FREE-FLOW SPEED FOR FOUR-LANE HIGHWAYS WITH LEVEL TERRAIN IN RURAL AND SUBURBAN AREAS IN PENINSULAR MALAYSIA

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by

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oleh

TUTI AZMALIA BINTI AZAI

Tesis yang diserahkan untuk

memenuhi keperluan bagi

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
BFFS	Base free-flow speed
CCTV	Closed circuit television
D	Divided highway
df	Degree of freedom
FFS	Free flow speed
GDOT	Georgia Department of Transportation
GPS	Global Positioning System
HCM	Highway Capacity Manual
IA	Index of Agreement
LOS	Level of service
NAE	Normalized Absolute Error
PA	Prediction Accuracy
pce	Passenger car equivalent
pcu/hr	Passenger car unit per hour
ROI	Region of interest
RMSE	Root Mean Square Error
R	Rural area
Sig.	Observed significant value
SMS	Space-mean speed
SPSS	Statistical Package for the Social Science
SU	Suburban area

TMS	Time-mean speed
TWLT	Two-way left-turn lane
UD	Undivided highway
V/C	Volume to capacity ratio

LIST OF SYMBOLS

FFV_W	Adjustment factor for road width (km/h)
FFV_{SF}	Adjustment factor for side friction conditions and shoulder width (km/h)
FFV_{RC}	Adjustment factor for road functional class and land use (km/h)
$FFV_{X,Y,Z}$	Adjustment factor for the influence of variables X, Y, Z (km/h)
FV_{CW}	Adjustment of carriageway width (km/h)
FFV_{LU}	Adjustment factor for land use and side friction
FV_{CLASS}	Adjustment for road function and road class (km/h)
F_M	Adjustment factor for median type (km/h)
F_{LW}	Adjustment factor for lane width (km/h)
F_A	Adjustment factor for access point (km/h)
$\bar{x}$	Arithmetic mean
H_1	Alternate hypothesis
f_{LW}	Adjustment for lane width (km/h)
f_{LC}	Adjustment for lateral clearance (km/h)
f_{APD}	Adjustment for access point density (km/h)
f_{LP}	Adjustment for lane position (Inner or Outer lane) (km/h)
β_{LW}	Adjustment factor for lane width
β_{LC}	Adjustment factor for lateral clearance
β_{APD}	Adjustment factor for access point density
β_{LP}	Adjustment factor for lane position
$\overline{P}$	Average of the predicted value

$\overline{O}$	Average of the observed value
FV_O	Base free flow speed of light vehicles for the studies road and terrain type
D	Density (pcu/km)
FV	Free flow speed of light vehicles in the actual conditions (km/h)
F_{LC}	Factor for left shoulder lateral clearance (km/h)
v	Free-flow speed (km/h)
V_{sf}	Harmonic-mean free flow speed (km/h)
x_x	Independent variable
D_j	Jam density, the maximum possible value for density (pcu/km)
v_f	Mean speed (space-mean speed) (km/h)
$\bar{x}_i$	Mean of group *i*
μ_i	Mean population
k	Number of groups
n_i	Number of observations in group *i*
H_0	Null hypothesis
O_i	Observed Value
v_o	Optimum speed at maximum flow (km/h)
D_o	Optimum density, the maximum possible value for density (pcu/km)
S_p^2	Pooled variance
P_i	Predicted value
SS_B	Regression sum of square between group
SS_W	Regression sum of square within group
β_x	Regression coefficients
S	Spacing between signalized intersection (km)

$\bar{v}_s$	Space-mean speed
σ	Standard deviation
S_i^2	Sample variance in group *i*
σ_p	Standard deviation of the predicted value
σ_o	Standard deviation of the observed value
$\bar{v}_t$	Time mean speed
n	Total sample size
SS_T	Total sum of square
σ^2	Variance

LAJU ALIRAN BEBAS UNTUK LEBUH RAYA EMPAT LORONG UNTUK KAWASAN RATA DI LUAR DAN PINGGIR BANDAR DI SEMENANJUNG MALAYSIA

ABSTRAK

Laju aliran bebas memainkan peranan penting dalam menentukan prestasi lebuh raya empat lorong. Objektif utama kajian ini adalah untuk menentukan model laju aliran bebas yang sesuai untuk lebuh raya empat lorong tanpa gangguan berdasarkan keadaan lalu lintas yang sedia ada di Malaysia. Untuk menjalankan kajian ini, data telah dikumpul di 16 tapak kajian (64 lorong) di seluruh semenanjung Malaysia. CCTV telah digunakan untuk mengumpul data lapangan dan data yang dikumpul telah dikenal pasti melalui perisian "TRAIS^{TM} Advanced SRM 3.2". Analisis statistik dengan menggunakan perisian SPSS 20 telah digunakan untuk menganalisis data laju aliran bebas. Laju aliran bebas untuk setiap lorong telah diukur dengan menggunakan tiga kaedah iaitu berdasarkan kepada hubungan linear laju-ketumpatan iaitu Kaedah 1, purata laju kenderaan dalam kadar aliran rendah iaitu Kaedah 2 dan purata laju kenderaan dengan jarak kepala sama atau lebih daripada 8 s iaitu Kaedah 3. Keputusan menunjukkan purata laju aliran bebas di antara Kaedah 1, 2 dan 3 adalah didapati tidak jauh berbeza. Teknik regresi linear telah digunakan untuk meramalkan model laju aliran bebas. Model regresi yang dibangunkan menunjukkan korelasi yang baik dengan nilai pekali penentuan, R^2 yang tinggi. Di samping itu, petunjuk prestasi (PI) menunjukkan bahawa model yang berdasarkan laju aliran bebas untuk kereta dengan jarak kepala sama atau lebih daripada 8 s telah dipilih sebagai model yang paling sesuai untuk digunakan untuk keadaan jalan raya di Malaysia. Akhir sekali, analisis sensitiviti menunjukkan bahawa laju aliran bebas

cenderung untuk menjadi lebih rendah semasa keadaan geometri yang paling teruk dan lebar lorong adalah parameter yang paling sensitif berbanding dengan parameter lain.

FREE-FLOW SPEED FOR FOUR-LANE HIGHWAYS WITH LEVEL TERRAIN IN RURAL AND SUBURBAN AREA IN PENINSULAR MALAYSIA

ABSTRACT

Free-flow speed plays an important role in determining the highway performance of four-lane highways. The main objective of this study is to determine the appropriate models of free-flow speed on uninterrupted four-lane highways based on local traffic conditions in Malaysia. To carry out this study, data was collected at 16 sites (64 lanes) around Peninsular Malaysia. CCTV was used to collect field data and the collected data was reduced using TRAIS™ Advanced SRM 3.2 software. Statistical analysis by SPSS 20 software was used to analyze the data of free-flow speed. Free-flow speed in each lane was measured using three methods which are based on linear speed-density relationship (Greenshield, 1935) which is Method 1, average speed of vehicles during low flow rate (U.S. HCM, 2000) which is Method 2 and average speed with headway $\geq$ 8 s which is Method 3. The results showed that the mean free-flow speed between Method 1, 2 and 3 was found to be not significantly different. Subsequently, multiple linear regression techniques was used to derive predictive free-flow speed models. The developed regression model showed good correlation with high value of coefficient of determination, R^2. In addition, performance indicator (PI) showed that the model which is based on free-flow speed of cars with headway $\geq$ 8 s was selected as the most suitable model to be used in Malaysia roadway condition. Finally, sensitivity analysis showed that free-flow speed tended to be lower during worst geometrical conditions and lane width was the most sensitive parameter compared with other parameters.

CHAPTER 1

INTRODUCTION

1.1 Background

Various types of highways and expressways are available in Malaysia including two-lane highways, multilane highways, four-lane expressways and six-lane expressways. Nowadays, most of the two-lane highways were upgraded to multilane highways due to increasing traffic demand on the highways. U.S. Highway Capacity Manual 2000 (U.S. HCM 2000) (Transportation Research Board, 2000) defines multilane highways as a highway with at least two lanes or more for the exclusive use of traffic in each direction, with no control or partial control of access, but that may have periodic interruptions to flow at signalized intersections no closer than 3.0 km. Multilane highways can be categorized into four categories which are undivided four-lane highways, divided four-lane highways, undivided six-lane highways and divided six-lane highways respectively. Divided multilane highways usually have a barrier or a concrete divider to separate the direction of vehicle travel along the road segment and undivided multilane highways do not have divider but has the strip line in the centered of the lane to separate the direction of the vehicle. Figure 1.1 and Figure 1.2 show the typical divided and undivided four-lane highways in Malaysia respectively.

Figure 1.1: Typical divided four-lane highways in Malaysia

Figure 1.2: Typical undivided four-lane highways in Malaysia

Most of the highway systems exist in rural, suburban and urban area. Different areas have different driving conditions. Rural and suburban areas consist of facilities that are outside from urban areas and usually have lower density of employment and widely scattered development (Transportation Research Board, 2000). Driving conditions in rural and suburban areas differ from those highways in urban areas. The differences between these facilities influence the travel pattern of the community to any destination in terms of capacity of the vehicle, existing of traffic control and roadway environment. Multilane highways can be operated under uninterrupted flow in long segments and usually located in rural and suburban areas (Transportation Research Board, 2000). An uninterrupted flow facility refers to the condition when there are no fix elements on the road such as traffic light at signalized intersections. Subsequently, Tseng, Lin and Shieh (2005) stated that uninterrupted flow is possibly located in sections of rural and suburban multilane highways between signalized intersections where signal spacing is sufficient to allow for uninterrupted flow.

Free-flow speed is defined as the speed of vehicle travel when the vehicle movement is not interfered by another vehicle or interrupted by control devices at low volume and low density (Transportation Research Board, 2000). It is the speed at which drivers feel comfortable to traveling under physical, environmental, and traffic-control conditions on an uncongested section of multilane highway. Free-flow speed is an important parameter in the measurement of capacity and performance of multilane highways. Capacity is used to estimate the maximum amount of traffic that can be accommodated by a facility while maintaining prescribed operational qualities. The evaluation of capacity at multilane highways is practically measured based on free-flow speed and flow rate. Table 1.1 shows the relationship between free-flow speed and capacity in which different free-flow speed has different capacity.

Table 1.1: Free-flow speed and capacity for multilane highway (Transportation Research Board, 2000)

Free-flow speed (km/h)	Capacity (pc/h/ln)
100	2200
90	2100
80	2000
70	1900

In the context of highway performance, the phenomenon of traffic congestion gives an impact on the reduction of speed and causing discomfort to the drivers especially during peak-hours. Therefore, due to rapid development of the country, highway management needs accurate estimation of free-flow speed especially for highways in rural and suburban area as poor operation on multilane highways may affect the performance of roadways. Thus, it is important to design multilane highways with a specific standard to prevent either under or over capacity of vehicle travel on the roadways. As a conclusion, various design methods should be proposed to overcome this problem and procedures for analysis with respect to Malaysian road condition are needed to design multilane highways so that the capacity is always greater than traffic demand.

1.2 Problem Statement

Most countries have their own guideline to evaluate the operational performance at highways. U.S. HCM 2000 (Transportation Research Board, 2000) is widely used to design the highway in United States of America and several developed countries refer to this guideline to design the highway based on their local conditions. Free-flow speed is one of the important parameters used to evaluate the level of services (LOS) at multilane highways. However, traffic flow, driving behavior and vehicle classification exist in United States of America is different to that in a developing country such as Malaysia. Due to these fundamental differences, the standard western relationships for predicting free-flow speed may not be appropriate for the Malaysian roadway condition. This issue needs to be investigated and hence requires a different approach to analysis free-flow speed based on local prevailing traffic condition.

Nevertheless, the current method adopted to measure free-flow speed and design the roadway for multilane highway is based on the study proposed by Arahan Teknik (Jalan) 8/86 and Traffic Study for Malaysia (Ministry of Works Malaysia, 1996). Arahan Teknik (Jalan) 8/86 (Ministry of Works Malaysia, 1986) do not provide a proper method to measure free-flow speed. However, volume to capacity ratio (V/C) method is used to estimate the capacity of the roadway. Subsequently, a Traffic Study for Malaysia (Ministry of Works Malaysia, 1996) proposed two general methods to measure free-flow speed which is from field measurement or estimation using free-flow speed equation. However, this guideline is outdated and must be renewed based on local empirical studies at the present time.

1.3 Objectives of the Study

In this research, the goal is to develop a free-flow speed prediction model based on Malaysian roadway conditions and to statically compare the suitable method to analyze empirical free-flow speed on flat terrain on four-lane rural and suburban highways with different roadway geometry. The specific objectives of this research are as follows:

(a) To determine a suitable method to measure free-flow speed of four-lane highways from the empirical field data;

(b) To examine the relationships between free-flow speed and roadway conditions for four-lane highways such as roadway geometries, traffic volume, vehicles type and variation of time;

(c) To develop a regression model to predict free-flow speed for four-lane highways;

(d) To perform sensitivity analysis on the developed free-flow speed models in order to explore the sensitivity of each predictor.

1.4 Scope of the Study

The scope of this study is to analyze an empirical speed data collected at multilane highways in Malaysia in order to develop free-flow speed regression models.

This study only focused on four-lane highways located in rural and suburban areas. Geometric parameters for the data collections such as lane width, shoulder width, median clearance, access points and segment length were measured at each study segment. The data for this study were collected at flat terrain roadways during peak-hour and off peak-hour period and speed data were collected for about six hours at each segment. The segment under studied are located far away from signalized intersections to avoid interruption in traffic flow.

Subsequently, this study proceeded to develop a regression model to predict free-flow speed of vehicle travel along four-lane rural and suburban highways using roadway geometries such as lane width, lateral clearance, access point density and lane position as the independent variables.

1.5 Organization of the Thesis

This thesis consists of five chapters. The contents of the following chapters are outlined in this section. Chapter 1 provides a comprehensive introduction of four-lane highways, the statement of the objectives and scope of the thesis is presented in this chapter. Chapter 2 focuses on the review of literature addressing related to multilane highways such as free-flow speed, factors affecting free-flow speed and regression model of free-flow speed. Chapter 3 explains the approach and methodology used for field observation and describes the methods to collect the data. The estimation of free-flow speed, model development and sensitivity analysis are described in Chapter 4. Conclusions drawn from this study are summarized in Chapter 5. This chapter also provides some recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents the literature review related to free-flow speed analysis and factors affecting free-flow speed on multilane highways. Factors affecting free-flow speed such as roadway geometries, traffic conditions, roadway environments and vehicle types are highlighted in this chapter. Apart from that, definition and methods to measure free-flow speed are also discussed in this chapter. Lastly, this chapter emphasizes on the development of free-flow speed model by other researchers from various regions and countries.

2.2 Concept of Space Mean Free-Flow Speed

The space-mean speed is the harmonic mean of the speeds of vehicles passing a point on a highway during an interval of time (Transportation Research Board, 2000). It is called a space-mean speed because it is the average time each vehicle spends in the defined roadway segment or space. Space-mean speed can be categorized into three type which are average travel speed, running speed and free-flow speed.

Free-flow speed can be described as the most important parameter for the traffic designer to measure and analyze the performance of a roadway. Free-flow speed can be defined as the speed at which a driver can travel on a roadway under favorable climatic conditions and unaffected by other traffic (Schutte & Roodth, 1994; Ye, Tarko, & Sinha, 2001; Tseng et al., 2005; Chiguma, 2007; Asamer & Reinthaler, 2010). Generally, free-flow speeds is the term used to represent the average desired speed at which a driver can travel on a given highway under prevailing traffic condition and unaffected by other environmental factor with respect to topography and road type.

Apart from that, Traffic Study for Malaysia (Ministry of Work Malaysia, 1996) defines free-flow speed with two conditions. Firstly, free-flow speed of a vehicle is defined as the speed at which the drivers feel comfortable to travelling under prevailing geometric, environmental and traffic control conditions; and not restrained by any other vehicles. The second condition is free-flow speed is defined as the theoretical average speed of traffic when there is no vehicles present on the actual roadway condition.

2.3 Measurement of Free-Flow Speed

Free-flow speed can be measured either empirical or estimated using theoretical approach. Empirical free-flow speed can be measured directly from the field. Meanwhile for theoretical approach, free-flow speed can be estimated based on regression models or speed-density models such as the models developed by Greenshield, Greenberg, Drake and Underwood.

There are numerous studies which presented the method to measure free-flow speed from the field. Several authors noted that the criterion used to consider vehicles in free-flow condition is based on the headways of vehicles travel in the traffic stream.

However, another study claims that free-flow speed can be measured by averaging the speed of vehicles.

Figueroa and Tarko (2005), Gong and Stamatiadis (2008), Himes and Donnell (2010), Tseng et al. (2005), Saifizul et al. (2011) concluded that vehicles with headway greater than or equal to 5 s are considered to be under free-flow speed condition. Subsequently, Ali et al. (2007) reported that vehicles travelling in free-flow conditions were considered to have time headways of at least 7 s and consecutive vehicles of at least 4 s. Subsequently, Bang et al. (1996), Chiguma (2007), and Traffic Study for Malaysia (Ministry of Work Malaysia, 1996) similarly recommended that vehicles with headways greater than 8 s would be considered in free-flow conditions.

Dixon et al. (1999) and U.S. HCM 2000 (Transportation Research Board, 2000) suggested that average operating speed is similar to free-flow speed for low volume conditions. Based on the method suggested by U.S. HCM 2000 (Transportation Research Board, 2000), the measurement of mean free-flow speed of vehicles must be observed during low to moderate traffic volume which is the flow of vehicles must be less than 1400 pc/h/ln. Method to define speeds of impeded and unimpeded vehicles were also included in the U.S. HCM 2000 (Transportation Research Board, 2000) in order to measure free-flow speed. However, the method to measure free-flow speed proposed by U.S. HCM 2000 (Transportation Research Board, 2000) is different with a study conducted by Deardoff et al. (2011). Deardoff et al. (2011) concluded that vehicles with headway more than 7 s is considered as a free-flow condition and observation of speed must be conducted at low traffic volumes which are 500 veh/h/ln.

Subsequently, in many studies, theoretical approach is another alternative method used to estimate free-flow speed. Theoretical model is used when speed data from the field is not available. Speed-density models developed by Greenshield, Greenberg, Underwood and Drake are the more popular methods used by researchers to estimate free-flow speed as shown in Figure 2.1. The graphs in Figure 2.1 show that free-flow speed occurs when the driver could drive at any desirable speed at low density on a single roadway. When more and more drivers begin using the roadway, density increases and the speed decreased significantly till the road capacity is reached (May, 1990). At a point in time, density becomes so high such that all vehicles stop and speed is now zero (this condition is known as the jam density, D_j)

First, Greenshield developed free-flow speed model for uninterrupted traffic flow in year 1935. This model assumed that speed and density relationship is a linear model as illustrated in Figure 2.1 (a). Based on Figure 2.1 (a), speed-density relationship shows that when the density and flow of the vehicle approaches to zero, the speed of the vehicle will approaches to free-flow speed condition. The equation of speed-density proposed by Greenshield is as shown in equation (2.1) in Table 2.1.

A second model was developed by Greenberg. This model suggested that the logarithmic curve is a suitable curve to express the relationship between speed and density. However, a main drawback of this model is that as density tends to zero, speed tends to infinity (Axay et al., 2011). This model shows the inability of the model to predict the speed at lower densities. Figure 2.1 (b) and equation (2.2) in Table 2.1 show the speed-density graph and equation of speed-density proposed by Greenberg.

Another model of free-flow speed was developed by Underwood and Drake. Both models assumed exponential relationship between speed and density. Speed-density graph developed by Drake and Underwood appears as a bell-shaped curve (Drake et al., 1967 as cited in Ahmad Raqib, 2003). These developed models show that speed becomes zero when density approaching to infinity. Equation (2.3) and (2.4) in Table 2.1 shows speed-density for these models.

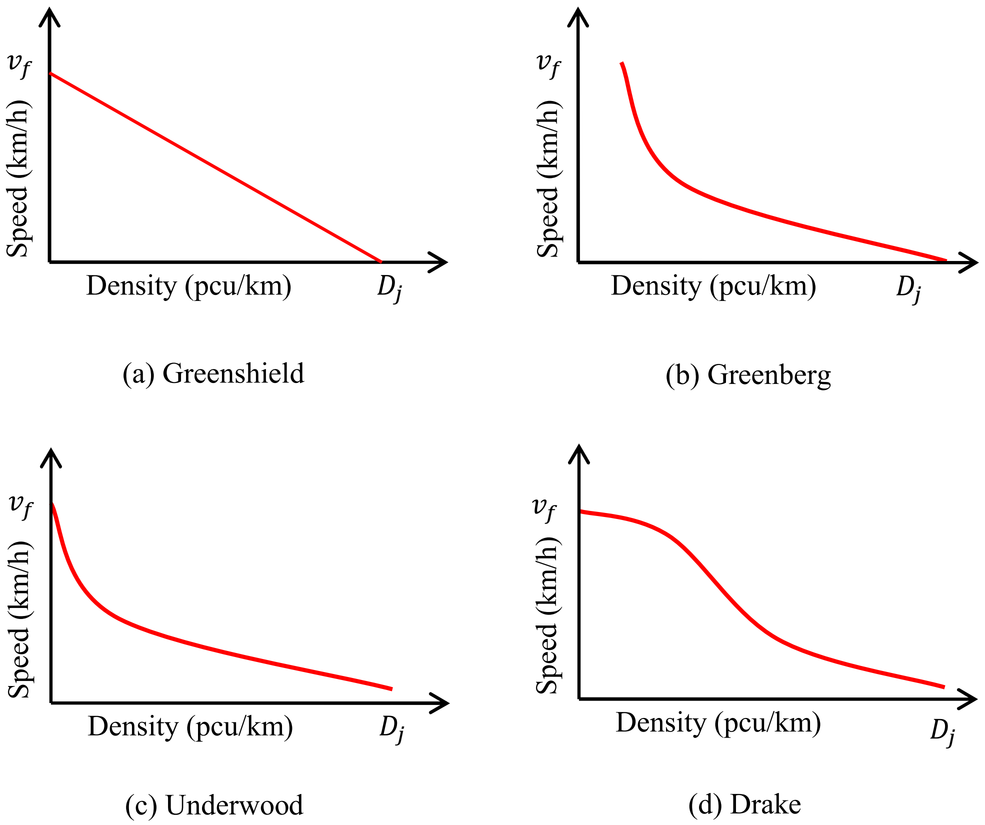

Figure 2.1: Speed-density relationship

Table 2.1: Speed-density models

Model	Equation
Greenshield	$v = v_f - \left(\frac{v_f}{D_j}\right) D$ (2.1)
Greenberg	$v = v_o ln\left(\frac{D_j}{D}\right)$ (2.2)
Underwood	$v = v_f exp^{\left(\frac{-D}{D_o}\right)}$ (2.3)
Drake	$v = v_f\ exp^{-1/2\left(\frac{D}{D_o}\right)^2}$ (2.4)

Where

v = Mean speed (space-mean speed) (km/h)

v_f = Free-flow speed (km/h)

v_o = Optimum speed at maximum flow (km/h)

D = Density (pcu/km)

D_j = Jam density, the maximum possible value for density (pcu/km)

D_o = Optimum density, the maximum possible value for density (pcu/km)

2.4 Field Data Collection for Free-Flow Speed

There are various methods and equipments which can be used to measure free-flow speed at the sites such as pneumatic tube, radar gun, laser gun, video camera and et. cetera.

Bang et al. (1996) and Traffic Study for Malaysia (Ministry of Work Malaysia, 1996) used pneumatic tubes in order to measure the speed of vehicles from the field. The survey equipment was equipped with a pair of pneumatic tubes (spacing of 3 m) connected to data loggers for recording vehicle axle passage times. These two pneumatic was laid across the lane in which data are to be collected and when moving vehicles passes over, an impulse is transmitted to the data loggers. Figure 2.2 shows the illustration set up for data collection using pneumatic tube. However, this method is difficult to set up on the busy roadway and these tubes rather conspicuous and may therefore affect the driver behavior, resulting in a distortion of the speed distribution (Nicholas & Lester, 2009). In addition, the pneumatic tube is normally used for longer time period of data collection and not suitable for short time period of data collection (Currin, 2001).

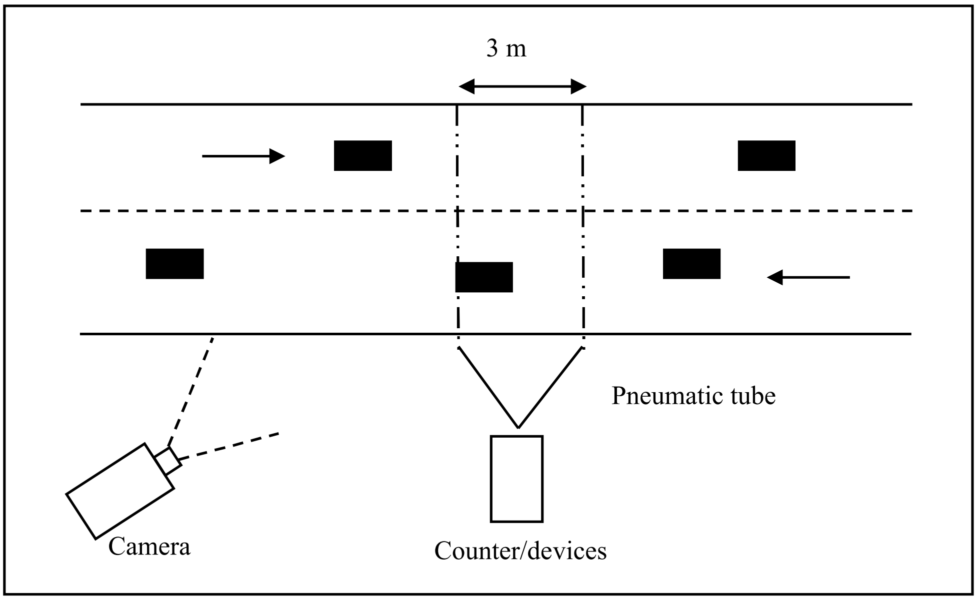

Figure 2.2: Illustration of equipment set up using pneumatic tube

Another method that can be used is using a video camera. Video recording provides continuous data collection on the position and speed of the road users passing the video-observed area (Laureshyn, 1996). Apart from that, Grant et al. (2000) stated that the accuracy of video image detection system is dependent upon factors such as the camera height, location and angle above the road. Chiguma (2007) used the video camera in his research to record vehicle speed. During observation, measurement of speed, flow and roadside activities are based on video and manual observation along the study segment. The survey was set up at road segment within more or equal to 200 m long. The ends of the segment were clearly marked with paint or tape across the roadway and video recorder was placed at upstream and downstream of the segment. Figure 2.3 shows the illustration set up for data collection using video camera.

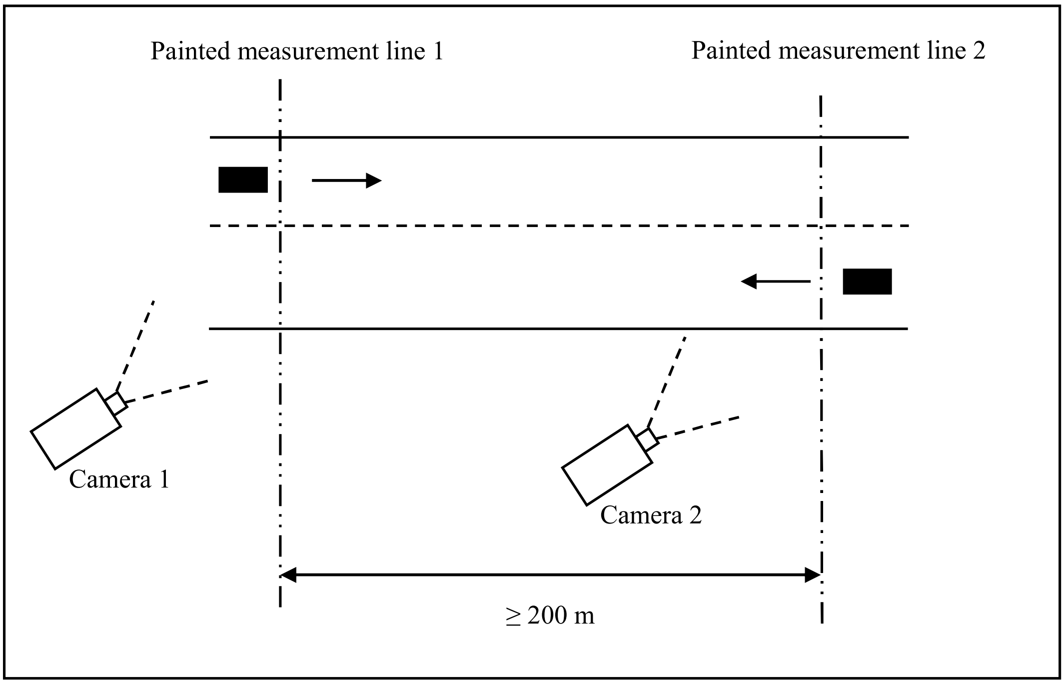

Figure 2.3: Illustration of equipment set up using video camera

Apart from video camera and pneumatic tube, speed of vehicles also can be measured using a radar gun and laser gun. Deardoff et al. (2011), Tseng et al. (2005), Gong and Stamatiadis (2008) measured speed of vehicles in the middle of the uniform multilane highway segment using a radar gun. For this method, the data collectors were required to be located where they can see the measurement point while the drivers could not see them to avoid influencing the driver operating speed (Gong & Stamatiadis, 2008). However, this method still cannot guarantee to obtain accurate results. Misagi and Hassan (2005) stated that speed data collected using radar gun can introduce bias errors such as human error in measuring speed and driver might change their driving speed upon perceiving test equipment as speed enforcement. In addition, Hassan (2004) noted that a statistically significant drop in speed averaging 7 km/h was reported when a radar gun was being used.

2.5 Ideal Conditions of Free-Flow Speed

The ideal conditions is the condition that occurs under ideal situation and represents the highest operating speed including good weather, good pavement conditions, good visibility, user's familiarity with the facility and no incidents holding back traffic flow (Transportation Research Board, 2000). Table 2.2 shows the summary of geometric characteristics of ideal conditions proposed by others studies.

U.S. HCM 2000 (Transportation Research Board, 2000) recommends that the ideal conditions for multilane highways included 3.6 m lane width, level terrain, 3.6 m total lateral clearance, no direct access point along the roadway, only passenger cars in the traffic stream, divided multilane highway and free-flow speed higher than 100 km/h. Total lateral clearance in this manual refers to the total of clearance from the left edge of the travel lane to roadside obstruction (paved and unpaved shoulder) and clearance from the right edge of the travel lanes to obstructions in the roadway median.

Based on the Malaysia roadway conditions, Arahan Teknik (Jalan) 8/86 (Ministry of Work Malaysia, 1986) defines the ideal conditions of multilane highways as level terrain, lane width of 3.65 m or more, lateral clearance of 1.83 m or more between the edge of lanes and obstructions at the roadside or on the median, only passenger cars in the traffic stream and rural divided highways. However, Traffic Study for Malaysia (Ministry of Work Malaysia, 1996) defined ideal conditions for multilane highways as lane width of 3.5 m, effective outer shoulder width of 3.0 m, 0.5 m of marginal strips (median clearance), flat terrain, no roadside development, very low side friction and divided highway (median width more than 3.0 m).

Table 2.2: Summary of ideal conditions for multilane highways proposed by other studies

Geometric characteristics	U.S. HCM 2000	Traffic Study for Malaysia (1996)	Arahan Teknik (Jalan) 8/86	Indonesian HCM
Base free-flow speed (BFFS)	100	78	-	78
Lane width (m)	3.60	3.50	3.65	3.50
Lateral clearance				
Left edge of the travel lanes	1.80	3.0	1.83	1.50
Right edge of the travel lanes	1.80	0.5	0.5	1.00
Access point density (/km)	0	Very low	0	Very low
Terrain type	Flat	Flat	Flat	Flat

Therefore, base free-flow speed (BFFS) refers to the free-flow speed under ideal conditions or known as the highest operating speed of vehicle travel on the roadways. The base free-flow speed must be reduced to account for the effects of geometric characteristics such as lateral clearance at the shoulder or median, median type, lane width, and density of access points (Bang et al., 1996). For multilane highways, U.S. HCM 2000 (Transportation Research Board, 2000) recommends that free-flow speed under base condition is 100 km/h. Nevertheless, U.S. HCM 2000 (Transportation Research Board, 2000) found that the speed limit is another factor that affects free-flow speed. Therefore, the suggested base free-flow speed for multilane highways is approximately 11 km/h higher than the speed limit of between 65 and 70 km/h and it is 8 km/h higher for speed limit between 80 and 90 km/h. Apart from that, other studies define base free-flow speed as free-flow speed of each vehicle class. Traffic Study for Malaysia (Ministry of Work Malaysia, 1996) and Indonesian Highway Capacity Manual (Ministry of Public Works, 1995) recommended that base free-flow speed of each vehicle is different. Table 2.3 shows the base free-flow speed based on vehicle category recommended by Traffic Study for Malaysia (Ministry of Work Malaysia, 1996) and Indonesian Highway Capacity Manual (Ministry of Public Works, 1995).

Table 2.3: Summary of recommended base free-flow speed for multilane highway based on each vehicle category

	Light vehicle	Medium heavy vehicle	Large buses	Large trucks	Motorcycles
Traffic Study for Malaysia (1996)	78	67	73	64	58
Indonesian HCM					
• Divided	78	81	65	62	-
• Undivided	74	78	63	60	-

2.6 Factors Affecting Free-Flow Speed

Figure 2.4 shows the factors affecting free-flow speed under different categories such as traffic conditions, roadway geometries, roadway environment, vehicles and others. As can be seen in Figure 2.4, traffic conditions such as traffic volume, speed limit, control of access and passing maneuvers has significant influence on free-flow speed. Roadway geometry such as lane width, shoulder width, lane position, median type, lateral clearance, access point density, curvature, gradient and roughness plays an important role in determining free-flow speed. Apart from that, other factors affecting free-flow speed are vehicle type, vehicle condition, weather, land use and driver behavior.

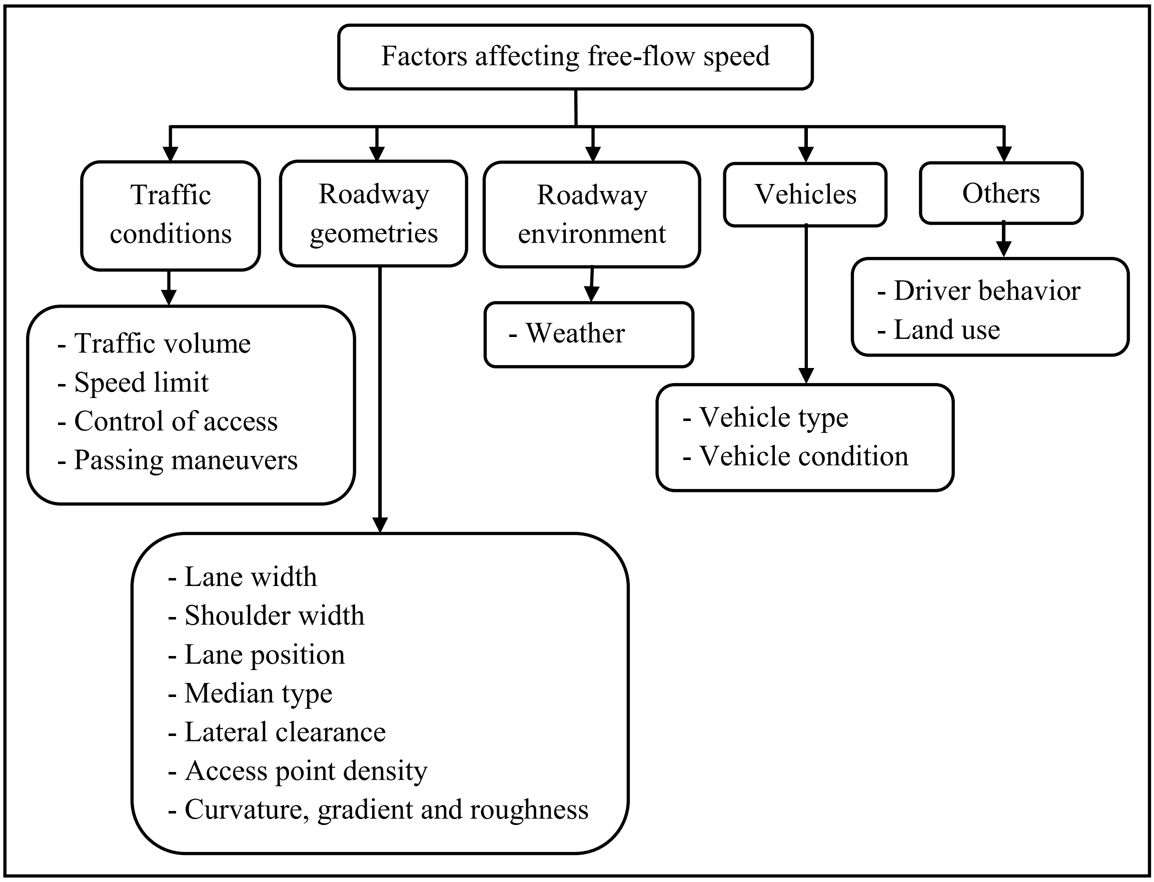

Figure 2.4: Factors affecting free-flow speed (Madhu et al., 2011)

2.6.1 Roadway geometries

A. Carriageway/lane width

The effect of lane width to free-flow speed has been discussed in various studies. Free-flow speed increase as the lane width increases (Transportation Research Board, 2000; Ma et al., 2010). Nicholas and Lester (2009) found that vehicle speed tends to be restricted when lane widths are narrower than 3.6 m (12 ft), where vehicles need to travel closer together in the lateral direction and driver tend to compensate by reducing their travel speed. Farouki and Nixon (1976) as cited in (Cao & Sano, 2012) studied the effect of lane width on free-flow conditions in suburban roads in Belfast, Ireland. The authors found that the mean free speed of cars increases linearly with carriageway width over a range of width from 5.2 m to 11.3 m.

However, different studies have drawn contradictory conclusions on the effect of lane width. Studies conducted by Bang et al. (1996) and Gattis and Watts (1999) showed a weak relationship between lane width and speed of vehicles. Bang et al. (1996) found that the relationship between lane width and free-flow speed is generally not strong. Figure 2.5 illustrates the average light vehicle speed on undivided roads and its relationship to lane width. From this figure, speed of vehicle travel on the roads with a carriageway width of 7 m is in the range of 60 km/h to 80 km/h. Meanwhile for speed of vehicle travel on the roads with a carriageway width of 8 m or more is increased from 70 km/h to 80 km/h.

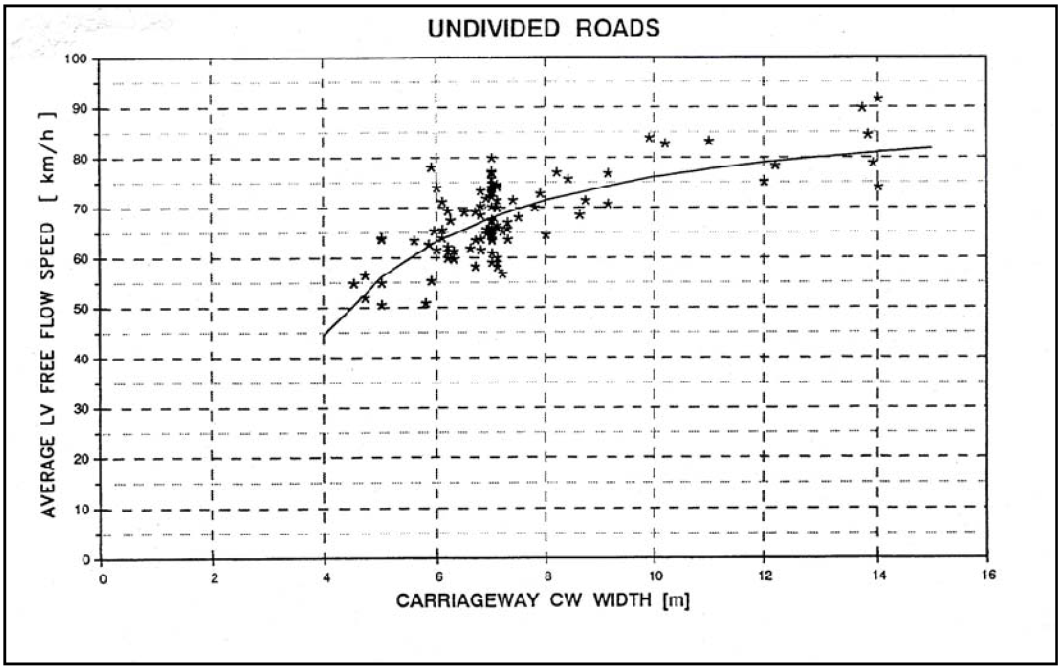

Figure 2.5: Relationship between lane width and free-flow speed for undivided road (Bang et al., 1996)

B. Lateral clearance

According to U.S. HCM 2000 (Transportation Research Board, 2000), lateral clearance is defined as the roadside clearance at left and right side which consider from the outside edge of travel lanes to fixed obstructions such as trees, light pole, traffic barriers, signs, retaining walls and abutments on a multilane highway. Nicholas and Lester (2009) reported that the effect of lateral clearance is more obvious for the left shoulder as compare to clearance from the median. The drivers in the adjacent lane tend to shy away when roadside or median objects are located too close to the edge of the pavement. Therefore, the drivers tend to compensate by reducing their speed.

Figueroa and Tarko (2005) studied speed factors on four-lane highways in free-flow speed conditions. Based on the results obtained, it was concluded that an increase in the lateral clearance increases the free-flow speed and roadside obstructions such as curbed sidewalks, guardrails and ditches located at 7 m (20 ft) or less from the outside edge of the travelled way impact negatively on the mean speed. Conversely, reducing the total lateral clearance increases the spread of the individual speeds as cautious and slow drivers responds to the extra risk represented by the narrower highway segment more strongly than fast and aggressive drivers.

C. Access point density

The number of access points is one of the elements in reducing free-flow speeds along a section of multilane highways. Access point density refers mainly to the number of intersection or driveways on the left side of the roadway within a roadway segment (Transportation Research Board, 2000). Dixon et al. (1999) and Figueroa and Tarko (2005) found that the mean speed reduced slightly as the number of access point increase. Figure 2.6 illustrates the relationship between mean speed and access point density. U.S. HCM 2000 (Transportation Research Board, 2000) suggested that for every 6 access points per kilometer reduced speed by 4.0 km/h. Also, Poe et al. (1996) concluded that access point had a direct impact on free-flow speed where increased of access point density leads to decrease of free-flow speed due to the increased interaction with vehicles from driveways and intersections.

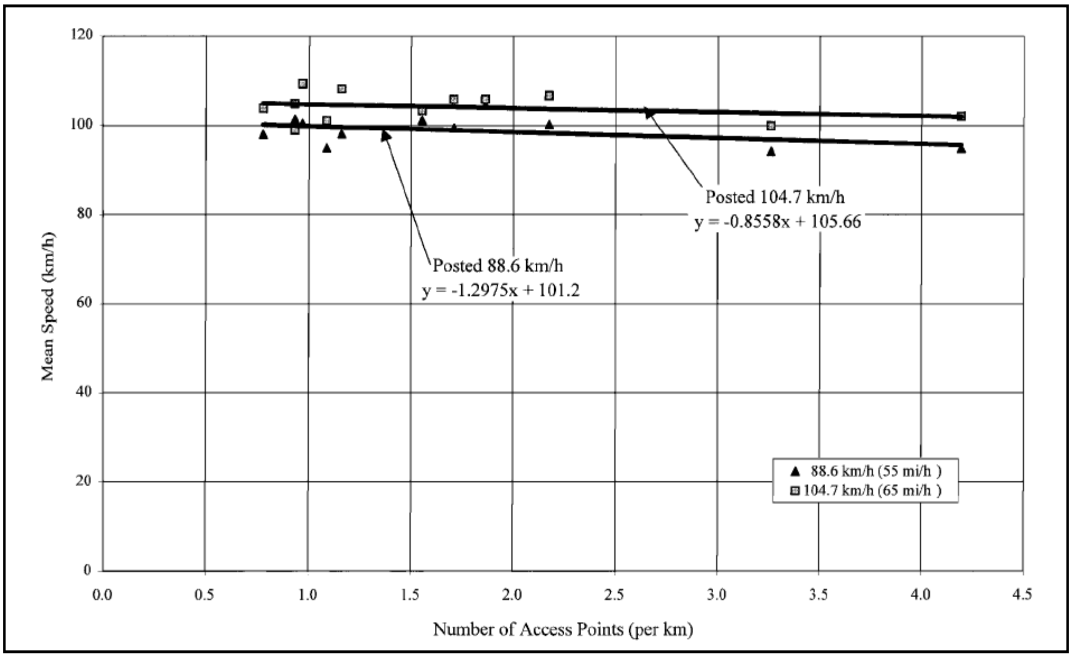

Figure 2.6: Mean speed against access point density (Dixon et al., 1999)

D. Median width and type

The primary function of the median is to separate the opposing traffic stream. Gong and Stamatiadis (2008) found that median type had significant impacts on operating speed in which four-lane with barrier or divided four-lane highways shows the higher operating speeds compared with four-lane without barrier or undivided highways. U.S. HCM 2000 (Transportation Research Board, 2000), stated that free-flow speeds for undivided multilane highway should be decreased by 2.6 km/h due to distractions caused by vehicles travel from opposing traffic in an adjacent lane. The two-way left turn (TWLT) median lanes provide some sense of separation between opposing traffic lanes and also allow vehicles to enter and exit the traveled way in a more effective way, thus reducing the impact on the traffic flow. Figueroa and Tarko (2005) found that the presence of two-way left turn (TWLT) median lanes has a positive impact on mean speeds.

E. Lane position

Gong and Stamatiadis (2008) developed the operating speed prediction models for horizontal curve on rural four-lane highways in Kentucky. Data of free-flow speed at inner and outer lanes showed that speeds at outer and inner lanes are different. Schutte and Roodth (1994) found that the average speed of inner lanes is between 3 km/h to 6 km/h faster than outer lane on roadway approaches to urban areas. Nonetheless, on the three lanes two-way highway, the average speed in the outer lane shows the normal linear decrease with an increase in volume, but the average speed in the center lane is faster and does not change with variation in traffic volume. The average speed on multilane highways reduced as the lane position progresses from the median, to the middle, to the shoulder lanes. The marked reduction in speeds for the vehicles in the curb lane is largely attributed to the presence of commercial vehicles in the outer lane, to the speed change maneuvers performed by ingress and egress traffic in the outer lane, and to the hazards of merging and diverging traffic anticipated by the through traffic.

2.6.2 Traffic conditions

Dixon et al. (1999) study the correlation between posted speeds and free-flow speed in Georgia. Two different speed limits which are 88.6 km/h and 104.7 km/h were used to compare the effect of speed limit. From their studies, they found that a comparison of the speed for both speed limits shows that, on average, the presence of heavy vehicle in the traffic stream did not substantially impact the mean speed. Subsequently, for low volume of heavy vehicle in rural conditions, measured free-flow speeds are not significantly impacted due to the presence of heavy vehicle in