Passenger Car Equivalents for Trucks on Level Freeway Segments

RAYMOND A. KRAMMES AND KENNETH W. CROWLEY

The term passenger car equivalent (PCE) was introduced in the 1965 *Highway Capacity Manual.* Since 1965, considerable research effort has been directed toward the estimation of PCE values for various roadway types. However, at present, there is neither a commonly accepted nor clearly defined theoretical basis for the concept of passenger car equivalency. Two components of a theoretical basis for equivalency are defined in this paper: *(a)* that the basis for equivalence should be the parameters used to define level of service for the roadway type in question, and *(b)* that the PCE formulation should be expressed in terms of variables that reflect the relative importance of three factors that contribute to the overall effect of trucks on that roadway type. The three factors are *(a)* trucks are larger than passenger cars, *(b)* trucks have operating capabilities that are inferior to those of passenger cars, and *(c)* trucks have a physical impact on nearby vehicles and a psychological impact on the drivers of those vehicles. The two components of the theoretical basis were used to evaluate the merits of three approaches to estimating PCEs for level freeway segments: *(a)* the constant volume-to-capacity ratio approach, *(b)* the equal-density approach, and *(c)* the spatial headway approach. It was concluded that the spatial headway approach was appropriate for level, basic freeway segments, and a PCE formulation expressed in terms of headway measurements was derived.

Examined is the estimation of passenger car equivalents (PCEs) for trucks on level freeway segments. PCEs are used in capacity analysis procedures to convert mixed traffic stream volumes into equivalent passenger-car-only volumes. Level freeway segments are important because they are prevalent in urban areas, where traffic congestion is most common.

The need for additional consideration of this topic stems from two problems. First, the research effort to estimate PCEs for trucks on level freeway segments has been limited. Second, there is neither a commonly accepted definition of equivalence nor a clearly defined theoretical basis on which to derive PCE formulations.

The term PCE was first used in the 1965 *Highway Capacity Manual* (HCM) *(1)*, and since its publication at least 12 studies have documented approaches to estimating PCEs. Most of the research applied to two-lane or multilane highways *(2–9)*. Considerable effort has also been expended to update PCE values for specific grades on freeway facilities *(10)*. However, of the three studies applicable to level freeway segments, two were limited to specific sites: the Baltimore Harbor Tunnel *(11)* and the M4 motorway in London, England *(12)*. Only a recent study by the Institute for Research (IFR) involved a broad-based data collection effort at 11 level freeway sites in 4 urban areas in the United States *(13)*. However, IFR estimated PCE values for use in a highway cost allocation study and not specifically for capacity analysis purposes, and the two uses may not be compatible *(13)*.

R. A. Krammes, Texas Transportation Institute, Texas A&M University, College Station, Tex. 77843. K. W. Crowley, Institute for Research, 257 South Pugh St., State College, Pa. 16801.

Roess and Messer *(14)*, co-editors of the 1985 edition of the HCM, reviewed most of the studies just referenced and concluded the following *(15)*:

> Because of the wide variance in pce philosophies adopted by researchers, it is difficult to directly compare numerical results. Unfortunately, there was no uniform understanding of what a pce *meant* before the above studies were undertaken, and indeed the *intended use* of results also varied.

Roess and Messer *(14)* identified three approaches that "appear to have direct relevance to highway capacity analysis":

1. The constant volume-to-capacity ratio approach,
2. The equal-density approach, and
3. The spatial headway approach.

The PCE value for trucks on level freeway segments in the 1985 *HCM (15)* is based on the study by IFR, which used a spatial headway approach *(13)*. However, Roess and Messer indicate *(14)*:

> Unfortunately, it will not be possible to reconcile these three approaches as new capacity techniques are developed in anticipation of a third edition of the *Highway Capacity Manual.* The data bases are incompatible, and do not allow revision of the results of these studies into a single format. Thus, elements of all three principles will survive into new techniques.

Evaluated in this paper are the merits of these approaches for level freeway segments. First, two principles are defined as components of a theoretical basis for the concept of passenger car equivalency. Then these principles are used as the basis for the evaluation of the three approaches and for the derivation of the PCE formulation used by IFR *(13)*. Finally, a more sophisticated headway-based formulation, which may be more appropriate for highway capacity analysis, is identified.

THEORETICAL BASIS FOR PASSENGER CAR EQUIVALENCY

Two basic principles should be applied to the estimation of PCE values for any of the roadway types identified in capacity analysis procedures. The first principle links the concept of passenger car equivalency to the level of service (LOS) concept. The second principle emphasizes the consideration of all factors that contribute to the overall effect of trucks on traffic stream performance.

Role of PCEs in Capacity Analysis

Highway capacity analysis procedures are based on the LOS concept, which correlates the driver's perception of operating conditions with traffic flow parameters such as speed or density. According to Roess, "The Level of Service Concept is defined to be quality of service as defined by the highway user" *(16)*. The 1965 *HCM* described LOS as "a qualitative measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating cost" *(1)*.

Operating conditions on a highway are divided into six levels, A through F. Each level represents a limited range of operating conditions and is defined in terms of minimum or maximum values of traffic flow parameters that reflect the driver's perception of the quality of service provided by the facility. Because, for each roadway type, the combination of factors that influence the driver's perception of conditions is different, the parameters that are used to define LOS also differ *(16)*.

The capacity analysis procedures are calibrated for a specific set of ideal conditions, one of which is that the traffic stream contains only passenger cars. Adjustments are made for deviations from those ideal conditions; the adjustment factor for the presence of trucks is based on PCEs. This adjustment factor correlates the flow rates of passenger cars only and of mixed traffic streams that are equivalent in terms of the driver's perception of the quality of service. Because the parameters that are used to define LOS reflect the factors that influence the driver's perception, the same parameters should be used to compare passenger cars and trucks and to estimate PCEs. Roess and Messer support this contention when they state, "As Level of Service criteria for capacity analysis are based upon performance parameters, it is logical that PCE values should relate to those same performance parameters" *(14)*.

Huber presented an equation that expresses this principle in mathematical form *(17)*. The equation was derived from flow–impedance relationships for a traffic stream consisting of basic vehicles (passenger cars) only and for a mixed traffic stream with a proportion of trucks, p, and a proportion of passenger cars $(1 - p)$. The equation, which expresses the PCE value as a function of the basic and mixed flow rates, q_B and q_M, that are equivalent in terms of the measure of impedance used to define LOS, is stated as follows:

$$PCE = (1/p)\ [(q_B/q_M) - 1] + 1 \qquad (1)$$

Effect of Trucks

The adverse effect of trucks on traffic-stream performance can be attributed to three factors:

1. Trucks are larger than passenger cars,
2. Trucks have operating capabilities that are inferior to those of passenger cars, and
3. Trucks have a physical impact on nearby vehicles and a psychological impact on the drivers of those vehicles.

The first two are the factors that have traditionally been considered *(1, 18)*. Krammes suggested that truck-related problems—such as aerodynamic disturbances, splash and spray, sign blockage, offtracking, and the underride hazard—may also contribute to capacity reductions because of their effect on how nearby vehicles use the roadway *(19)*.

For capacity analysis purposes, roadways are divided into several basic types: freeways (with basic, ramp, and weaving sections), rural highways (multilane or two lane), and urban streets (signalized or unsignalized intersections, arterial streets). The relative importance of the three previously described factors on the overall effect of trucks differs among the roadway types. For example, the impact of the inferior operating capabilities of trucks is more severe on two-lane rural highways than on multilane freeways, which provide more passing opportunities. The relative importance of each factor also depends on roadway characteristics, such as geometry and configuration. For example, on sustained upgrades the impact of the inferior operating capabilities of trucks is "extremely deleterious" *(18)*; however, on level terrain, there is little difference between the speeds that passenger cars and trucks maintain *(1, 10, 12)*. Furthermore, the effect of trucks on nearby vehicles may be more important in certain roadway configurations—such as ramps or weaving sections, where lane changes are frequent—than in others—such as level, basic freeway sections, where fewer lane changes occur.

Therefore, the formulation to estimate PCEs for a particular roadway type should be expressed in terms of variables that reflect the combination of factors contributing to the overall effect of trucks on the quality of service provided by that roadway type.

APPROACHES TO ESTIMATING PCEs FOR LEVEL FREEWAY SEGMENTS

This section includes a historical review of PCE values recommended for trucks on level freeway segments and an evaluation of the merits of three approaches to estimating PCEs.

Historical Review

The 1950 *HCM* introduced the estimate that, on multilane highways in level terrain, trucks have the same effect as two passenger cars *(20)*. The *HCM* intimates that this estimate was based on the number of passings of trucks by passenger cars compared with the number of passings of passenger cars by passenger cars.

The 1965 *HCM* formally introduced both the LOS concept and the term PCE *(1)*. LOS was defined in terms of two parameters: operating speed and volume-to-capacity ratio. However, the PCE value of 2.0 for trucks on freeways in level terrain was a carry over from the 1950 *HCM (20)*.

Roess, McShane, and Pignataro recommended a revised approach to freeway LOS, using average running speed and density as the defining parameters *(21)*; this revised approach was incorporated into *Transportation Research Circular 212 (18)*, which placed emphasis on density as the "primary measure of effectiveness" *(22)*. However, *Circular 212* continued to use a PCE value of 2.0 for trucks in level terrain *(18)*.

The 1985 *HCM* continues to define LOS in terms of density and average running speed but has revised downward the PCE for level terrain to a value of 1.7 *(15)*. Roess and Messer explain the reason for this revision *(14)*:

> The Institute for Research study *[13]* does, however, suggest that the PCE values currently used in the 1965 Highway Capacity Manual and in Circular 212 are higher than necessary. For example, the maximum PCE value of 2.0 applies only to tractor-trailers under the highest volume conditions. Maximum PCE values for single-unit trucks are 1.5 or 1.6, depending on the number of axles. . . . On the basis of these results, slight reductions in the level terrain PCE values of Circular 212 appear to be in order.

Alternative Approaches

Roess and Messer identified three approaches to estimating PCEs *(14)*:

1. The constant volume-to-capacity ratio approach,
2. The equal-density approach, and
3. The spatial headway approach.

The applicability of these approaches to freeway facilities is discussed in the following paragraphs.

The constant volume-to-capacity approach was appropriate when LOS was defined in terms of volume-to-capacity ratios. However, it is not applicable to the current procedure, which defines LOS using density and average running speed. Traffic streams that are equivalent in terms of volume-to-capacity ratio do not necessarily have equal speeds or densities.

The principal advantage of the equal-density approach is that density is the primary parameter used to define LOS. PCE values have not been estimated with this approach so far, although Huber developed a formulation with equal total travel time, which is numerically equal to density, as the basis for equivalence *(17)*. He used the linear relationship between speed and density, which was postulated by Greenshields *(23)*, to derive the formulation. Huber demonstrated that mixed and basic traffic streams that have equal densities operate at different speeds. As a characteristic of an approach for estimating PCEs this is undesirable because speed is the secondary parameter for defining LOS. This characteristic is also inconsistent with the intent of using density as the primary parameter for defining LOS; according to Roess, density is used because "it quantifies the proximity to other vehicles, and is directly related to the freedom to maneuver within the traffic stream" *(22)*. Certainly, when operating on the same freeway segment, traffic streams that have different speeds must have different degrees of freedom to maneuver. These observations lead to the conclusion that the basis for equivalence should not be equal density, but rather densities that feel the same to the driver in terms of proximity to other vehicles and freedom to maneuver. But how can this basis be implemented?

The answer lies in the spatial headway approach. As Roess and Messer note, "Average spacing and density are related on a one-to-one basis, and spatial headway could be argued to be a surrogate (more easily measured) parameter for density" *(14)*. The headway approach uses actual measurements of the relative position maintained by drivers in the traffic stream under prevailing conditions. Such measurements, if obtained in appropriate situations and with proper experimental control, should reflect the position that a driver chooses to maintain with respect to other vehicles. Those spacings maintained by drivers in the proximity of trucks and those maintained by drivers in the proximity of passenger cars should be equivalent in terms of the driver's perception of proximity to other vehicles and freedom to maneuver. Therefore, a formulation that properly relates these spacings should represent the driver's perception of equivalent densities.

FORMULATION OF HEADWAY APPROACH TO EQUIVALENCY

The derivation of a formulation that estimates PCEs based on the driver's perception of equivalent densities is described, and how to obtain appropriate headway measurements for use in the formulation is discussed.

Derivation of Formulation

The formulation is derived by introducing appropriate headway measurements into Huber's equation for PCEs, which was stated in Equation 1. This equation can be expressed in terms of time headway by introducing the fundamental relationship between flow rate and average time headway:

$$q_i = (3{,}600 \text{ sec/hr}) \,/\, \bar{h}_i \qquad (2)$$

where q_i is the flow rate of vehicles per hour for either a basic stream ($i = B$) or an equivalent mixed stream ($i = M$); and $\bar{h}_i$ is the mean time headway in seconds at that flow rate.

Substituting Equation 2 into Equation 1 and rearranging yields

$$\text{PCE} = (1/p)[(\bar{h}_M - \bar{h}_B) \,/\, \bar{h}_B] + 1 \qquad (3)$$

IFR advocated the use of lagging time headway, which includes the length of a vehicle and the intervehicular spacing that precedes the vehicle, as shown in Figure 1 *(13)*. The results of a statistical analysis by Krammes suggest that intervehicular spacings are affected by the types of the vehicles that delimit the spacing *(19)*. Because the objective is to derive a formulation for PCEs based on the driver's perception of equivalent proximity and freedom to maneuver and because the types of both the vehicle of interest and the leading vehicle may influence this equivalence, the headways in Equation 3 should be expressed in terms of the mean lagging time headways for each combination of pairs of vehicle types that are found in the traffic stream. The headways for each combination are expressed as $\bar{h}_{i_{jk}}$, where j refers to the vehicle of interest type

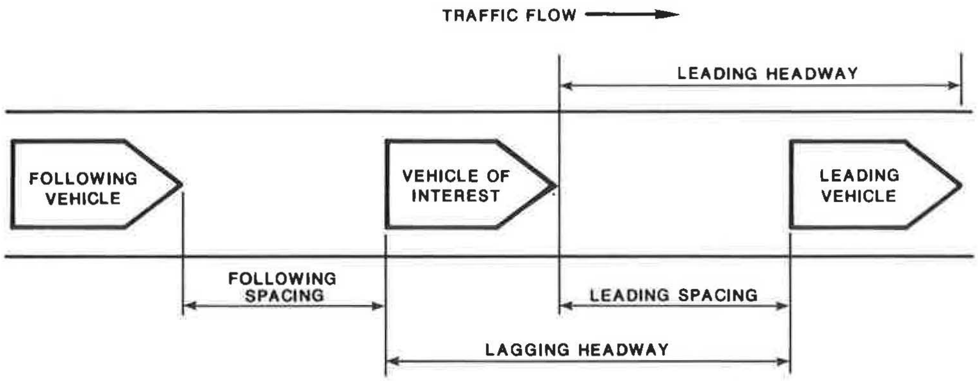

FIGURE 1 Schematic of vehicle headway and spacing measurements.

(either P for passenger car or T for truck) and k refers to the leading vehicle type.

Because the basic stream contains only passenger cars,

$$\bar{h}_B = \bar{h}_{B_{PP}} \quad (4)$$

In a mixed stream, four combinations of pairs of vehicle types occur. If the sequence of vehicle types in the mixed stream is random, the proportion of each combination in the traffic stream is the product of the proportion of each vehicle type. The assumption of randomness of sequencing of vehicle type in a mixed stream was examined by Krammes, whose results showed a slightly higher proportion of vehicle pairs of like type than would be predicted if sequencing were indeed random *(19)*. With this caveat in mind, the assumption of randomness of sequencing leads to the following expression:

$$\bar{h}_M = (1-p)^2\, \bar{h}_{M_{PP}} + p\,(1-p)\, \bar{h}_{M_{PT}} + p(1-p)\, \bar{h}_{M_{TP}} + p^2\, \bar{h}_{M_{TT}} \quad (5)$$

Substituting Equations 4 and 5 into Equation 3 yields

$$\text{PCE} = (1/p)\{[(1-p)^2\, \bar{h}_{M_{PP}} + p\,(1-p)\, \bar{h}_{M_{PT}} + p(1-p)\, \bar{h}_{M_{TP}} + p^2\, \bar{h}_{M_{TT}} - \bar{h}_{B_{PP}}] / \bar{h}_{B_{PP}}\} + 1 \quad (6)$$

Equation 6 could be simplified by assuming that $\bar{h}_{B_{PP}} = \bar{h}_{M_{PP}}$, which means that, on average, the lagging time headway a passenger car driver maintains when following another passenger car in a basic stream with flow rate q_B is the same as in a mixed stream at flow rate q_M and that the difference in flow rates and in mean lagging time headways for basic and mixed streams is due solely to the presence of trucks. This assumption implies that passenger car drivers in a mixed stream are affected only by trucks that are immediately preceding them. Research that analyzed the effect of following vehicle type on in-lane driver behavior *(19)* and research that examined the effect of the second vehicle ahead on car-following behavior *(24, 25)* support this implication.

By making this assumption, Equation 6 can be simplified to the formulation

$$\text{PCE} = [(1-p)\,(\bar{h}_{M_{PT}} + \bar{h}_{M_{TP}} - \bar{h}_{M_{PP}}) + p\, \bar{h}_{M_{TT}}] / \bar{h}_{M_{PP}} \quad (7)$$

This formulation has the advantage of using headway measurements from the mixed stream only. Estimates of PCEs for a site can be developed with data from that site only. Therefore, data would not be required from similar facilities that are used only by passenger cars: such facilities could be difficult to find. Also, problems of consistency, which could arise in using data from different facilities, would be avoided.

Krammes found that, after controlling for flow rate and speed, the effect of the leading vehicle type on the spacings maintained by combination trucks was significantly different from the effect on the spacings maintained by passenger cars *(19)*. Trucks maintained a significantly smaller spacing when traveling behind a leading truck than a leading passenger car (at a 95 percent confidence level), whereas passenger cars maintained slightly, but not significantly, larger spacings when traveling behind leading trucks than leading passenger cars. These findings apply to a data base that represented flow rates less than 1,300 vehicles per hour per lane. It may be reasonable to hypothesize that the effect of leading vehicle type on the spacings maintained by passenger cars would be significant at higher flow rates than were represented in the data base analyzed. Nonetheless, acceptance of these findings leads to the assumption that $\bar{h}_{M_{PT}} = \bar{h}_{M_{PP}}$, in which case Equation 7 would be reduced to

$$\text{PCE} = [(1-p)\, \bar{h}_{M_{TP}} + p\, \bar{h}_{M_{TT}}] / \bar{h}_{M_{P.}} \quad (8)$$

where $\bar{h}_{M_{P.}}$ refers to the mean lagging time headway for passenger cars, averaged across both leading vehicle types.

If it were further assumed that $\bar{h}_{M_{TP}} = \bar{h}_{M_{TT}}$, an assumption that the research by Krammes did not support *(19)*, then Equation 8 would be reduced to the following formulation

$$\text{PCE} = \bar{h}_{M_{T.}} / \bar{h}_{M_{P.}} \quad (9)$$

IFR used Equation 9 to estimate PCE values for use in a highway cost allocation study *(13)*. However, Equation 7 is recommended as the final formulation for use in highway capacity analysis because it accounts for the effect of leading vehicle type on the driver's perception of equivalent densities.

Although Equation 8 may be valid at low flow rates, Equation 7 would be equally valid at low flow rates and may be more accurate at higher flow rates.

Appropriate Headway Measurements

IFR computed overall means for passenger cars, $\bar{h}_{M_P}$, and trucks, $\bar{h}_{M_T}$, from data collected at 11 freeway sites in four urban areas for use in Equation 9 *(13)*. However, Equation 7 requires estimates of mean lagging time headways for the four combinations of pairs of passenger cars and trucks in a mixed traffic stream. A more sophisticated estimation procedure for estimating these headways, a procedure with features particularly suitable for highway capacity analysis, is described herein.

Headways should be measured while drivers are exhibiting steady-state, in-lane behavior. This implies, first, that drivers have maintained their lane placement and their position relative to other vehicles in the lane over some length of roadway and, second, that they have had the opportunity to adjust their speed and spacing relative to the leading vehicle. A sample of headways for vehicles exhibiting such behavior should reflect the spacings in the proximity of passenger cars and of trucks that are equivalent to the driver.

The data collected by IFR at six-lane, basic freeway segments on the Kingery Expressway in Chicago and on the La Porte Freeway in Houston were used in this analysis *(13)*. Drivers of a vehicle of interest were assumed to be exhibiting steady-state, in-lane behavior if they maintained the same lane placement and same position with respect to the leading and following vehicles for 300 ft before and after the point of measurement.

An analysis of covariance model was used to estimate the mean lagging time headways that are equivalent to the driver; the model has the following form:

$$\text{LNLTHD} = \text{INTERCEP}_{ijk} + B^1{}_{ijk}\text{LTYPE} + B^2{}_{ijk}\text{INVQ} + B^3{}_{ijk}\text{SPEED} + B^4{}_{ijk}\text{LSPEED} \quad (10)$$

where

LNLTHD = natural logarithm of lagging time headway (sec);
INTERCEP = parameter estimate for intercept;
i = site—Kingery or La Porte;
j = vehicle of interest type—passenger car or truck;
k = lane—1, 2, or 3;
B^1, B^2, B^3, B^4 = parameter estimates:
LTYPE = leading vehicle type—0 = passenger car, 1 = truck;
INVQ = [(3,600/flow rate in Lane k) – 6.00] (sec);
SPEED = speed of vehicle of interest – 55.0 (mph); and
LSPEED = speed of leading vehicle – speed of vehicle of interest (mph).

The dependent variable in the model is the natural logarithm of lagging time headway, LNLTHD. The logarithmic form is used because headway measurements have been found to fit a lognormal distribution *(26, 27)*. Separate equations are provided for each site, vehicle of interest type, and lane because Krammes has found that the leading intervehicular spacing maintained by a vehicle of interest is significantly affected by these variables and because it is unlikely that the effect is additive in nature *(19)*. Krammes also found that INVQ, SPEED, and LSPEED had a significant effect on intervehicular spacing and that the parameter estimates for LTYPE were significantly different in the equations for passenger cars and trucks *(19)*.

The overall R-square value for the model was 0.07, which reflects the tremendous variability in observed headways. The data support an observation by Breiman et al. that the mean and standard deviation of observed headways at a particular volume level are approximately equal *(28)*. Therefore, even though the variables in the model are significant, they explain only a small percentage in the tremendous variability in headways.

The data with which the model was calibrated represent a range of flow rates from approximately 400 to 1,300 vehicles per hour per lane. Therefore, to avoid extrapolating too far beyond the limits of the data, predicted values were estimated only for flow rates and speeds that approximate the upper limits of LOS A, B, and C. The flow rates (700, 1,100, and 1,550 passenger cars per hour per lane) and the speeds of the vehicle of interest (60, 57, and 54 mph) define the upper boundaries for LOS A, B, and C on basic freeway segments *(15)*. The relative speed of the leading vehicle was assumed to be zero because Krammes found that the difference between the speeds of passenger cars and trucks in a particular lane and at a particular volume level was generally less than 1 mph *(19)*. The predicted values for lagging time headway that correspond to these flow rates and speeds are presented in Tables 1 and 2 for the Kingery and La Porte sites, respectively.

Estimated PCE Values

Table 3 gives the estimates of PCE values for each lane and LOS at each site. These estimates were computed from Equation 7 by using the predicted values summarized in Tables 1 and 2 and the proportions of trucks for each lane and LOS. An estimate of the overall PCE value for each LOS, for all lanes combined, is also provided. This overall value is a weighted average of the value for each lane, weighted according to the distribution of trucks by lane at each LOS. This weighting scheme follows the approach recommended by Branston, who warned that PCE values that are based on a simple average of measurements for all lanes at a site may be inaccurate *(12)*.

The emphasis of this paper is on a theoretically based PCE formulation. The estimates in Table 3 are provided to demonstrate the approach. The PCE values fall within the range of values estimated by previous researchers *(1, 7, 13)*. The values estimated by IFR using Equation 9 are also included for comparison *(13)*. Because the values in Table 3 were based on limited data, especially at the lowest and highest flow rates, the actual values should not be considered precise.

TABLE 1 PREDICTED VALUES FOR LAGGING TIME HEADWAY AT KINGERY SITE (sec)

Lane	Vehicle of Interest Type[a]	Leading Vehicle Type[a]	Level of Service A	B	C
Right	P	P	3.89	2.62	1.99
		T	4.10	2.76	2.10
	T	P	5.12	4.35	3.90
		T	3.92	3.33	2.99
Center	P	P	3.80	2.34	1.71
		T	3.67	2.26	1.65
	T	P	3.72	2.73	2.20
		T	3.10	2.27	1.83
Median	P	P	2.54	1.73	1.31
		T	3.02	2.05	1.55
	T	P	4.23	3.37	3.13
		T	1.37	1.09	1.01

[a]P = passenger car and T = truck.

TABLE 2 PREDICTED VALUES FOR LAGGING TIME HEADWAY AT LA PORTE SITE (sec)

Lane	Vehicle of Interest Type[a]	Leading Vehicle Type[a]	Level of Service A	B	C
Right	P	P	3.65	2.91	2.48
		T	4.13	3.29	2.81
	T	P	4.91	4.32	3.92
		T	5.01	4.41	4.00
Center	P	P	3.24	2.37	1.92
		T	3.51	2.56	2.08
	T	P	4.10	3.53	3.28
		T	3.21	2.29	2.75
Median	P	P	2.76	1.97	1.54
		T	3.21	2.29	1.79
	T	P	3.64	3.52	3.39
		T	3.13	3.02	2.92

[a]P = passenger car and T = truck.

TABLE 3 ESTIMATES OF PCE VALUES FOR COMBINATION TRUCKS ON LEVEL FREEWAY SEGMENTS

Lane	Level of Service A	B	C
Kingery Site			
Right	1.2	1.6	2.0
Center	0.9	1.1	1.2
Median	1.8	2.1	2.6
All	1.0	1.2	1.2
LaPorte Site			
Right	1.5	1.6	1.7
Center	1.3	1.5	1.8
Median	1.5	1.9	2.3
All	1.4	1.6	1.8
Institute for Research Values			
All	1.1	1.2	1.4

However, three characteristics of the PCE values are interesting to note. First, the values for the two sites differ. Second, at a particular site, the values for each lane differ. Third, the values increase from LOS A to LOS C. Unfortunately, the statistical significance of these differences cannot be tested because the complexity of the PCE formulation makes the computation of confidence intervals intractable.

The difference between the PCE values for the two sites, lower values at the Kingery site than at the La Porte site, may reflect the differences in the percentages of trucks and in the truck management strategies at the two sites. At the La Porte site, the traffic stream included 10 percent trucks, whereas at the Kingery site there were 28 percent trucks. At the La Porte site, trucks were permitted in all lanes, whereas at the Kingery site trucks were prohibited from using the median lane. The truck management strategy at the Kingery site resulted in high percentages of trucks in the center lane (approximately 47 percent).

The PCE values for the center lane of the Kingery site are particularly interesting; these values are much lower than those for the other lanes at either site.The value of 0.9 at LOS A in the center lane of the Kingery site indicates that the mean lagging time headways for vehicle pairs including trucks are smaller than for pairs consisting of two passenger cars. Because trucks are larger than passenger cars, the reason for the smaller headways for trucks is that trucks maintained smaller leading intervehicular spacings than passenger cars. The resulting PCE values, which are considerably smaller for the Kingery site, overall and for the center lane in particular, suggest that the truck management strategy may be an effective way to minimize the adverse effect of trucks on freeway capacity.

The question of how PCE values vary with flow rate has been the subject of debate. The approach that this research recommends incorporates flow rate explicitly into the estimation procedure by including flow rate as an independent variable in the analysis of covariance model that estimates the headway measurements used to compute PCEs.

The proposed formulation estimates PCE values that increase with flow rate. IFR *(13)* and Cunagin and Messer *(7)* also found that PCE values increase with flow rate on level urban freeways and on level, four-lane rural highways, respectively. Huber in his author's closure states a preference for PCE values that increase with flow rate because "as the flow rate increases, the opportunity for interaction between basic vehicles and trucks is increased with a subsequent increase in PCE values" (*17*, p.69).

Both Roess and Messer *(14)* and St. John [in his discussion of Huber (*17*, pp. 68–69)] advocate PCE values that do not increase with flow rate because a constant value would simplify calibration of the values as well as computations with the values. St. John also observes that "constant PCE implies fundamental relationships that do not change in form between car-only and mixed flows" (*17*, pp 68–69). He cites results from a microscopic model of multilane flow, which imply that PCE values "would be essentially constant" *(29)*. Roess and Messer *(14)* also refer to these and other related results: "none of the studies looking at PCEs on specific grades showed significant variation with volume."

The responses to these arguments are as follows:

1. The available evidence does not clearly indicate that speed-flow relationships for car-only and mixed flows have the same form—St. John states that "there is evidence both supporting and conflicting with the idea that PCE is constant over flow rate" (*17*, pp. 68–69).

2. The data bases that have been used to estimate PCEs contained little or no data at high flow rates and, therefore, have not provided reliable estimates of PCEs over the entire range of flow rates.

3. The characteristics of PCE values for specific grades are not necessarily the same as those for level terrain.

The last point reinforces the desirability of the proposed theoretical basis for PCEs, which emphasizes that PCEs for a particular roadway type should reflect the effects of trucks on that roadway type and which provides a framework to account for the differences between PCEs for each roadway type. Although the current research suggests that PCEs increase with flow rate, it does not represent the final answer. St. John's conclusion appears appropriate (*17*, p. 69):

> I suggest that more attention be directed to the fundamental concepts of equivalence . . . . Also final decisions should be based on extensive field data or results from comprehensive models.

SUMMARY AND CONCLUSIONS

The needs for a commonly accepted definition of equivalence and for a clearly defined theoretical basis on which the concept of passenger car equivalency can be applied to any roadway type were addressed in this paper. Two principles were defined as components of the theoretical basis for estimating PCEs for capacity analysis:

1. The basis for equivalence should be the parameters used to define LOS for the roadway type in question.

2. The PCE formulation should be expressed in terms of variables that reflect the relative importance of the three factors that contribute to the effect of trucks on that roadway type.

Traditionally, the effect of trucks on highway capacity has been attributed to two factors: *(a)* trucks are larger than passenger cars, and *(b)* trucks have operating capabilities that are inferior to those of cars.

However, a third factor should also be considered: trucks have physical impacts on nearby vehicles and psychological impacts on the drivers of those vehicles that also contribute to reductions in capacity. It should be emphasized that research on the significance of this third factor has considered only the effect of leading and following trucks on the in-lane behavior of vehicles; no research has been performed on the effect of trucks on the lane-changing behavior of vehicles or on vehicles in adjacent lanes.

Huber's general equation for PCEs, which expresses the first principle in mathematical form, was used as the starting point for the derivation of a PCE formulation for level freeway segments that was expressed in terms of headways. The PCE value of 1.7, used in the 1985 *HCM* for trucks on level freeway segments (*15*), was influenced by estimates made by IFR, which used a headway-based PCE formulation (*13*). The assumptions inherent in IFR's formulation were identified. A more sophisticated formulation and estimation procedure was also discussed.

This more sophisticated headway-based approach has three advantages:

1. It accounts for the effect of leading trucks on the intervehicular spacings maintained by a vehicle of interest.

2. The percentage of trucks in the traffic stream, which has an important effect on PCE values, is included as a variable in the model.

3. The estimation procedure allows PCE values to be estimated for specific speeds and flow rates, enabling the effect of these variables to be considered explicitly.

ACKNOWLEDGMENT

The research described herein was conducted at the Pennsylvania Transportation Institute for Dr. Krammes's doctoral dissertation in civil engineering at the Pennsylvania State University. The contributions of Dr. Walter P. Kilareski, dissertation advisor, are gratefully acknowledged.

REFERENCES

1. *Special Report 87. Highway Capacity Manual—1965*, Highway Research Board, Washington, D.C., 1966, 411 pp.
2. D. W. Gwynn. "Truck Equivalency." *Traffic Quarterly*, Vol. 22, No. 2, 1968, pp. 225–236.
3. E. F. Reilly and J. Seifert. "Truck Equivalency." In *Highway Research Record 289*, HRB, National Research Council, Washington, D.C., 1969, pp. 25–37.
4. A. D. St. John. "Nonlinear Truck Factor for Two-Lane Highways." In *Transportation Research Record 615*, TRB, National Research Council, Washington, D.C., 1976, pp. 49–53.
5. A. Werner and J. F. Morrall. "Passenger Car Equivalencies of Trucks, Buses, and Recreational Vehicles for Two-Lane Rural Highways." In *Transportation Research Record 615*, TRB, National Research Council, Washington, D.C., 1976, pp. 10–16.
6. J. Craus, A. Polus, and I. Grinberg. "A Revised Method for the Determination of Passenger Car Equivalencies." *Transportation Research*, Vol. 14A, No. 4, 1980, pp. 241–246.
7. W. D. Cunagin and C. J. Messer. *Passenger Car Equivalents for Rural Highways*. Report FHWA/RD-82/132. H. G. Whyte Associates, Inc., Gary, Ind.; and Texas A&M University, College Station, 1982.
8. W. D. Cunagin and C. J. Messer. "Passenger-Car Equivalents for Rural Highways." In *Transportation Research Record 905*, TRB, National Research Council, Washington, D.C., 1983, pp. 61–68.
9. M. Van Aerde and S. Yagar. "Capacity, Speed, and Platooning Vehicle Equivalents for Highways." In *Transportation Research Record 971*, TRB, National Research Council, Washington, D.C., 1984, pp. 58–65.
10. E. M. Linzer, R. P. Roess, and W. R. McShane. "Effect of Trucks, Buses, and Recreational Vehicles on Freeway Capacity and Service Volume." In *Transportation Research Record 699*, TRB, National Research Council, Washington, D.C., 1979, pp. 17–26.
11. W. Berman and R. C. Loutzenheiser. *Study of Traffic Flow on a Restricted Facility, Report III-2, A Methodology to Measure the Influence of Trucks on the Flow of Traffic*. Report FHWA-MD-R-77-7. University of Maryland, College Park, 1976.
12. D. Branston. "Some Factors Affecting the Capacity of a Motor-

way." In *Traffic Engineering and Control*, Vol. 18, No. 6, 1977, pp. 304–307.
13. E. L. Seguin, K. W. Crowley, and W. D. Zweig. *Urban Freeway Truck Characteristics*, Vol. I: *Passenger Car Equivalents*. Report FHWA/RD-81/156. Institute for Research, State College, Pa., 1981.
14. R. P. Roess and C. J. Messer. "Passenger Car Equivalents for Uninterrupted Flow: Revision of the *Circular 212* Values." In *Transportation Research Record 971*, TRB, National Research Council, Washington, D.C., 1984, pp. 7–13.
15. *Special Report 209*: *Highway Capacity Manual*, TRB, National Research Council, Washington, D.C., 1985.
16. R. P. Roess. "Highway Capacity Manual Revisited." *Civil Engineering*, Vol. 54, No. 11, 1984, pp. 69–71.
17. M. J. Huber. "Estimation of Passenger-Car Equivalents of Trucks in Traffic Stream." In *Transportation Research Record 869*, TRB, National Research Council, Washington, D.C., 1982, pp. 60–70.
18. "Interim Materials on Highway Capacity." *Transportation Research Circular 212*, TRB, National Research Council, Washington, D.C., 1980, 276 pp.
19. R. A. Krammes. *Effect of Trucks on the Capacity of Level, Basic Freeway Segments*. Ph. D. dissertation. Pennsylvania State University, University Park, Pa., 1985.
20. Highway Research Board. *Highway Capacity Manual*. U. S. Government Printing Office, Washington, D.C., 1950.
21. R. P. Roess, W. R. McShane, and L. J. Pignataro. "Freeway Level of Service: A Revised Approach." In *Transportation Research Record 699*, TRB, National Research Council, Washington, D.C., 1979.
22. R. P. Roess. "Level of Service Concepts: Development, Philosophies, and Implications." In *Transportation Research Record 971*, TRB, National Research Council, Washington, D.C., 1984, pp. 1–16.
23. B. D. Greenshields. "A Study of Traffic Capacity." *Proc., Highway Research Board*, Vol. 14, 1934, pp. 448–477.
24. R. Herman and R. W. Rothery. "Car Following and Steady State Theory." *Proc., Second International Symposium on the Theory of Road Traffic Flow, London, 1963*; J. Almond (ed.), Organization for Economic Cooperation and Development, Paris, 1965, pp. 1–11.
25. P. Fox and F. G. Lehman. *Safety in Car Following—A Computer Simulation*. Newark College of Engineering, Newark, N.J., 1967.
26. I. Greenberg. "The Log-Normal Distribution of Headways." *Australian Road Research*, Vol. 2, No. 7, 1966, pp. 14–18.
27. J. E. Tolle. "The Lognormal Headway Distribution Model." *Traffic Engineering and Control*, Vol. 13, No. 1, 1971, pp. 22–24.
28. L. Breiman, W. Lawrence, R. Goodwin, and B. Bailey. "The Statistical Properties of Freeway Traffic." *Transportation Research*, Vol. 11, No. 4, 1977, pp. 221–228.
29. A. D. St. John, D. Kobett, W. Glauz, D. Sommerville, and D. Harwood. *Freeway Design and Control Strategies as Affected by Trucks and Traffic Regulations*. Report FHWA/RD-75/42. Midwest Research Institute, Kansas City, Mo., 1975.

Publication of this paper sponsored by Committee on Traffic Flow Theory and Characteristics.