DEVELOPMENT OF ENTRANCE RAMP MERGING DENSITY MODEL

BASED ON AN URBAN EXPRESSWAY TRAFFIC CONDITION

by

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LIST OF SYMBOLS

f_{HV}	Adjustment factor for heavy vehicle
f_p	Adjustment factor for driver population
Hi	Alternative hypothesis
V_{OA}	Average per lane flow rate in outer lanes (Lanes 3 and 4, where they exist) at beginning of ramp influence area (pc/h/ln)
V_D	Demand flow rate on adjacent downstream ramp (pc/h)
D_1	Density in lane 1 expressway (pc/km)
D_2	Density in lane 2 expressway (pc/km)
D_R	Density in merge influence area, (pc/km/ln)
D_{ramp}	Density in the acceleration lane (pc/km)
d	Distance traverse (km)
L_{UP}	Distance to adjacent upstream ramp (m)
L_{down}	Distance to adjacent downstream ramp (m)
y_i	Empirical value results for the i th dataset
$\hat{y}_i$	Estimate value for model calibrated for the i th dataset
V_F	Expressway demand flow rate immediately upstream of merge (pc/h)
v_i	Flow rate for movement i under base conditions during peak 15 min of hour (pc/h)
V_{12}	Flow rate in Lane 1 and 2 of expressway immediately upstream of merge (pc/h)
V_1	Flow rate in lane 1 on the expressway, (pc/h)
V_2	Flow rate in lane 2 on the expressway, (pc/h)
V_3	Flow rate in lane 3 on the expressway, (pc/h)
S_{FF}	Free flow speed of freeway approaching merge or diverge area (km/h)
S_{FR}	Free flow speed of ramp (km/h)
V	Hourly volume (veh/h)

V_i	Hourly volume for movement i (Veh/h)
U_i	Individual vehicle speed
M_S	Intermediate speed determination variable for merge area
L_A	Length of acceleration lane (m)
V_F	Maximum total flow approaching a major merge area on the expressway, (pc/h)
V_{FO}	Maximum total flow departing from a merge area on the expressway, (pc/h)
V_R	Maximum total flow entering the ramp influence area (pc/h)
V_{R12}	Maximum total flow entering the ramp influence area, (pc/h)
H_o	Null hypothesis
N	Number of dataset considered
n	Number of observed vehicle
N_{ik}	Number of the vehicle within the length of acceleration lane section in i th frame of k th interval
P_{FM}	Proportion of approaching freeway floe remaining in Lanes 1 and 2 immediately upstream of merge
S_O	Space mean speed of vehicles traveling in outer lane
S_R	Space mean speed
i	Time interval in seconds
t	Time to traverse (hours)
F	Total frame considered
DEN_{ij}	Traffic density in k-th i second interval in vehicles per kilometer for lane j
t_i	Travel time of the ith vehicle to traverse the section L
V_{15}	Volume during the peak 15 minutes of the peak hour

LIST OF ABBREVIATION

AASHTO	American Association of State Highway and Transportation Officials
CORSIM	Combined Traffic Simulation Software
DOTs	Department of Transportations
FFS	Free-Flow Speeds
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
JKR	Jabatan Kerja Raya
LOS	Level of Service
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MINITAB	Statistical Software
MOE	Measures of Effectiveness
MS	Mean Square
MSE	Mean Squared Error
P.C.U	Passenger Car Unit
PHF	Peak-hour factor
RDR	Ramp Data Reduction
SMS	Space Mean Speed
SS	Sum of Squares
TMS	Time Mean Speed
TRB	Transportation Research Board
US	United States
US HCM	United States Highway Capacity Manual

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PEMBANGUNAN MODEL KETUMPATAN SUSUR MASUK CANTUMAN BERDASARKAN KEADAAN SEBUAH LEBUH RAYA BANDARAN

ABSTRAK

Operasi cantuman lalu lintas di susur masuk lebuh raya mempunyai kesan yang penting ke atas rekabentuk geometri dan operasi lalu lintas. Walaubagaimanapun, sehingga ke hari ini tiada sebarang penyelidikan pernah dijalankan untuk menilai prestasi kelancaran lalu lintas di susur masuk cantuman berdasarkan keadaan lalu lintas tempatan. Kaedah dan model sedia ada yang terdapat di dalam *Highway Capacity Manual*, HCM 2000 adalah dibina dan dibangunkan berlandaskan keadaan lebuh raya dan lalu lintas di Amerika Syarikat, AS. Aplikasi HCM memerlukan suatu justifikasi yang jelas untuk digunakan di negara yang lain kerana terdapat perbezaan yang ketara dari segi budaya pemanduan, komposisi lalu lintas dan konfigurasi rekabentuk yang akan mempengaruhi keseluruhan aplikasi. Penggunaan aplikasi model yang berkaitan ini adalah sangat penting dalam memastikan rekabentuk lebuh raya yang akan dibina adalah berkeadaan selamat, berkesan dan ekonomi. Begitu juga isu-isu berkaitan rekabentuk susur masuk yang tidak memenuhi kriteria yang dikehendaki seperti rekabentuk yang tidak mencukupi atau melebihi keperluan yang sepatutnya dapat dielakkan. Selain daripada itu, dalam konteks garis panduan dan tatacara rekabentuk sedia ada di Malaysia yang digariskan di dalam buku panduan Arahan Teknik (Jalan): Rekabentuk Persimpangan Bertingkat terbitan tahun 1987 adalah ketinggalan dan ianya masih berpandukan piawaian edisi HCM 1985 yang mana pendekatan dan ukuran keberkesanan yang digunakan adalah jelas berbeza dengan apa yang diguna-pakai dalam edisi HCM 2000. Oleh kerana itu, suatu pembinaan model berasaskan kajian kerja di lapangan telah berjaya dijalankan dalam membangunkan model laluan lalu lintas di susur masuk cantuman di sebuah lebuh

raya bandaran di Malaysia. Dua model telah berjaya dibangunkan dan telah di sahkan kejituannya dalam pengkajian ini. Ianya digunakan untuk mengenalpasti paras kebolehkhidmatan di susur masuk cantuman. Model yang pertama dibangunkan adalah untuk mendapatkan anggaran kadar aliran lalu lintas di lorong 1 dan 2 lebuh raya sebaik sahaja sebelum kawasan cantuman berlaku manakala model yang kedua adalah model untuk mendapatkan anggaran ketumpatan kereta di dalam kawasan cantuman terganggu di persimpangan susur masuk cantuman. Analisis kepekaan ke atas model-model ini ada juga dilakukan dalam usaha untuk mengenalpasti kepekaan setiap satu parameter peramal model. Pembinaan carta untuk mendapatkan paras kebolehkhidmatan susur masuk cantuman yang dibina daripada model-model ini adalah sesuatu yang sangat berguna untuk pengamal-pengamal teknikal di lapangan. Beberapa graf telah direkabentuk daripada model-model yang telah dibangunkan berserta aplikasi penggunaan carta juga ada ditunjukkan. Hasilnya, jurutera lalu lintas dan perekabentuk lebuh raya boleh menggunakan carta yang telah dihasilkan ini untuk membuat penilaian ke atas prasarana lebuh raya di laluan susur masuk persimpangan dengan mengetahui aras perkhidmatannya secara lebih bersistematik dan berkesan.

DEVELOPMENT OF ENTRANCE RAMP MERGING DENSITY MODEL BASED ON AN URBAN EXPRESSWAY TRAFFIC CONDITION

ABSTRACT

Entrance ramp merging operation has significant impacts on expressway traffic operations and ramp junction geometric design. To date no research work has been conducted to assess the operational performance based on local entrance ramp expressway traffic condition. The current entrance ramp operational analysis methodology and models in the HCM 2000 are calibrated based on the United States (US) highway and traffic conditions. The application of the HCM needs to be justified for use in this country due to the fundamentally differences in driving habits, traffic composition and design configuration. Proper application of the models is crucial in order to ensure that the future designs of expressways are safe, efficient and economical where the issues of under-design or over-design of expressway will not occur. Also, the Malaysian guidelines and standard as in the Arahan Teknik Jalan: Interchange Design 1987 is out of date, which is based on the US HCM 1985 and the methodology approach and measure of effectiveness are totally different from the current HCM 2000 edition. Therefore a well-established empirical study had been implemented to calibrate entrance ramp merging models that are based on an urban entrance ramp expressway traffic condition in Malaysia. Two models were successfully developed in these studies that are needed in order to determine the Level of Service at entrance ramp merge junction. The first model is for estimating flow rates in lane 1 and 2 immediately upstream of the merge influence area and the second model is for prediction of density in merge influence area at entrance ramp junction. Sensitivity analysis had also been performed in order to measure how sensitive each of the predictor parameters for the two models. The development of the entrance ramp level of service estimation chart provides a valuable tool to be used by practitioners. Several graphs were created based on the models developed.

Application example of using the chart had been demonstrated. As a result, traffic engineer and highway planner can use the developed chart in order to evaluate the existing entrance ramp expressway facilities Level of Service in an effective and systematic manner.

CHAPTER 1
INTRODUCTION

1.1 Background

Expressway represents an important part of modern highway system in both urban and rural areas in Malaysia. This expressway facility provides limited access because its main function is to provide for through movement of traffic at high speeds. However, in recent years, motorist on this facility in urban area in Malaysia have experience increasing operational problems particularly in urban areas such as in Kuala Lumpur and Selangor. In this matter, congestion on urban Malaysian expressway system becomes normal occurrences and phenomena that must be 'accepted' by the road users in these areas. In the absence of incidents and lane drops, this congestion is usually associated with areas where entrance ramp, exit ramp and weaving section are connected to the expressway mainstreams.

The prediction of capacity and operational quality for expressway is very important to transportation engineers in order for planning, designing and maintaining the highways. Projected traffic demands along with the estimated ability of facilities in carrying traffic are crucial inputs to the planning of infrastructure expansions. In the design context, the understanding of capacity analysis can assist highway designers to justify the feasible alternative to be implemented. Traffic engineers normally utilize capacity prediction to anticipate congestion and potential breakdown at critical areas and through this approach they are able to develop appropriate countermeasures and route diversion strategies as well as in developing traffic management strategies to solve the congestion on the expressway.

Since 1965, the level of service (LOS) concept given in the US Highway Capacity Manual (HCM) has been used as a qualitative measure representing highway operational conditions. The LOS is defined by six letter grades from A through F with A representing the best condition while F representing the worst condition. Empirical models were established to predict and to evaluate the performance for these highway facilities with specific measures of effectiveness (MOE) for different type of highway facilities. However, these models have been calibrated in the United States (US) highway and traffic conditions. The application of the HCM to the analysis of Malaysian traffic condition need to be justified due to the fundamentally differences in driving habits, traffic composition and design configuration (Ibrahim et al., 2002; Vien et al., 2003). Proper application of the design procedure is crucial in order to ensure that the future designs of our expressways are safe, efficient and economical where the issues of under-design or over-design of expressway will not occur. This research evaluates the equation and model of the US HCM 2000 method for entrance ramp merging analysis and checks the suitability for Federal Highway traffic condition.

Furthermore, in term of the Malaysian guidelines and standard as in the Arahan Teknik (Jalan) 8/87: Interchange Design (JKR 1987) is out of date, which is based on the US HCM 1985 and the methodology approach and MOE are totally different from the current HCM 2000 edition. It is therefore an urgent need for a well-established empirical study being implemented so that representative models can be developed that is based on Malaysian expressway and traffic conditions.

1.2 Problem statement

An entrance ramp-expressway junction is generally designed to permit high speed merging movements to take place with a minimum disruption to the adjacent expressway traffic systems and provide a maximum safety to the drivers. The high speed merging is due to the different in design speed for a ramp and the design speed of the expressway mainstream. Normally, the difference is about 30 to 50 km/hr (Hunter et al., 2001). The entrance ramp junction often leads to breakdown in operation thus, reducing mobility drastically. Accordingly, entrance ramp junctions have been the subjects of interest to many traffic engineers (Roess, 1980; Eleftriadou, 1994; Jinchuan et al., 2000; Carlsson and Cedersund, 2000; Lorenz and Elefteriadou, 2000; Al-Kaisy, 1999; Hidas, 2005; Bloomberg, 2006; Dowling and Halkias, 2006). Traffic engineers need to evaluate operational quality and design features of ramp-expressway junctions. A precise analysis or design of the junction is a very important task to them because undesirable operation at any one junction can aggravate the operation for the entire expressway corridor. Assessment of operational quality in such junctions is most often needed.

To date there is no firm guideline, based on local empirical studies and research so far by researchers for Malaysian expressway condition. It is therefore necessary to establish an empirical study that evaluates the impact of the length of the acceleration lane on the operation of ramp junctions. The study also compensates for the gap of knowledge toward a more realistic merging model in reflective of Malaysian expressway condition. The model can be used to determine the LOS that was used as a MOE for entrance ramp expressway junction.

Entrance ramp area is one of the major highway facilities that have long been investigated by researchers. Even though the HCM 2000 presents capacity estimates of entrance ramp areas, they were calibrated based on US expressway and traffic condition. This research is an attempt to develop models for entrance ramp expressway at Malaysian urban expressway junction using multiple linear regressions. The HCM 2000 merging density models are compared to the newly developed models from this research study. In addition, the methodology adopted in Arahan Teknik (Jalan)8/87 : Interchange Design (JKR, 1987) were based on the US HCM 1985 which were almost two decades old and need to be updated.

1.3 Objectives of the study

The objectives of this study are:

1. To obtain and analyze local field data; vehicle classification, density and flow rates for determining operational performance of the merging areas based on Federal Highway traffic condition.
2. To develop empirical models with a function of acceleration lane length which are able to describe the operation of merging by ramp vehicles under the different ranges of an urban expressway density and flow rates.
3. To evaluate the accuracy of the developed empirical models and to compare the results against the US HCM 2000 merging models.
4. To validate and verify the proposed models with respect to an urban expressway entrance ramp conditions.

1.4 Scope and Limitation of the study

This research only considers isolated entrance ramp at an urban expressway facilities and investigates its effect on the operational quality of the junction. Its primary concern resides in manifesting the role of acceleration lanes in operation of merge junction area. The scope of the study is limited to the cases where an isolated taper type single-acceleration lane entrance ramp urban expressway with exclusive motorcycle lane merges with six-lane expressway facilities on a level ground profile. In order to investigate the impact of the acceleration lane length on the operational characteristics of the entrance ramp junction, various ranges of flow rates and density were measured on six sites at Federal Highway Shah Alam – Kuala Lumpur expressway. In this study, considerable efforts were devoted to data collection and reduction process. Expressway merge traffic data were collected on taper type acceleration lanes ranging from 150m up to 250m lengths. Traffic data were collected by videotaping methods from a high vantage point from 40m to 70m heights from ground level that is placed on top of building roof. A high-resolution video camcorder was set up with the use of 5m specially fabricated telescopic stand-pole from which the operation of the entire merge area was videotaped. Condition in which demand exceeds capacity or in an unstable flow regime were not included because these condition induced very different style of driver behaviors such as forced merging into 'stop-and-go' expressway flow and were not the issues and intention of this study.

1.5 Organization of the Thesis

This thesis is structured as follows. First, the introduction chapter gives an overview of the problem statement, research conceptual framework, research objectives and principle contributions. A background review of related research in this field is summarized in the second chapter that starts with a review of the HCM 2000 entrance ramp methodology and is followed by discussion of the relevant research findings in the field. Specifically, the reviews included some necessary background of expressway systems, vehicular behaviors on expressway, classification of expressway system components and analysis procedure.

In the third chapter, the research methodology is described. The research methodology includes data collection and reduction techniques and methodology for modeling the entrance ramp models. The field data collection was designed to capture density data and flow rates data. Chapter four discusses the results of data analysis and model calibration. Several multiple linear regression models were developed for prediction of flow rates V_{12} and merging density models D_R that are needed in determining the Level of Service at entrance ramp expressway junction. All the models were validated in order to test its accuracy and had been discussed in chapter five. Sensitivity analysis and development of entrance ramp LOS application chart are presented in the sixth chapter. The last chapter summarizes the major conclusions of this thesis together with future research recommendations.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The expressway entrance ramp merging process has been studied since the 1960's (Reddy, 1966). Since the onset of the expressway era, many researchers and practitioners in the field of highway design and traffic engineering have showed their great interest in issues concerning the expressway entry process and entrance ramp junction design. This chapter provides review of design guides and available literature associated with the objectives of this research.

2.2 Review of Design Guides

The principal reference for highway capacity analysis for over 40 years has been the United States Highway Capacity Manual (US HCM). The version of the US HCM has been updated from time to time started from the first version published in 1965 to the latest version published in the year 2000. The manual presents techniques and methodologies for evaluating the capacity of different types of highway facilities and for analyzing their operating characteristics under various flow levels. Since the time that this manual appeared in the field of traffic engineering study, the procedures and techniques have been extensively exposed to actual applications. The relevant issues regarding this study are discussed in this section.

2.2.1 Expressway System: An Overview

Expressway represents an important and integral component of Malaysian highway network. These facilities are intended to provide mobility and uninterrupted traffic flow for both urban and rural areas. In Malaysia, expressway facilities started to be constructed in 1980's to accommodate the growth in vehicle ownership and accompanied the growth in Malaysian economy. Therefore, there was a need to provide highway facilities that could handle large traffic volumes at relatively high speeds through full control of access and with minimal vehicular conflicts and interactions.

As defined in AASHTO (2004), expressways or freeways are highways with full control of access. They are intended to provide movement of large volume of traffic at high speeds with high level of safety and efficiency. Urban expressways usually carry higher traffic volumes with four to sixteen through-traffic lanes in both directions (Al-Kaisy, 1999). However, their design is sometimes constrained due to limited space in urban area. In addition, design of alignment and cross section elements of rural expressway are more generous due to availability of the sufficient right-of-way at lower cost and usually associated with higher design speeds.

2.2.1.1 Expressway System Components

An expressway or a freeway is defined as a divided highway facility with full control of access and two or more lanes for exclusive use of traffic in each direction (TRB, 2000). In general, almost all expressway system is made up of the following types of components sections: basic segment, merge, diverge and weaving sections as shown in Figure 2.1.

Basic expressway sections are expressway segments that are located outside the influence area of merge, diverge or weaving sections and therefore they are not affected by turbulence due to intensive merge, diverge or weaving activities. In order to provide access to and exit from expressway system, entrance ramp as shown in Figure 2.2 and exit ramp as shown in Figure 2.3 are provided to the expressway facilities. These sections are characterized by merging and diverging traffic movements and are usually associated with a considerable amount of disturbance to the traffic stream on the mainline expressway. When a merge facility involves an entrance ramp or diverge involves exit ramp, the section is referred to as ramp-expressway junction. This type of merge and diverge sections is the most common on expressway systems and is normally associated with higher impacts on the expressway mainline traffic. Another section in expressway facilities is a weaving section as shown in Figure 2.4. When a merge section is closely followed by a diverge section and connected with auxiliary lane, a crossing movements of merging and diverging vehicle take place, thus creating "weave motion" of traffic as shown in Figure 2.4.

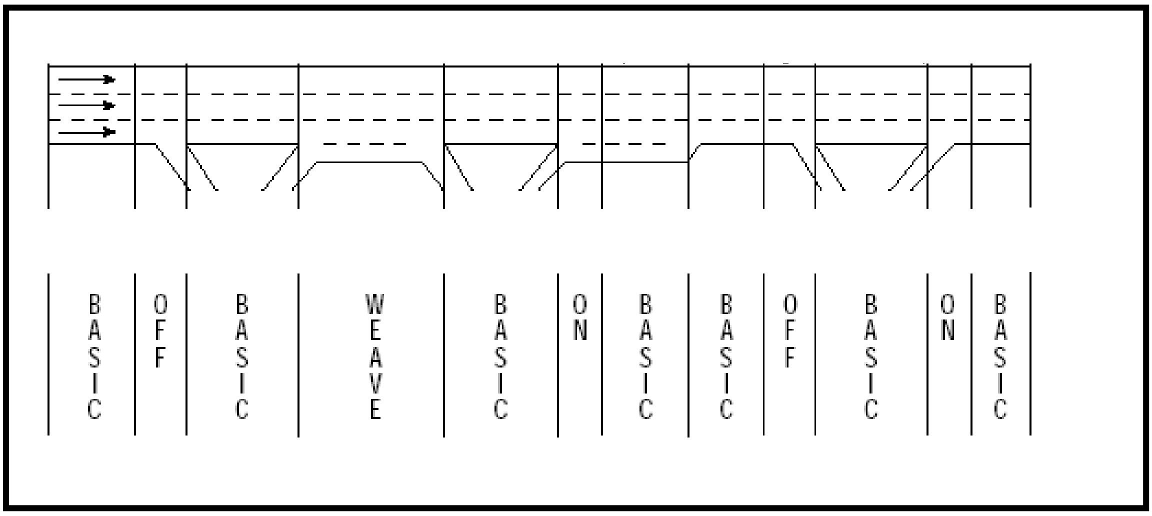


Figure 2.1: Freeway Facility Segments (TRB, 2000)

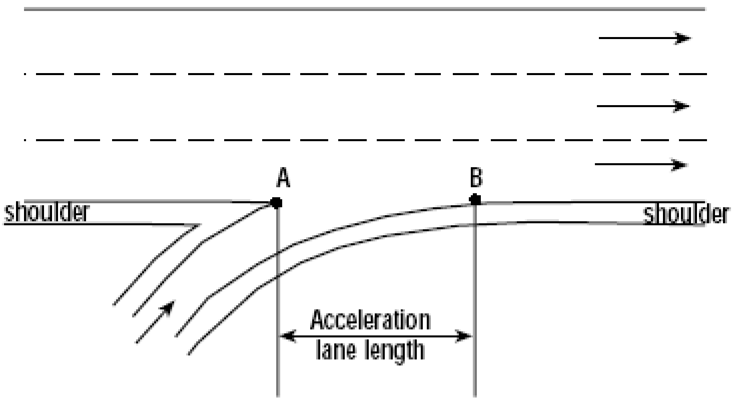


Figure 2.2: Entrance Ramp Diagram (TRB, 2000)

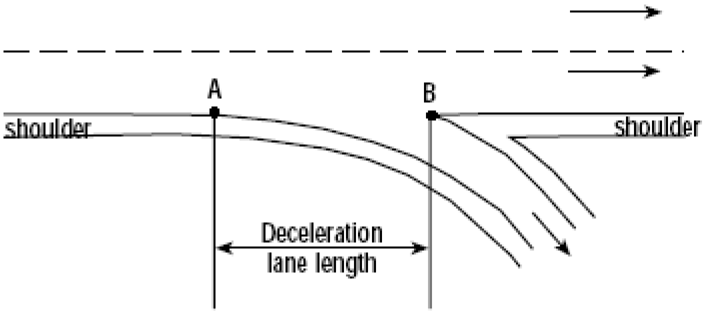


Figure 2.3: Exit Ramp Diagram (TRB, 2000)

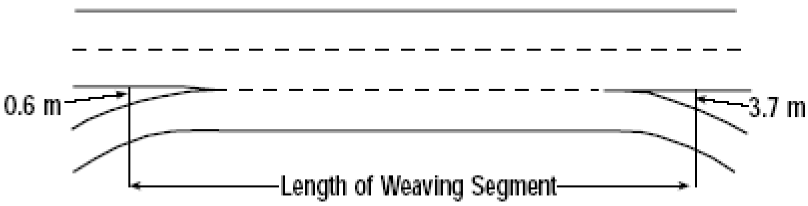


Figure 2.4: Weaving Segment (TRB, 2000)

2.2.2 Overview of the HCM 2000

The current edition, HCM 2000, is the first HCM to provide a technique for estimating the capacity and determining the LOS of transportation facilities, including not only intersections and roadways but also transit, bicycles and pedestrians (TRB, 2000). Each LOS is associated with a range of operating conditions and is assumed to represent traveler perceptions of various conditions (TRB, 2000). Table 2.1 shows the service measures recommended for use to determine the LOS of various system elements.

Table 2.1: Service Measures for Various System Elements in the HCM 2000

<table>
<tr><th colspan="2">Element</th><th>Service Measure</th></tr>
<tr><td rowspan="6">Uninterrupted Flow</td><td>Two-lane highway</td><td>Speed, percent time-spent-following</td></tr>
<tr><td>Multilane highway</td><td>Density</td></tr>
<tr><td>Freeway: Basic Segment</td><td>Density</td></tr>
<tr><td>Freeway: Ramp Merge</td><td>Density</td></tr>
<tr><td>Freeway: Ramp Diverge</td><td>Density</td></tr>
<tr><td>Freeway: Weaving</td><td>Density</td></tr>
<tr><td rowspan="6">Interrupted Flow</td><td>Urban Street</td><td>Speed</td></tr>
<tr><td>Signalized intersection</td><td>Delay</td></tr>
<tr><td>Two-way stop interaction</td><td>Delay</td></tr>
<tr><td>All way stop intersection</td><td>Delay</td></tr>
<tr><td>Roundabout</td><td>n/a</td></tr>
<tr><td>Interchange ramp terminal</td><td>Delay</td></tr>
</table>

In term of MOE used for basic expressway sections and ramps junction, density has been used as the service measure in defining LOS in the HCM 2000. Density is defined as the number of vehicles occupying a given length of a lane or roadway at a particular instant (Garber and Hoel, 2002).

2.2.2.1 Measure of Effectiveness and Level of Service in the entrance ramp influence Area

Entrance ramp expressway junctions are generally designed to permit high speed merging movements to take place with a minimum of disruption to the adjacent expressway traffic stream (TRB, 2000). Areas around entrance ramps experience more turbulence and conflicts compared to basic expressway segments. Therefore, acceleration lanes are designed to allow vehicles to merge smoothly and without causing interference to expressway traffic streams. A well-designed acceleration lane should permit ramp drivers to perform a safe merge within the effective acceleration lane length. As such, the proper design and placement of ramps on high demand expressway is crucial for fast, efficient and safe operation. Determination of expressway capacity at ramp-expressway merge junction is important for several practical reasons (Al-Kaisy, 1999) :

- The development of appropriate design for expressway merge facilities depends largely on expressway capacity and ramp capacity.
- Most expressway management and ramp control strategies are developed based on the estimated capacity values of expressway components and ramp junctions.
- The quality of service and operational breakdown are directly associated with expressway capacity and represent the important part of any operational analysis.

Due to the dynamic nature of expressway merge situation, in-depth study and research needs to be carried out in order to understand the impact of merging on the traffic operation at entrance ramp junction. Next section discusses in detail the idea and philosophies related to analysis of ramp merge influence areas and a ‘step by step’ process of the whole methodology structure for entrance ramp capacity analysis based on the HCM 2000.

2.2.3 Characteristics of Traffic Operation in Merge Influence Area

Merging occurs when two separate traffic streams join to form a single stream as illustrated in Figure 2.5. The ramp vehicle merging process is a complex pattern of driver behavior. A driver performs several different tasks during the merging process such as (Gettman, 1998);

- lane changes of ramp vehicles into the expressway mainstreams,
- lane changes of mainline traffic to other lane to reduce the merging ramp impact and turbulence,
- acceleration and deceleration behaviors due to intensive conflicts and turbulence such as searching for available gaps to make any movements.

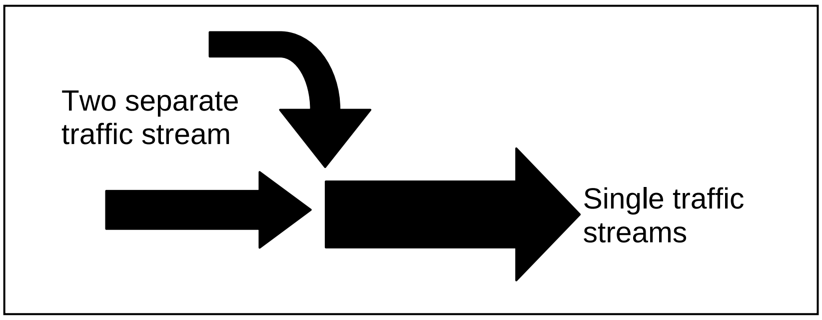


Figure 2.5: Illustration of merging traffic phenomenon

Various mathematical models have been developed to describe the relationships between flow, speed and density on expressway for any given instance (Fazio and Rouphail, 1986; Shin, 1993; Theophilopoulus, 1986; Choocharukul, 2003 and TRB, 2000). The most relevant one regarding the estimation and prediction of traffic operating condition is from the U.S HCM that is the core methodology adopted in this thesis.

Theoretically, capacity of the entrance ramp is mainly a function of the ability of the merge section to accommodate mainline traffic and ramp demand. The ability to accommodate mainline traffic is primarily governed by mainline geometric characteristics such as number of lanes, lane width, lateral clearance and etc. Apart from that, the ability of merge section to accommodate entrance ramp traffic is also influence by the availability of gaps on the adjacent expressway lane and gap acceptance process. However, this research is concerned with analysis of operational performance at ramp expressway merge sections which deals with macroscopic traffic parameters such as flow rate, density and speed.

2.2.4 Analysis of Capacity at Entrance Ramp Expressway Junction using HCM procedure

The 1985 US HCM uses traffic flow rate in merge influence area as the MOE whereas the HCM 2000 uses density in merge influence area as MOE. Figure 2.6 illustrates the methodology for determining the operational analysis of the entrance ramp junction using HCM 2000. Based on the HCM 2000, taper type acceleration lane and parallel type acceleration lane is treated as the same in the analysis procedure. Figure 2.7 illustrates the measurement of the length of acceleration lanes, L_A, for taper and parallel types.

The methodology for estimating and predicting the merge influence area level of service has three major steps. The first step is to calculate the flow entering lanes 1 and 2 (V_{12} pc/hr) immediately upstream of the merge influence area. The second step is to determine capacity values and to compare the capacity values with existing or forecast demand flows to determine the likelihood of congestion. In this process, several capacity values are evaluated:

- Maximum total flow approaching a major merge area on the expressway (V_F),
- Maximum total flow departing from a merge area on the expressway (V_{FO}),
- Maximum total flow entering the ramp influence area V_{R12} for merges areas and maximum flow on a ramp (V_R).

The capacity of a merge area is always controlled by the capacity of its entering roadways, that is, the expressway segments upstream and downstream of the ramps, or by the capacity of the ramp itself. Table 2.2 shows the Capacity of Ramp Roadways based on the HCM 2000 procedure. The density of flow within the ramp influence area (D_R) and the LOS are determined.

Although speed is a major concern of drivers as related to service quality, freedom to maneuver within the traffic stream and proximity to other vehicles are equally noticeable concerns. These qualities are related to the density of the traffic stream. Unlike speed, density increases as flow increases up to capacity, resulting in a measure of effectiveness that is sensitive to a broad range of flows (TRB, 2000).

Table 2.2: Approximate Capacity of Ramp Roadways (TRB, 2000)

Free-Flow of Ramp (km/h)	Capacity (pc/h)	
	Single lane ramps	Two lane ramps
> 80	2200	4400
> 65-80	2100	4100
>50-65	2000	3800
>=30-50	1900	3500
<30	1800	3200

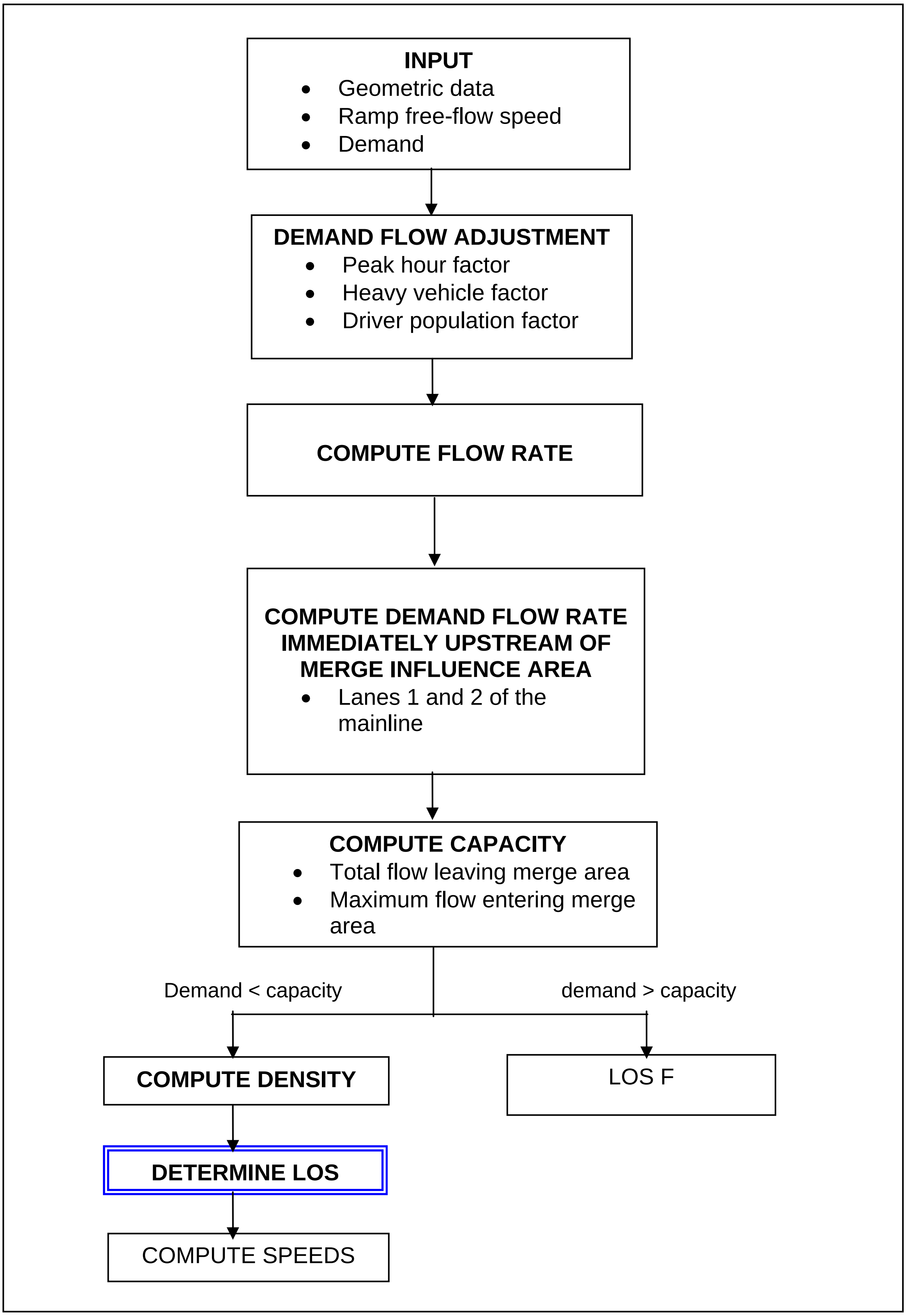


Figure 2.6: Entrance Ramps Junction Methodology (TRB, 2000)

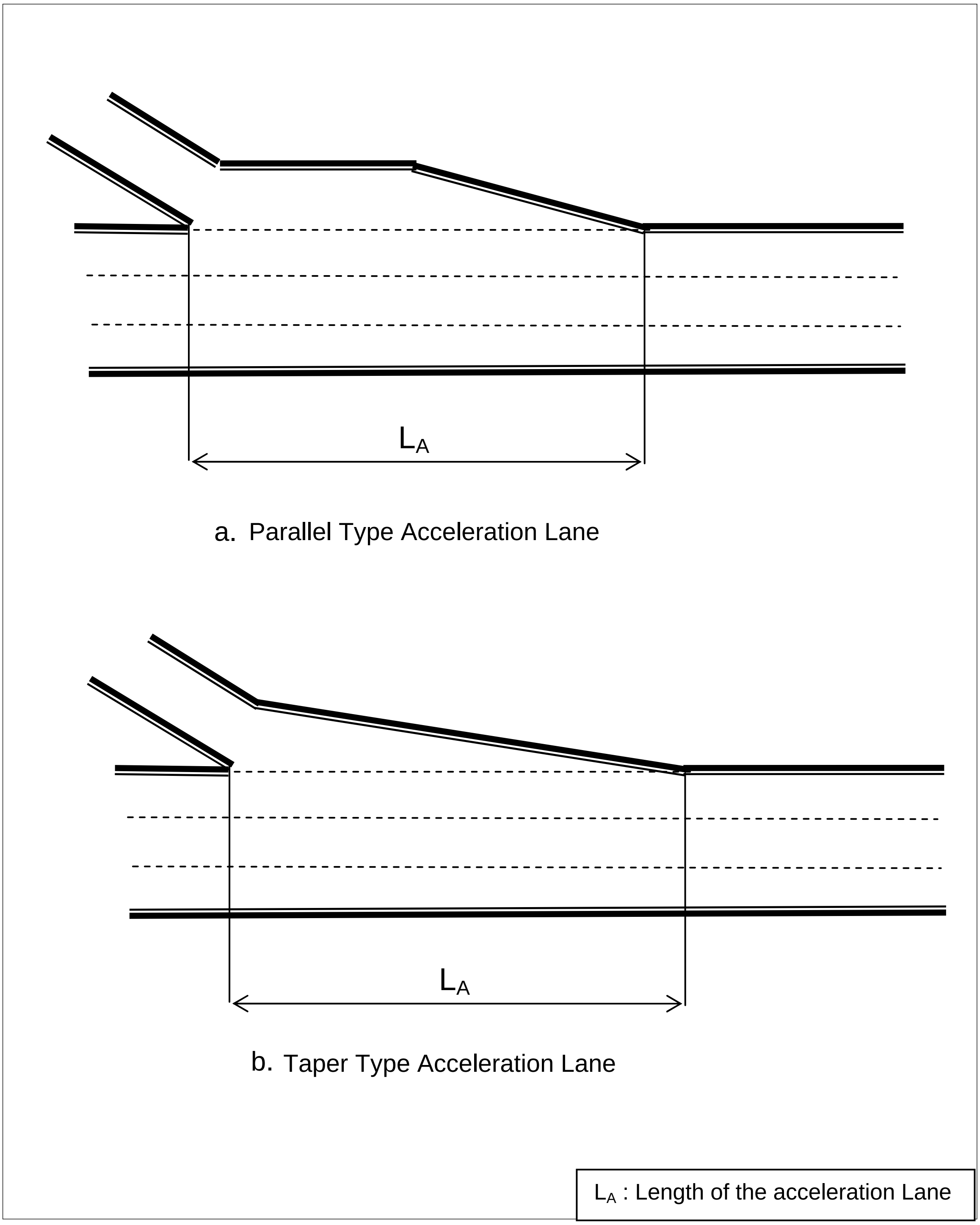


Figure 2.7: Measuring the length of acceleration lanes

(Modified from Roess et al., 2004)

Based on the HCM 2000, the free-flow speed of the ramp is best observed in the field but may be estimated as the design speed of the most restrictive element of the ramp. Figure 2.8 shows the ramp influence areas and key variables and their relationship to each other. A critical geometric parameter influencing operations at merge area is the length of the acceleration lane (L_A). The length of the acceleration lane is measured from the point at which the left edge of the ramp lane or of the expressway lanes converges to the end of the taper segment connecting the ramp to the expressway. The point of convergence can be defined by painted markings or physical barriers or by some combination of the two. To be noted here that both taper acceleration lane and parallel acceleration lane are analyzed in the same way (TRB, 2000).

All aspects of the model and LOS criteria are expressed in terms of equivalent maximum flow rates in passenger cars per hour (pc/h) under base conditions during the peak 15 min of the hour of interest (TRB, 2000). Therefore, before any of these procedures are applied, all relevant expressway and ramp flows must be converted to equivalent pc/h under base conditions during the peak 15 min of the hour, using Equation 2.1.

$$\mathbf{V}_i = \frac{V_i}{PHF * f_{HV} * f_p} \tag{2.1}$$

Where

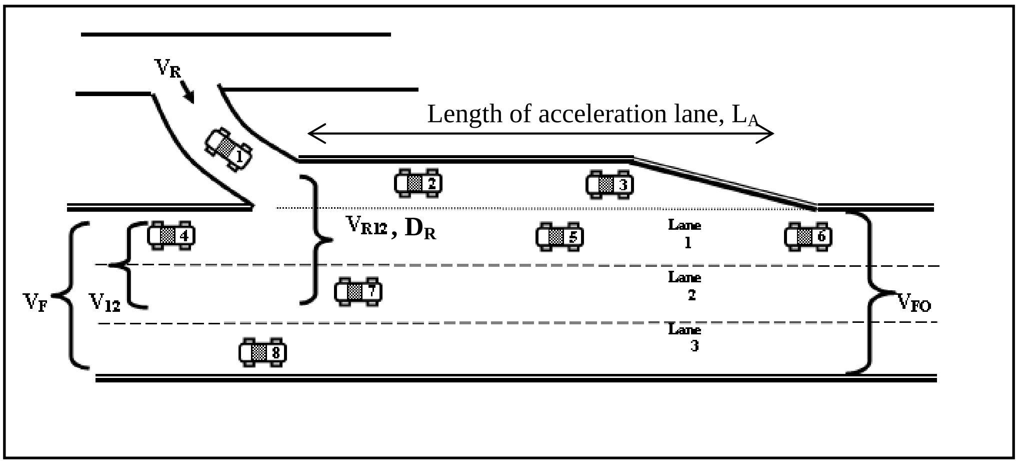
$\mathbf{V}_i$ = flow rate for movement i under base conditions during peak 15 min of hour (pc/h),

V_i = hourly volume for movement i (veh/h),

PHF = peak-hour factor,

f_{HV} = adjustment factor for heavy vehicles, and

f_p = adjustment factor for driver population.



V_{12} = Flow rate in Lanes 1 and 2 of expressway immediately upstream of merge (pc/h),
V_F = Expressway demand flow rate immediately upstream of merge (pc/h),
V_{FO} = Maximum total flow rate departing from a merge area on the expressway, (pc/h)
V_{R12} = Maximum total flow entering the ramp influence area, (pc/h)
V_R = Entrance ramp demand flow rate (pc/h),
D_R = Density in merge influence area, (pc/km/ln).

Figure 2.8: Illustration of critical entrance ramp Junction Variables, (modified from TRB, 2000)

A ramp-expressway junction is an area of competing traffic demands for space. Upstream expressway traffic competes for space with entering entrance ramp vehicles in merge areas. In a merge area, individual entrance ramp vehicles attempt to find gaps in the adjacent expressway lane traffic stream. Because most ramps are on the left side of the expressway in Malaysian roadway, the expressway lane in which entrance ramp vehicles seek gaps is designated as Lane 1 that is the closest lane to the ramp. By convention, expressway lanes are numbered from 1 to N, from the left shoulder to the median for Malaysian expressway condition. The action of individual merging vehicles entering the Lane 1 traffic stream creates turbulence in the vicinity of the ramp. Approaching expressway vehicles move toward the right to avoid this turbulence. The HCM 2000 stated that the operational effect of merging vehicles is heaviest in Lanes 1 and 2 and the acceleration lane for a distance extending from the physical merge point to 450 m downstream. Figure 2.9 shows this influence area for entrance ramp junctions and lane convention numbering based on Malaysian scenario.

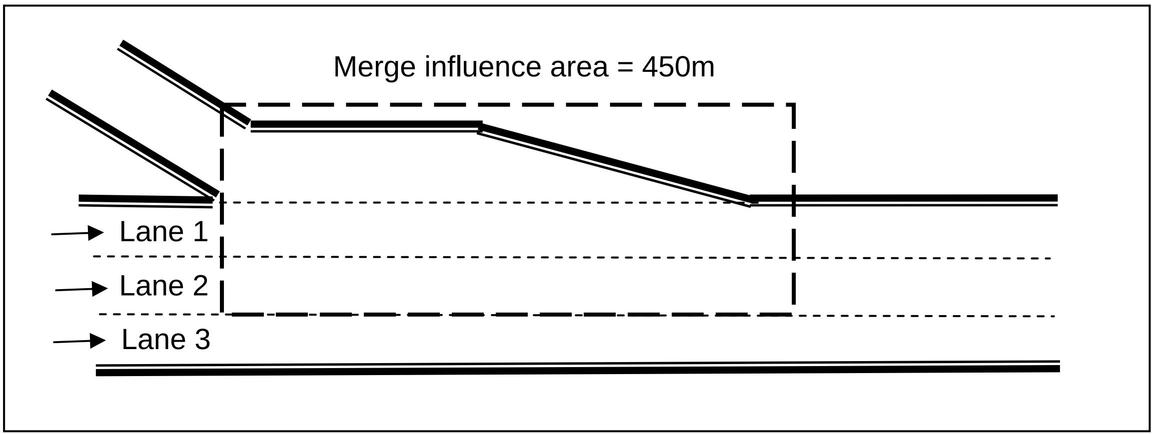


Figure 2.9: Merge Influence Area and Lane Numbering (Modified from TRB 2000)

2.2.5 Estimating Demand Flow Rates in Mainline Expressway for Lanes 1 and 2

The starting point for the analysis of the entrance ramp operational performance is the estimation of demand flow rates in lane 1 and 2, V_{12} (pc/hr). This is done using a series of regression-based modeling developed as part of a nationwide study of ramp-freeway junctions in the U.S. (Roess et al., 1998). For merge areas, the flow rate remaining in lane 1 and 2 immediately upstream of the junction is simply as a proportion of total approaching expressway flow.

Table 2.3 summarized models for estimating proportion of approaching expressway flow remaining in Lanes 1 and 2 immediately upstream of merge, P_{FM} for determining which model should be used for various analysis scenarios under 4 lane expressway, 6 lane expressway and 8 lane expressway.

Table 2.3: Models for Predicting V_{12} at Entrance Ramps (TRB, 2000)

$V_{12} = V_F * P_{FM}$	
For 4-lane expressway (2 lanes each direction)	$P_{FM} = 1.000$ (2.2)
For 6-lane expressway (3 lanes each direction)	$P_{FM} = 0.5775 + 0.000092L_A$ (2.3) $P_{FM} = 0.7289 – 0.0000135 (V_F + V_R) – 0.002048S_{FR} + 0.0002L_{up}$ (2.4) $P_{FM} = 0.5487 + 0.0801 V_D/ L_{down}$ (2.5)
For 8-lane expressway (4 lanes each direction)	$P_{FM} = 0.2178 – 0.000125V_R + 0.05887 L_A / S_{FR}$ (2.6)

Where;

V_{12} = flow rate in Lanes 1 and 2 of expressway immediately upstream of merge (pc/h),

V_F = expressway demand flow rate immediately upstream of merge (pc/h),

V_R = entrance ramp demand flow rate (pc/h),

V_D = demand flow rate on adjacent downstream ramp (pc/h),

P_{FM} = proportion of approaching expressway flow remaining in Lanes 1 and 2 Immediately upstream of merge,

L_A = length of acceleration lane (m),

S_{FR} = free-flow speed of ramp (km/h),

L_{up} = distance to adjacent upstream ramp (m), and

L_{down} = distance to adjacent downstream ramp (m).

For four-lane facilities (two lanes in each direction), the value is equal to 1, as the entire flow is in lane 1 and 2. For six and eight lane expressway, the values are determined using the relevance model as shown in Table 2.4. For six-lane expressway, the analysis is based on configuration of adjacent ramps. Table 2.4 lists the various sequences of ramps that may occur on six-lane expressway and the appropriate equation that should be applied in each case. For example, equation 2.3 in Table 2.4 is considered as an isolated ramp where there is no influence with the upstream and downstream adjacent ramp (Roess et al., 1998).

Table 2.4: Selecting Equations for P_{FM} for Six-Lane Expressway (TRB, 2000)

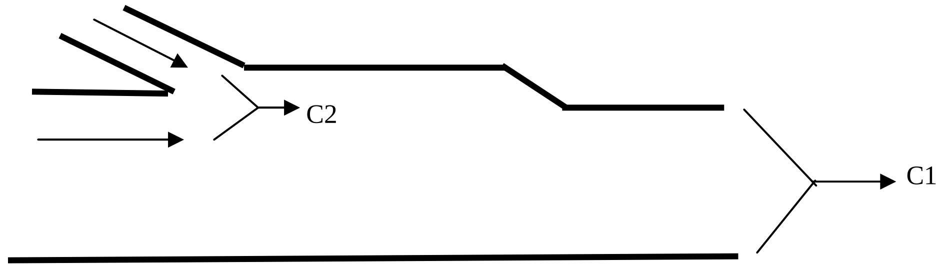
Adjacent Upstream Ramp	Subject Ramp	Adjacent Downstream Ramp	Equation Used
None	On	None	Equation 2.3
None	On	On	Equation 2.3
None	On	Off	Equation 2.5 or 2.3
On	On	None	Equation 2.3
Off	On	None	Equation 2.4 or 2.3
On	On	On	Equation 2.3
On	On	Off	Equation 2.5 or 2.3
Off	On	On	Equation 2.4 or 2.3
Off	On	Off	Equation 2.5, 2.4 or 2.3

2.2.6 Capacity Consideration for Merging Area

The analysis procedure for merge area is computed just for LOS A, B, C, D and E. If the level of service of the ramp merge area is F, no further analysis is needed since it is considered as demand exceeding capacity of the ramp area. Capacity is checked as illustrated in Figure 2.10 and the capacity values for merge area are given in Table 2.5.

Table 2.5 : Capacity Values for Merge Areas (TRB, 2000)

Expressway Free-Flow Speed(km/h)	Maximum Downstream Expressway Flow, V (pc/h)				Max. Desirable influence area, V_{R12} (pc/h)
	Number of lanes in one direction				
	2	3	4	>4	
120	4800	7200	9600	2400/ln	4600
110	4700	7050	9400	2350/ln	4600
100	4600	6900	9200	2300/ln	4600
90	4500	6750	9000	2250/ln	4600



C1 = capacity of merge area, controlled by capacity of the downstream basic expressway segment.

C2 = maximum flow into merge influence area.

Figure 2.10: Capacity of Merge Areas (Modified from TRB, 2000)

Studies have also shown that there is a practical limit to the total flow rate that can enter the ramp influence area. For an entrance ramp, the flow entering the ramp influence area includes V_{12} and V_R. Thus, the total flow entering the ramp influence area is given according to equation 2.7.

$$V_{R12} = V_{12} + V_R \tag{2.7}$$

The specific checkpoints that should be compared to the capacity criteria can be summarized as follows;

1. For merge areas, the maximum facility flow occurs downstream of the merge. Thus, the facility capacity is compared with the downstream facility flow using equation 2.8.

$$V_{FO} = V_F + V_R \tag{2.8}$$

2. In cases where lanes are added or dropped at a merge, both upstream V_F and downstream V_{FO} facility flows must be compared to capacity criteria.

3. For merge areas, the flow entering the ramp influence area is determined by equation 2.7. This sum is compared to the maximum desirable flow as indicated in Table 2.5.
4. All ramp flows, V_R must be checked against the ramp capacities.

Service volumes for ramps are difficult to describe because of the number of variables that affect operations. Table 2.6 gives example of service volumes of a single lane entrance ramp under a set of condition. Service volumes for LOS A through D are based on conditions producing the limiting densities for these LOS. Service volumes for LOS E are based on the minimum of three limiting criteria: the capacity of the freeway, the maximum volume that can enter the ramp influence area, and the capacity of the ramp. In some cases, capacity constraints are more severe than density constraints. In such cases, some levels of service may not exist in practical terms for combinations of ramp and expressway volumes (Roess et al., 2004)

Table 2.6: Example Service Volumes for Single Lane on Ramps (TRB, 2000)

Mainline Number of lanes	Service Volumes (veh/h) for LOS				
	A	B	C	D	E
Entrance Ramp					
2	N/A	290	1250	1760	1760
3	500	1660	1760	1760	1760
4	650	1760	1760	1760	1760

Note:

Condition for service volumes for this case are:

- Free Flow Speed mainline= 120 km/hr
- Mainline volume= 2000 veh/h/ln
- Free Flow Speed ramp = 55 km/hr
- Acceleration lane = 300 m
- 5 % truck