Approximation of Percentage Time Delay with Local Measurements

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In the 1985 *Highway Capacity Manual* (HCM), percentage time delay (PTD) is used as the main indicator of the level of service for two-lane, two-way highways. HCM defines PTD as the average percentage of time that all vehicles are delayed while traveling in platoons due to the inability to pass. For field measurement purposes, the HCM states that PTD is approximately the same as the percentage of vehicles traveling in platoons at headways less than 5 sec. The relationship between local platoon percentage, measured with a fixed 5-sec headway as the platooning criterion, and the previous estimate of PTD is analyzed. Theoretical considerations indicate that local platoon percentage is a biased estimate of PTD and must be corrected with a factor calculated as the ratio of space mean speed of all traffic and that of the platooned vehicles. If several measurements are made along a road, PTD can be estimated as a weighted average of local values using mean travel times and traffic flows as weights. Analysis of simulation and field data indicate that the local platoon percentage is usually about 3 to 5 percent lower than the corresponding PTD value. To make local measurements correspond more precisely to the basic definition of PTD, one could exclude from measurements situations in which a slower vehicle is behind a faster one inside the 5-sec headway. The effect of this exclusion, however, is not tested.

In the 1985 *Highway Capacity Manual* (HCM) (*1*), percentage time delay (PTD) is used as the main indicator of the level of service for two-lane, two-way highways. According to the HCM, PTD is defined as the average percentage of time that all vehicles are delayed while traveling in platoons because of the inability to pass.

In previous works, the author has used the percentage of vehicles driven with a headway of fewer than 5 sec, when measured at a fixed point, as the approximation of PTD (*2–4*). The aim of this paper is to analyze the relationships between PTD and this locally measured platoon percentage. The analysis is based on theoretical considerations, simulations, and real measurements.

THEORETICAL RELATIONSHIPS

Basic Considerations

The 1985 HCM (*1*) and the background report (*5*) state that in estimating PTD, motorists are defined to be delayed when traveling behind a platoon leader at speeds less than their desired speeds and at headways of less than 5 sec. The reports also state that for field measurement purposes, PTD on a road section is approximately the same as the percentage of all vehicles traveling in platoons at headways of less than 5 sec.

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The 5-sec criterion is commonly used as the limit value for time headway between free and platooned vehicles. As can be seen in Figure 1, field measurements indicate that when a faster vehicle is reaching a slower one, the adaptation of speed—and thus the hindrance—begins at headways between 5 to 10 sec (*3*). The same result is given by several researchers (*6,7*). The adaptation is, of course, dependent on the speed difference of the vehicles and the driver in question. So, a wide range of platooning criteria can be justified, among them the 5-sec criterion used in the HCM.

PTD is defined as the average share of time spent in platoons. From a road section, the number of vehicles in platoons is a dynamic variable that changes in value all the time. Thus, PTD can be calculated by averaging instantaneous road section values over time.

From the point of view of an individual driver, PTD is a variable related to a certain section of road. The percentage of time driven in platoons of the total travel time of the road section is the platooning experienced by the driver. Calculating PTD from individual total travel time values means averaging over drivers.

In the following, the PTD of the total traffic flow is expressed as the sum of the time that drivers are in platoons divided by the sum of the total travel time of all drivers on the same road section during the period in question.

The aim of the paper is to analyze the relationship of this PTD to the locally measured platoon percentage based on the 5-sec headway criterion. For simplicity, even though the word "percentage" is used in the text, PTD and platoon percentage in all equations are expressed as ratios, without multiplication to percentage values.

Simple Analysis with Shock Wave theory

First analyze a stable traffic flow given in Figure 2. The flow is divided into two densities, that is, to platoons (density k_1) and to free vehicles (density k_2). The speeds (u_1 and u_2) and the lengths (l_1 and l_2) of the platoons are given. In a stable situation, as many vehicles per unit time move from the faster traffic flow to the slower (and more dense) one as move from the slower traffic to the faster. This way, the lengths of the platoons do not change when traffic propagates along the road. The points of density change travel along the road with constant and equal speeds. This can be seen very easily from the equation of the shock wave speed (c in Figure 2), which gives the same value for both edges of density change.

Thus, using the symbols in Figure 2, one can estimate r, the PTD on the road section with one cycle of high- and low-density traffic. The estimation (Equation 1) is based on the fact that at any moment the number of vehicles on the road section, as well as the number of vehicles in platoons and outside platoons, is constant.

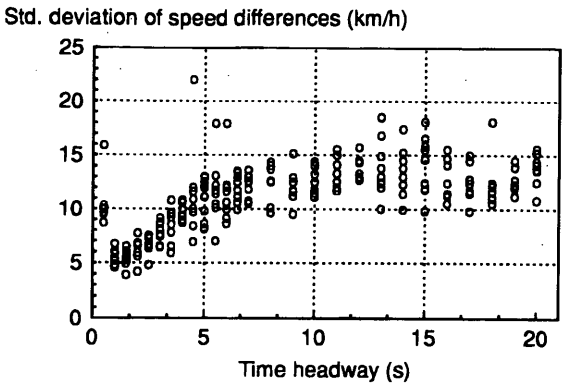

FIGURE 1 Standard deviation of speed differences of successive vehicles as function of time headway (*3*).

$$r = \frac{\text{veh-hr in platoon in section}}{\text{veh-hr in section}} = \frac{k_1 l_1 (t_1 + t_2)}{k_1 l_1 (t_1 + t_2) + k_2 1_2 (t_1 + t_2)}$$

$$= \frac{k_1 l_1}{k_1 l_1 + k_2 l_2} \tag{1}$$

where veh-hr equals vehicle hours.

If a local measurement is made at the end of the road section, the resulting local platoon percentage, p, can be calculated. For simplicity, the measurement is made over a period during which one pulse of high- and low-density traffic passes the measuring point.

In the local measurement if can be seen that the number of vehicles passing the observation point in platoon (N_1) and the number of vehicles passing outside the platoon (N_2) are

$$N_1 = q_1 t_1 \tag{2}$$

$$N = q_2 t_2 \tag{3}$$

These numbers are not the same as the number of vehicles in platoon ($k_1 l_1$) and outside the platoon ($k_2 l_2$) along the road. This is because during the time that the platoon passes the measuring point, new vehicles enter the platoon. The same applies for nonplatooned traffic.

Using Equations 2 and 3, the share of vehicles in platoons in the local measurement can be calculated:

$$p = \frac{N_1}{N_1 + N_2} \tag{4}$$

The times t_1 and t_2 can be calculated by the help of the speed of the density change, c, that is,

$$t_1 = \frac{l_1}{c} \tag{5}$$

$$t_2 = \frac{l_2}{c} \tag{6}$$

The fundamental flow relationship of traffic gives

$$q_1 = u_1 k_1 \tag{7}$$

$$q_2 = u_2 k_2 \tag{8}$$

Combining all these equations gives

$$p = \frac{N_1}{N_1 + N_2} = \frac{q_1 t_1}{(q_1 t_1 + q_2 t_2)} = \frac{u_1 k_1 \frac{l_1}{c}}{u_1 k_1 \frac{l_1}{c} + u_2 k_2 \frac{l_2}{c}} = \frac{u_1 k_1 l_1}{u_1 k_1 l_1 + u_2 k_2 l_2} \tag{9}$$

For the duration of the measurement,

$$t = t_1 + t_2 = \frac{l_1 + l_2}{c} = \frac{l}{c} \tag{10}$$

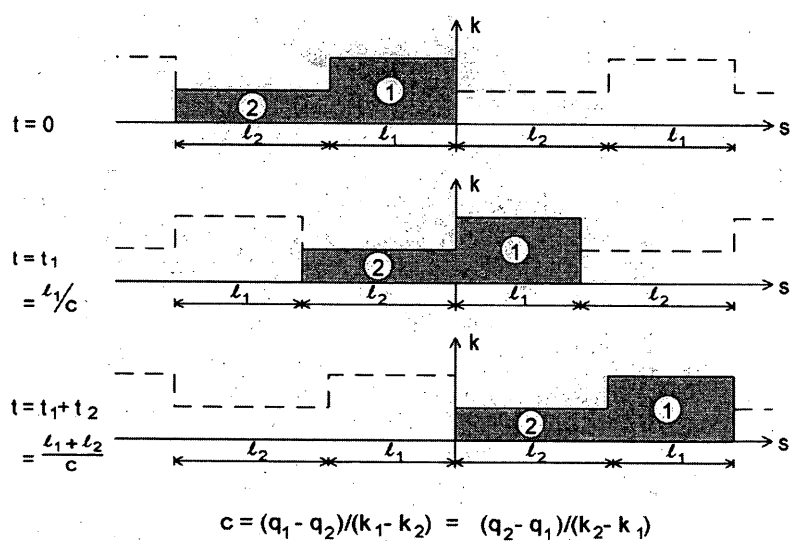

FIGURE 2 Simplified description of platooned and free traffic flow along a road.

and for the total flow rate,

$$q = \frac{N_1 + N_2}{t} = \frac{q_1 t_1 + q_2 t_2}{t} = \frac{u_1 k_1 \frac{l_1}{c} + u_2 k_2 \frac{l_2}{c}}{\frac{l}{c}}$$

$$= \frac{u_1 k_1 l_1 + u_2 k_2 l_2}{l} \tag{11}$$

This gives the local platoon percentage

$$p = \frac{q_1 l_1}{ql} = \frac{u_1 k_1 l_1}{ukl} \tag{12}$$

where u is the space mean speed of the total traffic flow and can, according to the definition, be calculated as

$$u = \frac{u_1 k_1 l_1 + u_2 k_2 l_2}{k_1 l_1 + k_2 l_2} \tag{13}$$

The space mean speed u in Equation 13 can be calculated from the locally measured speeds as the harmonic mean, that is,

$$u = \frac{N_1 + N_2}{\frac{N_1}{u_1} + \frac{N_2}{u_2}} = \frac{q_1 t_1 + q_2 t_2}{\frac{q_1 t_1}{u_1} + \frac{q_2 t_2}{u_2}} = \frac{u_1 k_1 \frac{l_1}{c} + u_2 k_2 \frac{l_2}{c}}{k_1 \frac{l_1}{c} + k_2 \frac{l_2}{c}}$$

$$= \frac{u_1 k_1 l_1 + u_2 k_2 l_2}{k_1 l_1 + k_2 l_2} \tag{14}$$

which is the same result as given in Equation 13.

Consequently, k in Equation 12 is the mean density of the total traffic flow and can be calculated as follows:

$$k = \frac{q}{u} = \frac{k_1 l_1 + k_2 l_2}{l} \tag{15}$$

Equation 1 for the PTD can now be rewritten as

$$r = \frac{k_1 l_1}{k_1 l_1 + k_2 l_2} = \frac{k_1 l_1}{kl} = \frac{k^p}{k} \tag{16}$$

where $k^p = k_1 l_1 / l$ is the mean density of platooned vehicles over the whole road section l.

If the equation of the local platoon percentage (Equation 12) is compared with that of the PTD (Equation 16),

$$p = \frac{u_1}{u} \frac{k_1 l_1}{kl} = \frac{u_1}{u} r = \frac{u^p}{u} r \tag{17}$$

where $u^p = u_1$ is the space mean speed of platooned vehicles.

In this way the relationship between the PTD, r, and the local platoon percentage, p, has been derived:

$$r = \frac{u}{u^p} p \tag{18}$$

This equation gives the result that PTD is calculated from the local platoon percentage by multiplying the local percentage by the ratio of the space mean speed of the whole traffic and the space mean speed of the platooned traffic.

Generalization of Relationship

In the preceding analysis, the traffic flow was simplified to two densities traveling at constant speeds typical of the density in question. In this kind of traffic flow, no overtakings are made. In real traffic, all sorts of situations exist and they can be described with vehicle trajectories in time-space domain (Figure 3).

The fundamental flow relationship of traffic can be generalized for situations given in Figure 3 [for example, see the work by Leutzbach (*8*)]. The three variables—flow, density, and mean speed—are then defined in the following way:

- Traffic flow q = total vehicle kilometers of travel (S) in the domain divided by the area of the domain, that is,

$$q = \frac{S}{LT} \tag{19}$$

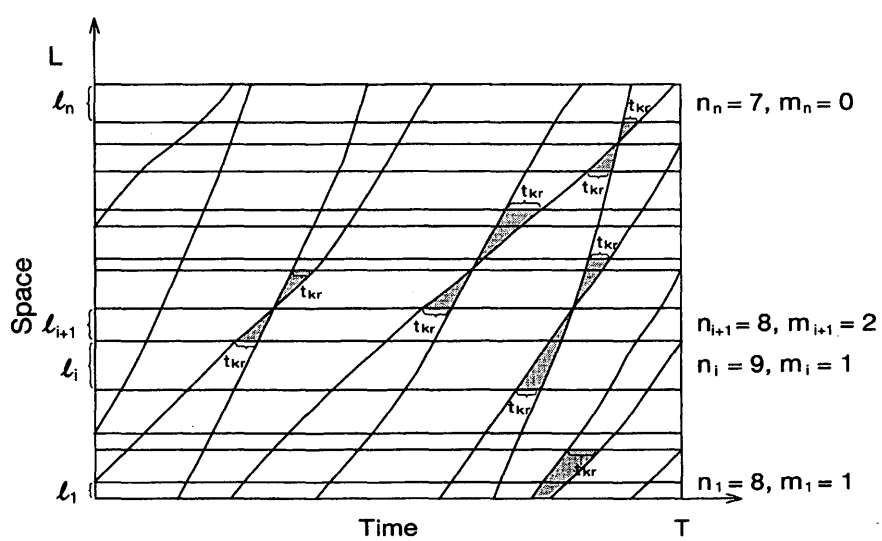

FIGURE 3 Time-space trajectories of vehicles in generalized description of traffic flow.

- Traffic density k = total vehicle hours of travel (T_{tot}) in the domain divided by the area of the domain, that is,

$$k = \frac{T_{tot}}{LT} \tag{20}$$

- Space mean speed of traffic u = total vehicle kilometers of travel in the domain divided by the total vehicle hours of travel in the domain, that is,

$$u = \frac{S}{T_{tot}} \tag{21}$$

The aim now is to generalize the relationship of local platoon percentage, p, and PTD, r. To do that, first define the criterion of platooning as a constant headway of t_{kr}. After that, divide the time-space domain (Figure 3) with horizontal lines into sections of road (length l_i) with a constant number of vehicles (n_i) and a constant number of vehicles in platoons (m_i) inside each section during the whole period of time T. Because of different speeds of vehicles, the vertical (space) distances between platooned vehicles at the borderlines of the road sections do not have a constant value.

For each of the sections i,

$$p_i = \frac{m_i}{n_i}$$

or (22)

$$m_i = p_i n_i$$

where p_i is the local platoon percentage at any cross section inside the road section i.

The PTD r_i is calculated as the sum of travel times in platoons divided by the total travel time in section i during the time T.

The sum of the travel times of individual vehicles in section i is T_i:

$$T_i = \sum_{j=1}^{n_i} t_{ij} = n_i t_i = \frac{n_i l_i}{u_i} \tag{23}$$

where

$i = 1 \ldots, n$ = section index,
$j = 1 \ldots, n_i$ = vehicle index inside section i,
u_i = mean travel speed of vehicles in section i, and
t_i = mean travel time of vehicles in section i.

For the travel time in platoons in section i, these corresponding relationships exist:

$$T_i^p = \sum_{h=1}^{m_i} t_{ih}^p = m_i t_i^p = p_i n_i t_i^p = \frac{p_i n_i l_i}{u_i^p} \tag{24}$$

where $h = 1 \ldots, m_i$ is the platoon vehicle index in section i, and superscript p indicates platooned vehicles only.

For the PTD,

$$r_i = \frac{T_i^p}{T_i} = \frac{\dfrac{p_i n_i l_i}{u_i^p}}{\dfrac{n_i l_i}{u_i}} = p_i \frac{u_i}{u_i^p} \tag{25}$$

Furthermore,

$$r_i = p_i \frac{u_i}{u_i^p} = \frac{p_i \dfrac{q_i}{k_i}}{\dfrac{q_i^p}{k_i^p}} = \frac{k_i^p}{k_i} \tag{26}$$

So, for a single road section i, the same relationship is valid that was found before for the simplified case using the shock wave theory.

For the whole road section L, the following relationships are valid:

$$S = \sum_{i=1}^{n} n_i l_i \tag{27}$$

where S gives the total amount of vehicle kilometers of travel inside the domain,

$$S^p = \sum_{n=1}^{n} m_i l_i = \sum_{n=1}^{n} p_i n_i l_i \tag{28}$$

where S^p is the total amount of vehicle kilometers in platoons inside the domain,

$$T_{tot} = \sum_{i=1}^{n} n_i t_i \tag{29}$$

where T_{tot} gives the total number of vehicle hours inside the domain, and

$$T_{tot}^p = \sum_{i=1}^{n} m_i t_i^p = \sum_{i=1}^{n} p_i n_i t_i^p \tag{30}$$

where T_{tot}^p gives the total number of vehicle hours in platoons inside the domain.

Before going further, it is worth noting that the general definitions of traffic flow variables given in Equations 19 through 21 are valid for the platooned part of the traffic in the same way as for the traffic flow as a whole.

For the mean platoon percentage of the whole domain, p,

$$p = \frac{\sum_{i=1}^{n} m_i l_i}{\sum_{i=1}^{n} n_i l_i} = \frac{S^p}{S} = \frac{q^p LT}{qLT} = \frac{q^p}{q} \tag{31}$$

Equation 31 has used the general definitions of traffic flow (Equation 19) for platooned traffic.

For the PTD of the whole domain, r,

$$r = \frac{\sum_{i=1}^{n} T_i^p}{\sum_{i=1}^{n} T_i} = \frac{T_{tot}^p}{T_{tot}} = \frac{k^p LT}{kLT} = \frac{k^p}{k} \tag{32}$$

Here, again, the general definition of traffic density (Equation 20) for platooned traffic has been used.

Now, by using the fundamental flow relationship of traffic and Equations 31 and 32,

$$p = \frac{u^p k^p}{uk} = r \frac{u^p}{u} \tag{33}$$

or

$$r = p\frac{u}{u^p} = p\frac{\frac{l}{u^p}}{\frac{l}{u}} = \frac{pt_{av}^p}{t_{av}} \tag{34}$$

where t_{av} is the average travel time of vehicles in the whole time-space domain, and t_{av}^p is the average travel time of platooned vehicles in the whole time-space domain.

In this way the relationship between the local platoon percentage, p, and the PTD, r, has been generalized to any kind of traffic flow. For the relationship to be valid, one must bear in mind the way in which the variables in the relationship are defined. The considerations have been made for one direction of traffic only, but they easily generalize for two-way flow also.

In general, the mean platoon percentage of a time-space domain is calculated by dividing the vehicle kilometers driven in platoons by the total vehicle kilometers driven in the domain. Consequently, the PTD is calculated by dividing the vehicle hours driven in platoons by the total vehicle hours driven in the domain. So platoon percentage is proportional to vehicle kilometers (or traffic flow rates), and PTD is proportional to vehicle hours (or traffic densities).

Furthermore, the mean speed of all vehicles in the domain is calculated by dividing the total vehicle kilometers by the total vehicle hours in the domain. Consequently, the mean speed of platooned vehicles is calculated by dividing the vehicle kilometers driven in platoons by the vehicle hours driven in platoons inside the domain.

Usually it can be expected that the space mean speed of platoons is lower than the space mean speed of the whole traffic. In principle, this gives the relationships between PTD and platoon percentage given in Figure 4. The difference between the curves can be quite small if the speed variation of traffic flow is small. On the other hand, if there are great differences in speeds of different vehicle categories, the difference between platoon percentage and PTD can be quite remarkable. For example, this type of situation can exist on roads where the percentage of heavy vehicles is high and the terrain is hilly.

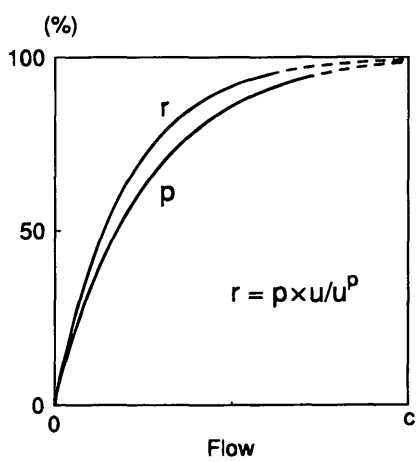

FIGURE 4 Hypothetical relationship between PTD (r) and local platoon percentage (p).

Calculation of PTD from Several Local Measurements

If several local measurements are made along the road, then the mean platoon percentage, p, can be calculated using Equation 35 (see Equation 31).

$$p = \frac{\sum_{i=1}^{n} m_i l_i}{\sum_{i=1}^{n} n_i l_i} = \frac{\sum_{i=1}^{n} p_i n_i l_i}{\sum_{i=1}^{n} n_i l_i} = \frac{\sum_{i=1}^{n} p_i q_i l_i}{\sum_{i=1}^{n} q_i l_i} \tag{35}$$

(Here, and in the following, the same notation is used for local measurements as in the former analysis for road sections.)

If the traffic flow rate along the road section is constant, Equation 35 simplifies to Equation 36:

$$p = \frac{\sum_{i=1}^{n} p_i l_i}{L} \tag{36}$$

In this case the mean platoon percentage can be calculated as the weighted average of the platoon percentages of consecutive road sections by using the section lengths as weights.

Consequently, the mean PTD can be calculated using Equation 37:

$$r = \frac{\sum_{i=1}^{n} T_i^p}{\sum_{i=1}^{n} T_i} = \frac{\sum_{i=1}^{n} r_i T_i}{\sum_{i=1}^{n} T_i} = \frac{\sum_{i=1}^{n} r_i n_i t_i}{\sum_{i=1}^{n} n_i t_i} = \frac{\sum_{i=1}^{n} r_i q_i t_i}{\sum_{i=1}^{n} q_i t_i}$$

$$= \frac{\sum_{i=1}^{n} r_i q_i \frac{l_i}{u_i}}{\sum_{i=1}^{n} q_i \frac{l_i}{u_i}} = \frac{\sum_{i=1}^{n} r_i k_i l_i}{\sum_{i=1}^{n} k_i l_i} \tag{37}$$

If the basic relationship between p_i and r_i is used (Equation 25), then on the basis of Equation 37,

$$r = \frac{\sum_{i=1}^{n} r_i k_i l_i}{\sum_{i=1}^{n} k_i l_i} = \frac{\sum_{i=1}^{n} p_i \frac{u_i}{u_i^p} k_i l_i}{\sum_{i=1}^{n} k_i l_i} = \frac{\sum_{i=1}^{n} p_i q_i \frac{l_i}{u_i^p}}{\sum_{i=1}^{n} q_i \frac{l_i}{u_i}} = \frac{\sum_{i=1}^{n} p_i q_i t_i^p}{\sum_{i=1}^{n} q_i t_i} \tag{38}$$

If q_i along the road is constant, then Equations 37 and 38 can be simplified to Equation 39:

$$r = \frac{\sum_{i=1}^{n} r_i t_i}{\sum_{i=1}^{n} t_i} = \frac{\sum_{i=1}^{n} p_i t_i^p}{\sum_{i=1}^{n} t_i} \tag{39}$$

So, in the case of constant flow, the mean PTD can be calculated as the weighted average of the PTD values of consecutive road sections by using the section travel times as weights. The mean PTD can in this case also be calculated on the basis of local platoon percentages, mean travel times in platoons, and mean travel times of the whole traffic.

By comparing Equations 37 and 38,

$$r = \frac{\sum_{i=1}^{n} r_i q_i t_i}{\sum_{i=1}^{n} q_i t_i} = \frac{\sum_{i=1}^{n} p_i q_i t_i^p}{\sum_{i=1}^{n} q_i t_i} \tag{40}$$

Equations 35 through 40 describe the estimation for the mean platoon percentage and mean PTD on the basis of local measurements. The speed values u_i^p and u_i must be calculated as the harmonic means of the spot speeds of the individual vehicles at each measuring point to represent the corresponding travel speeds.

Equation 40 describes the relationship of PTD to mean travel times of platooned and all vehicles through the individual road sections. The travel times, t_i and t_i^p, can be calculated by using the section lengths and harmonic mean speeds of platooned vehicles and all vehicles at each measuring point.

SIMULATION RESULTS AND MEASUREMENTS

Simulation Results with TRARR

Simulation is a suitable tool for estimating the relationship between PTD and platoon percentage. In simulation one can register exactly when vehicles are hindered by others and how long they do travel in platoons, thus resulting in a PTD estimate over the whole simulated road section. For platoon percentage, local registration of platooned vehicles can be made at several cross sections. As far as we know, no program uses the previous derived definition based on vehicle kilometers to create an average platoon percentage for the whole simulated road section.

Hoban has described the difference of PTD and percentage following observed in simulations (*9*). He uses a 4-sec headway as the platoon criterion. Whether the platoon leaders are included in the platoon percentage is not clear because the report (*9*) refers only briefly to the research in question. Hoban also states that the average of several consecutive cross sections is used, but he gives no indication of any kind of weighing in the calculation of the average platoon percentage.

The reported platoon percentages in Hoban's work are, with one minor exception, lower than the percentage following values that basically are PTD values (*9*). This is in accordance with the preceding theory if it is assumed that the mean speed in platoons usually is lower than the mean speed of the whole traffic. The report does not give any results about the relationship between the average speed in platoons and traffic as a whole.

From the data of some Finnish simulation studies on a highclass rural road (*10*), simulated local platoon percentages and simulated PTD values can also be compared. The simulation program used was the Australian TRARR. A short English description of the calibration and use of the program, including some results, is given elsewhere (*11*). The platoon percentages given here were calculated as the weighted average of local percentage values given by the simulation program. A 5-sec time headway was used as the platoon criterion, and local platoon percentages were printed at about 1-km intervals. The program calculated the actual PTD values over the whole simulated road section on the basis of travel times in platoons and outside platoons, thus enabling the comparison with the local platoon percentages. The headway distributions for the incoming flows were given as measured in the field.

In Figure 5, the Finnish and Australian results are compared. The Finnish values are for one direction of traffic only. The simulated local platoon percentages in the figure are usually 3 to 5 percent lower than the simulated PTD values (maximum difference in the Australian data is 7.0 and in the Finnish data, 7.8 percent), but in some cases the PTD value is up to 2 percent lower than the corresponding platoon percentage. The results appear to correspond with each other quite well, despite the differences in platoon criteria and the flow in question.

In the Finnish simulation data, the mean platoon percentage was calculated as the weighted average of 14 to 16 local measurements over 16 to 22 km of road, and PTD values were taken directly from the simulation output. The variation of the individual local platoon percentages ranged from 3 to 19 percent; usually it was about 10 percent. So, quite a lot of variation in the local platoon percentages can exist, even on a high-class road with a low percentage of heavy vehicles.

The TRARR outputs of the Finnish simulations do not give any information about the speeds of platooned vehicles. In the following, Finnish field measurement data are used to analyze more closely the relationship between the speeds of platooned vehicles and all vehicles.

Results of Field Measurements

The field measurements used here were done on ordinary two-lane rural roads in Finland in 1984 (*4*). The data were gathered with several individual local measurements on different kinds of roads by using double induction loops. The space mean speeds were calculated as the harmonic means of the measured individual speeds.

Figure 6 presents the ratio of the speeds (u/u^p) as a function of flow in both directions of travel together. It can be seen that the ratio usually varies between 1.00 and 1.05. The ratio is decreasing when the flow is increasing. This is natural because in higher flow rates, more vehicles drive in platoons.

The analysis of one-way traffic shows very similar values for the u/u^p ratio for the main direction of flow. In the direction of the

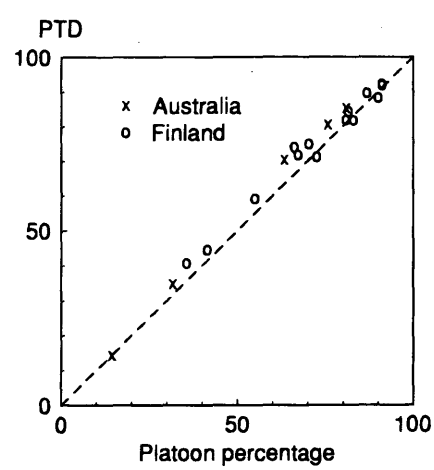

FIGURE 5 Comparison of simulated mean platoon percentage and simulated PTD on Australian (*9*) and on Finnish two-lane roads.

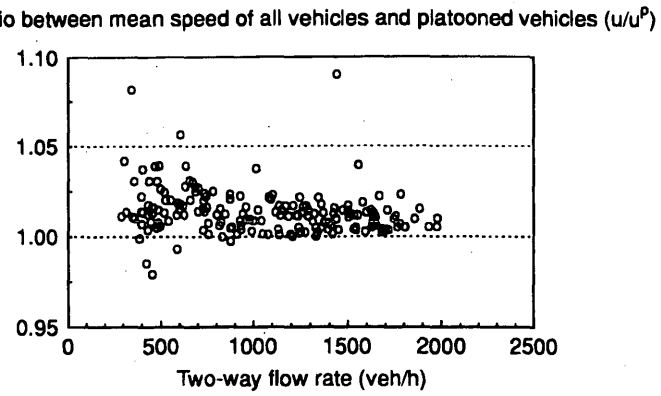

FIGURE 6 Ratio between space mean speed of all vehicles and space mean speed of vehicles in platoons as function of flow (15-min intervals).

minor flow, the ratio varies somewhat more—the usual range being from 1.00 to 1.10. (Figures of these analyses are not given here.)

As Figure 6 indicates, the u/u^p ratio can also have values less than 1.00. Thus in some 15-min intervals the platoons travel faster than free vehicles. These values are, logically, located in the area of low volumes; at high volumes platoons appear to be slower than free vehicles.

A simple linear regression analysis for the ratio u/u^p was made, resulting in Equations 41 and 42. For both directions together,

$$\frac{u}{u^p} = 1.0204 - 0.00000656q \tag{41}$$

For the main direction of travel,

$$\frac{u}{u^p} = 1.0171 - 0.00000984q \tag{42}$$

Because of the very low slope of the regression lines, the coefficients of determination (r^2) are very low, between 0.05 and 0.09. The equations are given here as rough approximations of the interdependence between the u/u_p values and flow. Equation 41 gives a u/u^p value of 1.00 at a flow rate of 3100 veh/hr; the corresponding flow value for the main direction, from Equation 42, is 1740 veh/hr. These values can be seen as approximate capacity values for the whole set of measuring locations.

In Figure 7 the platoon percentage observations and the corresponding PTD values calculated with Equation 34 are given for one location. The *r*- and *p*-points do not differ very much from each other, as could be expected from the low values of the u/u^p ratio in the data in Figure 6.

DISCUSSION OF RESULTS

Locally measured platooning is a biased estimate of platooning along the road. This bias is of the same origin as the difference in all local and space variables of traffic flow, like the difference of time mean speed and space mean speed. The paper shows how this bias can be corrected. The correction is important if local platooning data are used to approximate the PTD and level of service on two-lane, two-way roads.

The general relationship derived between the local platoon percentage and the approximate PTD is quite simple. In a local measurement with induction loops, all the variables needed for the unbiased estimation of the approximate PTD value can easily be achieved. The harmonic means of speeds can be used to estimate the space mean speeds, and platoon percentage is directly calculated as the share of vehicles driving with headways of fewer than 5 sec.

For a long road section, the estimate of the PTD can be calculated as the weighted average of the results of different local measurements inside the section. The measuring sites must then be chosen with care to represent different road and traffic characteristics. The length of road that each measuring site is representing must also be known.

Simulation study results are well in accordance with the theoretical analysis of the relationship of PTD and local platoon percentage. The differences between corrected and uncorrected local platoon percentages, as estimated from field measurements, appear

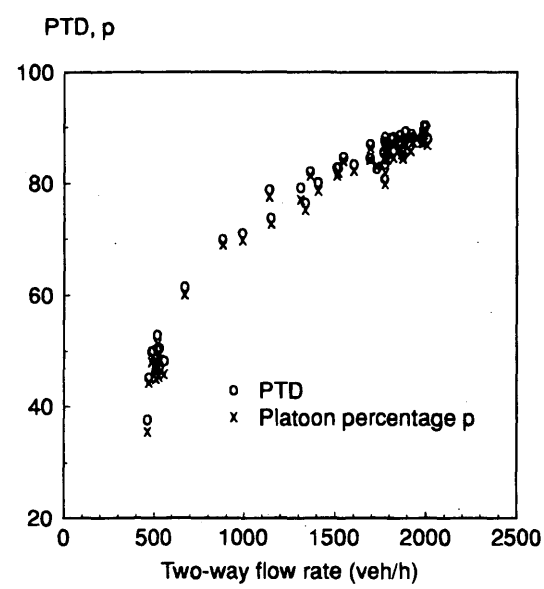

FIGURE 7 Example of observed local platoon percentages and corresponding PTD estimates as function of flow rate on two-lane road.

to be similar to the differences between PTD and local platooning observed in simulation. On roads with poor alignment and high percentages of heavy vehicles, the differences can be clearly higher than those observed in the data of this work. Even small (2 to 3 percent) corrections to the PTD values can greatly affect the level-of-service estimation because of the low slope of the PTD-flow curve in the critical level-of-service areas (LOS D and E).

According to the assumptions in the estimation, with a fixed-time headway as the platooning criterion, vehicles with a faster vehicle close in front of them are classified as platooned (or delayed). In principle, this can lead to an overestimation of the PTD. The general equation for the relationship of local platooning and the PTD estimate derived earlier is valid also if these situations are excluded from the measurement data with a speed difference criterion. The effects of such a change in the measurements, as well as a suitable criterion for speed difference, were not analyzed in this paper.

There are many problems in the precise definition and measurement of platooning and hindrance experienced by drivers. So a simple and locally measurable estimate of PTD, like the corrected local platoon percentage described here, is needed for practical purposes, at least until more thorough field data of real driver experience are available.

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