Malaysian Journal of Civil Engineering 27 Special Issue (1):103-111 (2015)

FREE-FLOW SPEED ON TWO-LANE RURAL HIGHWAYS: AN EMPIRICAL EVALUATION OF ESTIMATION MODELS

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Abstract: Free-flow speed (FFS); a fundamental parameter in the analysis of two-lane highways, is either estimated through direct field measurement or using analytical model. Regarding the latter approach, the Malaysian Highway Capacity Manual (MHCM) established a model for estimating FFS based on base-free-flow speed (BFFS), roadway's geometric features and proportion of motorcycles in the traffic stream. Likewise, the Highway Capacity Manual (HCM) suggested an approach for direct field measurement of FFS; preferably, at a combined two-way flow rate not in excess of 200 veh/h. For most two-lane highways, observing a two-way flow rate of 200 veh/h or less is rarely possible. In such a case, the HCM recommended that mean speed could be observed at flow rates higher than the limiting value and adjusted accordingly based on an analytical model provided by the manual. This paper presents an empirical appraisal of the MHCM and HCM – FFS estimation models. Data for the study were collected from four directional segments of rural two-lane highways in Johor, Malaysia. A video recording intrumented test vehicle was used for observing the relevant variables needed in this study. An analysis of the obaseved data resulted in mean FFS values of 83.35 km/h and 83.03 km/h from HCM and MHCM models, respectively. FFS estimates from the two data sets were compared to ascertain the degree of their consistency or otherwise using statistical analysis. Results from statistical analysis using t-statistic at 0.05 significance level indicates that there is no statistically significant difference between the FFS estimates from the two approaches. Thus, finding from this study suggests that either of the two approaches could be used for measuring FFS; particularly, at combined two-way flow rates exceeding 200 veh/h.

Keywords: *Two-lane highways, free-flow speed, estimation models, Malaysian Highway Capacity Manual*

1.0 Introduction

Free-flow speed (FFS) refers to an average speed of vehicles on road segment away from the influence of an intersection under low vehicular density condition. It is a significant variable used in estimating the expected operating conditions of highways and only possible when the traffic volume on the road segment is below capacity. FFS determination is a key step in the capacity and level of service analyses for uninterrupted flow facilities. FFS together with demand flow rates are used in determining average travel speed of roadway facility. It has been established that various factors relating to road geometry, visibility and weather conditions influence FFS (Brilon and Ponzlet, 1996; Ibrahim and Hall, 1994; Kyte *et al.*, 2000; Medina and Tarko, 2005; TRB, 2010; Yagar and Van Aerde, 1983).

FFS can either be determined using direct field measurements or estimated indirectly using a model (TRB, 2010). Regarding the direct field measurement, the Highway Capacity Manual, (HCM) (TRB, 2010) recommended that FFS can be measured directly in the field at a two-way flow rate not exceeding 200veh/h. According to the HCM, average running speed of the stream under such flow rate limit can be reported as FFS. However, for conditions where the flow rate exceeds 200 veh/h, a model was established by the manual for adjusting the stream's speed to FFS; provided that the data was based on direct field measurement. For the indirect approach, the Malaysian Highway Capacity Manual (MHCM) (HPU, 2011) provides an analytical model for estimating FFS based on base-free-flow speed (BFFS), roadway's geometric features and proportion of motorcycles (in the traffic stream) as the model's inputs. However, other studies (Al-Kaisy and Karjala, 2008; Bang *et al.*, 1995) suggested that FFS is measured as the mean speeds of unimpeded vehicles traveling with time headways longer than 8 seconds based on spot observation.

This paper presents an empirical evaluation of MHCM and HCM free-flow speed estimation models on two-lane rural highways at two-way flow rates exceeding 200veh/h.

2.0 Experimentation

Four (4) directional roadway segments of two-lane rural highways were used for data collection in this study. The sites used were along Pontian – Kukup (PTN – KKP) and Renggam – Kulai (REN – KUL) roads in Johor, Malaysia. Data collected comprised of roadways' geometric features, speed and flow rates, being the major inputs for estimating FFS using both the HCM and MHCM models as the case may be. Inputs regarding the roadways' geometric features were measured manually using measuring tape. Speed and flow rates related parameters were collected using moving car observer (MCO) method in accordance with the procedures described in the Manual of Transportation Engineering Studies (Robbertson and Findley, 2010) based on floating-car driving technique. In floating-car driving style, the test vehicle is driven into the traffic stream under study and overtakes as many vehicles as overtaking it; through this, the test car estimates the behaviour of an average vehicle in the traffic stream (Roger *et* *al.*, 2004). The speed of the test vehicle is thereby regarded as the average speed of the traffic stream evaluated.

While applying the MCO method, a segment length of 3.50 km was used for the data collection by performing six test runs on each directional segment; as six runs were found to be satisfactory for consistent and unbiased estimates of measured variables (Mortimer, 1957). A passenger car equipped with video recording system was used as the test vehicle. The video recording system captures real time traffic events over the entire period of the test runs and stores the recorded events onto an SD memory card inserted into the recorder and subsequently uploaded to computer for processing. The recorded traffic events were then played back in a computer to extract the required data. During the playback, the time taken to traverse the study segment was noted while the numbers of vehicles against the test car travel direction, vehicles overtaking the test car and vehicles passed by the test car were extracted respectively. The hourly flow rates for northbound and southbound directions were determined using equations (1) and (2), respectively.

$$V_n = \frac{60(M_s + O_n - P_n)}{(T_s + T_n)} \quad (1)$$

$$V_s = \frac{60(M_n + O_s - P_s)}{(T_n + T_s)} \quad (2)$$

Where V = Directional hourly volume (veh/h), M = Opposing vehicles to the test car's direction of travel (veh), O = Vehicles overtaking the test car (veh), P = Vehicles passed by the test car (veh) and T = Directional travel time taken to traverse the study segment (minutes). And the subscripts n and s refer to northbound and southbound directions, respectively.

Average directional running speeds were also obtained from the MCO data by taking the ratio of the total distance travelled to the travel time taken to traverse the segment in accordance with procedure presented in the Manual of Transportation Engineering Studies (Robbertson and Findley, 2010).

2.1 MHCM Model for FFS Estimation

The MHCM provided an FFS estimation model for two-lane highways, based on BFFS, adjustment for the effect of lane and shoulder widths narrower than 3.65 m and 1.80 m respectively, as well as the effect of proportion of motorcycles in the traffic stream. Equation (3) shows the MHCM model in which BFFS of 90 km/h was recommended for Malaysian two-lane highways.

$$FFS = BFFS - f_{LS} - f_{APD} - f_m \quad (3)$$

Where FFS = Free-Flow Speed (km/h), $BFFS$ = Base Free-Flow Speed (km/h), f_{LS} = Adjustment for lane and shoulder widths less than 3.65 m and 1.80 m, respectively (km/h), f_{APD} = Adjustment for access points density (km/h) and f_m = Adjustment for proportion of motorcycles (km/h).

2.2 HCM Adjustment Model for FFS Estimation

Based on the HCM, for speed study conducted at a two-way flow rate exceeding 200veh/h, a volume adjustment must be made in order to estimate FFS of the facility. The adjustment model is as shown in Equation (4).

$$FFS = S_{FM} + 0.00776 \frac{V_f}{f_{HV}} \quad (4)$$

Where FFS = Estimated Free-Flow Speed (km/h), S_{FM} = Mean Speed of traffic measured in the field (km/h), V_f = Observed flow rate for the period when field data were obtained (veh/h) and f_{HV} = Heavy-vehicle adjustment factor, computed using equation (5).

$$f_{hv} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)} \quad (5)$$

Where P_T = Proportion of trucks in the traffic stream, expressed as a decimal, P_R = Proportion of recreational vehicles (RVs) in the traffic stream, expressed as a decimal, E_T = Passenger-car equivalent for trucks and E_R = Passenger-car equivalent for RVs

Mean speed of traffic stream for each directional segment was also obtained using the appropriate relationship in accordance with MCO procedure. Directional traffic flow rates and composition of heavy traffic (trucks) were extracted from the field data recorded using the MCO method. Heavy vehicles adjustment factors were obtained from exhibits provided by the HCM.

3.0 Results and Discussions

As mentioned in preceding section, FFS estimation models were employed for an indirect FFS measurement; specifically at two-way flow rates exceeding 200 veh/h (by making observations during medium to high volume periods, i.e., non-off-peak period).

3.1 Geometry of the Study Segments

As stated earlier, four directional segments were chosen for this study. For each of the segments, data were collected and reported as northbound (NB) and southbound (SB) directions respectively. Table 1 presents the geometric features of the segments utilized in this study.

Table 1: Roadways Geometry

Road	Direction	L_w (m)	SH_w (m)	APD (access/km)
PTN – KKP	NB	3.09	0.25	1.71
	SB	3.09	0.26	1.71
REN – KUL	NB	3.65	1.50	0.29
	SB	3.65	1.60	0.29

L_w = Lane width, SH_w = Shoulder width, APD = Access point density

3.2 Free Flow Speed Estimation

Free-flow speeds were estimated on the selected two-lane highway segments using both the MHCM and HCM as described in the subsequent sections. FFS estimates from the two indirect approaches were also compared.

3.2.1 FFS Estimation Using MHCM Estimation Model

Equation (3) was used for the determination of the FFS and the estimates are as shown in Table 2. Geometric measurements presented in Table 1 were used in determining the effects of the variables presented on FFS. Proportions of motorcycles were determined from the traffic configurations recorded for each direction. All adjustment factors were obtained from tables provided by the MHCM.

Table 2: FFS Using MHCM Estimation Model

Road	Direction	q (veh/h)	PMc (%)	f_{LS} (km/h)	f_{APD} (km/h)	f_m (km/h)	FFS (km/h)
PTN – KKP	NB	299	0.26	7.80	2.04	2.60	77.56
	SB	195	0.09	7.80	2.04	1.70	78.46
REN - KUL	NB	164	0.06	1.00	0.35	0.78	87.87
	SB	259	0.06	0.70	0.35	0.78	88.17

$FFS = 90 - f_{LS} - f_{APD} - f_m$, PMc = Proportion of motorcycles, f_{LS} = Adjustment for lane and shoulder widths, f_{APD} = Adjustment for access points density, f_m = Adjustments for motorcycles' proportion

3.2.2 FFS Estimation Using HCM Adjustment Model

Equations (4) and (5) were used for the estimation of FFS in this case. Directional mean speeds of the segments were first obtained using MCO after which the directional traffic volumes were determined alongside with the proportion of trucks for each direction. Exhibits presented in HCM were used for the determination of passenger car equivalents (PCE) for trucks used in equation (5) for the determination of heavy-vehicle adjustment factor. Trucks were the only type of heavy vehicle for Malaysian traffic condition, as such recreational vehicles (RV) were not considered in the analysis. Table 3 shows the flow rates, mean speeds, heavy-vehicle adjustment factors, as well as the estimated FFS for the four directional roadway segments.

Table 3: FFS Using HCM Adjustment Model

Road	Direction	*q* (veh/h)	Travel time (min)	Mean Speed (km/h)	P_T	PCE (E_T)	f_{HV}	FFS (km/h)
PTN – KKP	NB	299	2.82	74.42	0.08	1.40	0.97	76.82
	SB	195	2.74	76.60	0.03	1.50	0.98	78.13
REN - KUL	NB	164	2.40	87.62	0.07	1.60	0.96	88.95
	SB	259	2.40	87.44	0.05	1.40	0.98	89.49

q = average directional flow rate, P_T = proportion of trucks, PCE = Passenger Car Equivalent, f_{HV} = Heavy-vehicle adjustment factor.

3.3 Comparison of FSS Estimation Models

Table 4 presents a summary of the FFS estimates for the four directional segments for both HCM and MHCM models.

Table 4: Comparison of FFS Estimation Models

Road	Direction	FFS_{HCM} (km/h)	FFS_{MHCM} (km/h)
PTN – KKP	NB	76.82	77.56
	SB	78.13	78.46
REN – KUL	NB	88.95	87.87
	SB	89.49	88.17
Mean values (km/h)		83.35	83.02

From Table 4, it could be seen that FFS estimates from the two models seem to differ slightly. However, for PTN – KKP segment FFS values based on HCM model were slightly lower than those from MHCM model; this could be due to the high two-way traffic volume on the roadway. Higher volumes reduce the chances to travel at higher speeds due to influences from the interacting vehicles which limit passing manoeuvres. In the case of REN – KUL segment, an opposite outcome was recorded. Meanwhile, FFS estimates based on HCM were slightly higher in this case, which could be due to the low travel time caused by lower two-way flow rate on the segment, thereby resulting in relatively higher travel speed. This indicates that estimates from the two approaches do not follow a particular pattern.

Based on the irregular trend shown by the FFS estimates from the two models, a more reasonable comparison could be drawn using the mean FFS values and a 45^o diagonal. On the basis of the mean FFS values, the two models resulted in consistent estimates even though, MHCM estimates were slightly lower than HCM values by about 0.4%. This difference could be deemed negligible enough that may not cause any considerable effect. A 45^o diagonal line plot (Figure 1) was also generated to see how the data points are scattered around the diagonal line, for the purpose of examining the extent of the difference between the FFS estimates from the two models evaluated.

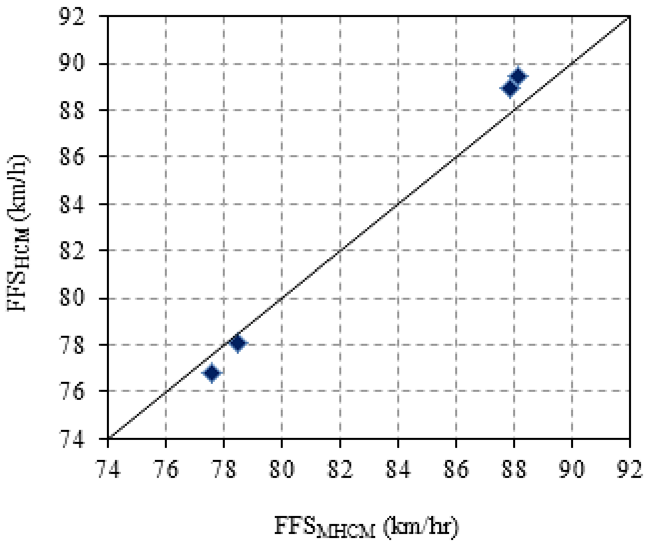

Figure 1: Comparison between FFS$_{HCM}$ and FFS$_{MHCM}$

From Figure 1, the data points are relatively scattered around the diagonal line. This shows that, the FFS estimates using the two models do not differ considerably.

To ascertain the extent of the effect that the little difference could cause, if any, a statistical analysis using t-test at 95% confidence level was carried out to find out whether the difference between the means of the FFS is significant or otherwise. Results from the statistical analysis revealed that there is no statistically significant difference between the two sets of data as p- value (0.5610) is far greater than 0.05. This finding suggests that either of the equations can be used to estimate FFS on two-lane highways; particularly at a combined two-way flow rates exceeding 200 veh/h.

4.0 Conclusions

Free-flow speed (FFS) is an essential parameter in the capacity and level of service analyses for two-lane highways. Its estimation is either made through direct field measurement at two-way flow rate not exceeding 200 veh/h or indirectly using analytical model. Direct field measurement of FFS is seldom realistic as roadways mostly operate at flow rates higher than the specified level. This made it necessary to utilize analytical models alongside with some adjustments to estimate FFS. The current study presented an evaluation of FFS on two-lane highways based on the indirect measuring approach using HCM and MHCM models. Results obtained from the two approaches were compared and found that the FFS estimates from the two models seems to be consistent even though MHCM model mean estimate was slighltly lower than that of HCM. However, statistical analysis using t-test revealed that there is no statistically significant difference between the two data sets as p – value (0.5610) is far greater than 0.05. A key implication of this finding is that either of the models could be used for indirect estimate of FFS; especially for situations where the combined directional flow rates exceed 200 veh/h.

5.0 Acknowledgements

The authors would like to express deep appreciations to the Ministry of Higher Education, Malaysia, through Research Management Centre (RMC), Universiti Teknologi Malaysia (UTM) and UTM for providing a research grant (Q.J130000.7801.4L100), opportunity and necessary facilities to support this research work.

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