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Review of Percent Time Spent Following (PTSF) as Performance Measure for Two-lane Highways

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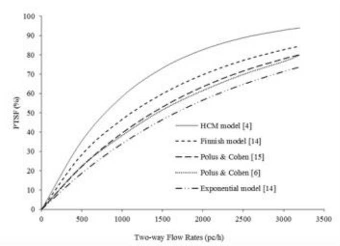
Graphical abstract



Abstract

The Highway Capacity Manual (HCM) uses Percent Time Spent Following (PTSF) as key service measure for assessing the level of service of two-lane highways. However, the indicator is difficult to measure directly in the field. For this reason, its estimation to date has been based on analytical procedures using equations derived from simulations and field observations at representative location based on surrogate measure; as the percent of vehicles traveling with headway less than 3 seconds (3 s). Findings from empirical studies confirmed that the HCM analytical procedures used in estimating PTSF yield results that are inconsistent with the 3 s surrogate measure and mostly overestimate the indicator. This paper presents a review on the estimation of PTSF on two-lane highways and suggests probable approach to substantiate the application of the current practice. Further, the authors of this paper argued that the use of 3 s as surrogate for estimating PTSF based on field observation at a specific point may not represent the actual time spent following over a long segment of two-lane highway since PTSF is space related measure. Hence, the authors suggest the use of test vehicle approach over the highway segment to be evaluated to identify the variables that are required for the development of a representative PTSF measurement model. It is expected that this review and suggestion offered will contribute in advancing performance analysis of two-lane highways.

Keywords: Two-lane highways; HCM; platooning; PTSF; service measure

Abstrak

Manual Kapasiti Lebuhraya (HCM) menggunakan Peratus Masa Digunakan untuk Mengekor (PTSF) sebagai ukuran khidmat utama bagi menilai paras khidmat jalan raya dua lorong. Walau bagaimanapun, penunjuk tersebut sukar untuk disukat secara langsung di lapangan. Atas sebab ini, PTSF dianggar berdasarkan prosedur analitikal menggunakan rumus yang diterbitkan hasil daripada simulasi dan pemerhatian data lapangan di lokasi-lokasi tertentu yang dicerap menggunakan kaedah gantian di mana PTSF disukat berdasarkan peratus kenderaan yang bergerak dengan ruang lolos kurang daripada 3 saat. Walau bagaimanapun, hasil beberapa kajian empirikal mendapati kaedah analitikal HCM adalah tidak konsisten dengan kaedah gantian ruang lolos 3 saat yang mana kebanyakannya menghasilkan keputusan yang melebihi anggaran. Kertas kerja ini membentangkan hasil sorotan literatur berkaitan anggaran PTSF bagi jalan raya dua lorong dan mencadangkan kaedah yang sesuai untuk menambahbaik aplikasi amalan semasa. Di samping itu, penulis berhujah bahawa penggunaan 3 saat sebagai andaian untuk menganggar PTSF berdasarkan ukuran aliran lalu lintas pada satu titik tertentu adalah tidak mewakili jumlah masa sebenar yang digunakan untuk berada dalam keadaan mengekor bagi segmen jalan raya dua lorong yang lebih panjang kerana PTSF adalah ukuran yang berkaitan dengan ruang. Oleh itu, penulis mencadangkan kaedah mencerap data menggunakan kenderaan ujian bagi segmen jalan yang akan dinilai digunakan untuk mengenalpasti pembolehubah yang diperlukan untuk pembangunan model pengukuran PTSF yang lebih jitu. Dijangkakan bahawa kajian dan cadangan yang dikemukakan ini akan meningkatkan kebolehgunaan analisis prestasi jalan raya dua lorong.

Kata kunci: Jalan raya dua lorong; HCM; gerombolan; PTSF; ukuran khidmat

1.0 INTRODUCTION

Traffic flow on two-lane highways is different from that on other type of roads mainly because vehicles traveling on either lane are facing oncoming traffic in the opposite lane and they may be subject to delay because of their inability to pass slow moving vehicles. It is also characterized by vehicular interactions in the traffic stream; not only in the same direction of travel but also in the opposing one. The effect of these interactions generally strengthens with increase in traffic flow in both directions. This, in turn, leads to the formation of platoons as for a fast moving vehicle to safely pass a slow moving one; it requires the use of opposite travel lane which depends on sufficient sight distance and permissible gap in the opposing lane. This phenomenon demonstrates that operational conditions on these types of roads are based on the interaction between vehicles in the traffic stream which increases as the number of vehicles increases. However, the vehicular interaction between lead and following vehicles generally ceases when the time headway exceeds a specific value that fell in the range of 5-7 seconds [1-3]. These unique operational characteristics of traffic flow on two-lane highways made their operational performance assessment relatively difficult and compelled traffic engineers to continue searching for appropriate methods to define the capacity and quality of traffic flow for these facilities.

The Highway Capacity Manuals; HCM 2000 [4] and HCM 2010 [5] identified and use Percent Time Spent Following (PTSF) as key service measure for two-lane highways and to assign a particular level-of-service (LOS). PTSF is defined as the average percentage of travel time that vehicles must spent traveling in platoons behind slower vehicles due to the inability to pass [4, 5]. In spite of its wide acceptance in the field of traffic engineering for performance assessment of two-lane highways, PTSF is difficult to measure directly in the field. For this reason, estimation of PTSF has been based on analytical procedures using equations derived from traffic simulations and field observations at a representative location based on surrogate measure; as the spot proportion of vehicles with headways less than 3 s [4, 5].

Estimating PTSF using traffic simulation has the shortcoming that the approach requires a lot of assumptions regarding the traffic characteristics, more especially driver's behaviour in performing overtaking maneuvers [6]. Regarding the use of 3 s as surrogate measure for field measurement of PTSF, the major weakness with this approach is that PTSF is a segment related measure, whereas the application of the criterion is based on spot measurement and assume applicable over a long section. Also, in applying the 3 s criterion, the HCM does not suggests guidance about the observation procedure with respect to selection of measurement location and duration of observation period [7]. Hence, these inadequacies may cause errors and inconsistencies in PTSF estimates using either of the approaches suggested by HCM.

Further, the application of the 3 s headway as surrogate measure to PTSF based on field observations at a specific location has the possibility of being observed both in free flow and congested conditions. For this reason, PTSF estimates based on 3 s headway at a point could be high even at low traffic volume. Thus, translating into poor LOS under low traffic volume that would be too low to warrant upgrading [8]. Equally, the use 3 s headway at specific point to measure PTSF could result in the same PTSF values for two different traffic streams (one having high traffic volume with comparatively uniform speeds, and another with relatively low volume and uneven speeds); this also increases worry on the accuracy of the surrogate measure [9]. Another point of contention is that whether the 3 s headway criterion used for field measurement of PTSF based on spot observation really represents the time spent in platoon over a long segment of two-lane highway or not? Because spot measurement has been identified as the major problem in collection of headway data [10].

Considering spot PTSF estimates as representative of segment values could be true for short, straight and flat sections with adequate sight distance. Estimates on sections with varied field conditions form this, such as segments with insufficient sight distance and involving substantial proportion of hilliness and bendiness could result in higher PTSF values. Because spot observation may not accurately capture the effects of these characteristics as they could cause reducing effects on passing opportunities on two-lane highways; which would consequently results in longer time spent following. Hence, the need for segment evaluation rather than at a point and assumed applicable for long section.

Another drawback of the HCM procedures used in estimating PTSF is the disagreement among PTSF values produced between the analytical and the 3 s criterion approaches. Findings from empirical studies in many countries [6, 11-18] discovered that HCM analytical procedures produce results that are inconsistent with the 3 s surrogate measure and mostly overestimated values. Even though differences could occur between analytical procedure and field PTSF estimates, yet it is not expected that the difference be large enough as average differences in the range of about 20-40% were reported in some studies [9, 11, 12] between the two approaches. Variation in drivers' behaviour from one place to the other could be a factor resulting in the different PTSF values from the two approaches. However, studies conducted under USA conditions [11, 12] where the HCM 2000 [4] and 2010 [5] were developed based on, reported significant differences in PTSF estimates between analytical and field methods. Neither the HCM, nor other studies specified an acceptable difference or error between PTSF estimates from the two approaches. Hence, this lack of boundary on acceptable errors among the procedures left users with the choice of an approach they feel more comfortable with and not minding the accuracy of the chosen method and this could be misleading.

Heavy reliance on traffic simulation in developing HCM procedures has been blamed as the key cause of the difficulty for direct field measurement of PTSF [19]. Some studies suggest that those estimates are far from accurate and questionable at most [12, 20]. Difficulty associated with direct field measurement of PTSF should not be a convincing and acceptable reason for not exploring the possibility of measuring the indicator along the road segment, especially to justify expenditure on facility improvement or upgrading. Because for situations where operational performance varies along a highway segment, multiple times spent following could be observed (and summed up) to estimate percent followers for a particular highway segment [9]. It is therefore, essential to examine the current practice of estimating PTSF based on HCM procedures and discuss the agreement of the estimates or otherwise among the different approaches. This paper presents a review on the estimation of PTSF procedures and suggests probable approach for field estimation of the measure along road segment to substantiate the application of the current practice.

■2.0 EVOLUTION OF PTSF

PTSF was first introduced as performance measure for two-lane highways in the fourth edition of highway capacity manual, HCM 2000 [4] and also presented in its latest edition; HCM 2010 [5]. Prior to this, other performance measures had been used by the earlier editions of HCM; HCM 1950 [21] and HCM 1965 [22] of the Highway Research Board (HRB), and HCM 1985 [23] of the Transportation Research Board (TRB) which went through several revisions as discussed in previous literature [14, 19, 20, 24]. Among the revised service measures, percent time delay (PTD); defined as the average percent of travel time that all vehicles are delayed while traveling in platoons due to inability to pass [23], was the one closely related to PTSF. It was observed that PTD was difficult to measure directly in the field; hence, the proportion of vehicles traveling at headways less than 5 s was recommended as surrogate measure for its field measurement [23]. Although PTD had been used for operational analysis of two-lane highways, other studies reported that the use of 5 s headway is not consistent with field data [25-29].

Guell and Virkler [25] criticized the 5 s criterion for field estimation of PTD and suggested that revising the 5 s headway criterion to a range of 3.5 to 4 s would provide more useful LOS classes, reasonable and regular results. Similarly, a study conducted in Canada reported that PTD estimates in accordance with HCM 1985 procedures are higher than those observed in the field [27]. It was also demonstrated that fast vehicles were only impeded by headways not exceeding 3 s [28]. In another reaction, Johnson [26] reported that field observations on different segments of rural two-lane roads in Sierra county, California shown that the average headway of vehicles traveling in platoons at or above posted speed limit was approximately 2 s. Thus, the author suggested 2.5 s criteria as cut-off headway for platooning vehicles (on the basis of incorporating a built-in safety buffer) as against the 5 s surrogate measure for PTD that produced unacceptable results. Persula [29] demonstrated that local platooning is a biased estimator for PTD. He added that vehicles traveling with 5 s headway behind another are not followers, especially; slower vehicles should not be classified as platooning.

PTD values reported in these studies are quite lower than the 5 s headway which evidently confirmed the disagreement between the recommended surrogate measure [23] and field data. In spite of the fact that PTD had been used for some time as a service measure for two-lane highways, some limitations necessitated the improvement of the indicator. Included among the limitations were; confusion about the meaning of PTD, and the 5 s headway criterion for its field estimation was disputed by a number of users as well as misapprehended by others [30].

Worries such as those reported made the Transportation Research Board of the National Science Academies [4] to replace PTD with PTSF for assessing the operational performance of two-lane highways as the measure is deemed clearer when related to time spent following rather than time delayed. In estimating PTSF on two-lane roads, the HCM 2000 [4] uses two types of analytical procedures; two-way and directional analyses. The latest version of the manual, HCM 2010 [5] eliminated two-way analysis procedure and uses only directional analysis method after which results from both directions are aggregated to obtain two-way estimates. While HCM2010 consider directional analysis procedure more appropriate compared to two-way and thus dropped the latter approach. Reason for which could be due to the findings that directional analysis avoided estimation based on averaging the characteristics of traffic flow such as density, and the procedure is more compatible with the analysis method for multilane highways and freeways [14]. However, in an attempt to validate the HCM 2000 approaches, a study was conducted in Idaho, USA [12] using field data specifically to examine the differences in PTSF estimates produced by the two-way and directional analysis procedures. Findings from the study [12] established that the two-way analysis was more accurate than the directional analysis as the latter produced more discrepancies in relation to the field estimates using 3 s surrogate measure. In other words, the two-way analysis more closely approximates the field estimates, even though both approaches produced overestimated results. Hence, there is still the need to evaluate the measure using both two-way and directional analysis procedures with the method suggested in this paper to discover the extent of the differences; as to date, the question as to which procedure is more accurate is still ambiguous.

Both analytical procedures involve the application of equations derived from traffic simulations. A part from the use of equations, recommendation was also made for an alternative method for field estimation of PTSF on the basis of surrogate measure; as the percentage of vehicles traveling with headways less than 3 s [4, 5]. However, empirical studies [6, 11-18] discovered high discrepancies among the procedures. Particularly, the HCM analytical procedures were found to be extensively overestimating the PTSF as compared to field observed values.

■3.0 ESTIMATION OF PTSF

As mentioned in the preceding section, HCM 2000 [4] uses two types of analytical procedures for estimating PTSF; two-way and directional analyses and HCM 2010 [5] uses only directional analysis approach to compute the service indicator. HCM 2000 [4] applies equations 1 and 2 for two-way and directional analyses respectively; while HCM 2010 [5] uses equation 3 (same form of expression used in HCM 2000 directional analysis) for the directional analysis, being the only approach adopted for this version of the manual. In two-way analysis, flow rate, percent no-passing zones and directional split are the factors affecting PTSF in which an increase in any these variables results in an increase in PTSF. While in the case of directional analysis, increase in flow rate and percent no-passing zones results in corresponding increase in PTSF.

$$PTSF = 100\{1 - e^{-0.000879 v_p}\} + f_{d/np} \qquad (1)$$

v_p = Two-way passenger-car equivalent flow rate for peak 15-minutes period (pc/h).

$f_{d/np}$ = adjustment for the combined effect of the directional distribution of traffic and of the percentage of no-passing zones on PTSF.

$$PTSF_d = 100\left\{1 - e^{a v_d^b}\right\} + f_{np} \qquad (2)$$

$PTSF_d$ = Percent time-spent following in the direction analyzed.

v_d = Passenger-car equivalent flow rate for the peak 15-min period in the analysis direction (pc/h).

f_{np} = adjustment for percentage of no-passing zones in the analysis direction.

a, b = Coefficients used in estimating percent time-spent-following for directional segments.

$$PTSF_d = 100\left\{1 - e^{a v_d^b}\right\} + f_{np} \qquad (3)$$

All variables have the same meaning as defined for equation 2.

An alternative approach to analytical procedures for field estimation of PTSF was also recommended on basis of surrogate measure as the proportion of vehicles traveling with headways less than 3 s [4, 5].

A number of studies were conducted by various researchers to evaluate the HCM procedures for estimating PTSF on two-lane highways. In these studies, field estimates of PTSF using spot observation were compared with those according to analytical procedures. Conclusions were drawn regarding the agreement of the estimates or otherwise.

Luttinen [14] estimated PTSF values in Finland using the proportion of vehicles with headways less than 3 s. He examined PTSF on Finnish roads with 80 and 100 km/h speed limits. Findings from the study established that PTSF on Finnish roads was lower than suggested by HCM 2000. More so, PTSF values on roads with 80km/h speed limit were slightly lower than on 100 km/h speed limit roads. This is not surprising, as the trend is in accordance with the suggestion according to the steeper speed-flow curve [14]. The study proposed a model for Finnish two-lane highways based on flow rates, geometric and other operational characteristics. An exponential headway model shown in equation 4 was also developed in this study based on the principle that in random flow, vehicular headways follow a negative exponential distribution. Both models produced PTSF values lower than those according to HCM 2000 two-way analytical model which supports the inconsistency among the estimates methods as shown in Figure 1.

$$F(3/q/2) = 1 - e^{-q/2400} \quad (4)$$

q = flow rate (pc/h)

$F(3/q/2)$ = Proportion of vehicles with headways less than 3 s for both directions of flow

However, it was established that negative exponential distribution is only more realistic under very low traffic flow conditions [10, 31]. Thus, application of the model over the wide range of flow rates (up to 3200 pc/h) used in the study could be responsible for the large difference in PTSF values between the exponential model and others shown in Figure 1. Because the model may not be able to accurately capture the headway distribution pattern for higher range traffic flow conditions used in the study.

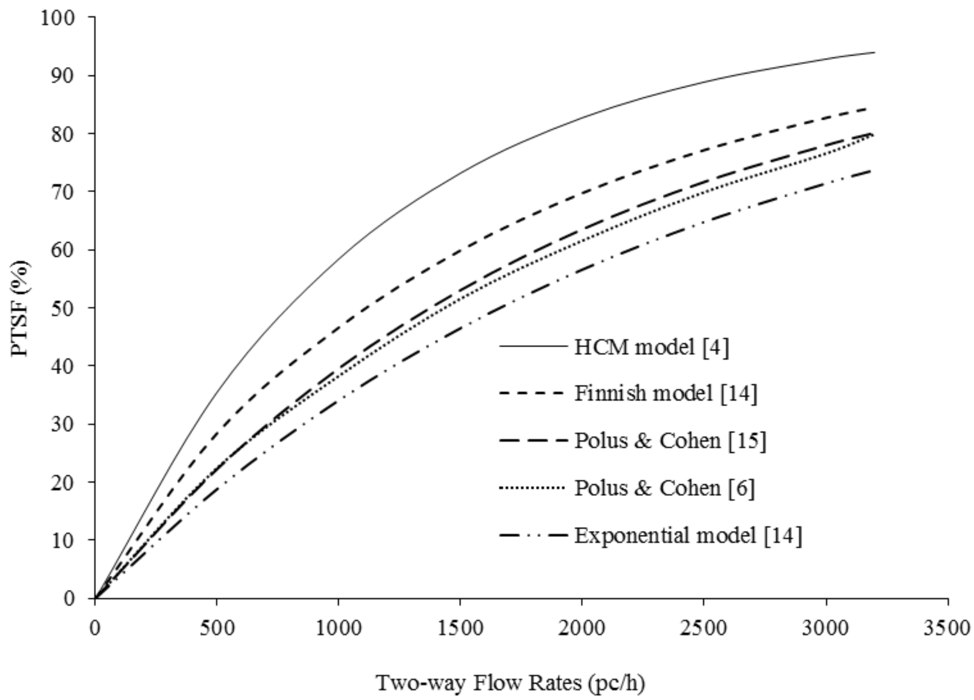


Figure 1 Comparison of PTSF Estimates Using HCM Two-way Model and Field Observed Values Using 3 s

Polus and Cohen [15] estimated PTSF in Israel based on the number of headways inside and outside platoons. In the study, vehicles were only considered inside platoon when their headway is less than 3 s, else they are outside platoon. A PTSF function was developed and compared with that of HCM 2000. PTSF estimates obtained in this study were found to be significantly lower than those according to HCM 2000 values computed using two-way analytical procedure as shown in Figure 1. Similar study was also conducted in the same country by the same authors [6] in which PTSF was estimated based on average number of headways between and outside platoon on the basis of 3 s cut-off headway derived from vehicles arrival times. In this case, the authors assumed that overtaking opportunities were not impeded by no-passing zones. A relationship between PTSF and two-way flow rate was proposed. PTSF estimates from the proposed model were compared with those of HCM 2000 which also indicated that the HCM 2000 model's values were considerably higher than those of the proposed model.

Even though these studies were conducted in the same country under similar local and traffic conditions, different results were obtained in which the second study [6] produced lower PTSF values compared to the first [15]. This could be due to the assumption made in the second study [6] that passing opportunities along the roads are not impeded by no-passing zones (effect of no-passing zones was neglected in developing the model). Neglecting the effect of no-passing zones would in turn reduce PTSF because an increase in proportion of no-passing zone results in corresponding increase in PTSF. Thus, incorporating the effect of no-passing zones would most likely produce same or close PTSF estimates by the two studies.

Figure 1 depicts a comparison of PTSF estimates based on HCM 2000 two-way analytical procedure relative to 3 s surrogate measure approach for field measurement of the indicator for various studies [4, 6, 14, 15]. Generally, the variations among the plots in Figure 1 could be due to variation in driver's behaviour and local conditions in the countries where those studies were conducted. Though, these might not be the key causes of different results between HCM 2000 model and others. Because, even under USA conditions where the HCM 2000 [4] and 2010 [5] were developed based on, studies in Idaho [12] and Montana [11] reported significant differences in PTSF estimates between analytical and field methods. Secondly, another cause of the variation between HCM 2000 PTSF estimates and those from other models might be as a result of spot headway observations and considered representative of segment. Because should operational performance and geometry vary along the segment, especially high flow rates, and increase in grades and curvature, increase in proportion of followers would result with corresponding increase in PTSF and also causing an upward shift of the lower lines towards the HCM 2000 line. By extension, the upward shift of the lower lines would make the spot PTSF estimates based on 3 s closer to those of HCM 2000 analytical approach. This would have made the surrogate estimates more representative of analytical ones. Otherwise, the two approaches may not represent each other. Hence, the need for evaluation of PTSF along segment to justify the application of the current practice is essential.

A study on US-12 highway in northern Idaho [12] evaluated HCM two-lane highways analytical procedures using field data and TWO-lane PASing (TWOPAS) simulation approaches. Field observations were based on vehicles traveling with headways less than 3 s and referred to as percent followers (PF). Table 1 presents an evaluation of the results based on field PF, HCM directional analysis and TWOPAS. On comparing the estimates, it was found that directional analysis PTSF values were approximately 30% and 10% higher than those estimated using spot field measurement and TWOPAS respectively. Similarly, PTSF estimates based on field PF and HCM 2000 two-way analysis were determined as presented in Table 2. To acquire further details on the discrepancies among the HCM procedures, simulation runs were made using TWOPAS to estimate PTSF and PF. On comparing the estimates in Table 2, field PF values were about 23%, 24% and 21% lower than those using HCM two-way analysis procedure, TWOPAS PF and TWOPAS PTSF respectively. Findings from this study imply that HCM analytical procedures and TWOPAS do not accurately represent field conditions and vice-versa. These disagreements among the HCM procedures are well consistent with those according to [6, 14, 15].

Table 1 US-12 Evaluation of HCM directional analysis [12]

Time Interval	Field PF		$PTSF_d$		TWOPAS PTSF	
	NB	SB	NB	SB	NB	SB
10:15-10:30	15.5	11.0	46.0	43.9	36.2	30.2
13:30-13:45	24.1	21.8	52.1	50.7	40.6	40.8
13:45-14:00	19.4	20.8	51.9	53.2	40.0	44.9
15:45-16:00	19.7	28.3	55.4	57.0	43.5	49.1

$PTSF_d$: HCM Directional PTSF, NB: North-Bound, SB: South-Bound

Table 2 US-12 Evaluation of HCM two-way analysis [12]

Time Interval	Field PF[a]	HCM Directional Analysis, [b]PTSF	HCM Two-way Analysis, PTSF	TWOPAS	
				PF	PTSF
10:15-10:30	13.6	45.0	36.9	36.3	33.6
13:30-13:45	23.1	51.4	43.1	43.7	40.7
13:45-14:00	20.1	52.5	44.2	45.6	42.6
15:45-16:00	24.1	56.2	48.0	49.9	46.5

[a]Weighted average of northbound and southbound observed PF values
[b]Weighted average of northbound and southbound estimated PTSF values

Data collected on 25 two-lane highways in South Africa demonstrated that PTSF estimates using HCM two-way model produced results that were on the high side of those obtained based on spot percent followers measured in the field [18]. Results obtained in this study also confirmed the inconsistencies of PTSF estimates by HCM approaches. Figure 2 depicts the findings for both HCM model and percent followers observed in the field. HCM model is shown by the curved line while the spot platooning is indicated by the dots most of which are considerably below the HCM model curve.

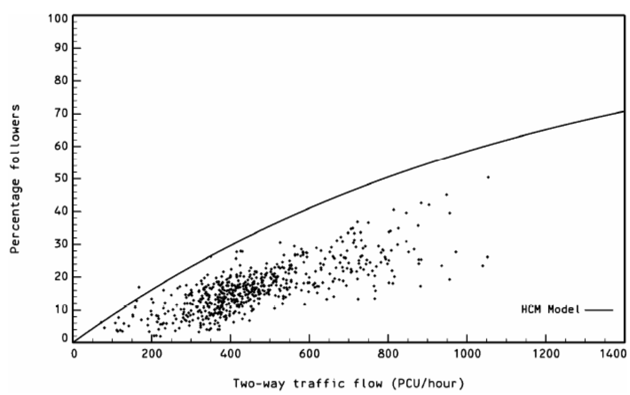


Figure 2 Comparison of PTSF estimates using HCM two-way model and field values using 3 s [18]

HCM directional analysis procedure was also evaluated in this study and the findings were in accord with those of two-way analysis as illustrated in Figure 3. The spot percent followers according to the South African model (Highway Traffic Model (HTM)) were considerably lower than the HCM model values. Inconsistencies in both cases might be attributed to the fundamental assumption that spot measurement of percent followers represents segment estimates, as variation in operational performance and geometric features along the road section could affect the proportion of followers. Particularly, higher flow rate and restricted passing opportunities will result in increased number of followers.

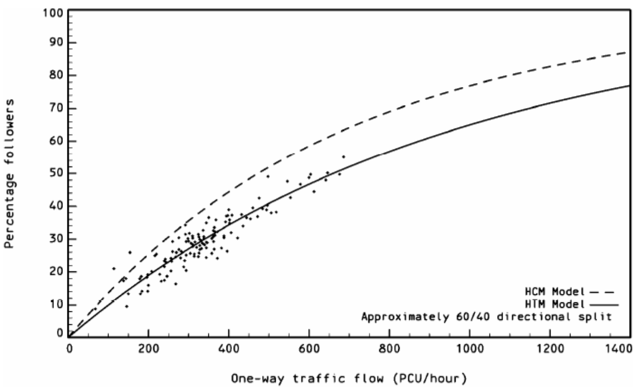


Figure 3 Comparison of PTSF estimates using directional analysis and field values using 3 s [18]

Al-Kaisy and Durbin [11] estimated PTSF using HCM directional analysis and field measurement based on 3 s criterion from three study sites (6 directions) in Montana. An evaluation of the results shown in Table 3 revealed that field PTSF values were approximately found as 39%, 25% and 43% lower than those obtained using HCM directional analysis for the three study sites respectively, with an overall average overestimation of about 40%.

Table 3 Comparison of HCM analytical PTSF estimates and field observations using 3 s [11]

Study Sites	HCM Directional Analysis	HCM Field Estimation
HWY 287 South – NB	68.4	39.31
HWY 287 South – SB	82.2	32.59
HWY 287 North – NB	72.2	41.33
HWY 287 North – SB	59.9	40.49
Jackrabbit Lane – NB	81.3	34.24
Jackrabbit Lane – SB	90.3	52.32

In response to the difficulty associated with direct field measurement of PTSF and inconsistencies among the HCM procedures, two proposed new methods for field estimation of PTSF were evaluated [9]. Field data on headways and vehicular speeds were collected from three study sites in Montana. In the proposed methods, percent followers (PF) was used as surrogate measure for spot measurement of PTSF using *probabilistic* and *weighted average* methods. PTSF estimates from the proposed new methods were compared with those according to both HCM analytical and field observation approaches. Table 4 shows the PTSF estimates using HCM directional analysis and field observation methods, and the new proposed methodologies respectively. Results from the study showed an overestimation of PTSF values by the HCM directional analysis procedure compared to the HCM field estimates and those according to the two proposed new methods. For instance, HCM directional analysis overestimated PTSF by an overall average value of about 23%, 20% and 22% relative to HCM field PF, probabilistic PF and weighted average PF respectively. These irregularities are not surprising as the results are well consistent with the confirmation in previous studies [11, 12, 14, 18]. However, on the basis of individual directions, PF estimates from probabilistic method are in most cases comparable with HCM field observed values.

Table 4 Comparison of PTSF estimates based on HCM procedures and new proposed methods [9]

Location	HCM Directional Analysis	HCM Field Values	Probab-listic Approach, PF	Weighted-average Approach, PF
Site 1 NB	61.20	34.24	38.15	33.48
Site 1 SB	74.80	52.32	55.35	44.74
Site 2 NB	61.20	39.31	40.94	44.47
Site 2 SB	67.90	32.59	31.75	35.73
Site 3 NB	54.10	41.33	53.79	42.66
Site 3 SB	60.35	40.49	41.69	21.04

Likewise, PF values from weighted-average method demonstrated more variation when compared with the HCM field and probabilistic approach estimates respectively. Nevertheless, they are comparable in few cases; and nearly all the estimates from weighted-average method are quite lower than those according to HCM directional analysis. This shows that the two proposed methods exhibited a high degree of consistent estimates of PTSF [9]. Although the two new proposed methods exhibited some consistent estimates of PTSF among themselves and HCM field estimates, there is still the need to establish whether they are actually consistent when a long section of road is considered as opposed to the estimation at specific location. Because the data used in the study were derived from field observation based on percent followers at representative point as surrogate measure for PTSF, which is widely known as segment measure. Also, using PF alone as service measure has the disadvantage that it does not reflect the effect of traffic level which is a vital condition in HCM LOS concept.

Empirical study conducted on 32 two-lane highways in Malaysia estimated PTSF based on 3 s criterion. In the study, a directional analysis model was developed for performance analysis of two-lane highways and documented in Malaysian Highway Capacity Manual, MCHM [32]. A slight deviation from the results reported in other studies was observed in this case. HCM model overestimated PTSF values over certain range of flow rates (about 50 – 1150 pcu/hr) beyond which the MHCM model values exceeded those of HCM for flow rates of about 1150 (pcu/hr) and above as shown in Figure 4. This unique variation in MHCM model [32] relative to HCM model as compared to other studies reported could be due to the differences in driver following behaviour as it was demonstrated that Malaysian drivers are aggressive and they tend to follow other vehicles closely [33]. As such, it should be expected that high proportion of vehicles will follow with short headways which will cause an increase in percent followers and hence PTSF. The close following behaviour of Malaysian drivers was suspected as the key cause why the MHCM model showed different trend compared to other studies which made its curve close to that of HCM and even exceeded at some points.

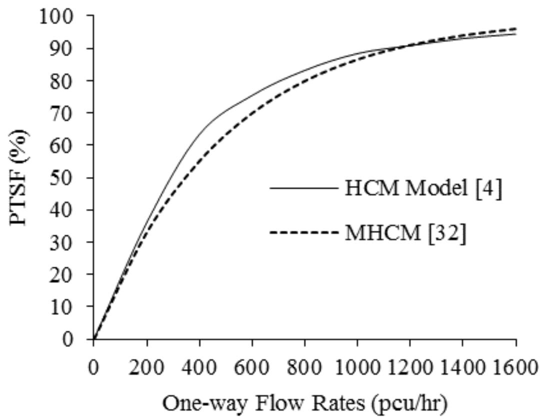


Figure 4 Comparison of PTSF estimates using HCM directional analysis model and MHCM [32] field values

■4.0 ALTERNATIVE SERVICE MEASURES FOR TWO-LANE HIGHWAYS

In response to the limitations of the existing practice in estimating PTSF as performance measure for two-lane highways, especially the difficulty associated with its direct field measurement and discrepancies among the HCM procedures, many researchers suggested other alternative service measures. In an attempt to explore for alternative service measures for two-lane highways in South Africa, Van As [34] suggested follower density (number of followers with short headways per unit length) as a new and promising performance measure for two-lane roads in South Africa. In the same study, the author investigated other service measures of which included are percent followers (proportion of vehicles with short headways), followers flow (number of followers with short headways per hour), percent speed reduction due to traffic, total queuing delay and traffic density. Follower density was also recommended as good service measure for two-lane highways based on studies conducted in Idaho [19] and Japan [35]. Threshold speed, was another indicator recommended as alternative performance measure for two-lane highways, specifically, a substitute for PTSF [7]. Other proposed alternative service measures for the road class under discussion include Average travel speed, Average travel speed of passenger cars, Average travel speed as percentage of free flow speed, Average travel speed as percentage of free flow speed of passenger cars, Percent followers [7, 19, 36] and Percent impeded [37]. The advantages and shortcomings of these proposed measures are discussed as follows:

- *Follower Density (FD):* Referred to as the number of directional followers with short headways per unit length, usually 1 kilometer or mile. The advantages of this measure are it accounts for freedom to maneuver and congestion level in the traffic stream [36]. A major drawback of this indicator is that it is does lend itself easy to measure in the field, as such it is usually derived from flow rate and speed from spot measurements despite it is a space related measure.

- *Threshold Speed:* This is defined as the lowest speed drivers consider satisfactory while traveling on a uniform section of a road under heavy and platooning traffic whose value is based on user perception and good judgment [7]. Although this indicator is easy to measure, yet it is difficult to assign a particular cut-off speed acceptable to all users. For instance, what a patience driver consider as an acceptable speed, an aggressive driver may not. Hence, this measure is more of user bias.

- *Average Travel Speed (ATS):* ATS is one of the measures used by HCM. This measure is considered as a good performance indicator for two-lane roads as it relates well with user perception and also easy to measure. However, its key drawback is lack of specific yardstick across the performance level due to variations in two-lane highways in terms of geometry and operating speeds. Thus, using ATS alone may not explicitly describe the performance without a reference point.

- *Average Travel Speed of Passenger Cars (ATS_{pc}):* ATS_{pc} is recommended as a service measure in Finland [7] and Germany [38] because the indicator more precisely describe reduction in speed as a result of traffic as ATS_{pc} are more affected by high volumes of traffic [38]. ATS_{pc} has the same advantages and weakness as those of ATS.

- *Average Travel Speed as Percentage of Free Flow Speed (ATS/FFS):* This is measure of the extent of speed reduction due to traffic. A high percentage of ATS/FFS indicates a low vehicular interaction and high performance. The opposite of this results in high vehicular interaction and low level of service. Like ATS, ATS/FFS is also easy to measure in field but lack definite benchmark regarding the level of interaction between the vehicles in the traffic stream as against PTSF in HCM which specified a cut-off headway value.

- *Average Travel Speed as Percentage of Free Flow Speed of Passenger Cars (ATS_{pc}/FFS_{pc}):* This measure is similar to ATS/FFS except that heavy vehicles were excluded in the speed measurements. The use of this indicator is based on the rationale that passenger cars are more sensitive to speed reduction due to traffic as their speed are more affected by high traffic volumes than those of heavy vehicles [19, 38]. ATS_{pc}/FFS_{pc} is also easy to measure in the field but has the same limitation as that of ATS/FFS.

- *Percent Followers (PF)*: This measure indicates the proportion of vehicles with short headways in a traffic stream. The indicator can be measured in the field in the same way suggested by HCM [4, 5] using 3 s. A key disadvantage of solely using PF as service measure is that it does not reflect the effect of traffic level which is a vital condition in HCM LOS concept. Theoretically, low traffic levels could still yield high PF if speed variation is relatively high and passing opportunities are restricted. Consequently, the use of PF alone could be misleading [39]. Another weakness of the indicator is that it is measured based on spot observation and assume applicable over long section.

- *Percent Impeded (PI)*: PI is referred to as the percentage of vehicles impeded by slower moving vehicles in traffic stream measured at a particular point. It is derived from equation 5 [37]. In comparison with other service measures, PI relatively correlates well with other measures and platooning variables excluding traffic volume [37].

This indicator is also measured at a point location and applied over segment, and does not even correlate well with traffic volume which is expected to have effect on the amount of impeded vehicles. Its derivation is also associated with desired speed which is usually based on user perception and could affect its reliability.

$$PI = P_p \times P_i \quad (5)$$

where P_p is the probability of a vehicle being part of a vehicular platoon using cut-off headway definition of platoon and P_i is the probability of a vehicle being impeded and traveling at a speed less than the desired speed.

■5.0 DISCUSSIONS

Based on the existing literature and/or various studies reviewed in this paper, it is evidently confirmed that the HCM analytical and field observation procedures for estimation of PTSF do not produce consistent results. In fact, the analytical procedures produced overestimated values; or the field observed values based on 3 s surrogate measure were generally lower than those according to the analytical estimates. An extract of an approximate overestimation of PTSF values by the HCM two-way analytical procedure relative to field data [6, 14, 15] at 1000, 2000 and 3000 flow rates (pcu/hr) is presented in Table 5. The results showed that even at same values of flow rates, the level of overestimation differs from one study to the other. At flow rate of 1000 (pcu/hr), an overestimation of about 12%, 24%, 19% and 20% were recorded by [14], [14], [15] and [6] respectively. At the same flow rate, Van As and Van Niekerk [18] PTSF field estimates were consistently lower than those according to HCM curve. Similar variations in PTSF overestimations were recorded at flow rates of 2000 and 3000 (pcu/hr) respectively. Using the same procedure, an average overestimation of about 23% was recorded [12].

Table 5 Approximate overestimation (%) of PTSF by HCM two-way analysis relative to field values for selected flow rates (pcu/hr)

Study	Flow Rates (pcu/hr)		
	1000	**2000**	**3000**
Finnish model [14]	12	13	10
Exponential model [14]	24	26	22
Polus & Cohen [15]	19	19	15
Polus & Cohen [6]	20	21	16

Similarly, the directional analysis procedure resulted in an overestimated PTSF values relative to field observed values. As is the case with the two-way analysis, different levels of overestimation were observed in various studies. While [12] recorded about 30% overestimation, [11] and [9] attained an overestimates of about 40% and 23% respectively. PTSF values recorded in South African study [18] based on field observation and model developed (Figure 3) were also comparable with those of other studies mentioned earlier. While other studies recorded overestimation of PTSF for all values of flow rates (except zero) by HCM model relative to spot observed values, a different pattern was observed in the case of MHCM model [32]. Figure 4 depicts a comparison between HCM and MHCM models which shows that HCM model overestimated PTSF values only for the range of flow rate of about 50 to 1150 (pcu/hr) with a maximum overestimation of about 8% at a flow rate of 400 (pcu/hr). Thereafter, the MHCM model estimates exceeded those of HCM with about 2% at a flow rate of 1600 (pcu/hr).

For the HCM analytical and field observation procedures to represent each other, PTSF estimates from the two approaches should at least be approximately the same if not equal. To date, the question as to which procedure is more accurate is still ambiguous. Overestimation by the analytical procedures could be as result of heavy reliance on simulations while developing the models which involved a lot of assumptions pertaining traffic characteristics; especially drivers' behaviour in performing overtaking maneuver [6]. Likewise, the consistent low values of field observed PTSF using the 3 s headway relative to the analytical method estimates could be as a result of the fundamental assumption that spot observed values represent long segment estimates. This could probably be true for short straight sections on level terrain with sufficient sight distance and passing opportunities. Field conditions different from these; such as road sections with inadequate sight distance and involving sizeable proportion of hilliness and bendiness could result in higher PTSF values. In other words, the field spot observation may not accurately take care of the effects of these characteristics as they could cause considerable reducing effects on passing opportunities on two-lane highways; which would consequently results in longer time spent following. Thus, measuring PTSF along the segment may produce results that are closer to reality as opposed the current practice of spot measurement and assume to represent time spent following along a stretch of the road.

The present unanswered question on the estimation of PTSF based on the current practice of 3 s rule is that whether the 3 s cut-off headway used for field observation at representative spot really represents the actual time spent following over a long section of two-lane highway or not? While researchers confirmed that HCM equations overestimate PTSF values as compared with those obtained based on spot observation in the field using 3 s as surrogate measure, the level of overestimation varies from one study to the other. This is clearly shown in Figures 1 through 3 which are consistent with other findings [9, 11, 12]. Moreover, neither the HCM, nor other studies specified an acceptable difference or error between estimates from the two approaches. Hence, this lack of boundary on acceptable errors among the procedures left users with the choice of an approach they feel more comfortable with and not minding the accuracy of the chosen method and this could be misleading. The authors of this paper are therefore on the opinion that provision of alternative method for field estimation of PTSF along two-lane highway's segment could be more realistic and also substantiate the application of the existing practice.

■6.0 CONCLUSIONS AND SUGGESTION FOR FURTHER STUDY

Utilization of PTSF by HCM as service measure for two-lane highways faces criticism from numerous researchers not because of its inadequacy as performance indicator; simply because, it is difficult to measure directly in the field. Also, the two approaches for estimating PTSF; analytical procedures and use of 3 s surrogate measure for field observations were confirmed to produce inconsistent results. In fact, the analytical procedures significantly overestimate PTSF as compared to field values. The point here is not about questioning the criterion of using 3 s as a surrogate measure for field estimation of PTSF as the cut-off headway has been widely deemed satisfactory, but the procedure used in applying the criterion. For the fact that PTSF is a segment related measure, the authors argued its observation at representative point and its applicability over a long section of two-lane road. Although, there has been studies that proposed the use of other service measures for evaluating the performance of two-lane highways; yet it is equally essential to search for alternative method that is closer to reality for field measurement of PTSF. Especially, one that would observe the indicator in the field along the road's segment as opposed the current practice of spot observation and considered as representative of a long section. Coming up with an alternative method for field measurement of PTSF along road segment will serve as a basis to justify the application of the 3 s headway criterion at representative point.

Since PTSF is travel time related measure, the most likely way to evaluate the indicator along a road segment is to employ the use of observer(s) within the traffic stream under study. This could be achieved through the use of test vehicle (moving car observer) technique. Hence, the authors suggest the use of test vehicle approach over the highway segment to be evaluated to identify the variables that are required for the development of a representative PTSF measurement model. This would enable the estimation of PTSF over a segment based on actual time spent following as against the existing practice of using surrogate measure on the basis of local platooning. It is hoped that this review and suggestion offered on the alternative method for field measurement of PTSF along segment will provide basis to substantiate the current practice of estimating PTSF based on spot observation and contribute in advancing the performance analysis of two-lane highways.

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