INVESTIGATION OF FREE-FLOW SPEED AT BASIC SEGMENT EXPRESSWAYS FOR LEVEL TERRAIN IN MALAYSIA

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INVESTIGATION OF FREE-FLOW SPEED AT BASIC SEGMENT EXPRESSWAYS FOR LEVEL TERRAIN IN MALAYSIA

by

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KAJIAN LAJU ALIRAN BEBAS DI SEGMEN ASAS

LEBUHRAYA UNTUK KAWASAN RATA

DI MALAYSIA

oleh

HAZWARUAIDA BINTI MUHAMMAD

Tesis yang diserahkan untuk

memenuhi keperluan bagi

Ijazah Sarjana Sains

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LIST OF ABBREVIATIONS

NSE	North–South Expressway
FFS	Free-flow speed
LOS	Level of service
BFFS	Base free-flow speed
v/c	Volume-to-capacity
CCTV	Closed circuit television
MW 4/2D	Motorway, four-lane, two-way divided road
MW 6/2D	Motorway, six-lane, two-way divided road
RW Distance	Real world distance
fps	Frame per second
NB	Northbound
SB	Southbound
WB	Westbound
EB	Eastbound
ROI	Region of interest
PCU	Passenger car unit
PCEs	Passenger car equivalent
ANOVA	Analysis of variance
K-S	Kolmogorov-Smirnov

NAE	Normalized Absolute Error
RMSE	Root Mean Square Error
IA	Index of Agreement
PA	Prediction Accuracy

LIST OF SYMBOLS

V	Mean speed at density, D
V_f	Free-flow speed
D_j	Jam density
D	Density
i	Grade in percent (%)
FV	Free-flow speed for light vehicles for the actual conditions (km/h)
FV_O	Base free-flow speed for light vehicles for the studied road and terrain type, near ideal, pre-defined conditions (km/h)
$FFV_{X,Y,Z}$	Adjustment factors for the influence of variable X, Y and Z (km/h)
f_{LW}	Adjustment for lane width
f_{LC}	Adjustment for right-shoulder lateral clearance
f_N	Adjustment for number of lanes
f_{ID}	Adjustment for interchange density
$\bar{v}_t$	Time mean speed
$\bar{v}_s$	Space mean speed
$\bar{x}$	Arithmetic mean
x_i	Individual observation
n	Total number of observation
s	Sample standard deviation
$s.e.(\bar{x})$	Standard error of the mean
μ	Mean of the population

$t_{\alpha/2}$	Statistic of the *t* distribution for (*n*-1) degrees of freedom and the probability defined by the subscript α
α	1.0 – confidence coefficient
H_0	Null hypothesis
H_1	Alternate hypothesis
μ_i	Mean of group *i*
$d.f.$	Degrees of freedom
$\bar{x}_i$	Mean of group *i*
n_i	Number of observations in group *i*
${s_p}^2$	Pooled variance
${s_i}^2$	Sample variance in group *i*
k	Number of groups
n	Total sample size
$\hat{y}_i$	Sample means for each group
$\bar{y}$	Overall mean
y_i	Sample means
Y_i	Dependent variable
X_i	Independent variable
β_0, β_1	Coefficients of the regression model
ε	Random error term
i	Number of observations
SS_T	Total sum of squares
SS_B	Sum of squares due to group
SS_W	Sum of squares due to error

SS_{YY}	Total corrected sum of squares
R^2	Coefficient of determination
P_i	Predicted data values
O_i	Observed data values
$\bar{P}$	Average of the predicted data
$\bar{O}$	Average of the observed data
S_{pred}	Standard deviation of the predicted data
S_{obs}	Standard deviation of the observed data
X	Lowest value of flow rate
Y	Highest value of flow rate
Z	Range for each level of flow rate
LW	Lane width
SH	Shoulder width
MC	Median clearance
ID	Interchange density
$LD1$	Lane dummy 1
$LD2$	Lane dummy 2

KAJIAN LAJU ALIRAN BEBAS DI SEGMEN ASAS LEBUHRAYA UNTUK KAWASAN RATA DI MALAYSIA

ABSTRAK

Laju aliran bebas merupakan parameter penting dalam hubungan laju-aliran, analisis kapasiti dan tahap perkhidmatan untuk segmen asas lebuhraya. Pihak berkuasa yang berkenaan di Malaysia telah merujuk kepada Arahan Teknik (Jalan) 8/86 untuk menganggarkan tahap perkhidmatan untuk segmen asas lebuhraya berdasarkan nisbah v/c. Walaubagaimanapun, kerana berbeza kemajuan teknologi dan peningkatan bilangan kenderaan di jalan raya, nilai yang diperolehi dalam kajian ini mungkin tidak menunjukkan persamaan sebenar keadaan trafik semasa di Malaysia. Terdapat beberapa model yang dibentangkan dalam rujukan utama dan kajian sebelum ini di seluruh dunia. Walaubagaimanapun, kesesuaian model tersebut untuk keadaan lalu lintas di Malaysia adalah terhad kepada tahap tertentu. Oleh itu, kajian ini dijalankan untuk memahami dengan lebih terperinci mengenai laju aliran bebas di segmen asas lebuhraya dan untuk membangunkan model laju aliran bebas berdasarkan standard tempatan semasa. Enam model laju aliran bebas yang dibangunkan berdasarkan analisis regresi. Walaubagaimanapun, satu model akhir dipilih sebagai model laju aliran bebas terbaik melalui petunjuk prestasi. Dalam kajian ini, laju aliran bebas kenderaan tanpa motosikal dengan jarak kepala ($\geq$ 8 s) dipilih sebagai model terbaik laju aliran bebas. Analisis kepekaan juga telah dilakukan untuk mengukur sensitiviti setiap parameter untuk model laju aliran bebas yang dibangunkan. Oleh itu, hasil kajian ini adalah berharga untuk jurutera trafik tempatan dan pihak berkuasa lebuh raya di Malaysia untuk pemahaman laju aliran

bebas yang lebih baik dan untuk menganggarkan tahap perkhidmatan di segmen asas lebuhraya.

INVESTIGATION OF FREE-FLOW SPEED AT BASIC SEGMENT EXPRESSWAYS FOR LEVEL TERRAIN IN MALAYSIA

ABSTRACT

Free-flow speed (FFS) is an important parameter in the speed-flow relationship, analyses of capacity and level of service (LOS) for basic segment expressways. Relevant authorities in Malaysia have been referring to the ArahanTeknik (Jalan) 8/86 to estimate LOS for basic segment expressways based on v/c ratio. However, due to the technological advancement and the surge of vehicle numbers on roads, the values obtained in the study may not show the actual resemblance of current Malaysian traffic conditions in Malaysia. There are several FFS models presented in major references and previous studies throughout the world. However, the suitability of these models for Malaysian traffic conditions is limited to some extent. Therefore, this study was conducted to understand in more detail about FFS at basic segment expressways and to develop FFS model based on current local standards. Six FFS models are developed based on regression analysis. However, one final model is selected as the best FFS model through the performance indicators. In this study, FFS of vehicles without motorcycles using headway ($\geq$ 8 s) is selected as the best FFS model. Sensitivity analysis had also been performed in order to measure the sensitivity of each parameter for the developed FFS model. Thus, the outcome of this study is valuable for local traffic engineers and highway authorities in Malaysia for better understanding of the FFS and to estimate LOS at basic segment expressways.

CHAPTER 1

INTRODUCTION

1.1 Background of study

According to U.S. HCM 2000 (Transportation Research Board, 2000), expressway is defined as a divided highway with full control of access and two or more lane for the exclusive use of traffic in each direction. There are no signalized or stop-controlled at-grade intersection and direct access to and from adjacent property is not permitted. Access to and from the expressway is limited to ramp locations. Opposing directions of flow are continuously separated by a raised barrier, an at-grade median or a continuous raised median. Operating conditions on an expressway primarily result from interactions among vehicles and drivers in the traffic stream and among vehicles, drivers, and the geometric characteristics of the expressway.

In Malaysia, there are 27 expressways with the total length of 1,630 km. The longest expressway in Malaysia is North–South Expressway (NSE) with the total length of 775 km running from Bukit Kayu Hitam in Kedah near to Malaysia-Thai border to Johor Bharu at the southern portion of Peninsular Malaysia and to Singapore. This expressway acting as the ‘backbone’ of the west coast of the peninsula and provides a faster alternative to the old Federal Route, thus reducing travelling time between various towns and cities. Plate 1.1 and 1.2 show the typical 4-lane and 6-lane basic segment expressways in Malaysia respectively.

Plate 1.1: Typical 4-lane basic segment expressways in Malaysia

Plate 1.2: Typical 6-lane basic segment expressways in Malaysia

Based on U.S. HCM 2000 (Transportation Research Board, 2000), basic segment is one of the facility types under the expressway categories where it is outside of the influence area of ramp or weaving areas of the expressway. Traffic flow within a basic segment expressway can be categorized into three flow types: under saturated, queue discharge and oversaturated. Each flow type is defined within general speed-flow-density ranges and each represents different condition on the expressway. Other than that, a traffic flow is being accommodated by the expressway with the performance of three measures. Three performance measures are density in terms of passenger cars per kilometer per lane, speed in terms of mean passenger-car speed and volume-to-capacity (v/c) ratio. However, in this study, the focus is for investigation of free-flow speed (FFS) at basic segment expressways for level terrain in Malaysia. Figure 1.1 shows a definition of basic segment expressways based on U.S. HCM 2000 (Transportation Research Board, 2000) and Figure 1.2 shows basic segment expressways in Malaysia from Google Earth.

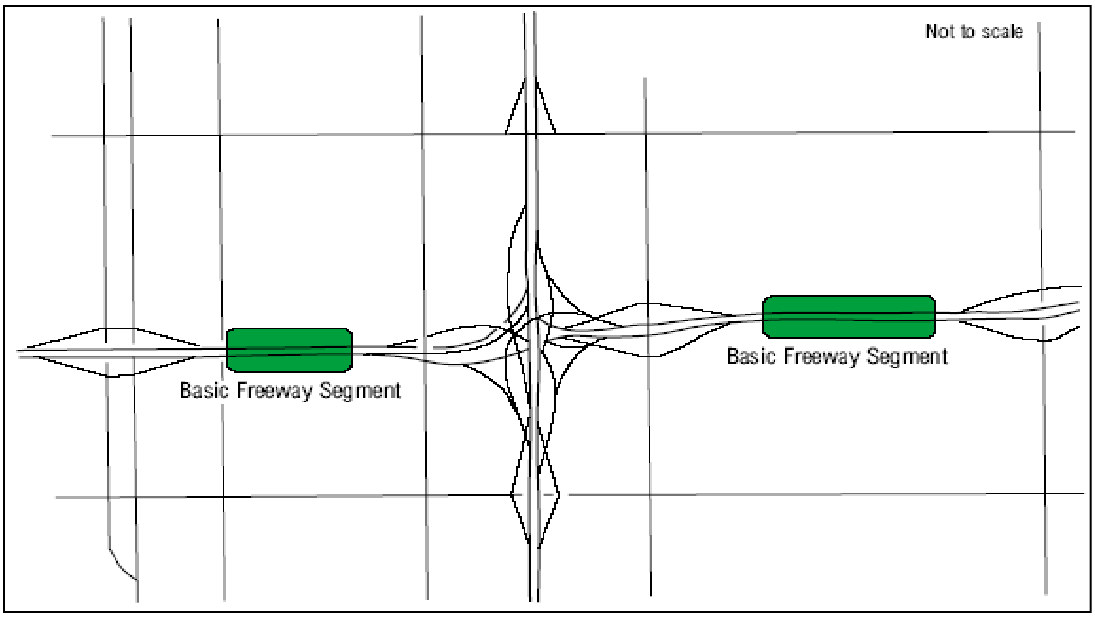

Figure 1.1: Basic segment expressways (Transportation Research Board, 2000)

Figure 1.2: Basic segment expressways in Malaysia

FFS is the speed of vehicle when driver tend to drive at their desire speed and not interfered by other vehicle or not constrained by control devices. It is becomes necessary to know the mean FFS before an appropriate speed-flow relationship can be established and used as a basic for estimating capacity and level of service (LOS) (Tseng et al., 2005). Meanwhile, LOS is a qualitative description of operating conditions within a traffic stream based on service measure including travel flow, travel speed, freedom to manoeuvre safely, driver comfort and convenience.

However, base free-flow speed (BFFS) and ideal conditions for basic segment expressways in Malaysia should be defined first before FFS can be determined. Traffic Study for Malaysia (Highway Planning Unit, 1996) stated that BFFS is the corresponding speed for a road segment with predefines (ideal) characteristics. The BFFS recommended in the Traffic Study for Malaysia (Highway Planning Unit, 1996) is 90 km/h, and U.S. HCM 2000 (Transportation Research Board, 2000) is 110 km/h (urban) and 120 km/h (rural). Meanwhile, ideal condition is assumed as good weather, good pavement conditions and users are familiar with the facility with no impediments to the flow of traffic. This study only covered the FFS at basic segment expressways for level terrain. Based on Arahan Teknik (Jalan) 8/86 (Ministry of Works Malaysia, 1986), level terrain is define as the topographical condition where highway sight distances as governed by both horizontal and vertical restrictions are generally long or could be made to be so without construction difficulty or expertise. The natural ground cross slopes (i.e. perpendicular to natural ground contours) in a flat terrain are generally below 3%.

1.2 Problem statement

For engineers in Malaysia, the current method of LOS estimation for basic segment expressways is based on v/c ratio in Arahan Teknik (Jalan) 8/86 (Ministry of Works Malaysia, 1986) as shown in Table 1.1 and Figure 1.3. However, the capacity value suggested has not been revised since the publication in year 1986. Therefore, it might not be suitable in present Malaysian traffic conditions.

Table 1.1: Design LOS and v/c ratio (Ministry of Works Malaysia, 1986)

Road category	Design LOS	v/c ratio
Expressway (rural)	C	0.70-0.80
Expressway (urban)	C	0.70-0.80

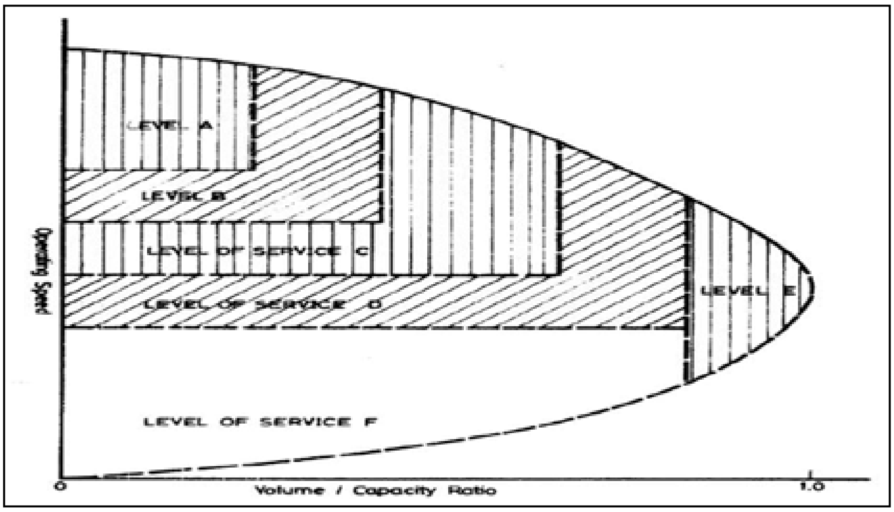

Figure 1.3: Relationship of LOS to operating speed and v/c ratio (Ministry of Works Malaysia, 1986)

Ministry of Works Malaysia had attempted to study FFS in Malaysia, as reported in Traffic Study for Malaysia (Highway Planning Unit, 1996). However, due to technological advancement and the surge of vehicle numbers on roads, the values obtained in the study may not show the actual resemblance of current Malaysian traffic conditions. Therefore, a study of FFS based on current Malaysian traffic conditions need to be carried and the outcomes of this study are valuable for local traffic engineer and highway authority in Malaysia for better understanding of the FFS at basic segment expressways.

Moreover, there are several FFS models presented in major references and previous studies throughout the world. However, the suitability of these models for Malaysian traffic conditions is limited due to certain differences such as roadway characteristics, traffic composition and driver's behaviour. Leong (2004) stated that this is not an appropriate practice as we have our own unique traffic conditions as compared to other countries and this leads to the need to carry out studies based on local traffic conditions. Thus, FFS model based on local traffic conditions is essential for the estimations of capacity and LOS at basic segment expressways in Malaysia.

1.3 Objectives of the study

The main objective of this study is to develop FFS model for Malaysian basic segment expressways based on current road conditions. In the development of FFS model, a few aspects need to be investigated and they are as listed below.

a. To investigate the effect of parameters such as roadway characteristics, flow rates, expressway types based on number of lanes, lane positions, time variations and vehicles classes on FFS.
b. To develop regression model to predict FFS for basic segment expressways.
c. To verify the sensitivity of the parameters in FFS regression models.

1.4 Scope of the study

According to U.S. HCM 2000 (Transportation Research Board, 2000), the speed study should be conducted at a location that is representative of the segment when flows and densities are low (flow rates may be up to 1,300 pc/h/ln). As such, the scope of this study focuses on inter-urban expressways area (uninterrupted flow) in Peninsular Malaysia. Both 4-lane and 6-lane of Plus Expressway E1 and E2 are considered in this study. Data are only collected at basic segment expressways with level terrain. The segment lengths of expressways are 10 km and point of data collection should be at least 1 km from on-ramp and off-ramp. Traffic flows data were recorded using Closed Circuit Television (CCTV) on weekdays (Tuesday, Wednesday and Thursday) under stable flow condition for duration of six hours during peak hours and off-peak hours. Raw data from video recording were reduced using the TRAIS™ Advance SRM 3.2 software to obtain volume**,** vehicle classification**,** speed and headway. Roadway characteristics such as lane width, shoulder width, median clearance and interchange density were recorded manually where the values of roadway characteristics were measured at least three spots along the segment (at downstream, midpoint and upstream). Using the data mentioned above, the FFS model was developed based on local conditions.

1.5 Thesis organization

First chapter starts with a brief introduction on some terminologies used in this study such as expressways, basic segment, FFS, LOS, BFFS, ideal conditions and level terrain. This is followed by the detail explanation on the importance of FFS to estimate capacity and LOS. The second chapter discusses on relevant studies conducted by other researches in other countries and references related to the study. The third chapter is study methodologies which describes the content of the study and explaining the sequence of work carried out throughout the study. Results and discussions are presented in Chapter 4. Lastly, Chapter 5 concludes the findings of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the findings from relevant studies conducted by researches from other countries as well as related guidelines or manuals. This chapter begins by giving a brief overview on the definition of FFS in Section 2.2. This is followed by discussion on the different methods to measure FFS in Section 2.3. Section 2.4 discusses the field data collection of FFS. Subsequently, the factor affecting FFS are discussed in Section 2.5 and Section 2.6 discusses the BFFS and ideal conditions for basic segment expressways. Section 2.7 discusses the review of existing FFS model. Finally, Section 2.8 summarizes this chapter.

2.2 Definition of FFS

Indonesia Highway Capacity Manual (Ministry of Public Works, 1995) defines FFS as the speed at flow level zero, corresponding to the speed a driver would choose if he/she was driving a motor vehicle which was not restrained by other motor vehicles on the motorway. Traffic Study for Malaysia (Highway Planning Unit, 1996) has two definitions of FFS. First definition is FFS as the theoretical average speed (km/h) of traffic when the flow at actual road conditions is zero that is when there are no vehicles present. Second definition is FFS as the speed of a vehicle when it is not restrained by any other vehicles, and speed at which drivers feels comfortable travelling under the geometry, environment and traffic control conditions existing on a road segment with no other traffic.

Meanwhile, Dowling (1997) considered FFS as the average travel speed at which a single vehicle traverses a segment of road if no other vehicles are present in that segment. U.S. HCM 2000 (Transportation Research Board, 2000) stated that FFS is a speed that the drivers can drive their vehicle without obstruction and can speed with their own desired speed and not be influenced by other road users but influenced by characteristics of the vehicle, the driver, the physical characteristics of the road, and external conditions such as weather and traffic rules such as speed limits.

Tseng et al. (2005) defines FFS as the speed of vehicle when the vehicle movement is not interfered by other vehicles or interrupted by control devices. According to study conducted by Mingjun et al. (2007) to investigate the implementation and validity of the FFS model of on expressway, the operation speed is related to traffic and road condition, the type of vehicle, and its performance where the road condition refer to the radius of curve, the road cross-section, the grade and length of slope and the combination of the curves and the slopes whereas FFS were define as the flow in which a driving vehicle is not inhibited by the presence of other vehicle but just by road characteristics.

Moreover, Mannering & Kilareski (1998) claimed that in theory, FFS is defined as the speed of traffic as the traffic density approach to zero. But in practice, FFS is determined by the design speed of the roadway (horizontal and vertical curve), the frequency of on-ramps and off-ramps and number of vehicles entering and exiting the traffic stream, the general density of the surrounding development, the complexity of the driving environment (possible distractions from roadway signs and so on) and speed limits. From other previous studies, FFS is the average speed that a vehicle would travel if there were no congestion or other adverse conditions (Burris & Patil, 2008).

Ma et al. (2010) stated that the FFS of vehicles is defined as the average speed of the traffic stream when the traffic flow is sufficiently low and vehicles do not interact, and also defined as the desired speed that the driver tends to drive under a certain condition of facility and vehicle. The definitions of FFS from U.S. HCM 2010 (Transportation Research Board, 2010) are the theoretical speed when density and flow rate on a study segment are both zero, and also the prevailing speed on expressway at flow rates between 0 and 1,000 passenger cars per hour per lane (pc/h/ln).

2.3 Measurement of FFS

Based on the study conducted by Traffic Study for Malaysia (Highway Planning Unit, 1996), FFS was measured by short-base sites (sites mainly relate to flat terrain with good sight distance) for unobstructed vehicles which defined as vehicles with a headway to the nearest vehicle in front of more than 8 s and with no recent or soon forthcoming meeting with a vehicle in the opposing direction (+ / - 5 s). Bang et al. (1996) in their study to develop speed-flow relationships for rural roads in Indonesia stated that FFS was determined for unobstructed vehicles based on the definition of vehicles with headway to the nearest vehicle in front of more than 8 s and no recent or immediate meeting with a vehicle in the opposing direction.

The estimated FFS for ideal condition may be based on either a known posted speed or a known 85^{th}-percentile speed and FFS may be estimated as 91% of the 85^{th}-

percentile speed for posted speed limits of 88.6 km/h and 104.7 km/h (Dixon et al., 1999). Moreover, Milliken (1998) stated that the 85^{th}-percentile speed is the speed at or below which 85% of drivers travel in free-flow conditions at representative locations on the highway or roadway section.

FFS as in the U.S. HCM 2000 (Transportation Research Board, 2000) is the mean speed of passenger cars that can be accommodate under the low to moderate flow rates (up to 1,300 pc/h/ln) on a uniform segment under prevailing roadway and traffic condition. The mean value of FFS of individual vehicles can be determined either as a space-mean (harmonic mean) or as a time mean (arithmetic mean) (Tseng et al., 2005). Meanwhile, Dowling (1997) stated that space-mean FFS is the basic of many planning models that are used to estimate average travel speeds and capacities.

However, in the U.S. HCM 2000 (Transportation Research Board, 2000), two methods are used to determine the FFS, the first is based on field measurement and the second is based on estimation using a set of guidelines provided in the manual. The average of all passenger-car-speed measured in the field under low-to-moderate-volume conditions can be used directly as the FFS of the basic segment. However, if field measurement of FFS is not possible, FFS can then be estimated indirectly based on the physical characteristics of the basic segment under studied. The physical characteristics include lane width, number of lanes, right shoulder lateral clearance and interchange density.

From other previous study, data for free-flowing vehicles with speeds that were more than 20 mph (32.19 km/h) below the normal FFS were removed from the data sets and the average speed of the rest of the free-flowing vehicles was used as the FFS (Chitturi & Benekohal, 2005). Meanwhile, Figueroa Medina & Tarko (2005) identified the speed of free-flow vehicles based on time headways of 5 s or more and FFS were measured on weekdays during daylight hours and favourable weather condition. Jian (as cited in Mingjun et al., 2007, p. 3453) on the study of basic segment expressway capacity found that when space headway is greater than 150 m, the traffic flow can be regarded as traffic in free flowing condition.

Speed-density graph is another method which can be used to estimate FFS. There are various types of speed-density graph such as Greenshield's model, Greenberg's model, Underwood's model, Drake's model and others. Greenshield found that FFS can measure by speed-density curve where he assumed a linear speed-density relationship to derive the model. The equation for this relationship is as shown in equation (2.1).

$$V = V_f - \left(\frac{V_f}{D_j}\right) D \tag{2.1}$$

where

V = Mean speed at density, D

V_f = Free-flow speed

D_j = Jam density

The equation (2.1) is often referred to as the Greenshield's model. It indicates that when density becomes zero, speed approaches FFS (i.e, $V \rightarrow V_f$ when $D \rightarrow 0$). Figure 2.1 shows the speed-density relationship established by Greenshield's model.

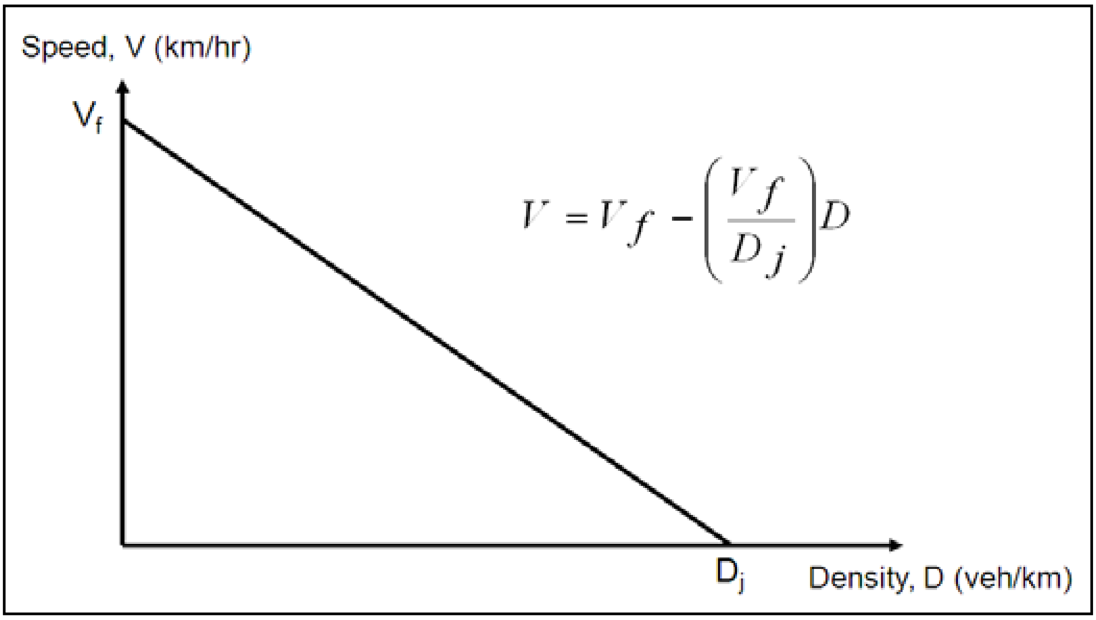

Figure 2.1: Speed-density relationship established by Greenshield's model

Moreover, Wang et al. (2009) stated that Greenshield, Greenberg, Underwood and Drake et al. were able to develop model of uninterrupted traffic flow that predicts and explains the trends that are observed in real traffic flows as well. They also claimed that Greenshield's model is derived based on seven data points only in which they were collected from one lane of a two-way rural road where six of the data points are below 96.6 km/h and the seventh data point was taken from a different road. The assumption has made that under uninterrupted flow conditions; speed and density are linearly related.

Ma et al. (2010) in their study to impact of lane width on vehicle speed of urban arterials indicate that speed data were collected during off-peak hours which are from 9:00 a.m. to 11:00 a.m. or 14:00 p.m. to 16:00 p.m. to obtain the FFS. However, based on U.S. HCM 2010 (Transportation Research Board, 2010), one preferably determines FFS by deriving it from a speed study involving the existing facility or on a comparable facility if the facility is in the planning stage. Many have used a ‘rule of thumb’ by adding 5 mi/h (10 km/h) above the posted limit to obtain FFS without justification (Deardoff et al., 2011). From other point of view, Deardoff et al. (2011) on the study of estimating FFS from posted speed limit signs found that to ensure the data collection in free-flow conditions, all speed observations were made at flow rates less than 500 veh/h and average headways more than 7 s.

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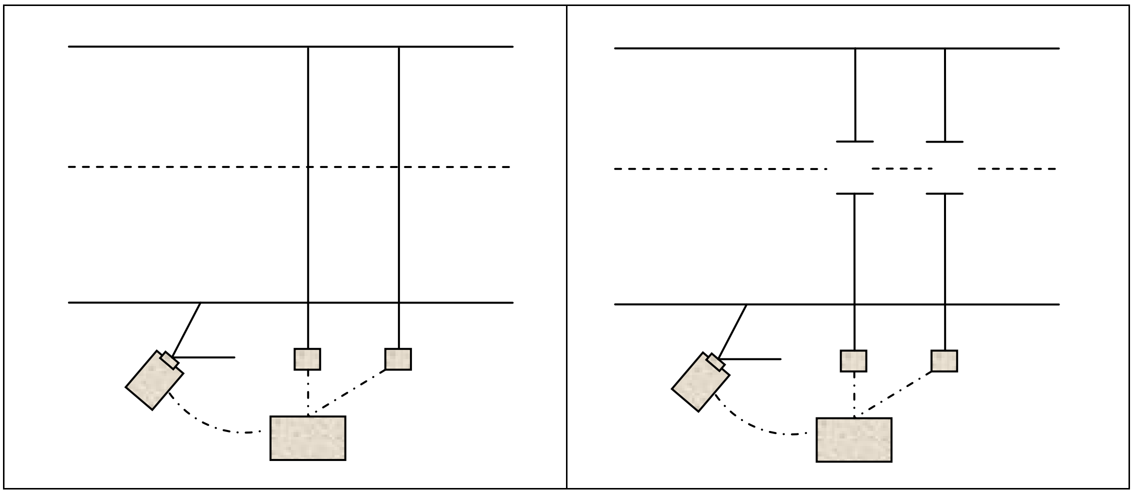
2.4 Field data collection of FFS

Traffic Study for Malaysia (Highway Planning Unit, 1996) and Bang et al. (1996) used the similar technique for collection of traffic flow, traffic composition and vehicle spot speed data. This technique is known as short base data collection. The short bases utilized two pneumatic tubes with 3 m spacing connected to a data longer for registration of the passage time of each axle as shown in Figure 2.2. Based on Figure 2.2(a), if the daily traffic is below about 10,000 vehicles per day, it is normally sufficient to use two tubes covering the whole road width. At higher traffic flows, it is necessary to use separate tubes in each direction to obtain sufficient counting accuracy based on Figure 2.2(b).



(a) For flow below 10,000 vpd (b) For higher flow

Figure 2.2: Equipment set-up for short base data collection (Highway Planning Unit, 1996 and Bang et al., 1996)

The output from the data logger is then processed with a specially-developed software (VTI: PRECDIA) to obtain traffic flow and composition, space mean speed and speed distribution, and time headway automatically and cross-checked with the backup video recordings. Besides the automatic data collection and the video recordings, a large amount of geometric and environment data were collected manually at short base site.

Tseng et al. (2005) in their study stated that FFS of vehicles were measured with a laser gun at the midpoint of each segment under fair weather conditions. For each study segment, speed samples were collected from the inside fast, outside fast and slow lane. The vehicles were classified into small vehicles, large vehicles and motorcycles. Small vehicles refer to passenger cars, vans and pickup trucks while large vehicles are trucks with more than two axles, heavy utility vehicles and large buses. However, only vehicles that were separated by headways of more than 5 s were sampled.

According to Baruzzi et al. (2008), studies on the effects of grades and visibility on expressway FFS indicate that speeds were determined using the floating vehicle technique. In this technique, every segment will be running with a test vehicle passing a vehicle each time the test vehicle was overtaken and recording the travel time. The vehicles entering and departing at interchanges were not considered for the floating vehicle. The test vehicle was equipped with a computer which was calculated the mean speed over a selected distance. The speed was calculated reflects the 50th percentile which for normally distributed data should be equal to the mean of speed. Under low to moderate flow rates (less than 1,300 pc/h/ln) and according to the U.S. HCM 2000 (Transportation Research Board, 2000) definition, the speed measured is the FFS.

2.5 Factor affecting FFS

2.5.1 Geometric conditions

Tseng et al. (2005) conducted a study to estimate FFS for multilane rural and suburban highways, and stated that lane location has an obvious but small impact on FFS. Figure 2.3 shows comparison of speeds for small vehicles in different lanes based on study conducted by Tseng et al. (2005). In this figure, harmonic-mean speed is space-mean speed which is the total distance traveled times the number of vehicles, dividing by the space-mean speed gives total vehicle hours traveled. Meanwhile, inside lane is the lane of the road nearest the vehicles going in the opposite direction and outside lane is the lane of the road nearest the edge, especially used by slower vehicles. Result from Figure 2.3 shows that the harmonic-mean FFS of small vehicles in an inside lane is higher than that in an outside lane. The average difference is about 4.3 km/h.

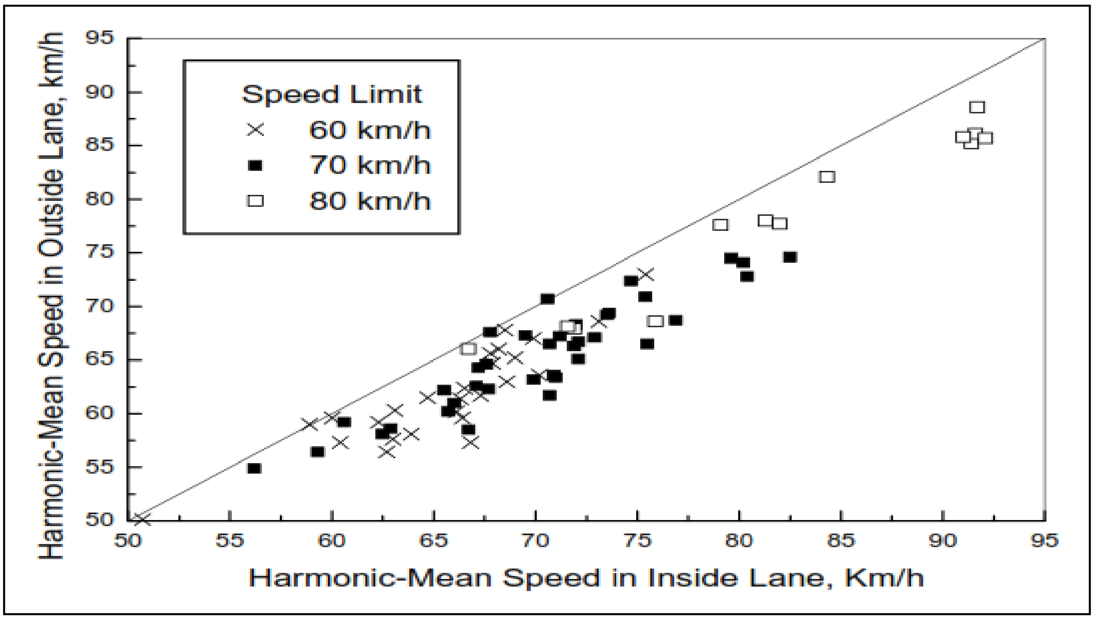


Figure 2.3: Comparison of speeds for small vehicles in different lanes (Tseng et al., 2005)

Heimbach et al. (as cited in Chitturi & Benekohal, 2005, p. 41) which studied the relationship of operating speeds and accidents on four-lane undivided arterials to traffic volume and roadway design characteristics, specifically found that operating speeds decrease and that the numbers of accidents increase as the traffic lane width decreases. Another study was conducted by Kemper et al. (as cited in Chitturi & Benekohal, 2005, p. 41) on the effects of narrow lanes in construction zones on safety. The study was conducted during the 17-month period before and during the reconstruction of bridge decks on the George Washington Memorial Parkway near Washington, D.C. They found that the use of 9-ft (2.74 m) lanes in Stage 1 of the reconstruction increased the accident rate statistically. In addition, the 9-ft (2.74 m) lanes caused slower speeds, resulting in fewer injury accidents, although there were a higher number of accidents during the reconstruction. That study indicates that narrower lanes in construction zones do have an effect on the speeds of motorists.

The speed reduction due to a lack of a shoulder on either side was found to be approximately 5.6 mph (9.01 km/h) in a work zone with a 12-ft (3.66 m) lane width. The narrower the lane was, the greater the speed reduction was. For 11-ft (3.35 m) lanes, the observed speed reduction was 133% more than the value of 1.9 mph (3.06 km/h) recommended by U.S. HCM 2000 (Transportation Research Board, 2000) for basic expressway. For 10.5-ft (3.20 m) lanes, the observed reduction was 69% greater than the U.S. HCM 2000 (Transportation Research Board, 2000) value for basic expressway. Narrow lanes reduced the speeds of heavy vehicles more than those of passenger cars (Chitturi & Benekohal, 2005).

Ali et al. (as cited in Ma et al., 2010, p. 1845) argue that a large difference in FFS between lanes with narrow (less than 11 ft or 3.35 m) and medium (11 ft or 3.35 m and 11.5 ft or 3.51 m) widths from a observation of 35 four-lane urban street segments in Fairfax County, Virginia. The mean speeds are 5 mph (8.05 km/h) higher and 85 percentile speeds are 7 mph (11.27 km/h) higher at sites with medium lane width as compared to sites with narrow lane width. However, no significant difference in FFS was observed at sites with medium or larger widths (greater than 11.5 ft or 3.51 m).

According to Tay & Churchill (2007) study, the results show that traffic speed increased after the installation of a rope barrier. It can be inferred that drivers perceived the median barriers more as a protective device than as a hazard and therefore adapt to their presence by increasing their speed to compensate for the perceived reduction in risks. This inference is also supported by anecdotal evidence from drivers who reported feeling safer driving along roads with median barriers.

However, this study shows contrary expectation by Swedish National Road Association where the installation of a barrier would reduce driver comfort and result in lower speeds.

Mingjun et al. (2007) on their study of implementation and validity of the FFS of on expressway claimed that the widths of lane, marginal strip, median and shoulder have different effects of FFS. The wider is the lane, marginal strip and shoulder, the bigger is lateral freedom, and the more comfortable and safe are the drivers. Generally, the speed of cars in the left-side lane is greater than cars in the right-side lane, so is the relation of the increment of speed. The elements of horizontal alignment (radius, super-elevation and length of curves) also have an effect on the speed of vehicle. Moreover, the degree of the effect is related to type of vehicle and the speed at which before driver enters the current curve.

A study conducted by Xiao-Ming et al. (as cited in Mingjun et al., 2007, p. 3454) indicates speed of all vehicles passing through straight line or curve or entering the curve with the radii of 1000 m or below is decreased to different degree and the smaller is the radius, the greater is the decrement of entrance speed. Meanwhile, De Luca et al. (2012) on the study of expressway FFS, a case study in Italy thought that the maximum speed in free flow conditions is to be found on flat straight stretches with a section width of around 11 m. In such conditions, the FFS is found to be at values of around 131 km /h. FFS tends to decrease in influence of slope, curvature, tortuousness and the width of the section. The lowest FFS value was encountered in ascent (+4, 5%) on a straight stretch, section width of around 9 m and tortuousness degree equal to 21 degrees/km. In these conditions, the FFS is found to be around the value of 105 km/h.

Moreover, Yuchuan et al. (2010) stated that FFS in the location close to the ramp junction is significantly lower than the middle section of main line. Table 2.1 shows the analysis results for free-flow speeds in several sections based on study conducted by Yuchuan et al. (2010). As shown in Table 2.1, NHWX22 - NHWX24 are three consecutive sections where section NHWX22 is close to on-ramp junction, section NHWX24 is close to off-ramp junction and section NHWX23 is located in the middle section of the main line. It is clear that FFS close to junction has decreased significantly. The alignment also has great affection to the FFS. Section NHWX20 and section NHWX21 are located in main line of Inner Ring Elevated Expressway where the alignment has greater curvature radius as compared with section NHWX22 - NHWX24 which is a straight section. The result shows that the FFS in curly line sections reduce about 10% (Yuchuan et al., 2010). Table 2.2 shows the partial results of FFS in different lane based on study conducted by Yuchuan et al. (2010).

Table 2.1: Analysis results for free-flow speeds in several sections (Yuchuan et al., 2010)

Sections	NHWX20	NHWX21	NHWX22	NHWX23	NHWX24
FFS (km/h)	72.9	73.9	79.4	83.5	79.9

From the results shown in Table 2.2 where lane 1 is inside lane close to the median strip, it can be found that in the same section, the FFS in outside lane is the minimum value and the discrepancy between inside lane and outside lane become larger with increase of lane quantity (Yuchuan et al., 2010).

Table 2.2: Partial results of FFS in different lane (Yuchuan et al., 2010)

Section	Lane	FFS (km/h)	Section	Lane	FFS (km/h)
NBXX10	1	71.0	YABX17	1	67.4
NBXX10	2	69.6	YABX17	2	71.2
NBXX10	3	65.8	YABX17	3	63.3
NBXX10	4	60.8	YABX18	1	77.6
NBXX11	1	75.7	YABX18	2	80.5
NBXX11	2	73.7	YABX18	3	71.2
NBXX11	3	72.8	NHWX22	1	82.3
NBXX11	4	67.9	NHWX22	2	78.4
NBXX12	1	80.7	NHWX23	1	83.0
NBXX12	2	78.1	NHWX23	2	80.6
NBXX12	3	79.4	NHWX24	1	78.7
NBXX12	4	71.8	NHWX24	2	76.9

2.5.2 Environment conditions

Side friction events such as stopping vehicles, pedestrians etc. reduce the desired speed as the drivers may want to maintain a safe speed with consideration to the risk for unexpected roadway blockage and conflict with other traffic elements which may suddenly appear (Bang & Indonesia, 1995). This effect is illustrated in Figure 2.4 with a FFS reduction from FV_o to FV when the speed-flow curve intercept with the Y-axis moves from A_o to A.

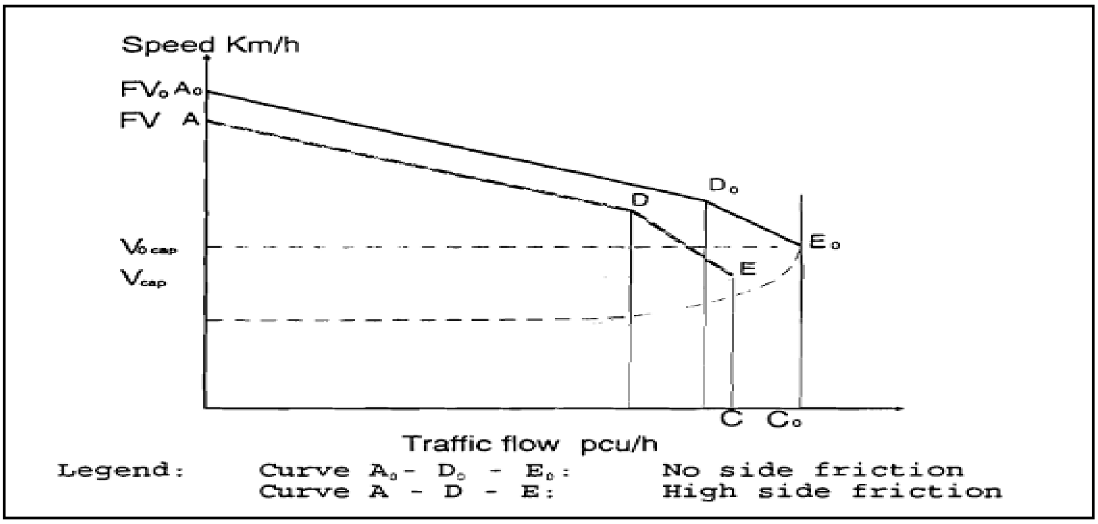


Figure 2.4: Impact of side friction on speed and capacity (Bang & Indonesia, 1995)

U.S. HCM 2000 (Transportation Research Board, 2000) stated that operation conditions on expressway can also be affected by environmental condition such as weather or lighting and FFS is reduced by 10 km/h during light rain and by 19 km/h during heavy rain. However, Ibrahim & Hall (as cited in Kyte et al., 2000, p. 109) on their study to investigate the effect of adverse weather on expressway operations in Canada found the following reductions in the FFS:

a. Light rain caused a 2 km/h drop.
b. Light snow caused a 3 km/h drop.
c. Heavy rain caused a 5 to 10 km/h drop.
d. Heavy snow caused a 38 to 58 km/h drop.

Meanwhile, Brilon & Ponzlet (as cited in Kyte et al., 2000, p. 109) investigated 15 sites in Germany to assess the effect of weather conditions, daylight or darkness and other factors on speed-flow relationships concluded that darkness reduces driver speeds by 5 km/h, and drop of 9.5 km/h and 12 km/h on two-lane and three-lane wet roadway segment respectively. May (as cited in Kyte et al., 2000, p. 109) considered the effect of capacity reducing occurrences on expressway operation where he propose the FFS reduction in his study as shown in Table 2.3 using two of previous studies by Ibrahim & Hall and Brilon & Ponzlet.

Table 2.3: FFS for different weather conditions (May as cited in Kyte et al., 2000, p. 109)

Conditions	Recommended value (km/h)
Clear and dry	120
Light rain and light snow	110
Heavy rain	100
Heavy snow	70

Liang et al. (as cited in Kyte et al., 2000, p. 110) reported on the effects of the snow and fog on driver speed during winter 1995-1996 where the first year that the storm warning system was in place found a 8.0 km/h reduction of driver speed during fog events and a 19.2 km/h reduction during snow events. The study identified several speed-related effects by using multiple regression analysis is as follows.

a. Wind speed reduces drivers speed by 1.1 km/h for every km/h of wind speed exceeding 40 km/h.
b. Drivers reduced their speed by 1.6 km/h during nighttime periods.
c. The presence of a snow floor reduced average speeds by 5.6 km/h.

According to study conducted by Kyte et al. (2000) to investigate the effect of environment factors on FFS, they shows the comparison results between their study (as presented by model 3), May and Ibrahim & Hall in Figure 2.5. The results shows that the effect of light precipitation from model 3 (14.1 km/h to 19.5 km/h speed reduction) is about 50% higher than the 10 km/h reduction recommended in the May study. The effect of heavy rain is also about 50% higher in model 3 than the value recommended by May (31.6 km/h and 20 km/h, respectively). Heavy snow has the most significant effect on driver speed and consistent for all three sources. High wind is a new variable identified in the study that can be used in estimating FFS. The estimated effect is a 9.0 km/h reduction in FFS for wind speeds above 48 km/h.