The theoretical and empirical relationships for the quality of flow and for a new level of service on two-lane highways

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Abstract: This study has three main objectives: (1) to develop new, theory-based, queuing relationships for the quality of flow on two-lane rural highways; (2) to estimate the relationships both from the empirical data that were collected on 15 two-lane rural highways and from the queuing models that were developed; and (3) to propose a new level-of-service variable that measures the quality of the flow both inside and between platoons. The paper presents five flow-characteristic measures for two-lane rural highways: the flow, the average platoon length, the traffic intensity, the percent-time-spent following, and the freedom of flow. It is shown that the five measures can be calculated from easily collectible data parameters and also from empirical models related to the two-way flow that are developed based on the field-data collected. It is proposed that the level of service be estimated from the freedom-of-flow parameter \(\eta\), which is developed in the paper. The relationship between \(\eta\) and the two-way flow is calibrated from traffic observations. Level-of-service thresholds, based on the flow and on \(\eta\) are presented and discussed.

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Introduction

The majority of highways in the United States and worldwide are two-lane highways. The flow on such highways is different from the flow on freeways mainly because vehicles are facing oncoming traffic in the opposite lane and they may be subject to delays because of their inability to pass slow-moving vehicles. Some vehicles travel in platoons, which can be long, depending on the volumes in each direction; other vehicles may travel between platoons and their speeds are not impeded. During an attempt to pass an impeding vehicle, drivers evaluate gaps in the on-coming traffic; they are willing to accept gaps, and perform the pass, if they assess that they can complete the pass successfully.

These flow characteristics are unique in the sense that they create queues and the passing of vehicles; these behaviors can be analyzed by Queuing Theory models with necessary adaptation. The second vehicle in the platoon after the slow vehicle is the first vehicle in the “queue;” it is getting the “service,” which is the gap-acceptance process. Vehicles in the queue move in line until they reach the second position, and then they, too, are able to get the service.

The level of service (LOS) on two-lane highways is derived from the flow characteristics of the stream of vehicles. The current approach is based mainly on average travel speed and percent-time-spent following (PTSF). There are two main problems with these measures: First, observations suggest that LOS is not sensitive to speeds on two-lane highways. Second, it is not easy to measure the PTSF parameter directly, and engineers have to resort to empirical models. It was suggested that the “official” empirical model (National Academy of Sciences 2000) has been overpredicting PTSF, and perhaps this is the reason that the related HCM (National Academy of Sciences 2000) thresholds have been relatively high for a given level.

This paper develops a queuing model to estimate flow characteristics on two-lane rural highways. The parameters developed are presented and evaluated; it is proposed that the LOS could be determined by up to five flow characteristics. The first of these parameters is the flow that is related to density and is a main indicator of driving attributes. The second parameter, one that measures the quality of flow, is “traffic intensity” \((p)\); it is another dimension of the driving conditions on two-lane highways and represents freedom of maneuver during driving. The third parameter is the average platoon length \((APL)\), as drivers are reluctant to drive in platoons and prefer unimpeded travel and the freedom to choose their own speeds. The fourth parameter is the well-known percent-time-spent following parameter, which is also related to the flow and length of platoons. The last, but hardly the least, important parameter is a measure of “freedom of flow” \((\eta)\), which is a ratio between free travel time when driving between platoons and the delay time of the second vehicle traveling behind the impeding vehicle when searching for an acceptable passing gap.

Literature Review

The starting point of this review is the LOS concept for two-lane rural highways that is proposed in the Highway Capacity Manual (National Academy of Sciences 2000). Separate LOS concepts are proposed for major (Class I) and secondary (Class II) highways. The parameters used to determine the LOS are average travel speed and PTSF on Class I highways and PTSF on Class II high-
ways. This parameter was also used in HCM 1994, whereas percent time delay was used in HCM 1985. It was defined as "the average percent of time that all vehicles are delayed while traveling in platoons due to the inability to pass." HCM 1985 noted specifically that this variable is difficult to measure in the field and suggested that the percent of vehicles traveling at headways less than 5 s can be used as a surrogate measure in field studies.

Luttinen (2001) conducted research on PTSF and suggested that PTSF was lower on Finnish two-lane highways than estimated by HCM (National Academy of Sciences 2000). He proposed several models to estimate PTSF based on the total flow, percentage of no-passing zones and directional distribution of traffic. Luttinen (2002) also conducted a study on uncertainty in the operational analysis of two-lane highways and showed that limitations in the accuracy of the analysis procedures were causing errors and reducing the usefulness of LOS concept.

Harwood et al. (2003) conducted National Cooperative Highway Research Program study on the HCM’s two-lane road-analysis methodology and indicated that the major source of concern to users was the overestimation of PTSF by HCM; consequently, they developed a revised set of curves to estimate PTSF. Luttinen et al. (2005) in a draft paper pointed to several shortcomings of the existing method of determining LOS, they proposed that only directional methods should be presented in the next edition of HCM and that models should incorporate better field observations. Earlier, Botha et al. (1994), who studied LOS on two-lane rural highways with low design speeds, introduced percent time delay as a measure to describe service quality.

Morrall and Werner (1990) developed an interesting supply and demand approach to estimate the LOS of two-lane highways. Their measure was the overtaking ratio, which was defined as the ratio of the achieved number of overtakings on two-lane rural highways to the desired number. They showed that this ratio approached zero hyperbolically as two-way volume increased.

Pollatschek and Polus (2005), who conducted an analysis of drivers’ impatience on two-lane rural highways, developed theoretical models for reducing the critical passing gap with longer delays prior to the passing maneuver. This impatience, which eventually lessens PTSF, could be one reason for HCM’s overestimating the PTSF parameter—it does not take into account drivers’ willingness to accept more risk as delay increases and thus reduce their PTSF. Earlier Polus and Pollatschek (2004), in a study of criteria for widening two-lane rural highways, developed delay models that eventually cause monetary losses and a need to add lanes.

### Data Collection

Data for this study were collected on rural two-lane highways in northern Israel. The data were collected on 30 one-way sections (15 highways in each direction at the same time), and at each site several hundred vehicles were observed; data were collected during dry pavement conditions and good weather. All sections were removed from intersections by at least 1 km. The raw data were collected by a commercial engineering firm that specializes in data collection; the data consisted of the speed of each vehicle in each direction and the time that the vehicle crossed the measuring device. Additional parameters were computed from the raw data, including volumes and headways inside and outside platoons. Level-of-service parameters are derived from the additional parameters as shown in the formulas developed in the paper. Platoons were defined, as in the HCM (National Academy of Sciences 2000), when the headways were less than 3 s. The hourly volumes, average speeds of fast and slow vehicles and the number of platoons and average platoon length are shown in Table 1.

Two intermediate parameters, $N_o$, number of headways outside platoons and $Q_{vo}$, number of headways inside platoons, can be computed by simple counts of headways inside and outside platoons. These quantities are necessary for evaluation of the measures of flow that are developed in the next sections.

### Five Prominent Flow Parameters

#### Flow

This parameter provides a measure of the amount of traffic, or "load," on the road and is naturally a measure of the LOS. It will be shown in the subsequent developments that all the other LOS parameters are dependent on flow and can be expressed as a function of the flow. Flow is obviously related to speed, and the calibrated relationship from the available data shows that speed decreases linearly as volume increases (Fig. 1). The data in this study are of flow that is not near breakdown conditions, as shown...
in Table 1 and Fig. 1 and therefore speeds for a given flow are in a fairly narrow range (and not breakdown speeds). The speeds are measured in the field, and for that reason they include the effect of the opposing traffic; these effects are expressed as the deviations of the points in Fig. 1 from the regression line. However, the speeds are significantly related to the volume, measured in the number of vehicles including the leading impeding vehicle, is obtained from empirical data, which almost certainly included some hesitant, as well as risk-taking drivers. Therefore, the calibrated models, reflecting the performance of all drivers in the driver population, are not breakdown speeds.

**Average Platoon Length**

The average length of platoon, measured in the number of vehicles including the leading impeding vehicle, is obtained from the average number of headways inside platoons, \( Q_0 \); thus

\[
\text{APL} = Q_0 + 1
\]  

(1)

The parameter \( Q_0 \) depends on the flow; Fig. 2 shows the number of headways versus the one-way volume on two-lane rural highways with relatively good geometry and high design speed. As can be seen, the number of headways grows first as a parabolic function up to a one-way volume of approximately 700 vehicles per hour (vph) and then linearly with a slope of 0.0017 headways per vehicle volume.

The relationships in Fig. 2 are given as

\[
Q_0 = \begin{cases} 
1 + 0.00343V - 1.255 \times 10^{-6}V^2 & \text{for } V \leq 700 \text{ vph} \\
1.6152 + 0.00168V & \text{for } V > 700 \text{ vph}
\end{cases}
\]

\[R^2 = 0.527\]  

(2)

(a combined \( R^2 \) of both the parabolic and linear models) where \( Q_0 \) = number of headways inside a platoon and \( V \) = one-way volume (vph). Note that the parabolic relationship starts theoretically at one because the minimum observable platoon length is two; from Eq. (1), it follows that the minimum number of headways inside a platoon is 1.

Obviously there are other parameters, such as geometry, that influence \( Q_0 \) and this is revealed in Fig. 2 by the dispersion of the data points around the regression line. Yet, the trend of the line is clear: it shows a significant increase in the number of headways inside platoons as the volume increases. Therefore, the average platoon length can be accepted as a first approximation for measuring level of service.

**Traffic Intensity, \( \rho \)**

The platoon formation on two-lane highways may be described as a queuing process, in which the fast vehicle just behind the slow vehicle wants to pass and is looking for a gap in the on-coming traffic that is sufficient for passing. There may be additional vehicles in the queue, and this is shown schematically in Fig. 3.

It is assumed, in the theoretical model, that all drivers are rational, willing always to overtake a slower vehicle, when possible. However, all measures were calibrated on the basis of empirical data, which almost certainly included some hesitant, as well as risk-taking drivers. Therefore, the calibrated models, reflect the performance of all drivers in the driver population.

“Service time” is the time until the first vehicle behind the impeding vehicle can pass; its average is denoted by \( E[T_Y] \). If the \( M/M/1 \) queuing model is assumed, the average number of headways observed in a queue is given as

\[
Q_0 = \frac{1}{1 - \rho}
\]

(3)

where \( \rho \) = ratio between the average time spent in the first position when waiting for and appropriate gap (\( E[T_Y] \)) and average inter-arrival times at the back of the queue. This ratio, \( \rho \), is termed “traffic intensity,” which is conventional in queuing theory and certainly could be a substitute measure for LOS.

The average number of headways inside platoons \( Q_0 \) can easily be observed, and hence \( \rho \) can be calculated as

\[
\rho = 1 - \frac{1}{Q_0}
\]

(4)

As \( \rho \) is a function of \( Q_0 \), it follows that it is also a function of the one-way volume; the relationship can be derived from Eqs. (2) and (4).
Percent-Time-Spent Following

Suppose that $\delta$ denotes the expected time spent by the fast vehicle in the platoon from the moment of joining the back of the platoon until the start of the passing maneuver. Suppose that $\theta =$ average travel time between platoons.

Therefore, the PTSF is given by

$$\text{PTSF} = \frac{100\delta}{(\delta + \theta)} \quad (6)$$

As noted previously, platoon formation is a queuing phenomenon. Little’s theorem (see, e.g., Asmussen 2003), which can be used for this development, states that the time that a vehicle spends in a platoon is given by the ratio of queue length to rate of arrival at the back of the platoon; hence

$$\delta = \frac{Q}{\lambda} \quad (7)$$

where $\lambda =$ arrival rate of fast vehicles at the back of the platoons and $Q =$ expected value of the number of fast vehicles behind an impeding slow vehicle. Note that the number of fast vehicles in theory could be zero, and then no platoon is formed. Therefore, in order to account for zero-length queues, the value of $Q$ may be given as

$$Q = Q_0 - 1 \quad (8)$$

The rate of arrivals at the back of the platoon can be expressed as the inverse of the average interarrival time of the fast vehicles joining a platoon ($1/h_b$). Note that $h_b$ is not measured directly in the field for the purpose of determining PTSF. Therefore, Eq. (7) can be written as

$$\delta = Q h_B$$

Substituting Eq. (8) into Eq. (6) yields the following term

$$\text{PTSF} = \frac{100Q_hB}{(Q_hB + \theta)} \quad (10)$$

where $\text{PTSF} =$ percent-time-spent following; $Q =$ expected value of the number of fast vehicles behind an impeding slow vehicle; $h_B =$ average interarrival time of the fast vehicles joining a platoon; and $\theta =$ average travel time between platoons.

The value of $\theta =$ average number of interarrival time intervals, $N_o$, multiplied by the average interarrival time duration (s). By substituting this $\theta$ value into Eq. (10) and simplifying, it is possible to obtain the value of PTSF as a function of the average number of headways inside and outside a platoon; thus

$$\text{PTSF} = \frac{100(Q_0 - 1)}{(Q_0 + N_o - 1)} \quad (11)$$

Note that in addition to $Q_0$, discussed earlier, one also has to measure $N_o$ in order to estimate the value of PTSF; however, the average values of both $N_o$ and $Q_0$ are very simple to observe; if needed, therefore, it is fairly simple to obtain the values of PTSF for a specific highway.

The relationship between PTSF and the two-way flow was calibrated following an analysis of the data collected on 30 one-way sections of 15 two-lane rural highways, and is shown in Fig. 5.

The proposed PTSF relationship in Fig. 5 was calibrated according to the best-fit method and is shown as

$$\text{PTSF} = 1 - e^{(1.000504V_p)} \quad (12)$$

where $V_p =$ two-way flow in passenger cars per hour (pcph).

For the relationship presented in Fig. 5, the conversion of volume to flow assumed that the average passenger car equivalent is equal to 1.5 and that the average rural highways’ peak-hour factor (PHF) is equal to 0.8. The HCM model is computed from Equation 20-7 in HCM (National Academy of Sciences 2000) and is also shown in Fig. 5. It can be observed that the actual PTSF values, as obtained in this study, are considerably lower than the HCM values. As was also noted previously, the literature also suggests that HCM overestimates PTSF values.
Hence toons multiplied by the average headway. Therefore two-lane highways.

The passing maneuver starts. Vehicle into a position behind the slow vehicle and the time when = expected value of the time interval between the arrival of a fast

Hence, it actually reflects an individual driver’s “undisturbed” travel time versus the delay in first position resulting from inability to pass. In other words, this parameter reflects the “freedom” in the stream, and therefore it represents the LOS within the traffic stream. It is proportionally related to the inverse of the interference of slow vehicles with fast vehicles under the given-flow and opposing-flow conditions.

Essentially η measures the same LOS quality as PTSF but from a different point of view. It provides another facet of the LOS and reveals additional information that is not included in PTSF. It is the ratio between the time of undisturbed driving (the driver is then not under pressure from other adjacent drivers) and the time interval in which the driver is in first position behind a slower-moving vehicle and tries to pass (a time of maximum attention to traffic and road conditions). Therefore, this ratio is called “freedom of flow,” and it reflects the amount of freedom (or lack thereof) that is experienced by drivers when traveling on two-lane highways.

The value of = average number of headways between platoons multiplied by the average headway. Therefore

\[ \eta = \theta / E[T_D] \]  \hspace{1cm} (13)

where \( \theta \) = average travel time between platoons and \( E[T_D] \) = expected value of the time interval between the arrival of a fast vehicle into a position behind the slow vehicle and the time needed to wait until an appropriate passing gap appears in the opposite flow.

Empirical values of \( \eta \) were calculated from the data from 15 two-lane highways (30 one-way segments).

The resulting hyperbolic relationship between \( \eta \) and the two-way flow is presented in Fig. 6. This relationship was chosen from among several alternatives that were tested. It can be noted that the change in \( \eta \) is smaller with higher values of the flow.

The bigger the value of \( \eta \), the higher is the LOS because it shows that the free-travel time between platoons is higher than the time needed to wait until an appropriate passing gap appears in the opposite flow.

\[ \eta = \theta / E[T_D] \]  \hspace{1cm} (14)

and

\[ E[T_D] = \rho h_B \]  \hspace{1cm} (15)

Hence

\[ \eta = N_s / \rho \]  \hspace{1cm} (16)

LOS thresholds can be determined based on the values of the PTSF parameter. The middle (“average”) of the LOS range is level C. For this analysis, this level is defined for a flow condition in which the number of headways inside and outside a platoon is approximately equal. This was analyzed from the headway data between and inside platoons and the result of this analysis is shown in Fig. 7. It can be noticed that the equality of headways inside and between platoons occurs at about a two-way flow of 1,000 pcph.

This flow, therefore, is determined to be approximately in the middle of the LOS C range. This corresponds to 2.5 “levels,” which is approximately 400 pcph per “level.” Therefore, the upper limit of LOS C is approximately 1,200 pcph in the two directions of flows. Referring to Fig. 5, this is equivalent to 45% PTSF. Thus for each “level,” when PTSF is equally divided, one gets 15% change in PTSF between each LOS. This may define the thresholds between the five initial levels of service, as shown in Table 2. For LOS F the value of PTSF exceeds 75%. The relevant two-way flow thresholds are obtained from Fig. 5 for these PTSF values. The relevant freedom-of-flow parameter (\( \eta \)) are obtained from Fig. 6, which provides the relationship between the two-way flow and the freedom of flow.

The study presented five flow measures that are highly relevant to estimate the flow characteristics on two-lane rural highways. The measures are flow \((V_p)\), which measures the amount of traffic on the highways; average platoon length (APL), which provides a measure of the length of platoons; traffic intensity (\( \rho \)), which is the ratio between the average time spent in the first position when waiting for an appropriate gap and average interarrival

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
Level-of-service & PTSF thresholds & Two-way flow thresholds & Freedom-of-flow thresholds \\
 & (%) & (pcph) & (Eta) \\
\hline
A & 0–15 & 0–300 & \geq 16.5 \\
B & 15–30 & 300–700 & 7.1–16.5 \\
C & 30–45 & 700–1,200 & 4.1–7.1 \\
D & 45–60 & 1,200–1,800 & 2.8–4.1 \\
E & 60–75 & 1,800–2,700 & 1.8–2.8 \\
F & 75–100 & \geq 2,700 & \leq 1.8 \\
\hline
\end{tabular}
\end{center}
times at the back of the queue; percent-time-spent following (PTSF); and freedom of flow (η). The third (ρ) and last (η) parameters are two new measures; they can easily be estimated from readily available traffic parameters. Similarly, it is shown, for the first time that the PTSF measure may be estimated directly from the number of headways inside and outside platoons.

In this study the traffic data collected were not near breakdown. At breakdown, the third parameter ρ should approach 1. However, the range of observations for the prevailing conditions in this study did not include breakdown or near-breakdown conditions and consequently ρ was relatively far from 1. The relationship between ρ and breakdown flow conditions is an important point, but perhaps it should be studied in a further study that includes such conditions.

PTSF is certainly an appropriate measure to estimate LOS and especially suitable for economic evaluations of delay costs, because it enables a calculation of the time lost in platoons that can be translated to monetary values. The parameter η may reflect more faithfully the perception of tension when driving and, therefore, may be an additional LOS measure because LOS is largely influenced by perceptions. The parameter η may be closely correlated to risk-taking by drivers and, hence, to safety levels.

A new method of estimating the LOS on two-lane highways is proposed by estimating the threshold flow values on both sides of the average, LOS C, which corresponds to approximately 1,000 pcp/h in the two directions of flow. This is converted to PTSF that is equally divided between the different levels of service. From the PTSF thresholds, the thresholds for flow and freedom of flow are also determined.

It should be noted that this method of estimating LOS, although it appears as a unidirectional method, is actually a bidirectional approach. The reason is that all parameters are dependent on the opposing flow. For example, the variables according to which the freedom of flow (η) is computed are based on both directions: the rate at which vehicles join the queue in the main direction, and the average time in the first position, which depends largely on the critical passing gap and the volume in the opposite direction. As η "captures" the flow characteristic in both directions, it is a two-directional estimate of the LOS. Consequently, the impact of the flow in the opposite direction is implicitly included in the calibrated models of this study as well as in any future study that will use the proposed methodology. Similar argumentation holds for the other proposed measures.

It should be noted that all calibrated regression models were significant in spite of some dispersion of the data points around the regression line. This dispersion resulted from the influence of other parameters (e.g., geometry). The significance of the models shows that the other parameters are secondary to the impact of the flow in the main direction.

Notation

The following symbols are used in this paper:

- APL = average platoon length (vehicles);
- \( h_B \) = time when the passing maneuver starts (s);
- \( N_o \) = average number of headways between platoons (dimensionless);
- PTSF = percent-time-spent following (→);
- \( Q \) = queue length (dimensionless);
- \( Q_o \) = average number of headways inside platoons (dimensionless);
- \( R \) = multiple correlation coefficient (dimensionless);
- \( V \) = one-way volume (vehicles/h);
- \( V_p \) = two-way flow in passenger cars equivalent (cars/h);
- \( \delta \) = average time spent in platoons (s);
- \( \eta \) = freedom of flow (dimensionless);
- \( \theta \) = average travel time between platoons (s);
- \( \lambda \) = arrival rate of fast vehicles to platoons (1/s); and
- \( \rho \) = traffic Intensity (dimensionless).

References


