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Evaluation of Performance Measures of Two-Lane Highways under Heterogeneous Traffic

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ABSTRACT

This paper evaluates the performance measures indicated by the Highway Capacity Manual (HCM) to assess the level of service (LOS) on two-lane highways under heterogeneous traffic conditions. The study is based on field observations and, accordingly, traffic data were collected on a two-lane National Highway in India. The measures, percent time-spent-following (PTSF) and average travel speed (ATS) were estimated using easily collectible field data considering both two-way and directional segments. The actual PTSF values were observed to be lower than the expected values. This lack of conformity is probably because of drivers' impatience that increases with the platoon length and delay. The ATS was also measured in the field and compared to those obtained using HCM. ATS was observed to be insensitive to flow in mixed traffic situations because of frequent platoon formation. In addition, a direct assessment of LOS in the field indicates over-prediction, which is attributed to the presence of a sizable proportion of slower vehicles based on users' opinion poll.

Keywords: Average travel speed, heterogeneous traffic flow; level of service, percent time-spent-following, platooning, two-lane highways

INTRODUCTION

Performance evaluation on two-lane highways has always been a complicated issue because of distinct operational characteristics manifested by the utilisation of a single lane for traffic operation in each direction of travel. This results in frequent interaction between vehicles travelling in the same as well as in the opposite directions. Quite often, faster vehicles get delayed when they approach a slower one, because they are forced to travel behind the impeding vehicle while searching for an acceptable passing gap. As a result, they start moving in a platoon. The amount of platooning depends on the passing opportunity and the impedance caused by the slower vehicles. Clearly, this increases with the increase of traffic flow as well as the proportion of slower vehicles in

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the traffic stream. These factors collectively make it difficult to maintain the desired travel speed in the traffic stream, which is a function of passing frequency on two-lane roads. Thus, the amount of platooning, in turn, significantly affects the quality of service.

The perceptions of the users of traffic facilities are expressed in terms of performance measure to describe the quality of traffic flow quantitatively. The Highway Capacity Manual (HCM) 2010 provides methods for obtaining performance measures as well as a level of service (LOS), which describes the performance of a traffic facility under given conditions. This recommends two performance measures: average travel speed (ATS) and percent-time spent following (PTSF) to assess LOS of two-lane highways. However, there are two major problems associated with these measures, which accordingly make LOS assessment inappropriate: LOS is not sensitive to speed on two-lane highways, direct measurement of PTSF is not easy, and empirical model is resorted to. In addition, a number of researchers (Luttinen, 2001; Harwood *et al*., 2003; Pollatschek & Polus, 2005) reported that the HCM empirical model overestimates the actual PTSF values. This is reasonably detectable, particularly if the traffic stream consists of a sizable percentage of slower vehicles.

It is therefore necessary to evaluate the effectiveness of the method suggested by HCM when the traffic is heterogeneous in character. To meet this objective, an attempt was made in the present study to suggest an alternative method of determining performance measures directly from field data that assess LOS under heterogeneous traffic conditions and compares the obtained values with those obtained according to HCM guidelines.

LITERATURE REVIEW

HCM Performance Measures: An Overview

HCM 1950 provided an analytical procedure for capacity analysis on two-lane highways. The manual introduced three different types of capacity: basic, possible and practical, representing capacity under ideal, prevailing and reasonable driving conditions, respectively. The manual recommended operating speed as performance measure for practical capacity to account for the "quality of service" on two-lane highways because engineers were concerned about the traffic conditions experienced by road-users; they were not interested in the maximum performance of the system only.

HCM 1965 extended the idea of practical capacity to the well-known LOS concept. Six LOSs (A–F) were defined therein; the concept is still in use today. LOS was expressed in terms of two performance measures: operating speed as the governing performance measure and volume-to-capacity ratio as the supplementary service measure.

Average speed was considered as an inadequate measure of the balance between passing demand and passing supply while developing the third edition of HCM. In addition, despite the previous presumption, this measure was found to be less sensitive to traffic flow rate. HCM 1985 thus introduced a new performance measure, percent time delay (PTD), on two-lane highways in addition to ATS. PTD was defined as "the average percent of time that all vehicles are delayed while travelling in platoons due to inability to pass." Vehicles are considered delayed while moving inside a platoon due to reduction of speed from their desired speed. HCM 1985 suggested the use of percent of vehicles with headways less than 5 s as a surrogate measure of PTD in field studies.

The phrase "percent time delay" was somewhat inappropriate because the criterion was not delay but time spent while travelling in platoons. HCM 2000 defined a more descriptive term, PTSF, which explains better the platooning effect and lack of passing opportunities on two-lane highways. The PTSF is defined as "the average percentage of travel time that vehicles must travel in platoons behind slower vehicles because of an inability to pass." To estimate PTSF, the HCM recommends a surrogate field measure of the percentage of vehicles in the traffic stream with headways less than 3 s. ATS was considered an auxiliary performance measure for high-class (Class I) highways as it makes LOS sensitive to design speed. For Class I highways, LOS is defined by threshold values of both PTSF and ATS, whereas for Class II highways, on which motorists do not necessarily expect to travel at high speeds, the performance measure is PTSF alone. Because motorists' expectation is considered lower on Class II highways than on Class I highways, a further increase of 5% to the PTSF threshold was made for Class II highways. The flow rate at the upper limit of a given LOS is higher in HCM 2000 than in HCM 1985, as the headway criterion was lowered from 5 to 3 s. Analysis procedure laid down for level and rolling terrain was extended by two-way segment methodology whereas, for specific upgrades and downgrades, it was directional segment methodology.

The most recent edition, HCM 2010, addressed directional segments analysis procedure in general terrain (level or rolling) as well. Based on the wide range of functions served, two-lane highways were classified into three categories: Class I, Class II and Class III. The first two classes, analogous with the earlier classification, explain rural two-lane highways, while Class III highways are defined as the portions of rural highways that serve moderately developed areas (small town or developed recreational areas). The Florida Department of Transportation developed the analysis approach for these highways by modifying the rural highway method. This edition also provided distinct performance measures taking automobile and bicycle mode into consideration. Prevalent ATS and PTSF conception continued unaltered, except that an introduction of a new measure, percent of free-flow speed (PFFS), was found appropriate on Class III highways, where passing restrictions are not a major concern, but drivers are expected to make steady progress at or near the speed limit. However, bicycle levels of service for two-lane highway segments are defined based on a traveler-perception model and assessed by bicycle LOS (BLOS) score. Threshold values of PTSF and ATS correspond to the previous edition but the adjustment factors to evaluate these measures were appropriately modified.

Evaluation of HCM Measures: Study Records

Following the tradition of HCM, a number of researchers (De Arazoza & McLeod, 1993; Brilon *et al*., 1994) suggested the use of ATS as a service measure in assessing LOS. In developed areas of the United States, De Arazoza and McLeod (1993) suggested ATS as the main LOS criterion for uninterrupted flow conditions. Brilon *et al*. (1994) reported that the LOS assessment on German two-lane highways is based on ATS. In Finland, Luoma and Jaatinen (1999) considered both ATS and the predictability of travel times as performance measure for goods transport. However, a couple of international studies (Brilon & Weiser, 2006; Al-Kaisy & Karjala, 2008) made it evident that lack of a benchmark point along a performance scale is a major limitation of using ATS and makes performance comparison across sites impractical.

In support of the German experience on two-lane highways, Brilon and Weiser (2006) reported the use of average speed of passenger cars as a significant performance measure. This could be estimated over a longer stretch of highway, considering the average of both directions. This was further investigated by Al-Kaisy and Karjala (2008) on four two-lane highway study sites in the state of Montana. Moreover, they proposed the use of ATS as PFFS and ATS of passenger cars as PFFS of passenger cars. The functional relationship of these measures with the platooning variables was apparently not observed to be strong.

The headway criteria adopted in the third edition of HCM (HCM 1985) was investigated further for more practical estimation of PTD. Guell and Virkler (1988) suggested headways not larger than 3.5 or 4 s and Luttinen (1992) suggested headways not greater than 3 s for the estimation of proportion of delayed vehicles. Besides this, Botha *et al*. (1994) reported the use of PTD as a measure to describe service quality on two-lane rural highways. However, the subsequent edition of HCM considered PTSF to be more appropriate as performance measure and was given more attention in later research. Several studies (Luttinen, 2001; Harwood *et al*., 2003; Pollatschek & Polus, 2005) reported that the method suggested by HCM to determine PTSF overestimates the values. Luttinen (2001) proposed several models to estimate PTSF based on the total flow, percentage of no-passing zones and directional distribution of traffic. These models gave lower value of PTSF than that estimated by HCM. Based on a study conducted on uncertainty in the operational analysis of two-lane highways, Luttinen (2002) showed that limitations in the accuracy of the analysis procedures cause errors and reduce the usefulness of the LOS concept. Similarly, Dixon *et al*. (2002) also evaluated the HCM 2000 two-lane highway analysis procedures using the TWOPAS simulation model and field data collected from northern Idaho. The PTSF values of one-directional procedure were observed to be overestimated by both simulation models: about 10 % overestimation and about 30 % overestimation in the field data. However, the values of two-way procedure were observed to be more accurate compared to those of one-directional method. Subsequent to this research, Harwood *et al*. (2003) conducted the National Cooperative Highway Research Program Study on the HCM's two-lane road analysis methodology and indicated an overestimation of PTSF by HCM. Accordingly, they developed a revised set of curves to estimate PTSF. Based on an analysis of drivers' impatience on two-lane rural highways, Pollatschek and Polus (2005) developed theoretical models for reducing the critical passing gap with longer delays prior to the passing maneuver. The impatience of the driver may cause willingness to accept more risk because delay increases, which eventually reduces PTSF. This could be one reason for overestimating the PTSF parameter by HCM. In a paper on the German experience, Brilon and Weiser (2006) reported that, in Germany, the PTSF has never been considered a substantial measure of effectiveness as it does not directly express the degree of efficiency of traffic operation. Polus and Cohen (2009) later developed a queuing model to estimate PTSF from the field data. This was used in a study conducted on 15 two-lane rural highway sections in northern Israel, and the actual PTSF values obtained from the study were also observed to be considerably lower than the corresponding HCM values. In another study, Cohen and Polus (2011) observed similar lower values of PTSF and provided improved relationship between PTSF and two-way flow by fitting the new estimates by means of the least-squares method. Bessa Jr and Setti (2011) recalibrated the HCM 2000 ATS and PTSF functions for Brazilian roads using a genetic algorithm. These new models were able to better represent the behaviour of traffic streams. In a recent paper, Rozenshtein *et al*. (2012) reported that they calibrated PTSF models using actual field data collected on 84 one-way segments of two-lane rural highways in Israel and compared those with HCM and other empirical models proposed in the past. Following the trend of past research, they also reported significant overestimation of the PTSF values, particularly during moderate- and low-flow condition. Meanwhile, Morrall and Werner (1990) proposed the use of overtaking ratio, which is obtained by dividing the number of passing achieved by the number of passing desired, as an indicator of LOS on two-lane highways; Romana and Pérez (2006) suggested an alternative way of using the HCM 2000 performance measures, that is, ATS and PTSF for evaluating the LOS on two-lane highways. On the basis of a study conducted in Egypt on evaluation of operational performance, Hashim and Abdel-Wahed (2011) defined seven performance measures and three platooning variables. They found follower density performance measure to have the strongest correlations to platooning variables.

The above studies, however, do not consider the effect on performance measures when the traffic is heterogeneous in character. This is significant in developing countries, where heterogeneity in traffic mix is prevalent. Even the traffic composition occasionally consists of countable percentage of non-motorized traffic. As a consequence, large speed variation in the traffic stream becomes one of the essential factors for frequent platoon formation and affects performance measures. The present study evaluates the HCM measures using actual field data comprising considerable proportion of slower vehicles collected on two-lane highways in northeast India; this has been a matter of great concern to the engineers analysing traffic flow on these roads.

STUDY DESIGN

An approach toward ATS measurement

On a two-lane highway segment, HCM recommends deriving ATS from free-flow speed (FFS) after incorporating appropriate adjustments for demand flow, heavy vehicle and grade and percentage of no passing zones, respectively. At free-flow condition, ATS corresponds to FFS, and the value starts decreasing with the increase of flow mainly because of the inability to pass slower vehicles. However, there is a difficulty in estimating average FFS at heterogeneous traffic because of the different perceptions of drivers and vehicular characteristics, even under similar roadway conditions. Noticeably, because of larger speed difference, standard deviation is observed to increase with the increase of the average FFS, thus causing error in the estimation (Luttinen, 2002).Therefore, in order to examine the suitability of ATS as a performance measure on two-lane highways if the prevailing traffic is heterogeneous in character, evaluation needs be resorted to using actual field data at different flow levels.

An approach toward PTSF estimation

The flow of traffic on two-lane highways is different basically because of the on-coming traffic in the opposite lane. Thus, the faster vehicles may get delayed due to impedance caused by slower ones and the lack of passing opportunities. This results in the formation of platoons.

On two-lane highways, this can be explained as a queuing process, wherein the second vehicle just after the lead one, i.e. the vehicle forced to move at a slow speed, is considered as the first vehicle in the "queue," and, normally, this second vehicle gets the first opportunity to overtake through gap acceptance process. Additional vehicles in the queue get their opportunity to pass slower ones as and when they reach the second position in the platoon. This flow characteristic is illustrated schematically in Fig.1.

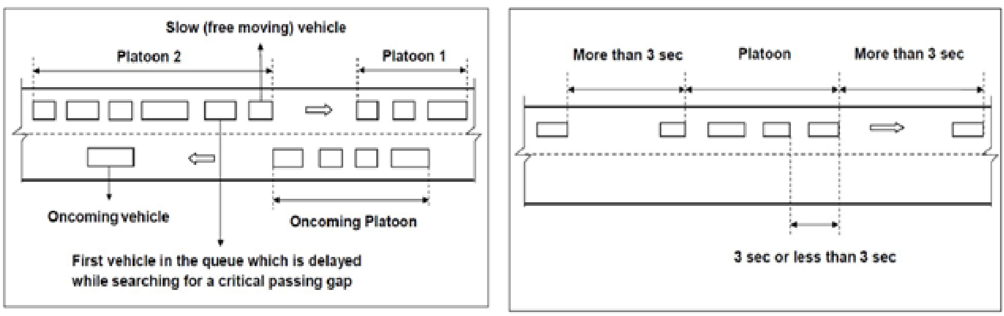

Fig.1: Schematic presentation of platooning on two-lane highways.

The determinants of PTSF on two-lane highways is certainly the amount of impedance to faster vehicles caused by slower one and the availability of passing opportunities, the effect of which is manifested in the amount of platooning. Therefore, to estimate this measure directly from the field, expected time spent by the faster vehicles while in platoon definitely needs to be measured, which is indeed not easy. Polus and Cohen (2009) developed a method to obtain PTSF as a function of average number of headways inside and outside a platoon. Adopting the same approach, Saha and Sarkar (2013) however incorporated minor modification and obtained the following equation (Eq. 1).

$$PTSF=100Q/(Q_o+N_o) \qquad (1)$$

The average values of both Q_o, average number of headways inside platoons and N_o and average number of headways between platoons are very simple to observe in the field, making field estimation of PTSF easy.

Study sites and field data

Field studies were conducted to observe ATS and the average number of headways inside and between platoons on NH-44 (two-lane highway; 7 m wide with 1 m shoulder on either sides of the road), a national highway passing through Tripura, a state in northeast India. Eight segments were selected along the 20-km highway section for conducting the study at different traffic flow levels. Due consideration was given in selection of the study locations so that they would be free from the effect of intersection, curvature and ribbon development. Pavement conditions were good and uniform in all the stretches and the posted speed was 50 kmph. Based on the functions served, the section could be categorised as Class I highway. However, shoulder conditions were not good and therefor, the same road space is used by both non-motorised and motorised traffic. In addition, there was no access control along the road stretch, resulting in a mixed traffic situation on the road. Video photographic survey technique was adopted to observe the platooning phenomenon appropriately. Two reference lines, 500-m apart, were marked, and four observation points were selected for installing the video cameras: two in each direction for recording the entry and exit of vehicles, respectively. The recordings were synchronised so that extraction errors due to time lag could be avoided. The video files were played on a computer to extract the traffic data. The necessary readings, i.e. vehicle type, registration number and the time, were noted down independently for the four specified locations when a vehicle just crossed the reference line. Presence of car and two-wheelers in the traffic stream was observed to be significant. Proportion of non-motorised traffic including both bicycle as well as paddle tricycle, three wheelers and heavy vehicles were observed to be about 15, 13 and 10 % respectively. From the extracted data, the average number of headways inside and between platoons (Q_o and N_o) were determined, and then the PTSF values were calculated using Eq. (1). Moreover, the average travel time taken by vehicles to traverse the reference lines was recorded to compute the ATS.

To estimate FFS in accordance with the HCM method, it was required to identify the time of the day as well as the duration of low flow condition (two-way flow ≤200 pc/h). Therefore, traffic volume count was made at two locations in order to determine the hourly traffic variation. The study was conducted only during the day time for 10 h (8:00 AM to 6:00 PM) because at night-time traffic flow reduces drastically and the variety of vehicle categories in the traffic stream cannot be clearly observed. Subsequent to this, the spot speed study was conducted at four locations in the study stretch by adopting video photographic survey technique only during identified time periods. A video camera was placed away from the longitudinal trap of 10-m length made on the carriageway to avoid any influence in the operating speeds of vehicles. Also, the video camera was mounted on a stand, the height of which was adjusted in such a way that it covered the entire trap length and kept some margin on both sides. The desired data were extracted from the recorded video in the laboratory using a computer. The time taken to cover the trap length by each vehicle was measured with an accuracy of 0.01 s. This time factor was used to calculate the spot speed of vehicles passing through the section. The observed speed was analysed and adjusted in accordance with the HCM guidelines to obtain FFS. ATS values were then determined as per HCM 2000 and HCM 2010 methodology at different flow levels to compare with the values obtained from the actual field data.

STUDY RESULTS

The highway section selected for the study connects the capital city Agartala of Tripura, a state in northeast India at its western end. Factually, as the highway approached the city, the traffic flow was found to be high and more heterogeneous. Thus, to cover a wide range of traffic flow level, data were collected from eight segments selected along the study section at different times of the day in accordance with the hourly traffic variation obtained from traffic volume count. Directional split in the traffic stream was observed to be nearly 50/50 in all the segments. The raw data was analysed and a wide spectrum of traffic flow was identified, which corresponded to volume by capacity ratios (v/c ratio) from 0.2 to 1.0. Both two-way segment and directional segment (west-bound and east-bound traffic) according to HCM (2000 and 2010 editions, respectively) was considered in the analysis. ATS was measured separately for motorised and non-motorised traffic in the field (Table 1). In addition, to compute Q_o and N_o by simple counts of headways inside and outside platoons, the phenomenon of platooning was studied for the study sections.The number of platoons and average platoon length (APL) observed during the field study at different flow level is shown in Table 2.

TABLE 1: Average Travel Speed of Motorized and Non-Motorized Vehicles Observed at Different Volume by Capacity Ratios

v/c ratio	Average Travel Speed (kmph)					
	West-bound traffic		East-bound traffic		Both directions of travel	
	Motorised vehicles	Non-motorised vehicles	Motorised vehicles	Non-motorised vehicles	Motorised vehicles	Non-motorised vehicles
0.2	40.00	13.70	36.79	12.50	38.09	12.15
0.3	36.92	13.82	37.66	12.67	37.27	13.15
0.4	33.10	14.02	36.45	13.00	35.17	13.32
0.5	25.96	15.42	29.29	13.59	28.13	13.83
0.6	25.56	13.01	28.01	13.47	26.85	14.52
0.7	27.04	14.08	28.91	14.81	27.77	13.35
0.8	24.97	13.06	27.53	16.32	26.17	14.60
0.9	28.46	14.83	19.28	10.83	26.12	12.92
1	26.64	12.80	25.26	17.50	26.36	14.86

TABLE 2: Observed Number and Average Length of Platoon at Different Volume by Capacity Ratios

v/c ratio	Number of platoons observed			Average platoon length (vehicle)		
	West-bound	East-bound	Both directions of travel	West-bound	East-bound	Both directions of travel
0.2	5	4	9	2.20	3.25	2.73
0.3	89	86	175	2.46	2.55	2.50
0.4	91	154	245	2.48	2.64	2.56
0.5	116	202	318	2.96	2.93	2.95
0.6	82	91	173	3.10	3.20	3.15
0.7	154	85	239	3.34	3.32	3.33
0.8	119	89	208	3.70	3.88	3.79
0.9	118	22	140	3.53	6.00	4.77
1	87	13	100	3.90	5.23	4.57

FFS values were derived from the observed field data using HCM procedure. The total two-way flow during the study was observed to exceed 200 pc/h even under low-flow condition. Accordingly, flow rate correction was applied to the arithmetic mean of the observed speed data to compute the FFS values. The coefficient of variation of the speed data was also estimated at each study site and was observed to be in the range of 0.29 to 0.35, which is in contrast to the estimated range of 0.11 to 0.14 by McLean (1989) for desired speed. This indicates an error in the estimated FFS and thus affects the values of ATS. At different demand flow levels, ATS values were obtained using both two-way and directional segment methodology of HCM 2000and 2010. The values thus obtained were plotted against v/c ratio (Fig. 2) to observe the trend and pattern and were compared to the actual field values. The figure shows a consistent decrease of the values obtained using the HCM method with the increase of v/c ratio, whereas no significant variation was observed when measured in the field. Even during low-flow condition, ATS measured in the field was around 20 % less than those obtained using HCM. This could be attributed to the frequent interaction with the slower vehicles. The ATS measured in the field was observed to decrease at a gradual rate of up to v/c ratio 0.5, beyond which it remained unchanged. To investigate the reason, this was plotted against APL (Fig. 3). Eq. 2 presents the exponential relationship that best fit (minimum sum of error squares) the data points.

$$\text{ATS} = 17.82 * \left(\frac{1}{1-e^{\left(-\frac{\text{APL}}{3.58}\right)}}\right) \qquad (2)$$

$R^2 = 0.88$

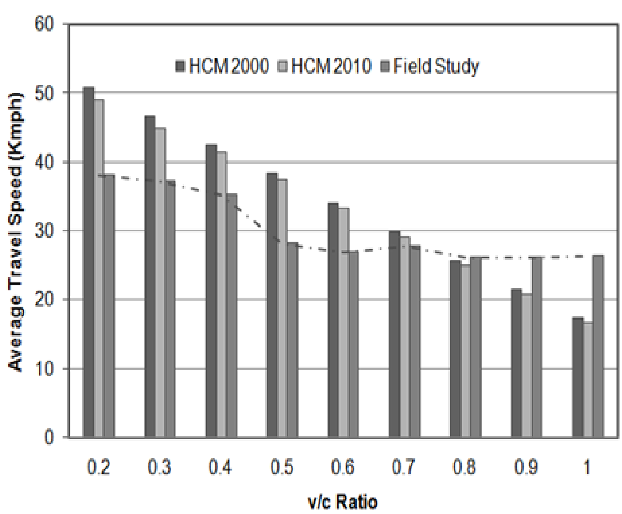

Fig.2: Comparison of average travel speed obtained from field study and Highway Capacity Manual (HCM) methods.

It may be noted from Fig.3 that ATS does not decrease sharply with the APL when its value is 3 or above. Also, an APL value of approximately 3 and above was observed against v/c ratio of 0.5 or more (Table 2). The hypothesised reason is passing opportunity reduces considerably if the queue length is 2 and above because vehicles inside the platoon must wait until the first vehicle in the queue gets an opportunity to pass the slower one; consequently, they follow the impeded vehicle. Thus, the effect of flow on speed significantly decreases as the APL increases to 3 and above. However, this hypothesis needs further investigation under heterogeneous traffic consisting of a sizeable percentage of slower vehicles. In addition, it is difficult to compare performances across sites without a reference point because of the wide range of geometric standards (Al-Kaisy & Karjala, 2008). Thus, the use of ATS as a performance measure without specifying the prevailing roadway and traffic condition is impractical.

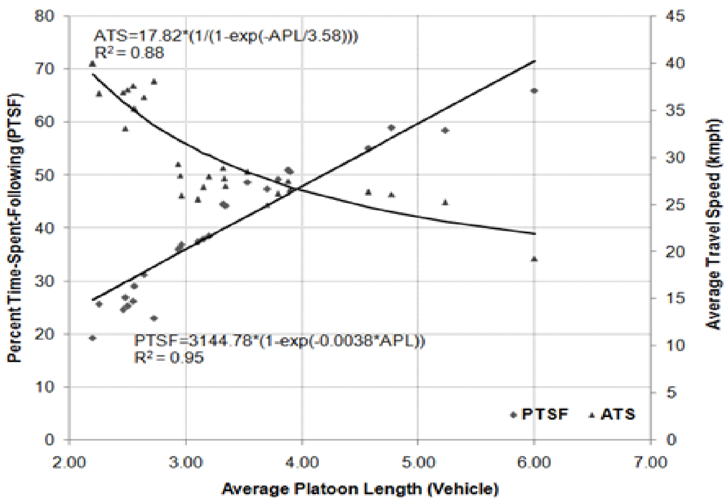

Fig.3: Effect of average platoon length on average travel speed and percent time-spent-following at study sites.

In plain terrain, HCM 2000 recommended two-way segment analysis procedure, which was subsequently modified to directional segment analysis to obtain a full estimate of operating conditions in the recent edition, HCM 2010. Thus, both two-way and directional segments were taken into consideration while computing PTSF values using field data. The actual PTSF values were plotted against v/c ratio (separately for two-way and directional segments); the relationships are presented in Fig. 4 and Fig. 5. The best-fit method was used to calibrate the relationship and was obtained as follows:

$$\mathrm{PTSF} = 80.28 * \left(1 - \mathrm{e}^{\left(-1.218 * \left(\frac{v}{c}\right)\right)}\right) \tag{3}$$

$R^2 = 0.97$ (For Two-way segment)

$$\mathrm{PTSF} = 64.74 * \left(1 - \mathrm{e}^{\left(-1.5656 * \left(\frac{v}{c}\right)\right)}\right) \tag{4}$$

$R^2 = 0.98$ (Directional segment: West-bound traffic)

$$\text{PTSF} = 95.30 * \left(1 - e^{\left(-1.0101*\left(\frac{v}{c}\right)\right)}\right) \tag{5}$$

$R^2 = 0.94$ (Directional segment: East-bound traffic)

It is evident from the observation that PTSF is sensitive to traffic flow and increases with it. This could be attributed to APL as the possibility of passing slower vehicles becomes more and more restricted with an increase in traffic flow, resulting in longer platoons i.e. higher number of following vehicles (Table 2). Figure 3 shows the relationship of observed APL and the corresponding actual PTSF values, in which PTSF increases exponentially with APL.

The calibrated curves based on HCM 2000 and HCM 2010 procedures (Figs. 4 and 5) show an overestimation of PTSF when compared to the field model. While approaching capacity, HCM model values were observed to be close to 90 % whereas field models indicate about 50–60 %. Similar lower values were also obtained by Luttinen (2001), Harwood *et al*. (2003) and Pollatschek and Polus (2005). In order to investigate the reason of overestimation, it is essential to identify the flow level in which the percent difference of HCM and field models is largest. Therefore, these values were also plotted against v/c ratio (Fig. 6), and the percent difference was observed to decrease consistently as the flow increases. However, significant variation was not observed between two-way and directional segments and a maximum value of about 50 % was found during low flow.

Study of overestimation of HCM model indicates that drivers become impatient while travelling in a platoon for a long time and sometimes take considerable risk to pass slower vehicles, disobeying lane discipline. The passing frequency thus increases, which in turn results in reducing the estimated value. At high flow level, despite the increasing risk, a few drivers even dare to overtake from the lower positions in the queue, which is explained with evidence in the subsequent development. This may also cause reduction in platoon length and thus affect PTSF. However, because of limited passing opportunities, the percent difference decreases with the flow. Driver impatience was also considered as one of the important factors that lessen actual PTSF values (Pollatschek & Polus, 2005; Rozenshtein *et al*., 2012).

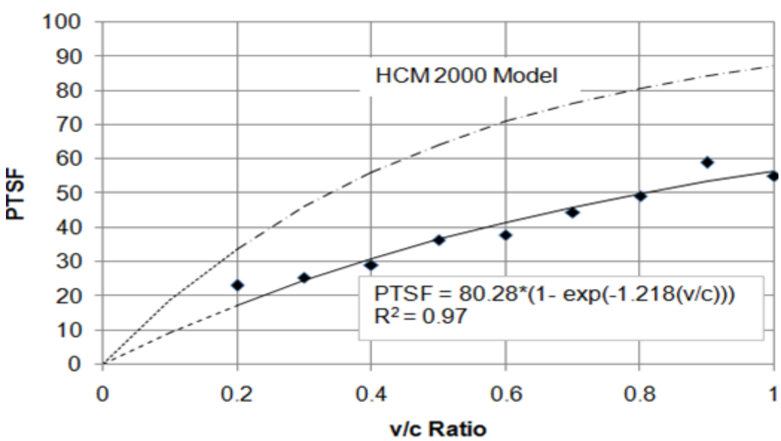

Fig.4: Comparison of percent time-spent-following (PTSF) obtained from field measurement and Highway Capacity Manual (HCM) 2000 model.

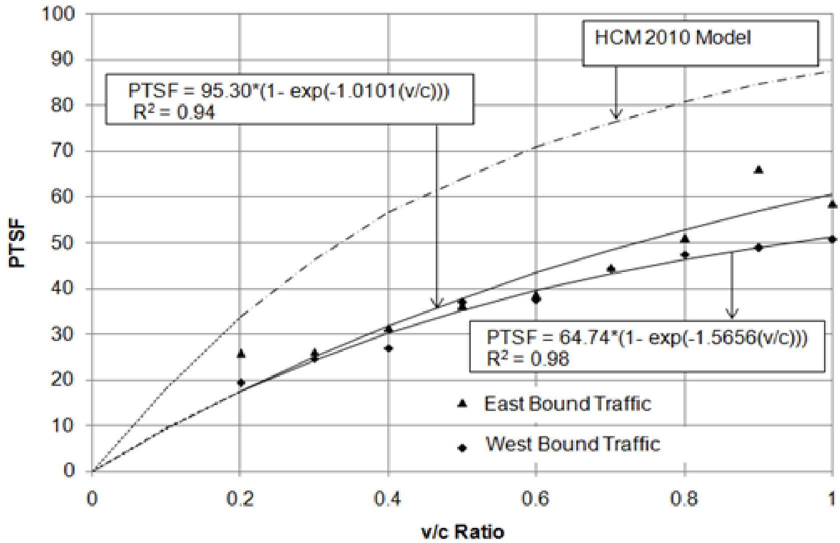

Fig.5: Comparison of percent time-spent-following (PTSF) obtained from field measurement and Highway Capacity Manual (HCM) 2010 model.

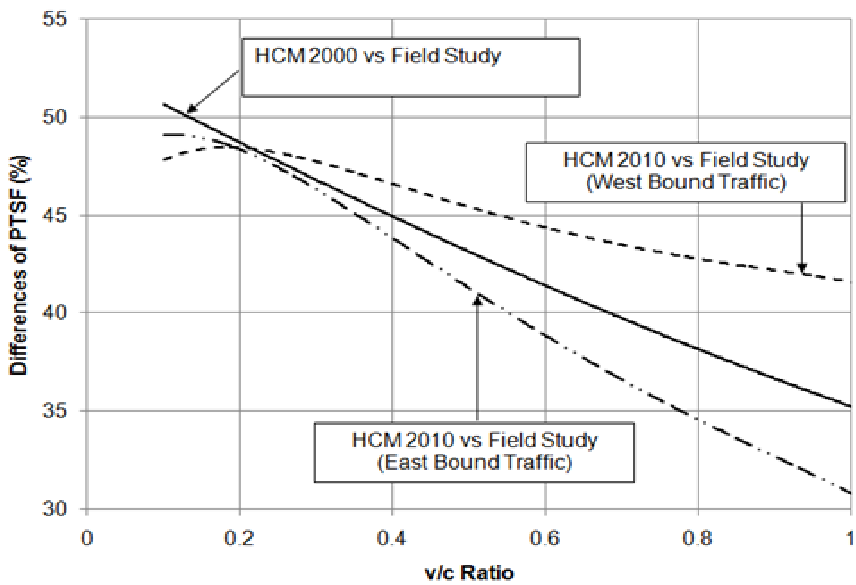

Fig.6: Differences in percent time-spent-following (PTSF) values, field study vs. HCM 2000 and HCM 2010.

The operating condition of a heterogeneous traffic stream at high flow was also investigated assuming M/M/1 queuing model (Poisson arrivals at the back of the queue and a single Poisson server for passing maneuver). For two-lane highway (single Poisson server), traffic intensity (ρ) can be expressed as a function of the number of headways inside platoons (Q_o) (Eq. 6).

$$\rho = 1 - 1/Q_o \quad (6)$$

The traffic intensity (ρ) is defined as the ratio of average time spent by a vehicle in the first position while waiting for an acceptable gap and average inter-arrival times at the back of the queue, and it is definitely <1. The ρ values were derived from the field data using Eq. 6 at different traffic flow level, independently for both the directions (west- and east-bound traffic). The values were then plotted against v/c ratio (Fig. 7) and Eq. 7 and Eq. 8 were calibrated accordingly using the best-fit method.

$$\rho = 0.909 * \left(1 - e^{\left(-1.342*\left(\frac{v}{c}\right)\right)}\right) \qquad (7)$$

$R^2 = 0.98$ (West-bound traffic)

$$\rho = 0.817 * \left(1 - e^{\left(-2.172*\left(\frac{v}{c}\right)\right)}\right) \qquad (8)$$

$R^2 = 0.72$ (East-bound traffic)

At high flow, growth of queues should not be sharp because reduced passing gaps restrict the rate at which a vehicle departs from one platoon and joins the next one. The traffic intensity, therefore, should also not grow sharply at high-flow level (Polus & Cohen, 2009). However, an apparent growth of traffic intensity with respect to flow was observed in the present study (Fig. 7), and both the models (Eq.7 and 8) were asymptotic to 0.817 and 0.909, respectively. This signifies that the average waiting time may reach about 80–90 % inter-arrival times in the queue, which consequently grounds the driver's frustration. This expected behavioural change was also noticed during the study. This change eventually results in willingness of the drivers to take more risk, which could perhaps be one of the reasons for PTSF overestimation even during high flow.

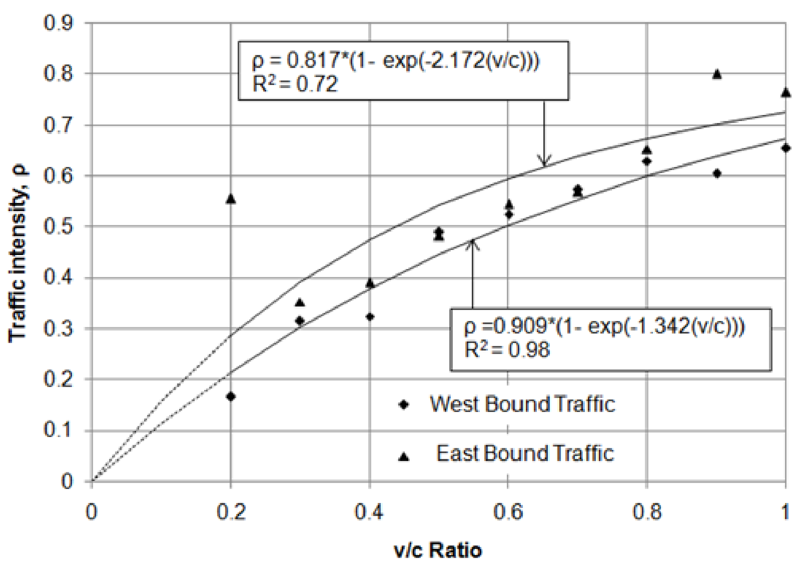

Fig.7: Relationship between observed traffic intensity (ρ) at study sites and volume by capacity (v/c) ratios.

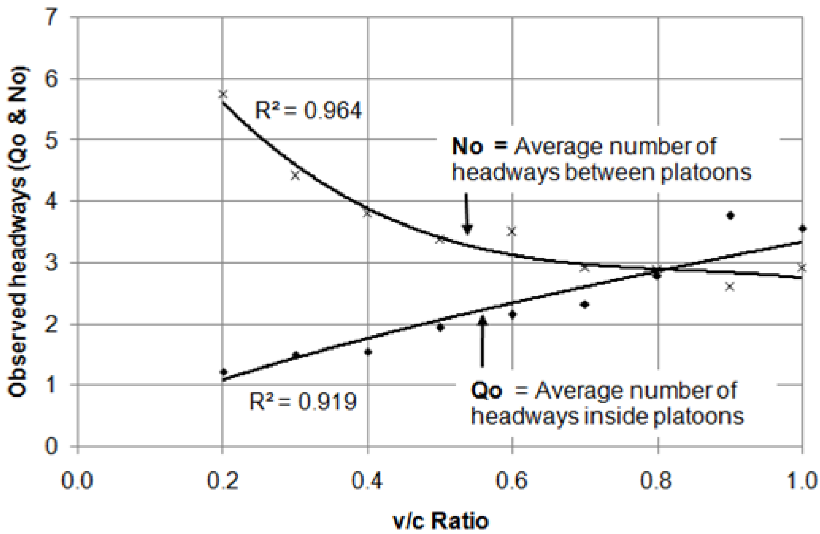

Fig.8: Average number of headways inside and outside platoons over different volume by capacity (v/c) ratios.

The endeavour of the study was to realise the root cause of the inadequacy of HCM measures in assessing LOS of two-lane highways. The method to assess LOS using field data proposed by Polus and Cohen (2009) was adopted in the present study, and the evaluation was subsequently compared with the results that could have been obtained using the HCM criteria. The method defines LOS C as the flow condition when the average number of headways inside and outside platoons is approximately equal. Figure 8 shows the headways inside and between platoons observed in the field, which points to equality of headways at v/c ratio of 0.8. However, this flow level corresponds to LOS in the range of E to F when assessed according to the HCM criteria. This implies that a large proportion of slower vehicles is present in the traffic stream, the speed of which is not impeded. These vehicles were categorically identified and about 50 road-users (including drivers and passengers of these vehicles) were invited for informal discussions; however, their responses indicated that the speed was more or less similar to their expectations. They also opined that the difference between the average times spent between and inside the platoon was relatively less for such vehicle categories. HCM performance measures, therefore, lead to an inappropriate assessment of service quality, particularly if the heterogeneity in the traffic stream is prevalent.

SUMMARY AND CONCLUSION

Quality of service is greatly compromised on two-lane highways when the traffic is heterogeneous in character. This is predominant in developing countries, where the prevailing traffic consists of a wide range of vehicle category, including a substantial percentage of slower vehicles. The evaluation of HCM performance measures is therefore imperative to assess the effectiveness of those measures under this condition. The present study therefore attempted to estimate PTSF and ATS directly from field observations and compared them with those obtained using HCM method. Both two-way segment and directional segments were examined. It was observed that the estimated PTSF was considerably lower than those expected from HCM empirical models. However, the percent difference between field and HCM models was observed to decrease with the flow. The reason for this is acceptance of reduced passing gap during low and moderate flow, which eventually increases the passing frequency. However, during heavy flow, when drivers were forced to move in a platoon, few drivers were observed to take increased risk to overtake and thus disobey the lane discipline. Therefore, drivers' impatience may be considered as one of the possible reasons of lack of conformity between the estimated and expected values, which are perhaps not considered by the HCM models.

Usually, the average FFS becomes erroneous when the speed variation in the traffic stream is large and standard deviation of the speed data is high. This eventually affects ATS values when estimated using HCM guidelines. As a result, these values do not come in agreement with those measured directly in the field. Also, the field observation shows that speed is insensitive to flow, particularly when the platoon length becomes 3 or more. This is due to the fact that, with the increase of platoon length, the percentage of vehicles that follow increases and the average speed corresponds to the speed of the slower vehicles. At this stage, the average speed becomes insensitive to the flow. Thus, the use of ATS as a performance measure could be impractical if the formation of platoon is frequent; this is expected in mixed traffic situation. In addition, it is also important to specify the roadway and traffic condition as a benchmark and to use ATS as a performance measure.

In the present study, it was also attempted to assess LOS using direct field observations of headways. An equality of headways (inside and between) concept that defines LOS C was used for direct LOS assessment and, subsequently, compared to that obtained using HCM criteria. Based on the headway data, it was observed that LOS C corresponds to very high flow (v/c ratio 0.8) whereas it is in the range of E–F when assessed according to HCM at this flow level. This was followed by informal discussions with about 50 road-users, who indicated that the facility more or less met their expectations. Evidently, the presence of a large proportion of slower vehicles, speed of which is certainly not impeded, is the root cause of over-prediction as per HCM methodology. Further research is, however, required to understand the traffic behaviour on two-lane highways in mixed-traffic conditions for assessing LOS.

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