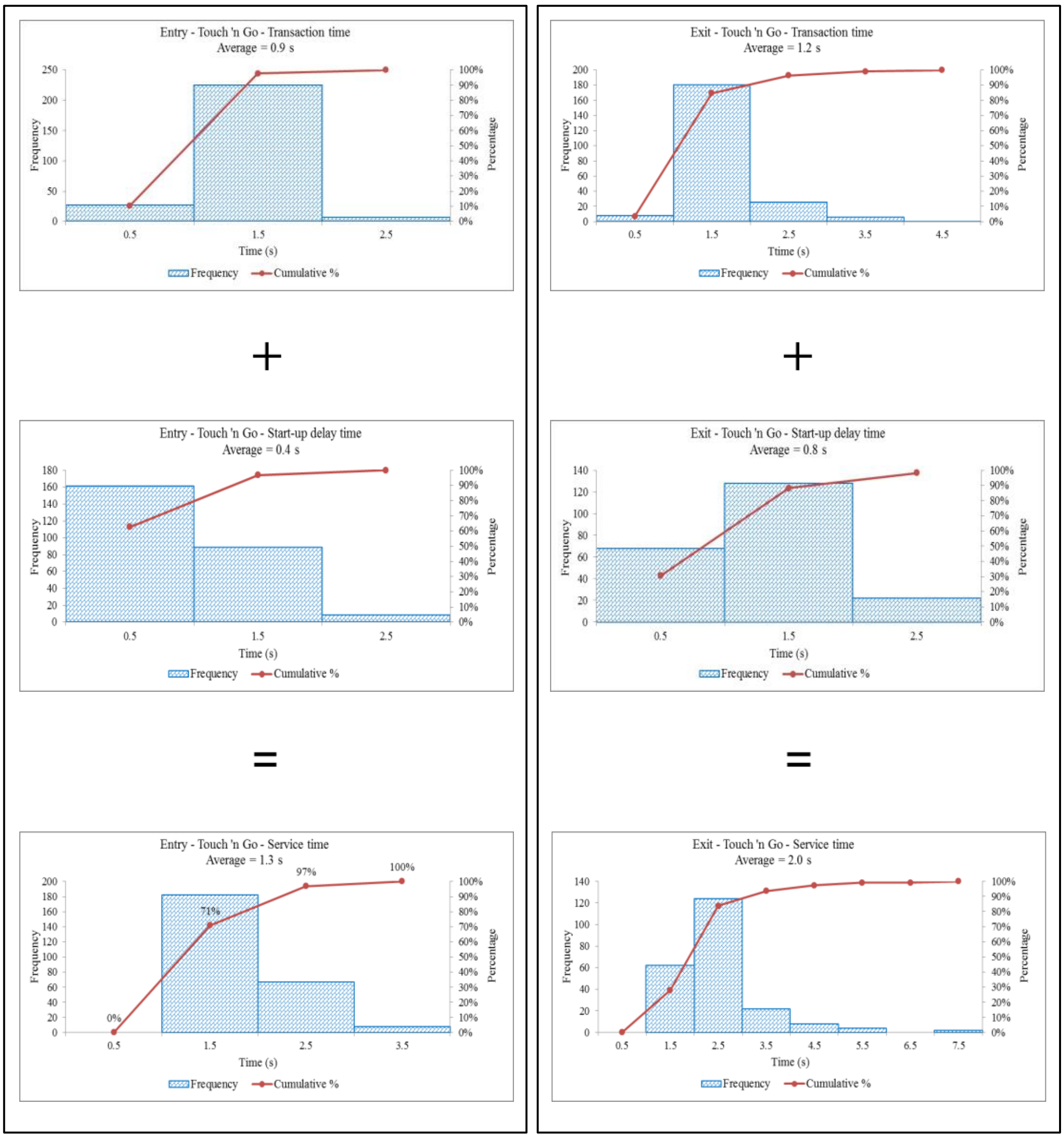
(a) (b)

Figure B.13 Frequencies and cumulative curves of transaction, start-up delay and service time for bus at Jawi toll plaza; (a) Entry - Ticket, (b) Exit - Cash.



(a) (b)

Figure B.14 Frequencies and cumulative curves of transaction, start-up delay and service time for bus – Touch 'n Go (multiclass lanes) at Jawi toll plaza; (a) Entry, (b) Exit.



(a) (b)

Figure B.15 Frequencies and cumulative curves of service time for Touch 'n Go – Single class lanes at Jawi toll plaza; (a) Entry, (b) Exit.

Appendix C Development of toll plaza models inputs

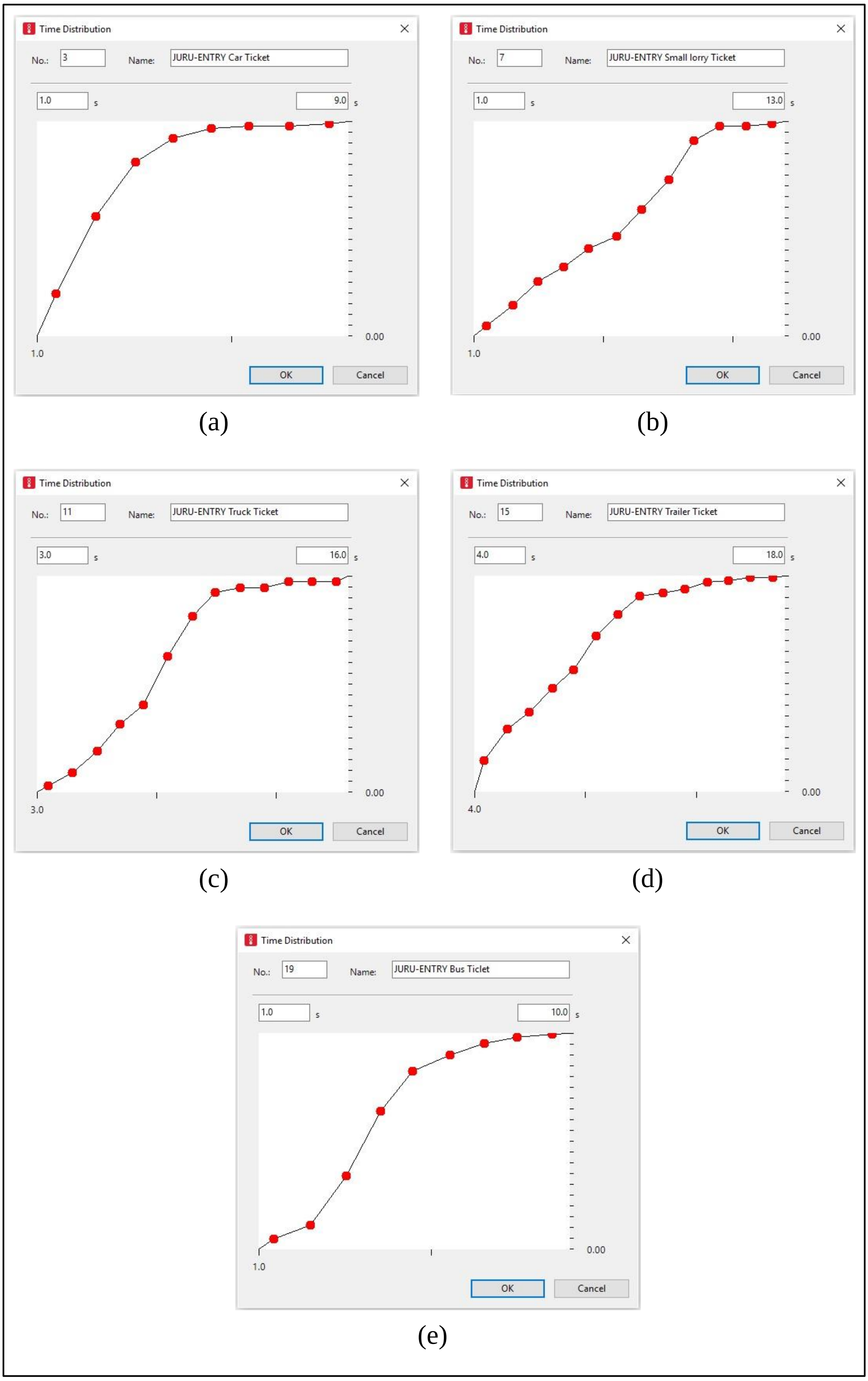


Figure C.1 Service time distribution for vehicle types at multiclass lane – Juru toll plaza - Entry - Ticket; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

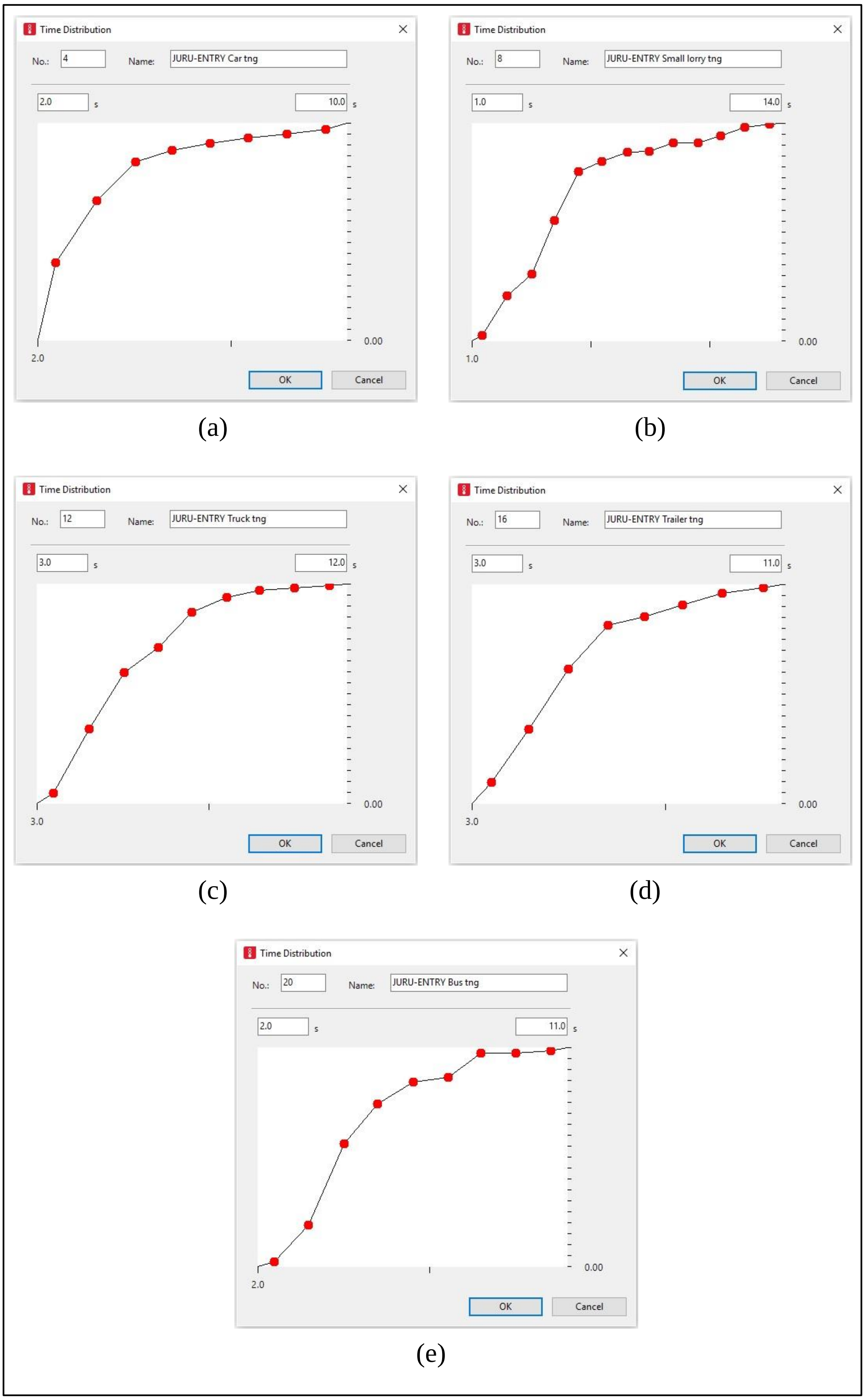


Figure C.2 Service time distribution for vehicle types at multiclass lane – Juru toll plaza - Entry – Touch ´n Go; (a) Car, (b) Small lorry, (c) Truck,(d) Trailer, (e) Bus.

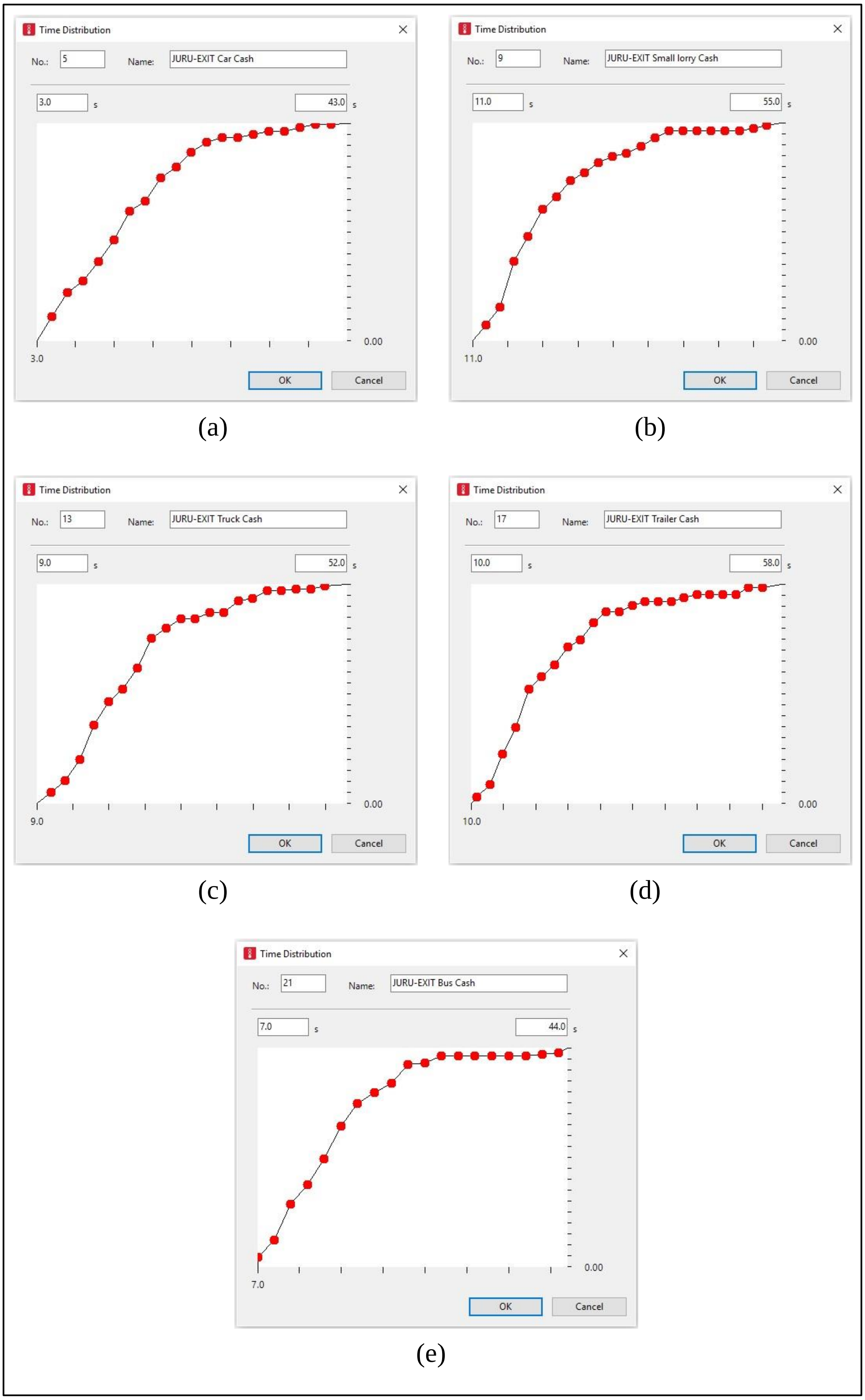


Figure C.3 Service time distribution for vehicle types at multiclass lane – Juru toll plaza - Exit – Cash; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

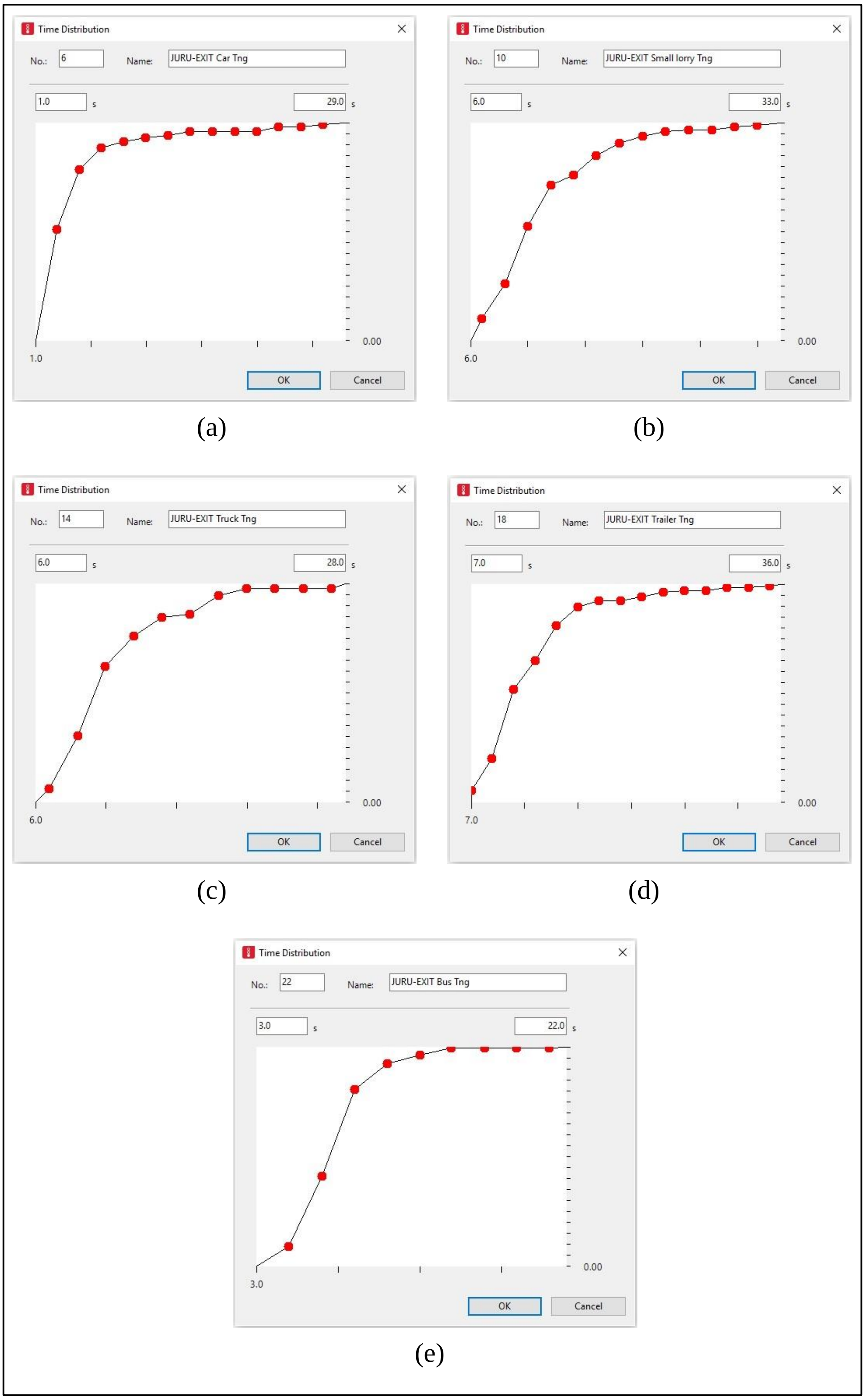


Figure C.4 Service time distribution for vehicle types at multiclass lane – Juru toll plaza - Exit – Touch 'n Go; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

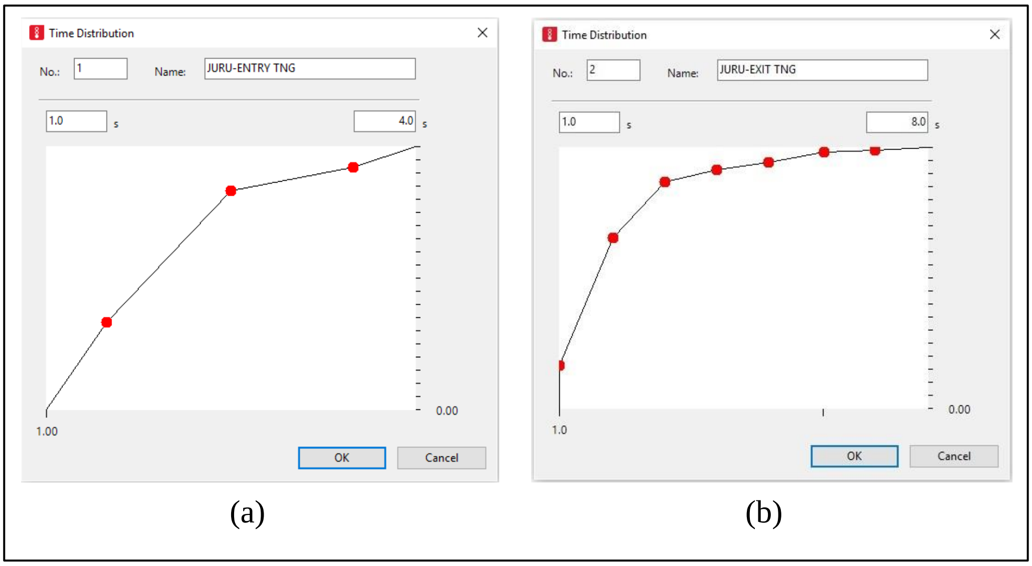


Figure C.5 Service time distribution for Car Touch ´n Go at single class lane – Juru toll plaza; (a) Entry, (b) Exit.

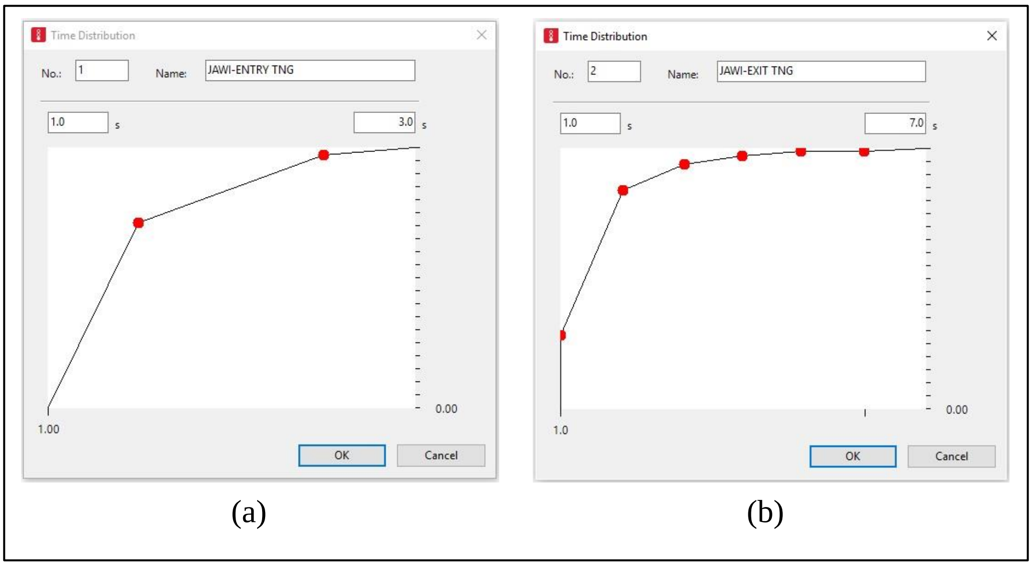


Figure C.6 Service time distribution for Car Touch ´n Go at single class lane – Jawi toll plaza; (a) Entry, (b) Exit.

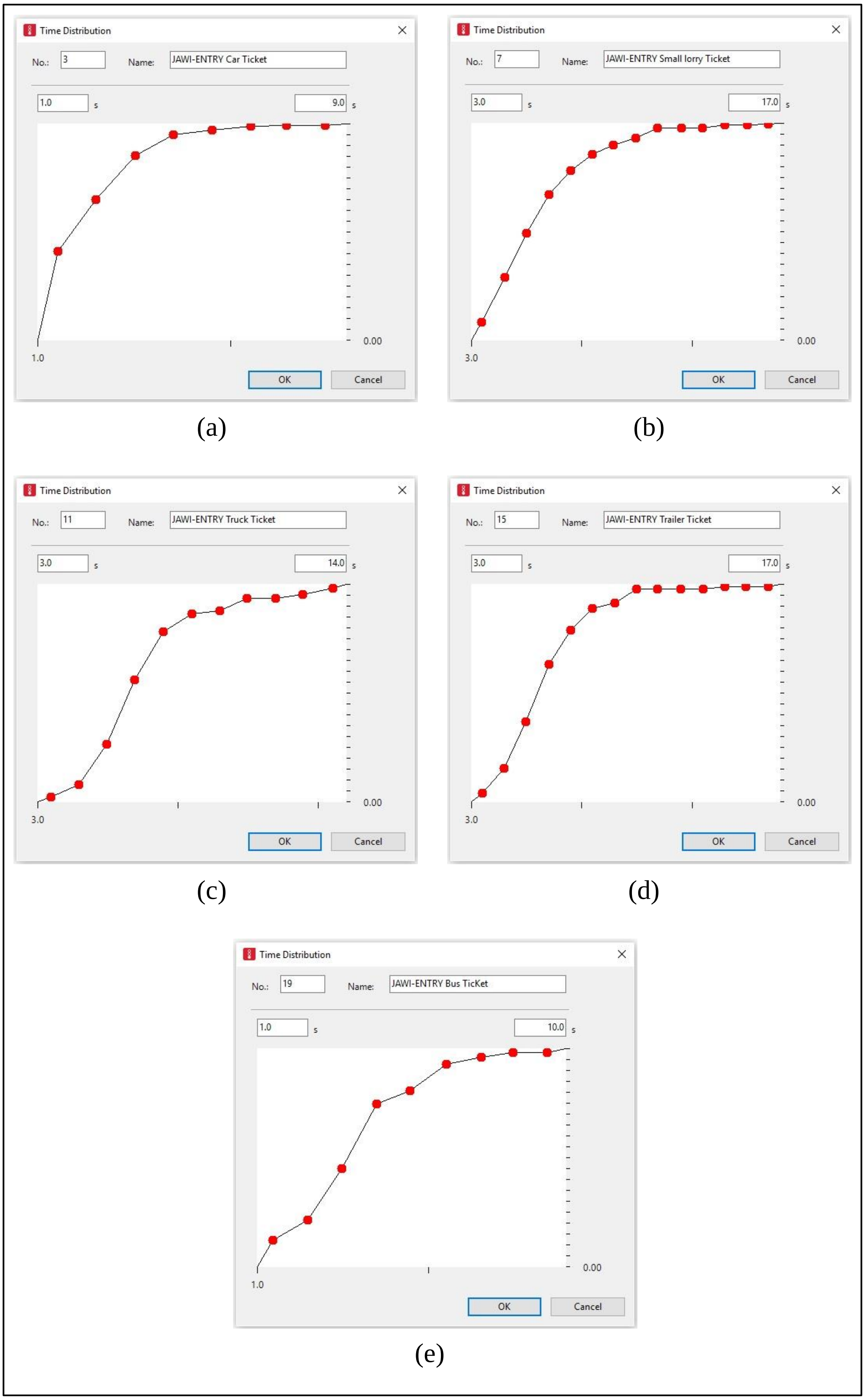


Figure C.7 Service time distribution for vehicle types at multiclass lane – Jawi toll plaza - Entry – Ticket; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

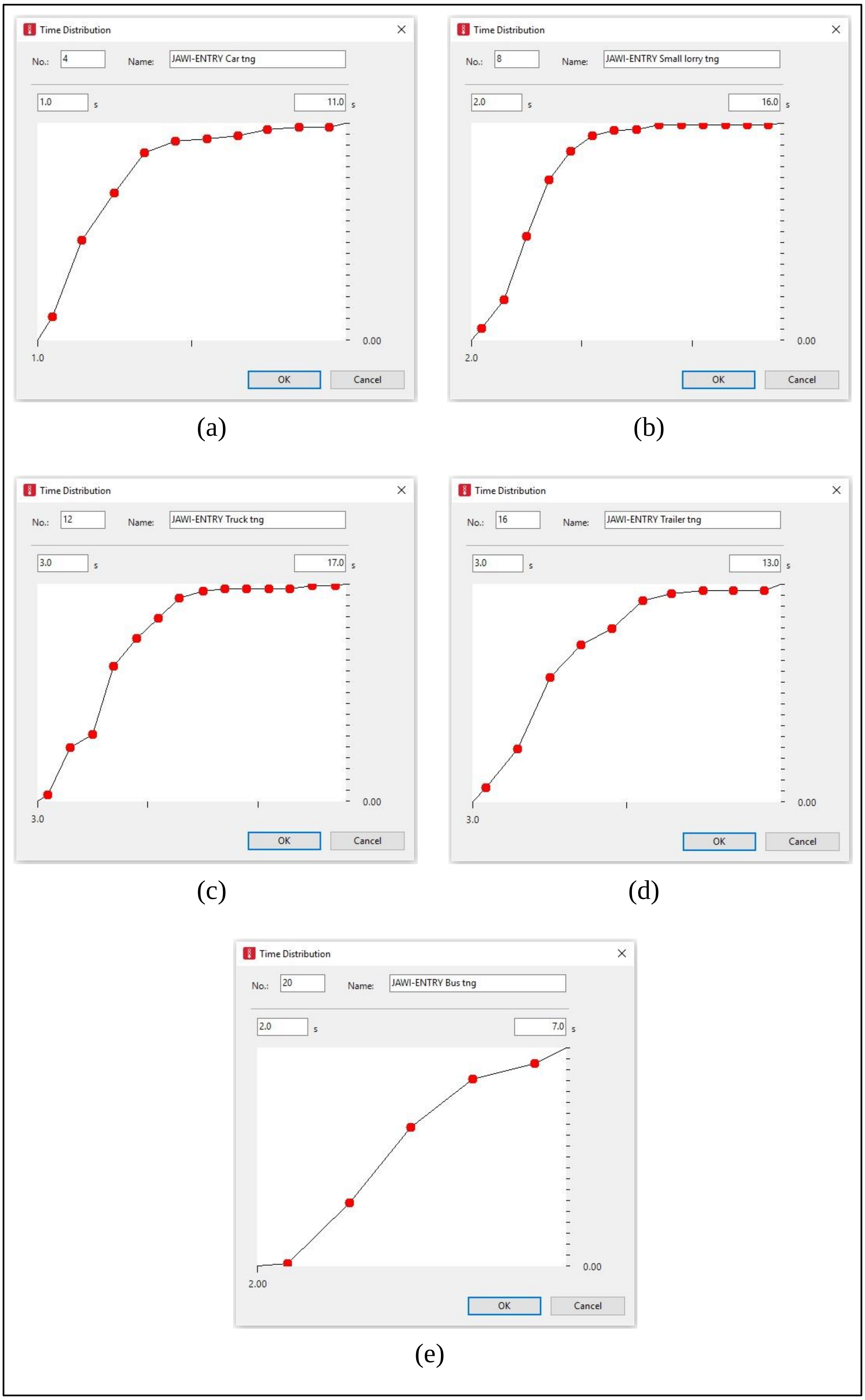


Figure C.8 Service time distribution for vehicle types at multiclass lane – Jawi toll plaza - Entry – Touch 'n Go; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

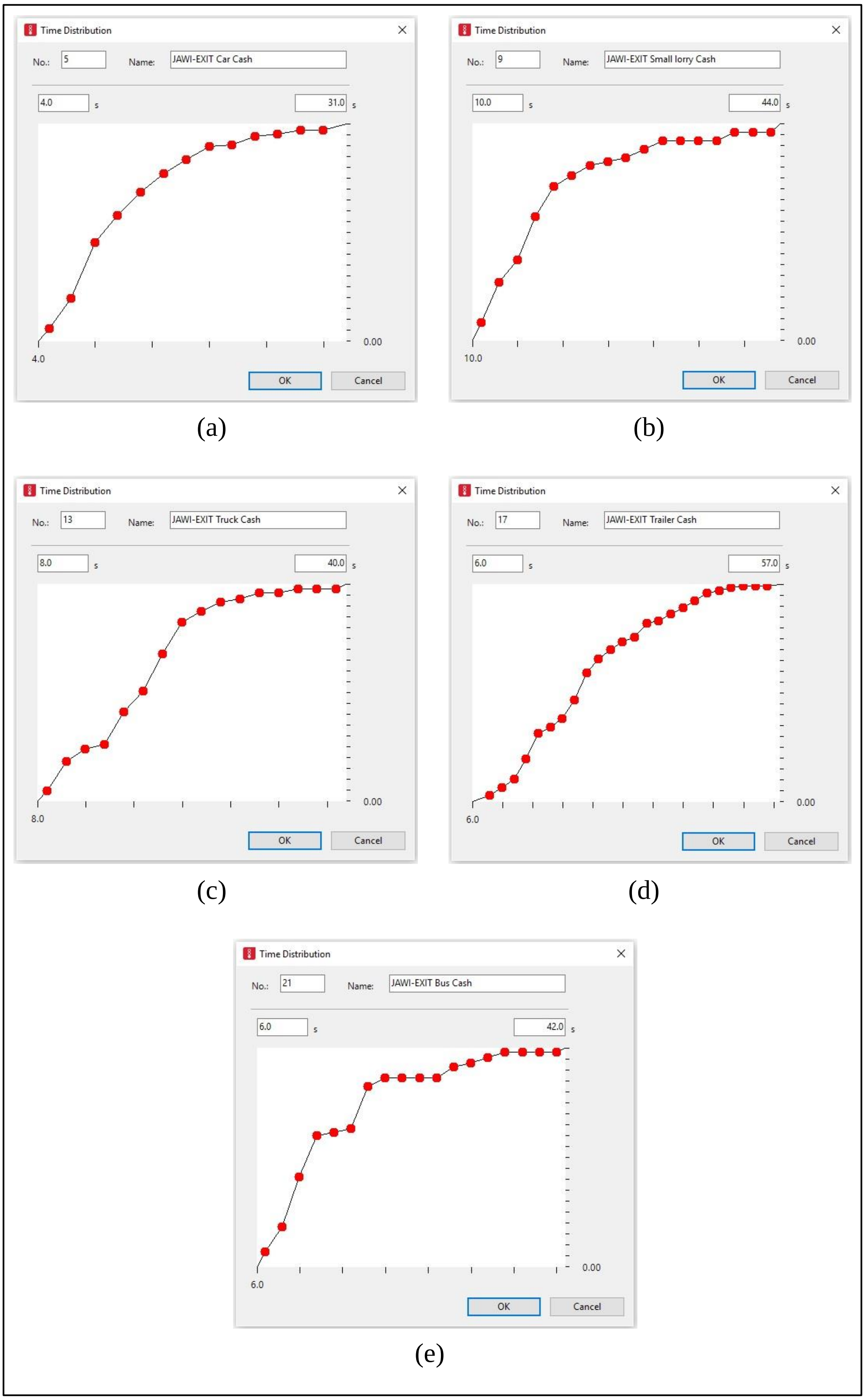


Figure C.9 Service time distribution for vehicle types at multiclass lane – Jawi toll plaza - Exit – Cash; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

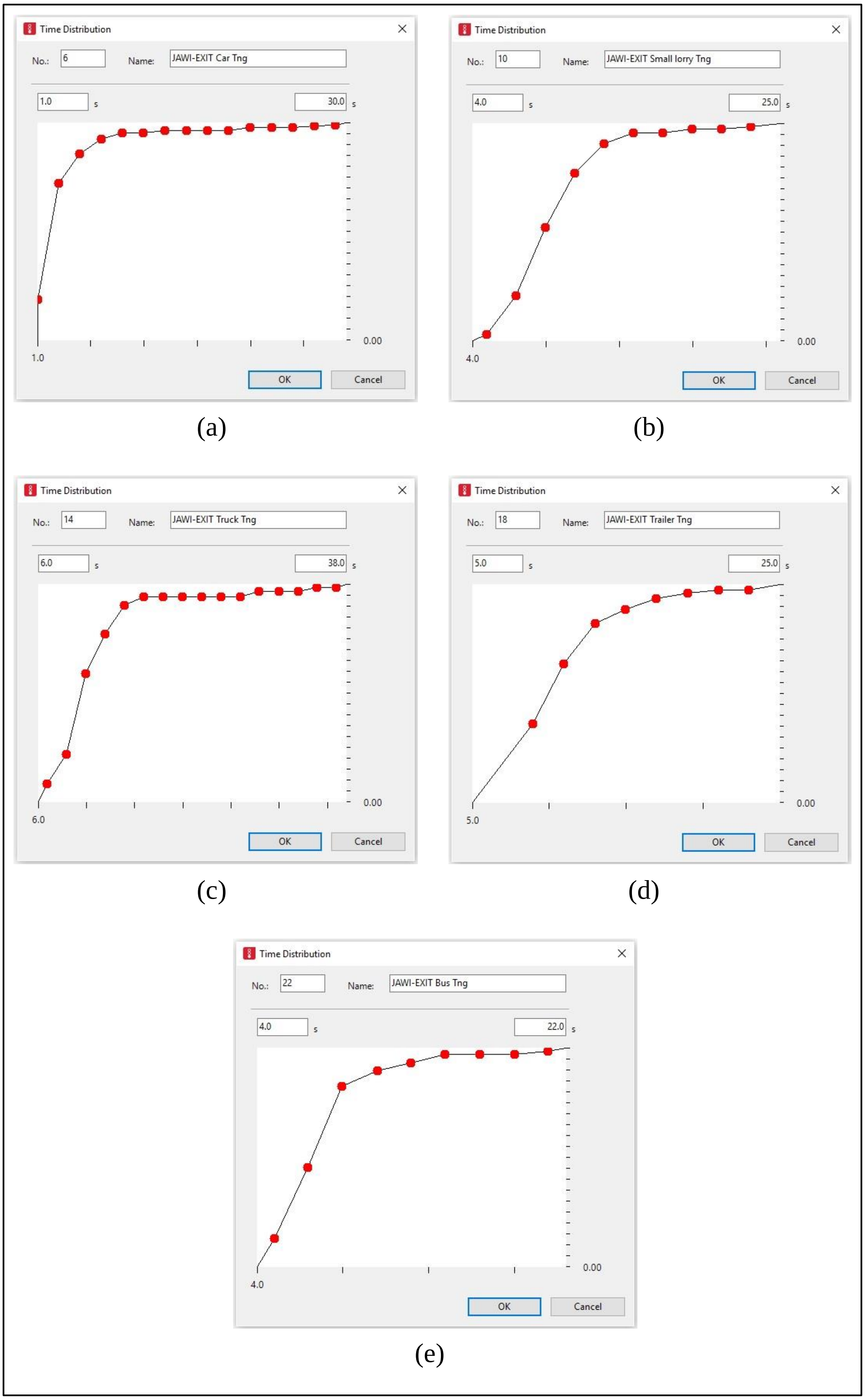


Figure C.10 Service time distribution for vehicle types at multiclass lane – Jawi toll plaza - Exit – Touch 'n Go; (a) Car, (b) Small lorry, (c) Truck, (d) Trailer, (e) Bus.

Appendix D Images of the results for the simulation models

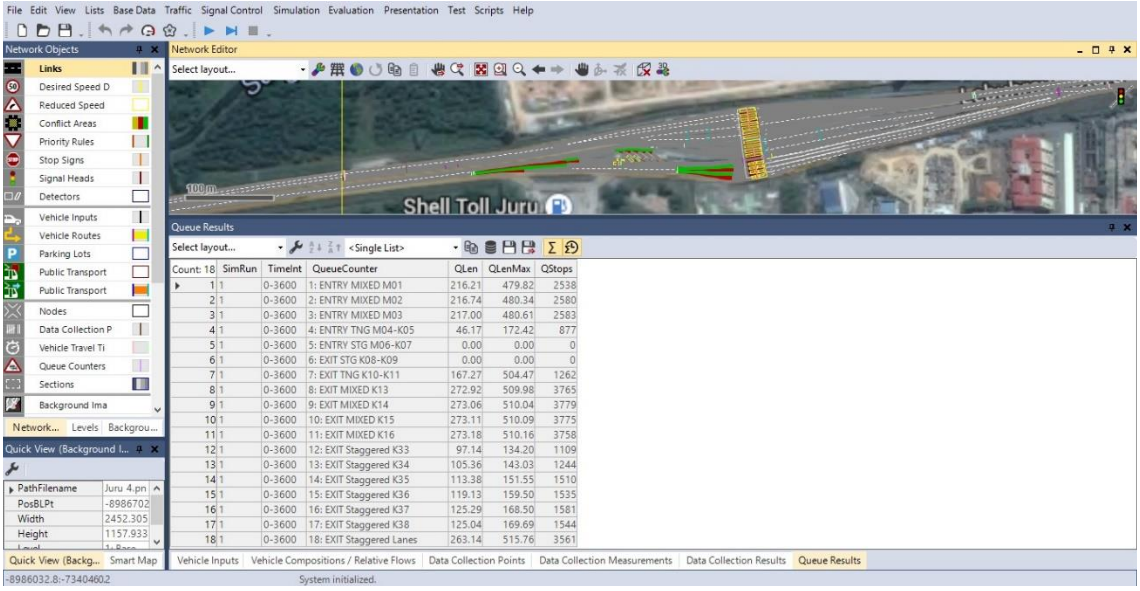


Figure D.1 Simulation results for Juru toll plaza model 12% HGV with high traffic volume

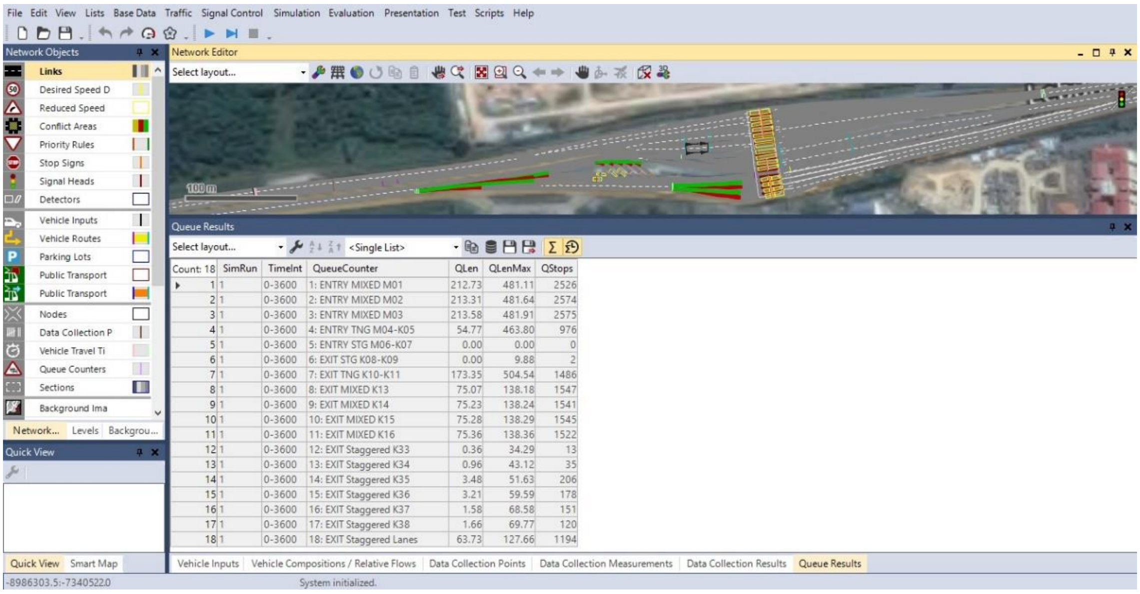


Figure D.2 Simulation results for Juru toll plaza model 12% HGV with high traffic volume _ Full ETC

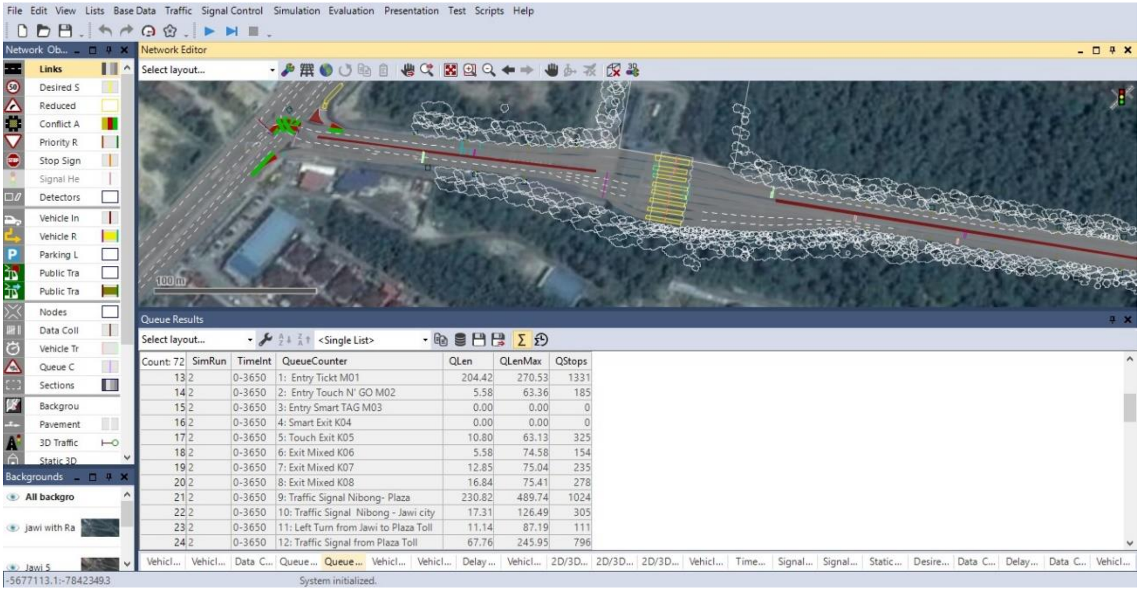


Figure D.3 Simulation results for Jawi toll plaza model 12% HGV with normal traffic volume

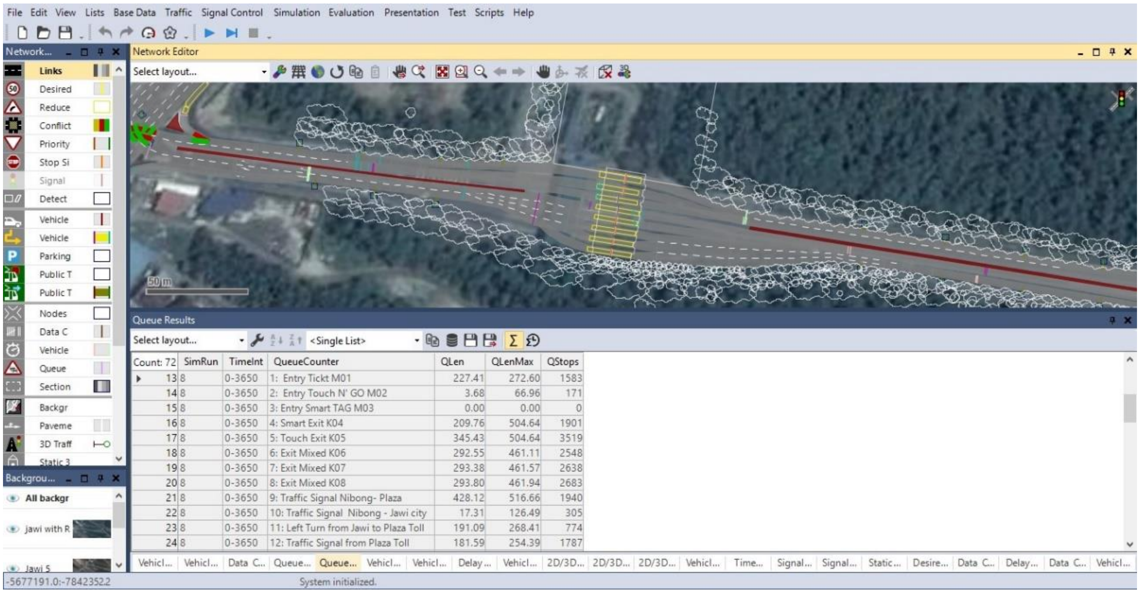


Figure D.4 Simulation results for Jawi toll plaza model 12% HGV with high traffic volume

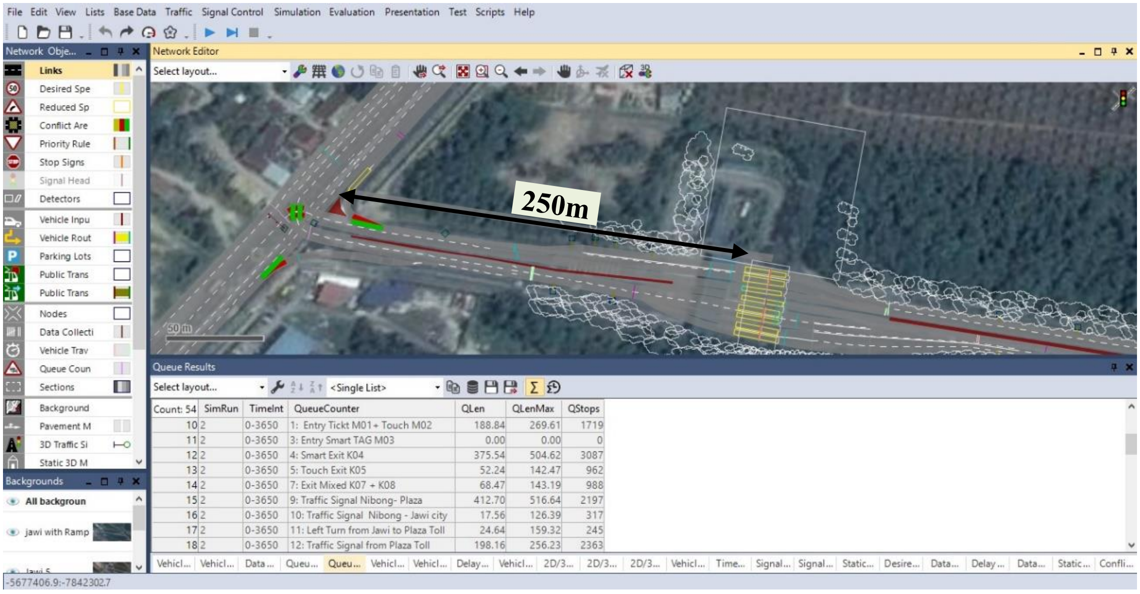


Figure D.5 Simulation results for Jawi toll plaza model 12% HGV with high traffic volume _ Full ETC_ distance between junction and Jawi toll plaza 250m

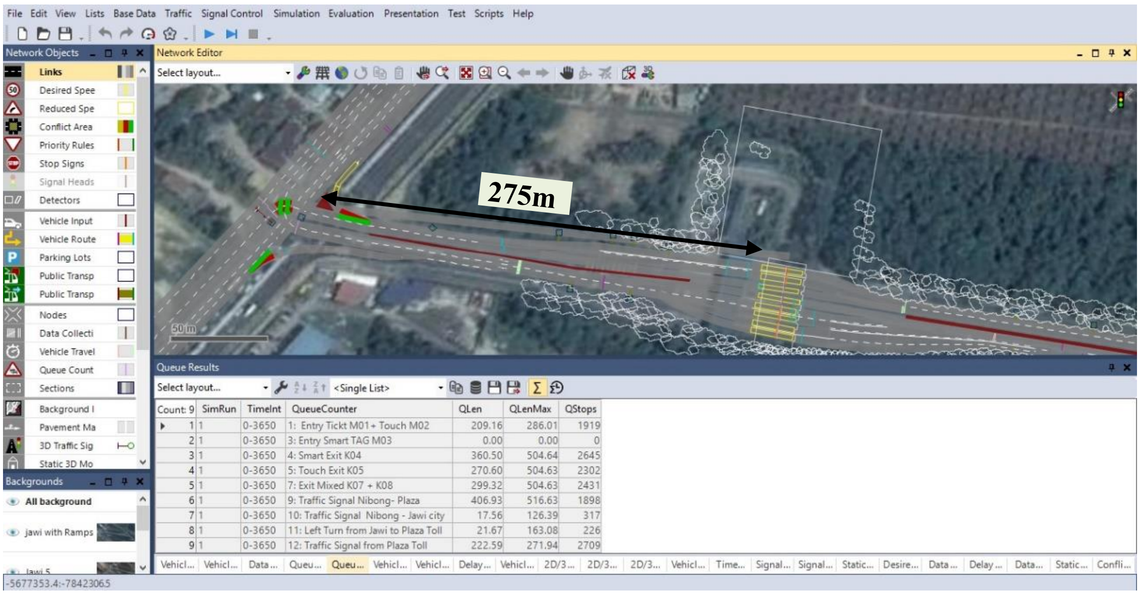


Figure D.6 Simulation results for Jawi toll plaza model 12% HGV with high traffic volume _ Full ETC_ distance between junction and Jawi toll plaza 275m

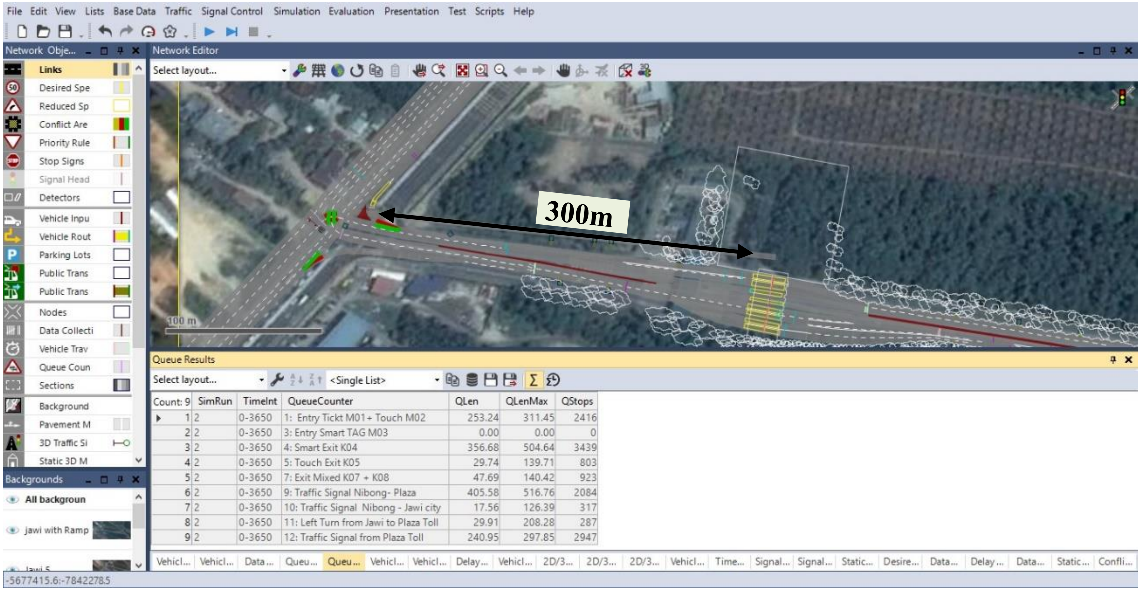


Figure D.7 Simulation results for Jawi toll plaza model 12% HGV with high traffic volume _ Full ETC_ distance between junction and Jawi toll plaza 300m

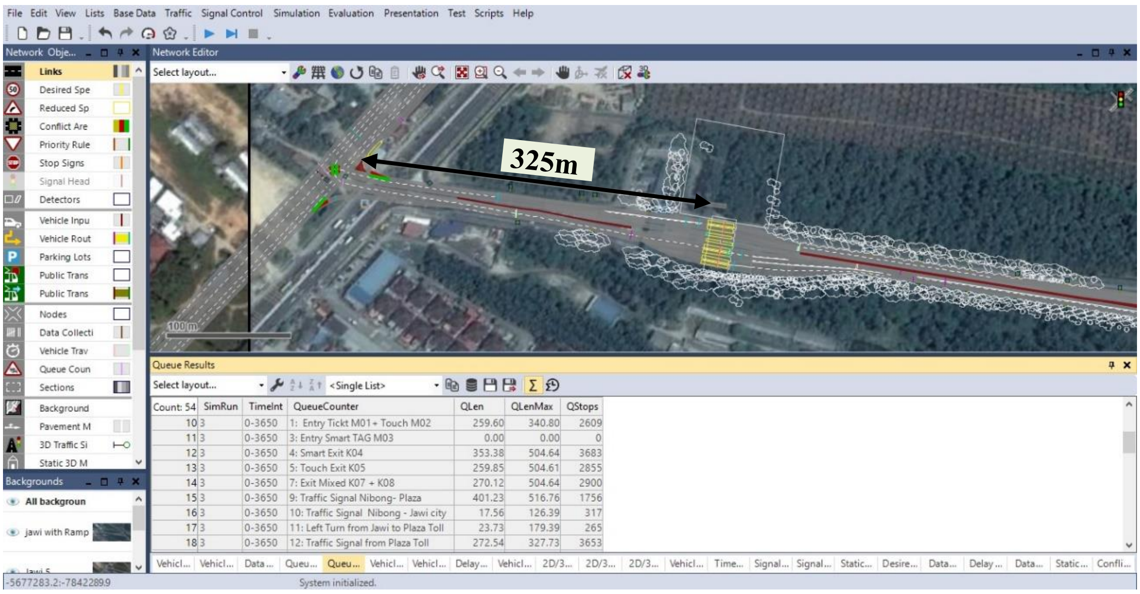


Figure D.8 Simulation results for Jawi toll plaza model 12% HGV with high traffic volume _ Full ETC_ distance between junction and Jawi toll plaza 325m

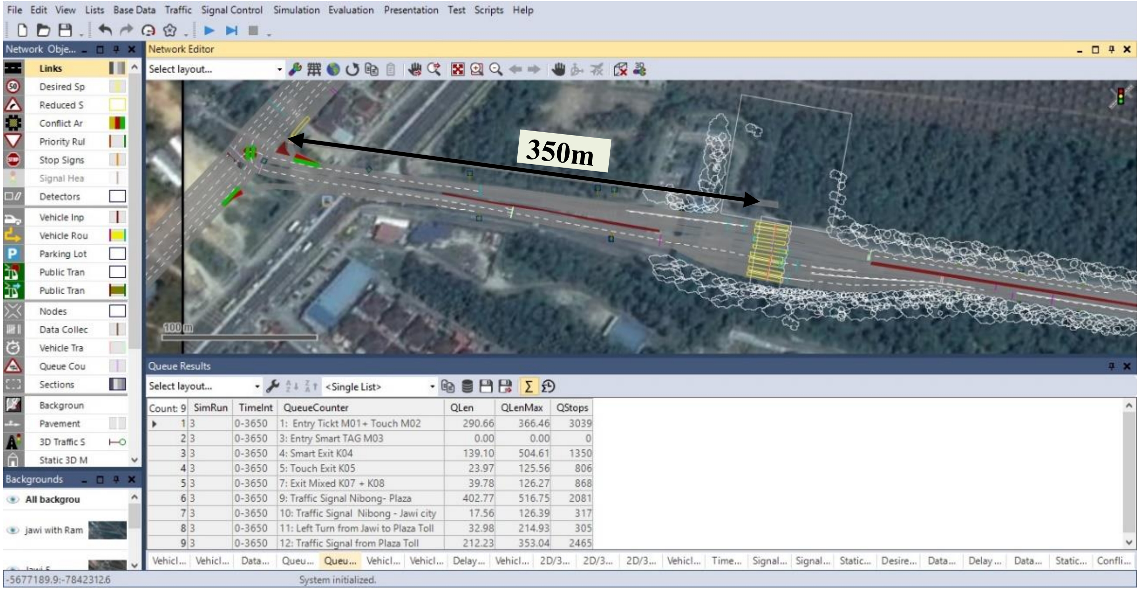


Figure D.9 Simulation results for Jawi toll plaza model 12% HGV with high traffic volume _ Full ETC_ distance between junction and Jawi toll plaza 350m

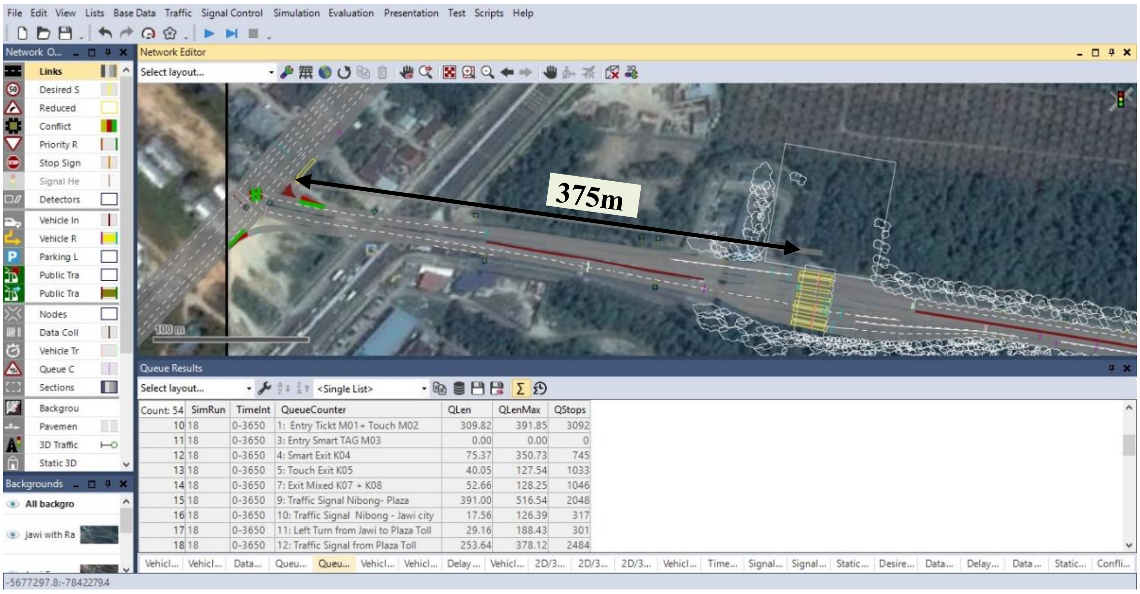


Figure D.10 Simulation results for Jawi toll plaza model 12% HGV with high traffic volume _ Full ETC_ distance between junction and Jawi toll plaza 375m

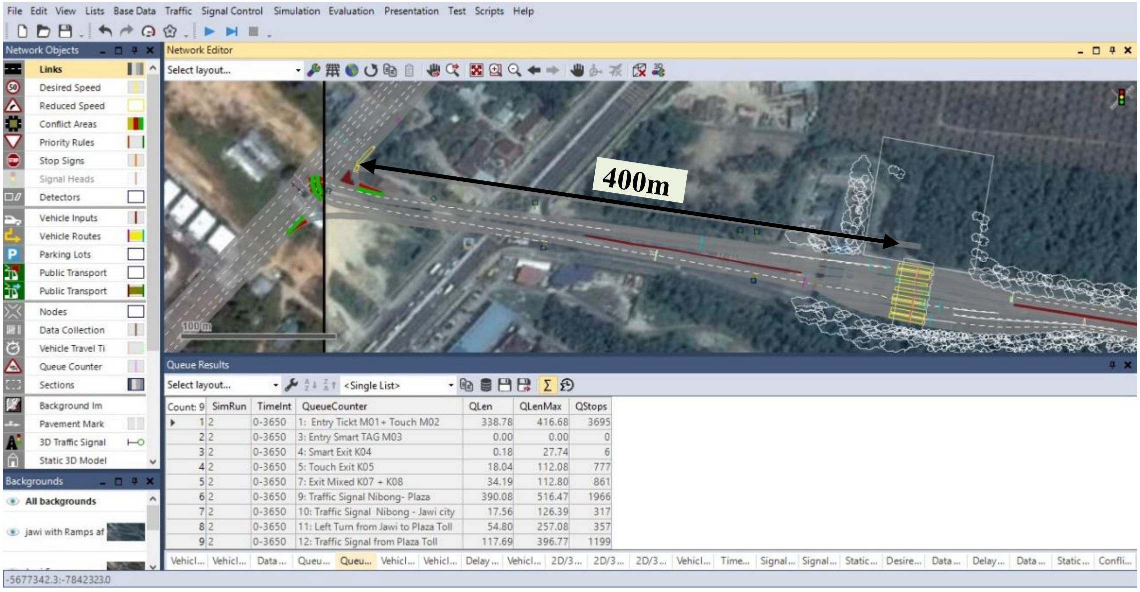


Figure D.11 Simulation results for Jawi toll plaza model 12% HGV with high traffic volume _ Full ETC_ distance between junction and Jawi toll plaza 400m

LIST OF PUBLICATIONS

1) Mahdi, M. B., and Leong, L. V. (2015). Assessment of Queue Length and Delay at Toll Plaza Using Microscopic Traffic Simulation. Applied Mechanics and Materials, 802, 387–392. http://doi.org/10.4028/www.scientific.net/AMM.802.387

2) Leong, L.V., Mahdi, M.B. and Chin, K.K. (2015). Microscopic Simulation on the Design and Operational Performance of Diverging Diamond Interchange. Transportation Research Procedia, 6, pp.198-212.

3) Mahdi, M. B., and Leong, L. V. (2013). Evaluation of Toll Plaza Performance Using Queuing Delay. Proceedings of 8th Malaysian Universities Transport Research Forum Conference (MUTRFC 2013)