Transportation Research Record 869

Estimation of Passenger-Car Equivalents of Trucks in Traffic Stream

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The passenger-car equivalent (PCE) of a truck represents the number of passenger cars (basic vehicles) displaced by each truck in the traffic stream under specific conditions of flow. A model is proposed for estimating PCE-values for vehicles under free-flowing, multilane conditions. Some measure of impedance as a function of traffic flow is used to relate two traffic streams—one that has trucks mixed with passenger cars and the other that has passenger cars only. PCE-values are related to the ratio between the volumes of the two streams at some common level of impedance. A deterministic model of traffic flow (Greenshields') is used to estimate the impedance-flow relationship. Three measures of impedance are considered, each of which will generate a separate PCE-value for a truck of given characteristics. PCE-values are also shown to relate to speed and length of subject vehicles and to vary with the proportion of trucks in the traffic stream.

The passenger-car equivalent (PCE) of a truck is introduced in the Highway Capacity Manual as follows (1, p. 101):

> Trucks (defined for capacity purposes as cargo-carrying vehicles with dual tires on one or more axles) reduce the capacity of a highway in terms of total vehicles carried per hour. In effect, each truck displaces several passenger cars in the flow. The number of passenger cars that each dual-tired vehicle represents under specific conditions is termed the "passenger car equivalent" for those conditions.

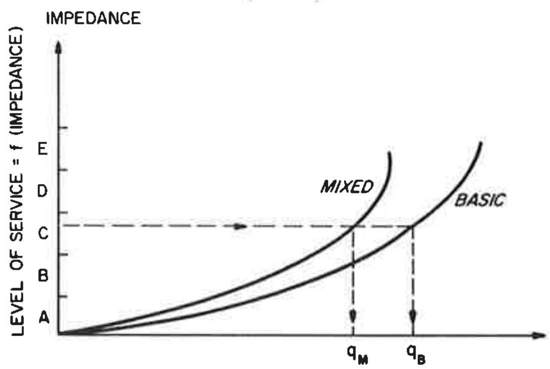
The Highway Capacity Manual lists PCE-values for two categories of vehicles--trucks and intercity buses. PCE-values for a third category of vehicles, recreation vehicles, have been determined from field observations made on Canadian highways (2,3).

It is evident that each of the three categories will include a wide range of vehicles. The truck category as now defined in the Highway Capacity Manual includes vehicles ranging from single-unit trucks with 6 tires to combination trucks with 18 or more tires. A single PCE-value for trucks does not adequately reflect the diverse characteristics of the many categories of vehicles that may be observed in the traffic stream.

The Federal Highway Administration is in the process of updating the national highway cost-allocation study. One factor in these cost-allocation studies is an analysis of the highway service capacity consumed by various classes of vehicles. To this end, the number of vehicle categories has been expanded to 15, as listed below [categories 1-13 are from a Federal Highway Administration report (4, Table III-2.1); categories 14 and 15 are from a Voorhees report (5)]:

1. Automobiles, large (15 ft and more);
2. Automobiles, small;
3. Motorcycles;
4. Buses;
5. Single-unit trucks, two axles, four tires;
6. Single-unit trucks, two axles, six tires;
7. Single-unit trucks, three or more axles;
8. Three-axle combination trucks;
9. 2S2 four-axle combination trucks;
10. Other four-axle combination trucks;
11. 3S2 five-axle combination trucks;
12. Other five-axle combination trucks;
13. Six-axle or more combination trucks;
14. Noncommercial vans; and
15. Four- and six-tire recreational vehicles (campers, mobile homes, trailers).

Figure 1. Flow-impedance relationship.



There are currently (July 1981) nationwide studies under way that are being conducted to determine PCE-values for the different categories of vehicles in the following situations: urban arterials, urban freeways, rural two-lane two-way roadways, and rural freeways.

The analysis that follows has been made in order to anticipate the results that will follow from the nationwide studies listed above and to determine the underlying relationships between vehicle characteristics and the determination of PCE-values for the different categories of vehicles. A simple model has been used to represent steady-state traffic flow with and without trucks present, and the relationships between the resulting flows have been used to calculate the PCE-values.

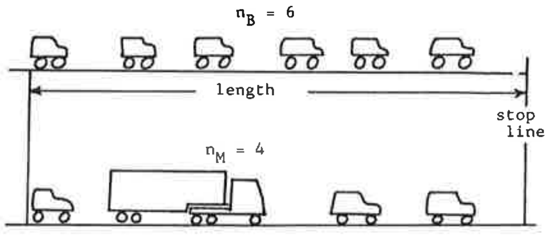
FRAMEWORK FOR ESTIMATING PCE-VALUES

Consider the relationship between some measure of impedance along a length of roadway and the flow rate along that same roadway for two different traffic streams. The flow-impedance relationship is shown in Figure 1, in which the basic curve represents a stream consisting solely of basic vehicles (passenger cars) and the mixed curve represents a stream with proportion of trucks p and of basic vehicles (1 - p). As the flow rate q increases, the impedance increases; the increase in impedance is at a greater rate for the mixed flow. The impedance in turn can be related to the level of service (LOS) on the roadway, where LOS A is the most desirable and LOS E is the least desirable.

For any given LOS (or impedance) it is possible to calculate corresponding flow rates q_B and q_M as shown. These flow rates for the basic and mixed streams will produce identical measures of LOS and can then be equated so that $q_B = (1 - p)q_M + pq_M(\text{PCE})$. Solving for PCE, the result is

$$\text{PCE} = (1/p)[(q_B/q_M) - 1] + 1 \quad (1)$$

Figure 2. Sample calculation of PCE-values.



where

PCE = passenger-car equivalent,
p = proportion of trucks in mixed traffic flow, and
q_B, q_M = flow rate at common LOS for basic and mixed traffic streams, respectively.

An example of the concept given in Equation 1 is shown in Figure 2, where a PCE-value is developed for a standing queue of vehicles as might be observed at a signalized intersection. In the first instance, there were six basic vehicles (n_B) observed over a length of roadway ℓ, while on an adjacent lane there were four vehicles (n_M) observed, one of which is a truck (p = 0.25), over the same length ℓ. The two queues, n_B and n_M, develop a common measure of length ℓ so that by reasoning similar to that of Equation 1, we calculate

$$PCE = (1/0.25)[(6/4) - 1] + 1 = 3.0.$$

There are several variables that may be used as a measure for the LOS or impedance shown on the vertical axis of Figure 1. A common measure is the average travel time [t(q)] over a length of roadway, where the travel time will increase as the flow q increases. For example, consider a single lane of a multilane urban roadway with a speed limit of 50 km/h (31 miles/h). At a flow rate q of 100 vehicles/h, the mean velocity is 50 km/h and the travel time t(q) will be 1/50 h/km or 1.200 min/km (1.931 min/mile). At 900 vehicles/h, the mean velocity is reduced to 40 km/h (24 miles/h) and the travel time t(q) will increase to 1/40 h/km or 1.500 min/km (2.414 min/mile).

An alternative measure is the time of occupancy or total travel time [T(q)], where T(q) is the volume q times the mean travel [t(q)]. For the same example cited above the time of occupancy becomes at q = 100 vehicles/h:

T(q) = 100 vehicles/h x 1/50 h/km = 2.00 vehicle-h/km-h,

and at q = 900 vehicles/h,

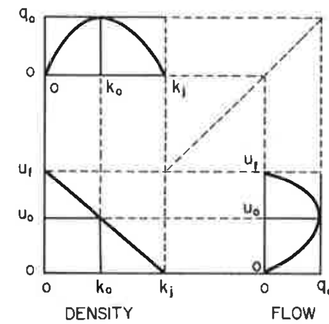
T(q) = 900 vehicles/h x 1/40 h/km = 22.500 vehicle-h/km-h.

The time of occupancy, in turn, is numerically equivalent to the density k, where density k = flow q ÷ speed u, or at 900 vehicles/h,

k = 900 vehicles/h ÷ 40km/h = 22.500 vehicles/km.

Either of these two measures of impedance, the mean travel time t(q) or the density k [numerically equal to the time of occupancy T(q)], can be used to calculate PCE-values as suggested in Figure 1. The

Figure 3. Greenshields model of traffic flow.



Greenshields (6) model of traffic flow, which assumes a straight-line relationship between density and velocity, is used to develop the interrelationships among the variables speed (u), density (k), and flow rate (q) for steady-state flow. These relationships are shown in Figure 3 where the parameters are jam density (k_j), free-flow speed (u_f), optimum density (k_O), optimum speed (u_O), and maximum flow (q_O).

FLOW PARAMETERS OF MIXED TRAFFIC

In a simplified case, mixed traffic is assumed to be made up of only two types of vehicles, basic vehicles with an effective length L_B and free-flow speed u_{FB} and trucks with an effective length L_T and free-flow velocity u_{FT}. The effective length of a vehicle is the distance the vehicle occupies when in a standing queue and is measured from the rear bumper of the preceding vehicle to the rear bumper of the subject vehicle. The free-flow speed is the speed of the vehicle when not influenced by other vehicles on the roadway.

The mixed-flow rate is the sum of the flow rate of basic vehicles plus the flow rate of trucks:

$$q_M = q_{MB} + q_{MT} \quad (2)$$

where

q_M = flow rate of mixed vehicles,
q_{MB} = flow rate of basic vehicles within mixed stream, and
q_{MT} = flow rate of trucks within mixed stream.

The proportion p of trucks in the mixed traffic stream flow is as follows:

$$p = q_{MT}/q_M \quad (3)$$

The density of the mixed flow is the sum of the density of basic vehicles plus the density of trucks:

$$k_M = k_{MB} + k_{MT} \quad (4)$$

where

k_M = density of mixed vehicles,
k_{MB} = density of basic vehicles within mixed stream, and
k_{MT} = density of trucks within mixed stream.

The proportion p' of trucks in the mixed traffic density is as follows:

$$p' = k_{MT}/K_M \quad (5)$$

The mean velocity of the mixed stream of traffic is the harmonic mean of the velocities of the basic vehicles and trucks:

$$u_M = 1/\{(p/u_{MT}) + [(1-p)/u_{MB}]\} \quad (6)$$

where

u_M = mean velocity of mixed traffic stream,
u_{MB} = mean velocity of basic vehicles within mixed traffic stream,
u_{MT} = mean velocity of trucks within mixed traffic stream, and
p = proportion of trucks in mixed traffic stream flow.

The development of the proportion p' of trucks in the mixed traffic density follows from the relationship $q_O = k_O u_O$ where the subscript O refers to maximum (optimum) flow rate:

$$q_{OMT} = pq_{OM} = k_{OMT}\,u_{OMT}$$

$$q_{OMB} = (1-p)q_{OM} = k_{OMB}\,u_{OMB}$$

and

$$k_{OMT} = q_{OMT}/u_{OMT} = pq_{OM}/u_{OMT} \quad (7)$$

$$k_{OMB} = q_{OMB}/u_{OMB} = (1-p)q_{OM}/u_{OMB} \quad (8)$$

Equations 7 and 8 are substituted into Equation 5:

$$\begin{aligned} p' &= k_{OMT}/k_{OMT}/(k_{OMT} + k_{OMB}) \\ &= 1/[1 + (k_{OMB}/k_{OMT})] \\ &= 1/\left(1 + \{[(1-p)q_{OM} \times u_{OMT}]/(pq_{OM} \times u_{OMB})\}\right) \\ &= 1/\{1 + [(1-p)u_{OMT}/pu_{OMB})\} \end{aligned}$$

Since, for the Greenshields model of traffic flow $u_O = u_f/2$, the final expression is as follows:

$$p' = 1/\{1 + [(1-p)u_{FT}/pu_{FB}]\} \quad (9)$$

The jam density (k_j)--the number of stopped vehicles in a length of roadway--becomes, for basic vehicles only,

$$k_{jB} = L/L_B \quad (10a)$$

and for mixed vehicles,

$$k_{jM} = L/[p'L_T + (1-p')L_B] \quad (10b)$$

where L is the unit length of roadway [1000 m (5280 ft)] and L_T, L_B are the effective length of trucks and basic vehicles.

NUMERICAL EXAMPLE OF TRAFFIC FLOW

Consider a steady-state stream of traffic on a single lane of a multilane urban arterial with 10 percent trucks (p = 0.10). The free-flow velocity of basic vehicles u_{FB} is 48.280 km/h (30.0 miles/h) and of trucks u_{FT} is 32.187 km/h (20.0 miles/h). The effective length of basic vehicles L_B is 7.62 m (25 ft), and the effective length of trucks L_T is 22.86 m (75 ft).

The free-flow velocity of the mixed flow is found from Equation 6:

u_{FM} = 1/[(0.10/32.187) + (0.90/48.280)] = 45.981 km/h (28.571 miles/h).

Substituting in Equation 9,

p' = 1/{1 + [(0.9/0.1) (32.187/48.280)]} = 0.143.

The jam density of mixed flow (k_{jM}) is found by substituting in Equation 10b:

k_{jM} = 1000/[0.143(22.86) + 0.857(7.62)] = 102.071 vehicles/km (164.267 vehicles/mile).

The optimum flow rate for mixed vehicles (q_{OM}) is found from the following relationship:

$$\begin{aligned} q_{OM} &= (k_{jM}/2)(u_{FM}/2) \\ &= (102.071/2)(45.981/2) = 1173.33 \text{ vehicles/h} \end{aligned}$$

For a stream flow of basic vehicles only, the parameters are as follows:

u_{FB} = 48.280 km/h (30 miles/h),
k_{jB} = 1000/7.620 = 131.234 vehicles/km (211.200 vehicles/mile), and
q_{OB} = (48.280/2)(131.234/2) = 1584.000 vehicles/h.

The relationships between pairs of variables for basic vehicles only and for mixed vehicles are shown in Figures 4, 5, and 6. Figure 4 represents the velocity-density relationship, Figure 5 the flow-density relationship, and Figure 6 the flow-velocity relationship. The curves shown are based on the data used in the numerical example.

ASSUMPTION OF EQUAL AVERAGE TRAVEL TIME

It is assumed that a flow rate q_B of basic vehicles only will produce the same average travel time $t(q)_B$ as is produced by a flow rate q_M of mixed vehicles, so that $t(q)_B = t(q)_M$.

For any given length of roadway, this results in equal average velocities for the two traffic streams, so that, as shown in Figure 7, $u_B = u_M = u$. If we recall Equation 1 and note that $q_B = k_B u$ and $q_M = k_M u$, it follows that $q_B/q_M = k_B/k_M$. By similar triangles in Figure 7, $k_B = k_{jb}(u_{FB} - u)/u_{FB}$ and $k_M = k_{jM}(u_{FM} - u)/u_{FM}$, so that the following holds:

$$q_B/q_M = k_B/k_M = [(u_{FM}/u_{FB})(k_{jB}/k_{jM})]\,[(u_{FB} - u)/(u_{FM} - u)] \quad (11)$$

Case 1 is the general case where $u_{FM} < u_{FB}$; $k_{jM} < k_{jB}$, so from Equation 1:

$$PCE = (1/p)\{[(u_{FM}/u_{FB})(k_{jB}/k_{jM})]\,[(u_{FB} - u)/(u_{FM} - u)] - 1\} + 1 \quad (12)$$

Case 2 is the special case where the truck is longer than the basic vehicle but has the same free-flow speed, so that $u_{FM} = u_{FB}$; $k_{jM} < k_{jB}$ and

$$PCE = (1/p)\,[(k_{jB}/k_{jM}) - 1] + 1 \quad (13)$$

Equation 13 can be further reduced by substituting for the values of k_{jM} and k_{jB} given in Equations 10a and 10b and further noting that p' = p:

$$k_{jB}/k_{jM} = (L/L_B)\,[pL_T + (1-p)L_B]/L = (pL_T/L_B) + 1 - p$$

Substitution into Equation 13 gives the final result:

$$PCE = L_T/L_B \quad (14)$$

which is a constant value over all ranges of p and for all volumes.

Case 3 is the special case where the truck is the same length as the basic vehicle but has a lesser free-flow velocity, $u_{FT} < u_{FB}$; $k_{jB} = k_{jT}$:

$$PCE = (1/p)\{(u_{FM}/u_{FB})\,[(u_{FB} - u)/(u_{FM} - u)] - 1\} + 1 \quad (15)$$

By inspection of Figure 7 and Equation 12 it will be seen that the PCE is undefined for $u > u_{FM}$. For $u < u_{FM}$ and by using the Greenshields model of traffic flow,

Figure 4. Speed-density relationship: numerical example.

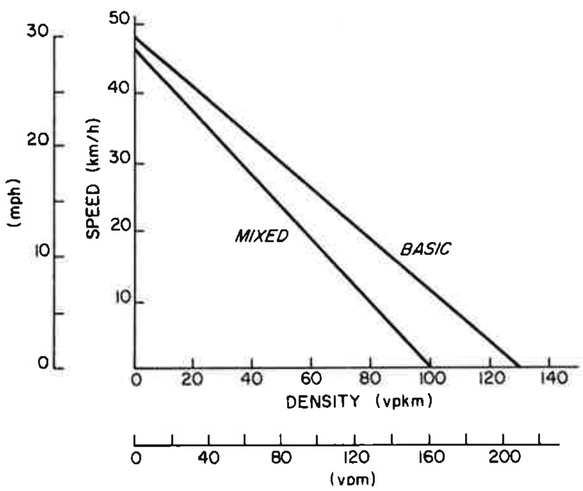
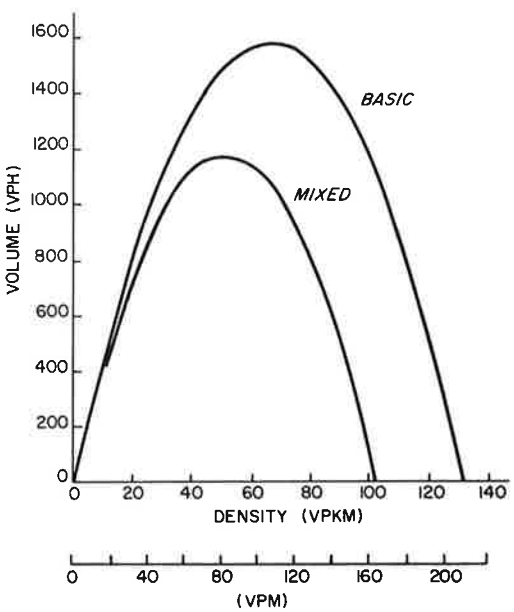


Figure 5. Flow-density relationship: numerical example.



$$u_B = u_M = (u_{FB}/2)\,[1 + (1 - y)^{1/2}] \qquad (16)$$

where $y = q_B/q_{OB}$ and other terms are as previously defined.

A numerical example incorporating the previously calculated data follows. Recall the earlier example of a traffic stream with 10 percent trucks with the following characteristics:

u_{FM} = 45.98 km/h (28.57 miles/h),
k_{jM} = 102.07 vehicles/km (164.27 vehicles/mile),
q_{OM} = 1173.33 vehicles/h,
u_{FB} = 48.28 km/h (30.00 miles/h),
k_{jB} = 131.23 vehicles/km (211.20 vehicles/mile), and
q_{OB} = 1584.00 vehicles/h.

Since $u_{FM} < u_{FB}$ and $k_{jM} < k_{jB}$, Equation 12 will apply. Consider the PCE-value when the flow in basic vehicles is 600 vehicles/h, y = 600/1584 = 0.379, and, by Equation 16, $u_B = u_M$ = 43.17 km/h (26.82 miles/h).

Figure 6. Flow-speed relationship: numerical example.

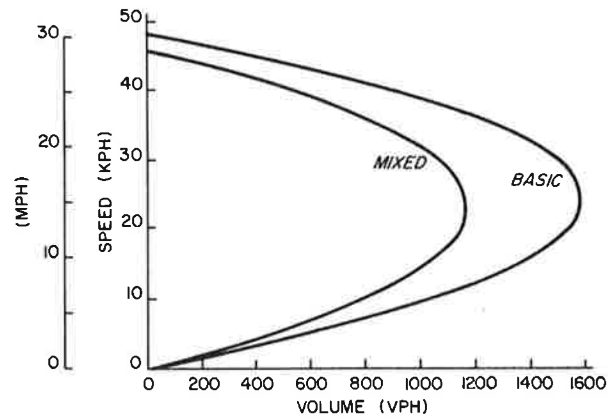
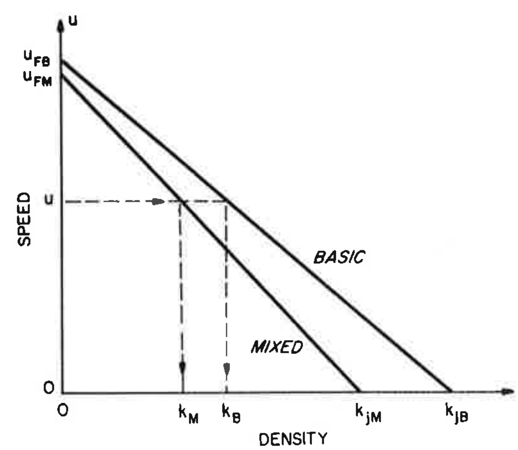


Figure 7. Determination of PCE-values by equal travel time.



If we substitute in Equation 12,

PCE = (1/0.10){[(45.98/48.28)(131.23/102.07)] x [(48.28 - 43.17)/(45.98 - 43.17)] - 1} + 1 = 13.247.

Each truck is equivalent to 13.247 basic vehicles if we are to satisfy the criterion that $u_B = u_M$. This is equivalent to substituting 269.7 mixed vehicles q_M (of which 10 percent are trucks) for 600.0 basic vehicles q_B, as demonstrated below:

$0.9q_M + 0.1q_M\,(13.247) = 600,$
$2.2247q_M = 600,$
$q_M = 269.7.$

Of particular interest is the PCE-value associated with low volumes on the mixed curve so that the mean speeds $u_B = u_M$ approach the free-flow speed of the mixed curve u_{FM}. For instance, at a flow rate q_M of 10 vehicles/h (10 percent trucks), $u_B = u_M$ = 45.88 km/h. The equivalent flow rate on the basic-vehicle-only curve q_B = 298.98 vehicles/h, so that

PCE = (1/0.10)[(298.98/10) - 1] + 1 = 289.98.

At low volumes, the value of the PCE is at a maximum and decreases as the volume of basic vehicles increases. This pattern is shown in Figure 8 for a traffic flow with 10 percent trucks. Also shown in Figure 8 are PCE-values associated with 1

Figure 8. PCE versus volume by percentage of trucks, equal travel time.

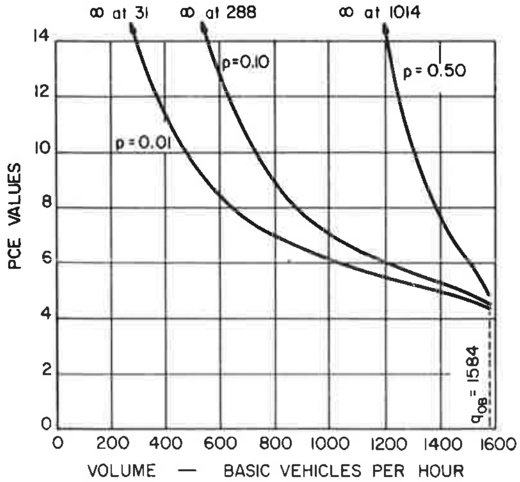
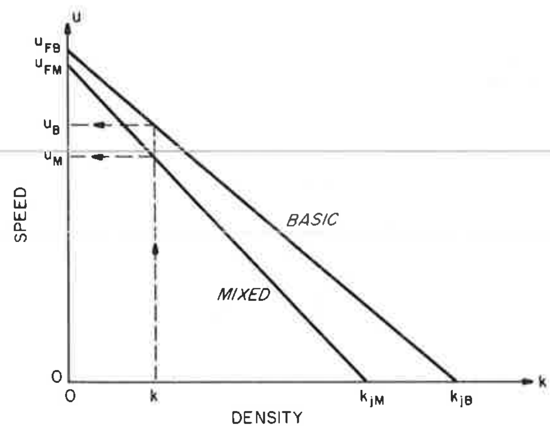


Figure 9. Determination of PCE-values by equal total travel time.



percent and 50 percent trucks in the traffic stream. As the percentage of trucks increases, the value of the PCE associated with a given volume of basic vehicles also increases as long as the free-flow velocity of trucks (u_{FT}) is less than the free-flow velocity of basic vehicles (u_{FB}).

ASSUMPTION OF EQUAL TOTAL TRAVEL TIME

It is assumed that a flow rate q_B of basic vehicles only will produce the same total travel time $T(q)_B$ as is produced by a flow rate q_M of mixed vehicles, so that $T(q)_B = T(q)_M$.

For any given length of roadway, this is equivalent to equal vehicle hours of occupancy per hour for the two traffic streams, and since T(q) is numerically equal to density k, $k_B = k_M = k$, as shown in Figure 9. If we recall Equation 1 and note that $q_B = ku_B$ and $q_M = ku_M$, it follows that $q_B/q_M = u_B/u_M$.

By similar triangles in Figure 9,

$$u_B = u_{FB}\,(k_{jB} - k)/k_{jB}$$

and

$$u_M = u_{FM}\,(k_{jM} - k)/k_{jM}$$

so that

$$q_B/q_M = u_B/u_M = [(u_{FB}/u_{FM})(k_{jM}/k_{jB})]\,[(k_{jB} - k)/(k_{jM} - k)] \quad (17)$$

Case 1 is the general case where $u_{FM} < u_{FB}$; $k_{jM} < k_{jB}$, so from Equation 1:

$$PCE = (1/p)\left\{[(u_{FB}/u_{FM})(k_{jM}/k_{jB})]\,[(k_{jB} - k) \div (k_{jM} - k)] - 1\right\} + 1 \quad (18)$$

Case 2 is the special case where the truck is longer than the basic vehicle but has the same free-flow speed, so $u_{FM} = u_{FB}$; $k_{jM} < k_{jB}$ and

$$PCE = (1/p)\left\{(k_{jM}/k_{jB})\,[(k_{jB} - k)/(k_{jM} - k)] - 1\right\} + 1 \quad (19)$$

Case 3 is the special case where the truck is the same length as the basic vehicle but has a lesser free-flow velocity, $u_{FT} < u_{FB}$; $k_{jB} = k_{jT}$:

$$PCE = (1/p)\,[(u_{FB}/u_{FM}) - 1] + 1 \quad (20)$$

Equation 20 can be further reduced by substituting the value of u_{FM} from Equation 6 into Equation 20:

$$u_{FB}/u_{FM} = u_{FB}\left\{(p/u_{FT}) + [(1 - p)/u_{FB}]\right\} = (pu_{FB}/u_{FT}) - (pu_{FB}/u_{FB}) + 1$$

Finally,

$$PCE = (1/p)\,[(pu_{FB}/u_{FT}) - (pu_{FB}/u_{FB}) + 1 - 1] + 1 = u_{FB}/u_{FT} \quad (21)$$

which is a constant value over all ranges of p and over all volumes.

Again, the Greenshields model of traffic flow is used for the interrelationships among flow rate (q), density (k), and velocity (u):

$$k_B = k_M = k_{jB}/2\,[1 - (1 - y)^{1/2}] \quad (22)$$

A numerical example employing the same data as were used to illustrate the model of equal average travel time follows. Since for this example, $u_{FM} < u_{FB}$ and $k_{jM} < k_{jB}$, Equation 18 will apply. With a flow rate of 600 basic vehicles/h, y = 600/1584 = 0.379 (as before) and by Equation 22,

$k_B = k_M$ = 13.90 vehicles/km (22.37 vehicles/mile).

By substituting in Equation 18,

$$PCE = (1/0.10)\{[(48.28/45.98)(102.07/131.23)] \times [(131.23 - 13.90)/(102.07 - 13.90)] - 1\} + 1 = 1.868.$$

Each truck is equivalent to 1.868 basic vehicles if we are to satisfy the criterion that $T(q)_B = T(q)_M = (k_B = k_M)$. This is equivalent to substituting 552.1 mixed vehicles, q_M (of which 10 percent are trucks), for 600.0 basic vehicles, q_B. Recall that to maintain equal average times $t(q)_B = t(q)_M = (u_B = u_M)$, it was possible to substitute only 269.7 mixed vehicles (10 percent trucks) for 600.0 basic vehicles, so that PCE = 13.247.

From Figure 9 it will be observed that PCE is undefined for $k > k_{jM}$. This is in the "backward-bending" portion of the total-travel-time curve where LOS is F (stop-and-go conditions) and is not an area in which PCE-values are of concern for steady-state flow.

The relationship between PCE-values and volume is shown in Figure 10. PCE-values are lowest at low volumes and increase gradually until the maximum mixed-flow rate q_{OM} is attained (point A on the curve) and then increase at a greater rate as the mixed-flow curve is operating on the backward-bending portion of the total-travel-time curve.

In Figure 10 curves are also shown for 1 percent and 50 percent trucks in the traffic stream. It is only after the equivalent flow rate on the mixed-vehicle curve has exceeded the point of maximum flow (corresponding to point A on the PCE curves) that there is a marked difference in PCE-value as related to percentage of trucks in the traffic stream.

The significance of the backward-bending point can be seen by reference to Figure 11, which shows the relationship between density k (total travel time) and flow for a basic-vehicle-only curve and a mixed curve with 10 percent trucks. Points B and B' are associated with a total travel time of 13.90 vehicle-h/km-h (22.37 vehicle-h/mile-h). A mixed flow of 552.1 or 600 vehicles/h, basic vehicles only, will give this value of total travel time, and the PCE-value is 1.868.

Points A and A' are associated with the maximum flow q_{OM} on the mixed curve. At this point the total travel time is 51.04 vehicle-h/km-h (82.13 vehicle-h/mile-h). The associated volumes are 1173.3 and 1505.8 while the PCE-value is 3.833. Beyond point A' the flow for mixed vehicles becomes stop and go with an associate decrease in volume. The volume associated with point A is noted on the PCE-versus-volume curves of Figure 10.

Points C and C' are associated with the maximum-flow q_{OB} on the basic-vehicles-only curve. The total travel time is 65.62 vehicle-h/km-h (105.60 vehicle-h/mile-h). The associated volume of basic vehicles has increased to 1584.0 vehicles/h while the mixed-vehicle flow has decreased to 1077.6 vehicles/h and the PCE-value has increased to 5.700.

Figure 10. PCE versus volume by percentage of trucks, equal total travel time.

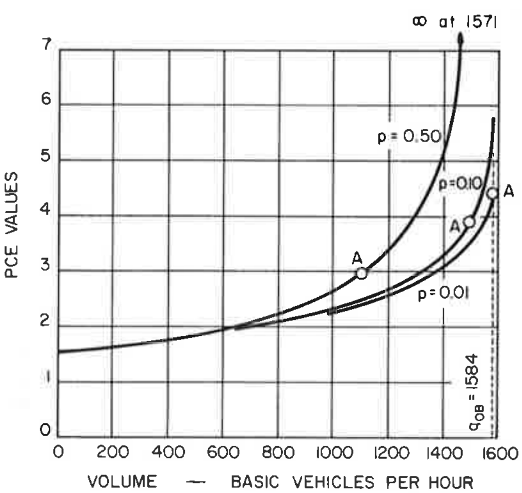
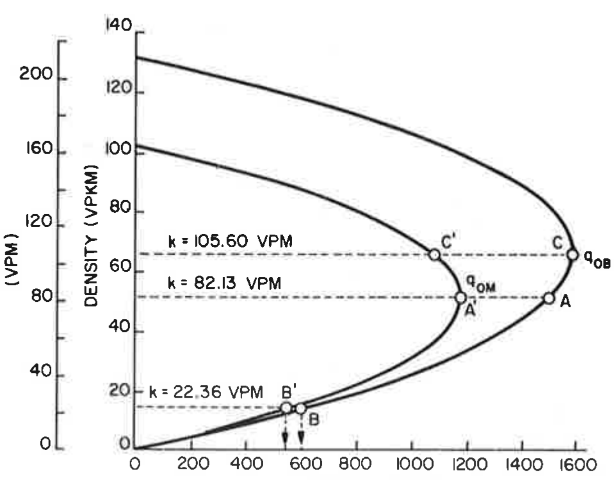


Figure 11. Calculation of PCE-values with backward-bending curves.



ASSUMPTION OF EQUAL AVERAGE TRAVEL TIME FOR BASIC VEHICLES

The mixed stream of traffic is made up of two component steady-state flows. The first component is basic vehicles within the mixed stream with parameters u_{FMB} (= u_{FB}) and k_{jMB} [$=(1 - p')k_{jM}$]. The second component is trucks within the mixed stream with parameters u_{FMT} (= u_{FT}) and k_{jMT} (= $p'k_{kjM}$). The speed-density curves for the mixed flow and the two component flows are shown in Figure 12.

From Figure 12 and by the Greenshields relationship,

$$u_{MB} = (u_{FMB}/2)\,[1 + (1 - y_{MB})^{1/2}] \quad (23a)$$

and

$$u_{MT} = (u_{FMT}/2)\,[1 + (1 - y_{MT})^{1/2}] \quad (23b)$$

where

$$y_{MB} = (1 - p)q_M/(1 - p)q_{OM} = q_M/q_{OM} = y_{MT}$$

Speeds calculated from the traffic stream with 10 percent trucks as used in earlier examples are presented in Table 1 along with flow rates and PCE-values. The top section is based on the assumption that PCE is defined by two traffic flow rates, q_B and q_M, such that the mean velocities of individual vehicles within the traffic streams are equal ($u_B = u_M$). It will be observed that the speed of basic vehicles within the mixed stream (u_{MB}) is greater than the speed of the basic vehicles in the basic stream (u_B).

The middle part of Table 1 is based on the assumption that PCE is defined by two traffic flow rates, q_B and q_M, such that the total travel

Figure 12. Speed-density relationships for mixed flow and two component flows.

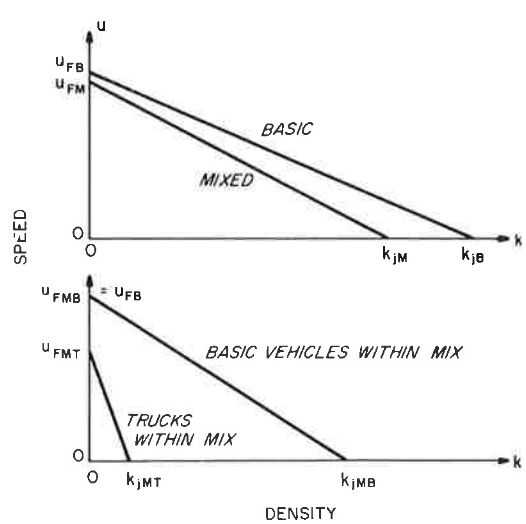
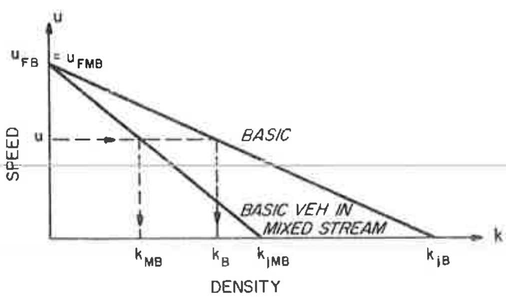


Table 1. Speed of vehicles within mixed flow.

q_B	u_B (km/h)	q_M	u_M (km/h)	u_{MD} (km/h)	u_{MT} (km/h)	PCE
Assumption of Equal Individual Travel Time						
288	45.98	0.56	45.98	48.28	32.19	5120.96
800	41.12	443.46	41.12	43.18	28.79	9.04
1584	24.14	1170.40	24.14	25.35	16.90	4.53
Assumption of Equal Total Travel Time						
288	45.98	270.36	43.16	45.32	30.21	1.65
800	41.12	724.02	37.22	39.07	26.06	2.05
1505	29.53	1173.33	23.03	24.17	16.11	3.83
Equal Individual Travel Time for Basic Vehicles						
288	45.98	213.33	43.79	45.98	30.66	4.50
800	41.12	592.59	39.17	41.12	27.42	4.50
1584	24.14	1173.33	22.99	24.14	16.09	4.50

Note: It is assumed that L_T = 22.86 m, L_B = 7.62 m, p = 0.10, u_{FT} = 32.187 km/h, and u_{FB} = 48.280 km/h. 1 km/h = 0.6 mile/h.

Figure 13. PCE-values by equal basic vehicle travel time.



times per kilometer are equal. Eight hundred basic vehicles per hour will require 19.45 vehicle-h to traverse 1 km (0.6 mile) of roadway [800 x (1/41.12)], as will 724.02 mixed vehicles [724.02 x (1/37.22)]. The speed of basic vehicles within the mixed stream (u_{MB}) is always less than the speed of vehicles in the basic stream, and the difference increases with increasing volume (and increasing PCE-values).

St. John (7) has used mean speed of basic vehicles as the criterion for determining PCE-values. A diagram of the situation is shown in Figure 13 where $u_{FMB} = u_{FB}$ and $u_B = u_{MB} = u$. By Equation 1,

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

where

$$q_M = q_{MB}/(1 - p) = uk_{MB}/(1 - p);\ q_B = uk_B$$

so that

$$q_M/q_B = (1 - p)\,k_B/k_{MB}$$

By similar triangles in Figure 13,

$$k_{MB} = k_{jMB}\,(u_{FB} - u)/u_{FB};\ k_B = k_{jB}\,(u_{FB} - u)/u_{FB}$$

so that

$$q_M/q_B = (1 - p)\,k_{jB}/k_{jMB}$$

But $k_{jMB} = (1 - p')\,k_{jM}$ and

$$q_M/q_B = [(1 - p)/(1 - p')]\,(k_{jB}/k_{jM}) \qquad (24)$$

By Equations 10a and 10b,

$$k_{jB}/k_{jM} = (L/L_B)\{[p'L_T + (1 - p')L_B]/L\} = [p'L_T + (1 - p')L_B]/L_B$$

Substitution in Equation 24 gives

$$q_B/q_M = (1 - p)\{[p'/(1 - p')]\,(L_T + L_B)\}/L_B \qquad (25)$$

From Equation 9,

$$p'/(1 - p') = \{pu_{FB}/[pu_{FB} + (1 - p)u_{FT}]\}\{[pu_{FB} + (1 - p)u_{FT}] \div (1 - p)\,u_{FT}\} = pu_{FB}/(1 - p)u_{FT}$$

Substituting in Equation 25,

$$q_B/q_M = [(pu_{FB}/u_{FT})(L_T/L_B)] + (1 - p)$$

so that by Equation 1,

$$PCE = (1/p)\,[(q_B/q_M) - 1] + 1 = (u_{FB}/u_{FT})(L_T/L_B) \qquad (26)$$

which is a constant value over all ranges of p and for all volumes.

Recall the numerical example previously cited in which the basic vehicle had an effective length of 7.62 m and free-flow velocity of 48.280 km/h and the truck was 22.86 m long and had 32.187 km/h velocity. By Equation 26, the resulting PCE is calculated as follows:

(48.280/32.187) x (22.86/7.62) = 4.50.

The speeds of vehicles within the traffic stream for these assumptions are shown in the bottom part of Table 1. Although the average velocity of all vehicles in the mixed flow (u_M) is less than the speed of basic vehicles only, the speed of the basic vehicles within the mixed flow (u_{MB}) is equal to u_B at all volume levels shown.

INFLUENCE OF VEHICLE SIZE AND SPEED ON CALCULATED PCE-VALUES

Table 2 contains a comparison of PCE-values for vehicles varying in effective length from 6.10 m (20 ft) to 22.86 m and free-flow velocity from 32.19 km/h to 56.33 km/h (35 miles/h). It will be recalled that the basic vehicle had an effective length of 7.62 m and a free-flow velocity of 48.28 km/h. There are 10 percent nonbasic vehicles in the mixed traffic stream and the flow of basic vehicles is 600 vehicles/h. The criterion for LOS is given as average travel time, so that $t(q)_B = t(q)_M$ ($u_B = u_M$).

Two entries are shown for each vehicle. The first is the PCE-value; the second is the volume of mixed vehicles that will produce the same mean travel time (or the reciprocal velocity) as is produced by 600 basic vehicles (V). As the size of the vehicle increases and the velocity decreases, the PCE-value increases; values range from a minimum of -0.23 for a short, fast vehicle to a maximum of 13.25 for a long, slow vehicle.

Of particular interest are the negative values of PCE in columns 1 and 3. Recall that the PCE-value represents the number of basic vehicles that are displaced by a nonbasic vehicle. For example, the truck 18.29 m (60 ft) long with a free-flow velocity of 40.23 km/h (25 miles/h) has a PCE-value of 5.01. The mixed traffic stream of 428.2 vehicles/h has the same mean travel time as 600 basic vehicles. The mixed stream contains 42.82 trucks and 385.38 basic vehicles. The 42.82 trucks have displaced 214.62 (600.00 - 385.3) basic vehicles.

Table 2. PCE-values by vehicle length and free-flow velocity, average travel time.

Free-Flow Velocity (km/h)	Effective Length of Truck (m) 6.10 PCE-Value	6.10 V	7.62 PCE-Value	7.62 V	9.14 PCE-Value	9.14 V	13.72 PCE-Value	13.72 V	18.29 PCE-Value	18.29 V	22.86 PCE-Value	22.86 V
56.33	-0.23	684.3	-0.08	672.4	0.08	660.9	0.54	628.6	1.01	599.4	1.48	572.8
48.28	0.80	612.2	1.00	600.0	1.20	588.2	1.80	555.6	2.40	526.3	3.00	500.0
40.23	2.75	510.7	3.03	498.7	3.31	487.2	4.16	455.8	5.01	428.2	5.86	403.7
32.19	7.81	357.0	8.30	346.8	8.80	337.1	10.28	311.2	11.76	289.0	13.25	269.7

Notes: It is assumed that p = 0.10, q_B = 600 vehicles/h; basic vehicle has effective length of 7.62 m and free-flow velocity of 48.28 km/h. 1 km/h = 0.6 mile/h; 1 m = 3.2 ft.
V = volume of mixed vehicles that will produce same mean travel time (or reciprocal velocity) as produced by 600 basic vehicles.

Table 3. PCE-values by vehicle length and free-flow velocity, equal total travel time.

Free-Flow Velocity (km/h)	Effective Length of Truck (m) 6.10 PCE-Value	6.10 V	7.62 PCE-Value	7.62 V	9.14 PCE-Value	9.14 V	13.72 PCE-Value	13.72 V	18.29 PCE-Value	18.29 V	22.86 PCE-Value	22.86 V
56.33	0.84	609.9	0.86	608.7	0.88	607.4	0.94	603.7	1.00	599.9	1.06	596.2
48.28	0.98	601.4	1.00	600.0	1.02	598.6	1.10	594.3	1.17	590.0	1.24	585.8
40.23	1.17	589.9	1.20	588.2	1.23	586.6	1.32	581.7	1.40	576.8	1.49	571.8
32.19	1.46	573.4	1.50	571.4	1.54	569.5	1.64	563.7	1.75	557.9	1.87	552.1

Notes: It is assumed that p = 0.10, q_B = 600 vehicles/h; basic vehicle has effective length of 7.62 m and free-flow velocity of 48.28 km/h. 1 km/h = 0.6 mile/h; 1 m = 3.2 ft.
V = volume of mixed vehicles that will produce same mean travel time (or reciprocal velocity) as produced by 600 basic vehicles.

Table 4. PCE-values by vehicle length and free-flow velocity, average travel time.

Free-Flow Velocity (km/h)	Effective Length of Truck (m) 6.10 PCE-Value	6.10 V	7.62 PCE-Value	7.62 V	9.14 PCE-Value	9.14 V	13.72 PCE-Value	13.72 V	18.29 PCE-Value	18.29 V	22.86 PCE-Value	22.86 V
56.33	0.69	619.5	0.86	608.7	1.03	598.3	1.54	569.1	2.06	542.6	2.57	518.5
48.28	0.80	612.2	1.00	600.0	1.20	588.2	1.80	555.6	2.40	526.3	3.00	500.0
40.23	0.96	602.4	1.20	588.2	1.44	574.7	2.16	537.6	2.88	505.1	3.60	476.2
32.19	1.20	588.2	1.50	571.4	1.80	555.6	2.70	512.8	3.60	476.2	4.50	444.4

Notes: It is assumed that p and q_B are variable; basic vehicle has effective length of 7.62 m and free-flow velocity of 48.28 km/h. 1 km/h = 0.6 mile/h; m = 3.2 ft.
V = volume of mixed vehicles that will produce same mean travel time (or reciprocal velocity) as produced by 600 basic vehicles.

Conversely, the short (6.10-m) vehicle with a free-flow velocity of 56.33 km/h has a mixed traffic flow rate of 684.3. Of these vehicles, 68.43 are fast vehicles and 615.87 basic vehicles. The presence of the 68.43 fast vehicles decreases the average travel time sufficiently that an extra 15.87 basic vehicles are added to the traffic (rather than displaced); hence the PCE sign is negative. The ratio of added basic vehicles to nonbasic vehicles is 0.23 (15.87/68.43). If the number of basic vehicles in the mixed stream, $(1 - p)q_M$, is greater than the number of basic vehicles, q_B, the PCE-value will be negative.

Table 3 is similar to Table 2 except that the criterion for comparable LOS values is that the total travel time for all vehicles over a length of highway be equal for the two traffic streams, $T(q)_B = T(q)_M$ $(k_B = k_M)$. The range of PCE-values is reduced but, again, increased PCE-values are associated with longer, slower vehicles. There are no negative PCE-values in Table 3, although, as is to be expected, there are PCE-values less than 1.0.

Table 4 is based on the criterion that $u_B = u_{MB}$. The PCE-values would be the same over all values of q_B, but the value of q_M in each cell is for the value q_B = 600.0.

DISCUSSION OF RESULTS

Three criteria for defining LOS have been considered. The first of these assumes equal mean travel time for two flows, mixed and basic vehicles. The introduction of slow-moving vehicles into the traffic stream will reduce average speed even at very low flow rates. A substantial number of basic vehicles can be expected to produce the same average speed. As a consequence, (a) PCE-values are undefined at very low volumes, and (b) PCE-values decrease as volumes increase.

It would be desirable to define PCE-values over all values of volume. It would also appear reasonable that at low volumes large, slow vehicles would have a minimum effect on traffic flow but that as volume increased, there would be greater interaction between vehicles, so the PCE-values should be increasing as volumes increase. Letting LOS be defined by $u_B = u_{MB}$ gives constant PCE-values over all volumes.

The definition of LOS by the criterion of total travel time satisfies the difficulties noted above and is recommended as a more desirable approach. In making this recommendation it should be recalled that the traffic flow model used (Greenshields') is a simple deterministic model that only partly represents observed traffic flow. Only two categories of vehicles have been considered; in reality an analysis of PCE-values should be based on a model that considers three or more vehicle categories simultaneously.

Despite the shortcomings noted above, it is felt that this analysis will provide some guidance to those doing research to determine PCE-values.

ACKNOWLEDGMENT

This paper was prepared while I was with the Traffic Systems Division, Office of Research and Development, of the Federal Highway Administration on sabbatical from the University of Minnesota. I am indebted to the Regents of the University of Minnesota for making the leave possible and to the Federal Highway Administration for the opportunity to engage in the research program of that organization.

Discussion

A.D. St. John

Huber has performed a timely service by examining alternative bases for the passenger-car equivalent (PCE). The analyses detect undesirable characteristics to be avoided and mandate a careful examination of definitions and concepts. This discussion presents alternative points of view, describes a few of the results from microscopic simulation models, and suggests additional factors to be considered in selecting bases for the PCE.

At the most fundamental level, Huber adheres to past practice. The ideal or reference vehicle mix is 100 percent passenger cars, and speed or its inverse, travel time, are examined in several forms as best bases for equivalence between moving traffic streams.

For the mixed traffic streams the paper analyzes speed in two forms, which differ significantly. In one form, the average speed is calculated with data for all vehicles in the stream; the other form uses speed data for passenger cars only. The paper selects the all-vehicle form as preferable because of the PCE characteristics estimated for it. I believe that the choice here should depend more strongly on the concept desired for equivalence between traffic streams. For example, if the all-vehicle form is used, a steep sustained upgrade would be calculated to reduce service for a car-and-truck mix even if the car speeds were not appreciably depressed by the presence of low-speed trucks. Alternatively, if the car-only form is used, there is no direct measure of the speed depression exprienced by trucks due to the upgrade.

Several facets of the 1965 Highway Capacity Manual (1) suggest that car-only data were meant to be used for the mixed stream. Operating speed must have been selected for its sensitivity at low flow rates, a sensitivity that would be distorted by including trucks. Also, the definition implies that operating speed is limited only by highway design speed and interactions with other vehicles. However, a passenger car is specified as the vehicle type only in the definition for free-flow operating speed.

I agree with Huber's requirements that the definition for PCE and the PCE-values be well behaved over the range of variables. It is also preferable that the PCE-values not conflict with engineering intuition. However, I question Huber's preference that the PCE for a truck be small at low flow rates and increase with flow rate when the percentage of trucks is held constant.

A PCE that is essentially constant with flow rate is desirable for two reasons. First, the constant PCE economizes the field or model data needed and, second, constant PCE implies fundamental relationships that do not change in form between the car-only and mixed flows. As an example of the latter aspect, consider Figure 14, in which the operating speed versus flow rate is sketched for a mixed flow and for a flow of cars only. If the form of the operating-speed function is constant, the curves of Figure 14 will merge into the single curve of Figure 15 when the abscissa is normalized to volume/capacity. The single, normalized curve is obtained only if the PCE is essentially constant over flow rate. The preservation of form in the single normalized curve is convenient computationally and conceptually.

For currently defined PCE estimates there is evidence both supporting and conflicting with the idea that PCE is constant over flow rate. The tables in the 1965 Highway Capacity Manual indicate only small changes in PCE between high and low service levels. An extensive collection of results from a microscopic model of multilane flow (8,9) conformed with normalized curves exemplifed in Figure 15. Although PCE-values were not derived, normalized organization indicated that they would be essentially constant over flow rate. More recent results with the same model (10) employed the free speeds observed under the 55-mile/h (89-km/h) speed limit. These results reveal cases in which PCE-values would diminish at high flow rates; that is, speeds of cars are depressed by impeding vehicles at low and intermediate flow rates (PCE > 1) but the approach to capacity is essentially unaffected (PCE ≃ 1).

Two considerations, absent in the paper, are given here to complete the set of important con-

Figure 14. Operating speed versus flow rate.

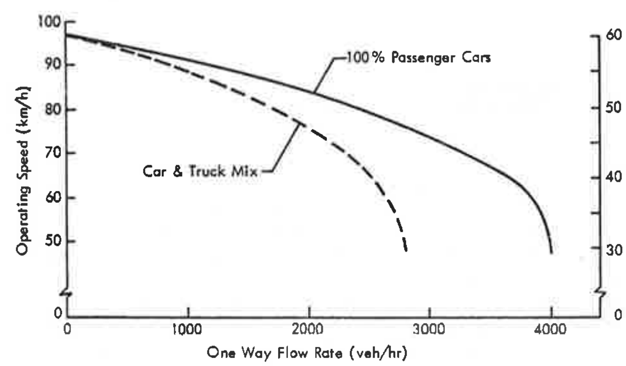
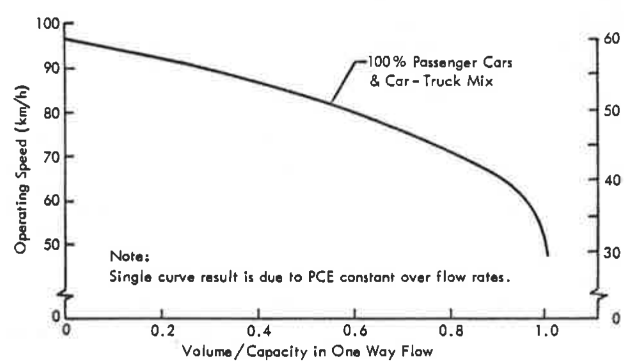


Figure 15. Operating speed versus volume/capacity ratio.



siderations. They are the field measurements and the nonlinear dependence of PCE-values on percentage of trucks.

The bases for the PCE should lead to field measurements that are feasible and economical. Operating speed exemplifies a measure that has desirable characteristics in equivalency but is difficult and expensive to measure in the field. Because it is not a central (average) measure, operating speed is at a disadvantage even in the analysis of results from models.

The nonlinear relationship between the PCE and percentage of trucks indicated by most available data constitutes a problem. Tables in the 1965 Highway Capacity Manual (1) and results from models (8,9,11) indicate that the PCE diminishes as the percentage of trucks increases. This is more than a computational inconvenience; it increases the field or model data required and complicates estimates for two or more types of impeding vehicles. A derivation (11) has been partly successful in establishing an analytical relationship between PCE and percentage of trucks. The results provide a measure that is invariant with percentage of trucks and a method for estimating the effects of two or more types of impeding vehicles. These possibilities should be considered in selecting the basis for PCE-values.

In summary, I agree with the aims of Huber's paper and with part of the conclusions. I suggest that more attention be directed to the fundamental concepts of equivalence, that it is desirable for the PCE to be constant over flow rate, and that additional considerations should be included in the selection of bases for equivalency. Also, final decisions should be based on extensive field data or results from comprehensive models. This does not detract from the value of simple models, however, since they frequently point to alternatives otherwise overlooked.

Randy Machemehl

The work by Huber is a significant contribution toward better characterization of the effects of commercial vehicles on traffic flow. The mathematical relationships developed through his work are understandable and reasonable. When viewed as a conceptual framework for PCE computation, the work is both interesting and useful. Huber notes several key weaknesses in his recommendations for further study.

These include the fact that only two vehicle categories--basic and nonbasic--are considered. Operational characteristics of the entire vehicle population and resulting effects on the traffic stream are known to vary widely. Recreational vehicles, for example, represent a vehicle class that generally has significantly different operational capabilities, and drivers of such vehicles often lack experience required to fully utilize the capabilities their vehicles possess. Variability in operational features of intracity-type commercial delivery vehicles versus over-the-road commercial trucks, local buses versus intercity commercial buses, and even small underpowered versus large passenger cars represents additional examples of the need for more than two vehicle classes. Huber notes that the Federal Highway Administration, as part of the national highway cost-allocation study, is in the process of developing PCE-values for as many as 15 categories of vehicles for four different roadway classes. This effort should answer many questions regarding operational effects of the spectrum of vehicle classes.

The Greenshields model of traffic flow, which uses a linear relationship between density and velocity, is employed by Huber to develop interrelationships among speed, density, and flow rate. This model probably is a good approximation for many density-velocity conditions. However, it may not be completely sufficient for the entire velocity-density range. A nonlinear relationship might very likely improve the validity of PCE estimates near boundary values. The deterministic nature of this model is also problematic. As noted earlier, tremendous variability among the driver-vehicle population and their performance on various roadway types is indicative of the need for stochastic modeling. Characterization of this variability and its effect on traffic flow would likely be achieved most efficiently through use of stochastic representation.

The analyses presented in Huber's paper represent a contribution that will be of value to those investigating PCE techniques. It is both direct and easily understood and Huber is to be commended for his efforts.

Author's Closure

I am indebted to Machemehl and St. John for their thoughtful reading and discussion of this paper.

Machemehl is correct in pointing out that the modeling should be extended to permit analysis of several (more than two) categories of vehicles within the mixed stream. Preliminary investigation has shown that this is possible if one continues to use the Greenshields model of traffic flow. Incorporation of stochastic modeling would require extensive computer simulation but should provide further insight.

As St. John has noted, one can only make intuitive analyses in establishing a basis for determination of PCE-values as discussed in the 1965 Highway Capacity Manual. This paper represents an attempt to examine the alternative bases for PCE-values.

My preference that the PCE for a truck be small at low flow rates and increase with increased flow rates is predicated on the intuitive feeling that at low volumes there are few basic vehicles that can be influenced by a truck; the greater time and distance spacing tends to minimize intervehicular interference. As the flow rate increases, the opportunity for interaction between basic vehicles and trucks is increased with a subsequent increase in PCE-values.

I agree with St. John in his preference for a constant PCE-value because this will economize data requirements. His second contention, that a constant PCE implies fundamental relationships that do not change in form, is illustrated by reference to Figure 14. Implicit to this relationship is a common free-flow speed at extremely low flow rates. My analysis differs by considering that the car and truck mix has a lesser free-flow speed (because of the slower trucks) as illustrated in Figure 6. It is only when one uses as a basis $t(q)_{MB} = t(q)_B$ that the analysis will be similar to that suggested by St. John. (Conversion of the form given in Figure 13 to that given in Figure 14 is straightforward.)

Again, I thank both discussants for their helpful comments.

REFERENCES

1. Highway Capacity Manual. TRB, Special Rept. 87, 1965.
2. A. Werner and J.F. Morrall. Passenger Car Equivalencies of Trucks, Buses, and Recreational Vehicles for Two-Lane Rural Highways. TRB, Transportation Research Record 615, 1976, pp. 10-17.
3. A. Werner, J.F. Morrall, and G. Halls. Effect of Recreational Vehicles on Highway Capacity. Traffic Engineering, Vol. 45, No. 5, May 1975, pp. 20-25.
4. First Progress Report on the Federal Highway Cost Allocation Study. FHWA, March 1980.
5. Passenger Car Equivalence Analysis Framework: An Interim Report as Part of Quality of Flow and Determination of PCE on Urban Arterials. PRC Voorhees, McLean, VA, Jan. 1981.
6. B.D. Greenshields. A Study of Traffic Capacity. HRB Proc., Vol. 14, 1934, pp. 448-477.
7. A.D. St. John. Nonlinear Truck Factor for Two-Lane Highways. TRB, Transportation Research Record 615, 1976, pp. 49-53.
8. A.D. St. John, D.R. Kobett, and others. Traffic Simulation of the Design of Uniform Service Roads in Mountainous Terrain. Midwest Research Institute, Kansas City, MO, MRI Project 3029-E, Final Rept., Jan. 1970.
9. A.D. St. John, D.R. Kobett, and others. Freeway Design and Control Strategies as Affected by Trucks and Traffic Regulations. FHWA, Rept. FHWA-RD-75-42, Jan. 1975.
10. A.D. St. John and W.D. Glauz. Implications of Light-Weight, Low-Powered Future Vehicles in the Traffic Stream--Volume 2. Midwest Research Institute, Kansas City, MO, MRI Project 4562-S, Final Rept., Oct. 1981.
11. A.D. St. John and D.R. Kobett. Grade Effects on Traffic Flow Stability and Capacity. NCHRP, Rept. 185, 1978.

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

Model for Calculating Safe Passing Distances on Two-Lane Rural Roads

EDWARD B. LIEBERMAN

A model describing the kinematics of vehicle trajectories during the passing maneuver on two-lane rural roads is presented. This model is based on the hypothesis that there exists a point in the passing maneuver that can be identified as a critical position. At this point, the decision to complete the passing maneuver will provide the same factor of safety relative to an oncoming vehicle as will the decision to abort the maneuver. The model locates the critical position in terms of exogenous parameters. The results of a series of sensitivity studies conducted with the model are also presented. These results provide insight into those parameters that strongly influence the required sight distances. It is shown that the current sight-distance specifications of the American Association of State Highway and Transportation Officials may be inadequate from a safety standpoint, particularly for high-speed passing maneuvers and for passing vehicles that are low-powered subcompacts.

The calculation of passing sight distance as presented in the Blue Book of the American Association of State Highway and Transportation Officials (AASHTO) (1) is based on several simplifying assumptions. In this paper we examine the kinematics of the passing maneuver in greater detail and offer another point of view. The results obtained with this new model are compared with those detailed in the Blue Book (1); the implications of these comparisons are then discussed.

The benefits of an analytical model describing the passing maneuver on two-lane rural roads include the ability to identify those factors that play a role in determining safe passing sight distances. Furthermore, it is possible to conduct sensitivity studies to determine which of these factors are important relative to the others.

With the changing composition of the traffic stream--larger, faster, more powerful trucks mixing with smaller, lower, less powerful automobiles--such a model can be very useful in assessing the associated changes in safety margins provided by current sight-distance standards. It would also be possible to determine whether there is a need for changes in these standards or whether more positive forms of control are required to improve the safety characteristics of two-lane rural roads. Clearly, any change in these standards could also affect rural road capacity as well as operating speed.

OVERALL APPROACH

When a vehicle traveling on a rural road desires to pass an impeding vehicle, the driver must assess a large number of factors in deciding whether to attempt a passing maneuver. This assessment is a continuous one that extends, after the initial decision is made, throughout the passing maneuver.

This model is based on the hypothesis that there exists a point in the passing maneuver that can be identified as a critical position whenever an oncoming vehicle is in view. This critical position is defined as follows: At the critical position, the decision by the passing vehicle to complete the pass will afford it the same clearance relative to the oncoming vehicle as will the decision to abort the pass.

This implies that if a decision to abort the pass takes place downstream of the critical position (i.e., later in the passing maneuver), the clearance (and therefore the safety factor) relative to the oncoming vehicle will be less than if the passing vehicle completes the pass. The converse applies to a decision to complete the pass if made upstream of the critical position.

The determination of this critical position is a central issue in the development of the model. The