Passenger Car Equivalencies of Trucks, Buses, and Recreational Vehicles for Two-Lane Rural Highways

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Passenger car equivalents or adjustment factors for trucks, buses, and recreational vehicles are often required in carrying out highway capacity calculations. This paper presents, in part, the results of a research project into the effect that recreational vehicles have on highway capacity. Described are the underlying methods referred to in the 1965 Highway Capacity Manual for determining passenger car equivalents, the methods used for developing equivalencies for recreational vehicles, and the use of the new equivalencies for typical highway capacity computations. Sensitivity testing of a recreational vehicle simulator model is discussed. Results of the sensitivity testing, which was extended to include highway capacity computations, strongly indicate that the present passenger car equivalent speed curves and adjustment factors in the 1965 Highway Capacity Manual require further refinement and updating, particularly at slower speeds. This paper estimates their correct placement by applying basic traffic engineering relationships.

During recent years there has been a phenomenal increase of recreational vehicles (i.e., travel trailers, campers, camper trucks, motorhomes, and vans) in the traffic stream. The 1965 Highway Capacity Manual (HCM) (1) does not make any provision for the effect of recreational vehicles; consequently, highway planning studies (2) have begun using adjustment factors for trucks and buses to estimate large-vehicle effect. Using such factors has not always proved to be accurate, particularly in cases where the site considered is rolling or mountainous terrain. Because little research has been done to quantify in absolute terms the effect of recreational vehicles and because most of Alberta's recreational areas are located in a mountainous region where recreational vehicles constitute as high as 30 percent of the traffic stream, a research project was initiated by Alberta Transportation and undertaken by the University of Calgary (3).

DETERMINATION OF PASSENGER CAR EQUIVALENTS

The HCM (1, p. 101) states:

> On two lane highways, passenger car equivalents of trucks are obtained relatively easily. They can be directly determined by obtaining detailed information on the speeds and headways of vehicles during various rates of flow on highways with different alignments and profiles. An average passenger car equivalent is obtained for trucks under each condition.... Passenger car equivalents can also be calculated with a high degree of accuracy from the separate speed distributions of passenger cars and trucks at any given volume level. The criterion used is the relative number of passings that would be performed per mile of highway if each vehicle continued at its normal speed for the conditions under consideration.

Passenger car equivalents (PCEs) for trucks or other large vehicles are needed because of two main factors:

1. A truck traveling more slowly than the passenger car traffic stream restricts and reduces capacity and level of service, and
2. A truck traveling at approximately the same speed as the passenger car traffic stream occupies more space because of its size and possibly requires greater stopping distance.

The first factor is prevalent on grades in rolling or mountainous terrain. For such conditions, Walker's method, which is described briefly in this paper, has been applied. This method was used to derive PCEs contained in the 1965 HCM. The second factor is more common in level terrain and the time interval (headway) method may be applied to determine the PCE.

The criteria developed by Walker are based on the number of passings or overtakings that would be performed per kilometer of highway if each vehicle continued at its normal speed for the conditions under consideration. The general case is

$$N = \sum_{i=1}^{n} \sum_{j=1}^{m} X_i Y_j \Big/ 60\left(\frac{60}{S_{2_i}} - \frac{60}{S_{1_j}}\right) \qquad (1)$$

in which N is the sum of the overtakings in terms of vehicles traveling at speed S_1 that will overtake X vehicles/h traveling at speed S_2 within 1 km (0.6 mile) of the highway when the number of vehicles traveling at speed S_1 is Y vehicles/h. The numbers of slower and faster vehicles are n and m respectively at a selected speed grouping.

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In Figure 1, for example, S_1 and S_2 are in units of kilometers per hour and the speed groupings increase in increments of 10 km/h (6.21 mph).

Equation 1 permits one to carry out computations for any particular speed distribution and any slower vehicle to arrive at a PCE (Figure 1). The final step is to calculate the ratio of passenger cars to a slower moving vehicle (truck) as follows:

$$\text{Ratio} = \frac{N/1\ \text{truck/h}}{N/100\ \text{passenger cars/h}} = \frac{3.25/1\ \text{truck/h}}{20.61/100\ \text{passenger cars/h}} \qquad (2)$$

The ratio of 15.8 is the PCE of a truck traveling 20 km/h (12.42 mph). By using speed distributions for various levels of service and equation 2 above, a PCE speed curve can be produced as shown in Figure 2.

The headway method is best suited to determine equivalencies on level terrain at low levels of service. The method is based on the concept that a truck occupies more space than a single passenger car and therefore reduces capacity. The procedure involves the measurement of the time interval (headway) between vehicles and their speed. This procedure does not consider the passing or the desire of drivers to pass as does the Walker method. The basic equation for the headway method is

$$E = (h/p - c)/t \qquad (3)$$

where

- E = PCE for truck,
- h = average headway for a sample of cars and trailers,
- p = average headway for all-passenger-car sample,
- c = proportion of cars, and

Figure 1. Matrix for determining passenger car equivalents.

No. of Vehicles X at slower speed S_2		No. of vehicles Y at faster speed S_1											Total
		0	0	2	10	19	37	22	8	2	0	Y	100
X	$\frac{1}{S_2}$	0.00911	0.0100	0.0111	0.0125	0.0143	0.0167	0.0200	0.0250	0.0333	0.0500	$\frac{1}{S_1}$	
	S_2	110	100	90	80	70	60	50	40	30	20	S_1	
0	0.0500	0.0409	0.0400	0.0390	0.0375	0.0357	0.0333	0.0300	0.0250	0.0167	-		
	20	-	-	-	-	-	-	-	-	-	-		
2	0.0333	0.0242	0.0233	0.0222	0.0208	0.0290	0.0166	0.0133	0.0083	-	-		
	30	-	-	0.0888	0.0416	0.7220	1.2284	0.5852	0.1328				3.1732
8	0.0250	0.0159	0.0150	0.0139	0.0125	0.0107	0.0083	0.0050	-	-	-		
	40	-	-	0.2224	1.0000	1.6264	2.4568	0.8800	-	-	-		6.1856
22	0.0200	0.0109	0.0100	0.0089	0.0075	0.0057	0.0033	-	-	-	-		
	50	-	-	0.3916	1.6500	2.3826	2.6862	-	-	-	-		7.1104
37	0.0167	0.0076	0.0067	0.0056	0.0042	0.0024	-	-	-	-	-		
	60	-	-	0.4144	1.5540	1.6872	-						3.6556
19	0.0143	0.0052	0.0043	0.0032	0.0018	-							
	70	-	-	0.1216	0.3420	-							0.4636
10	0.0175	0.0034	0.0025	0.0014	-								
	80	-	-	0.0280									0.0280
2	0.0111	-	-										
	90	-	-										
0	0.0100	-											
	100	-											
0	0.0091												
	110												
													20.6164

1	0.0500	0.0409	0.0400	0.0390	0.0375	0.0357	0.0333	0.0300	0.0250	0.0167	-		
	20	-	-	0.0778	0.3750	0.6783	1.2321	0.6600	0.2000	0.0334	-		3.2566

10 km/h = 6.21 mph

t = proportion of trucks.

For the study on the effect of recreational vehicles, the mean headway for any specific number of vehicles for each percentage of recreational vehicles was substituted in equation 3. The resulting plot is E versus volume for all ranges in recreational vehicle percentage for which data are available. The PCEs for recreational vehicles were calculated by using equation 2 in slightly modified form:

$$E_r = \frac{\{(\text{all}/\text{pp}) - [1 - (\%\ \text{recreational vehicles}/100)]\}}{\%\ \text{recreational vehicles}/100} \quad (4)$$

where

E_r = PCEs for recreational vehicles,
all = average headway for all vehicles in the traffic stream for the time interval considered, and
pp = average headway of a passenger car following a passenger car for the time interval considered.

The average PCE for 1-h intervals was 1.6 at an average volume of 1000 vehicles/h for the lane of the two-lane highway studied. A value of 1.6 was suggested for levels of service D and E.

Figure 2. Passenger car equivalent-speed curve for two-lane highways.

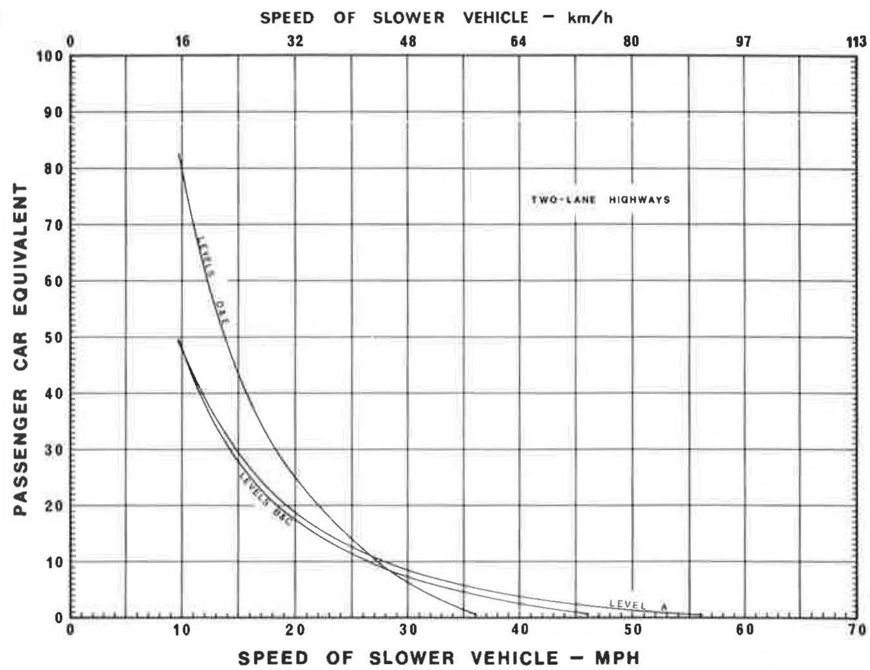


Figure 3. Average speed of recreational vehicles over entire length of grade on two-lane highways.

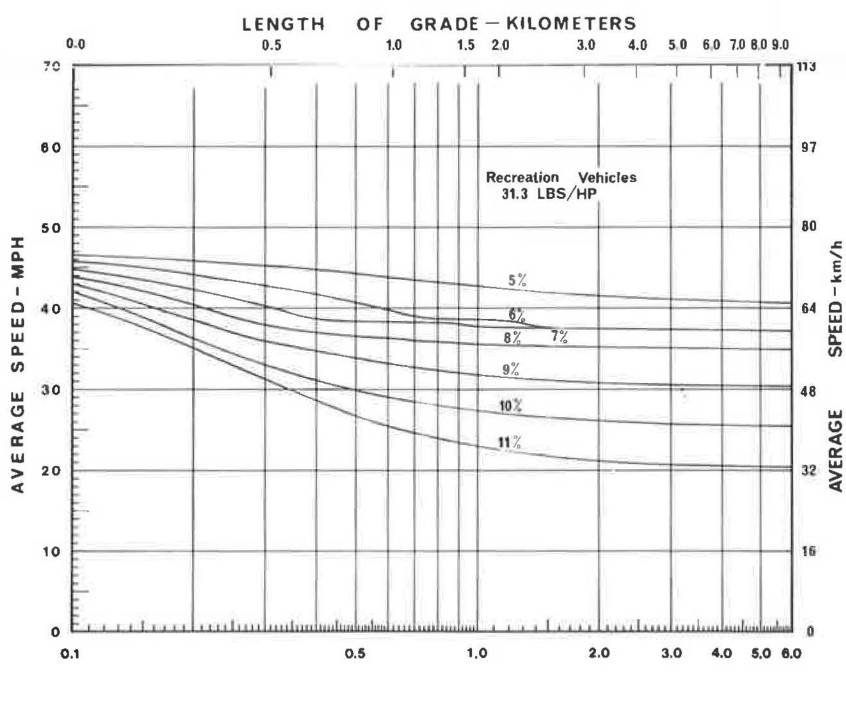


Table 1. Passenger car equivalents of trucks, buses, and recreational vehicles on two-lane highways by levels of service.

Grade (%)	Length of Grade (km)	Levels of Service A and B				Level of Service C				Levels of Service D and E			
		Trucks[a]	Buses[b]	RVs[c]	PVs[d]	Trucks	Buses	RVs	PVs	Trucks	Buses	RVs	PVs
0 to 2	All	2	2	2.3	1.0	2	2	1.6	1.0	2	2	1.6	1.0
3	0.4	5	2	2.3	1.0	3	2	1.6	1.0	2	2	1.6	1.0
	0.8	10	2	2.3	1.0	10	2	1.6	1.0	7	2	1.6	1.0
	1.2	14	2	2.3	1.0	16	2	1.6	1.0	14	2	1.6	1.0
	1.6	17	2	2.3	1.0	21	2	1.6	1.0	20	2	1.6	1.0
	2.4	19	2	2.3	1.0	25	2	1.6	1.0	26	2	1.6	1.0
	3.2	21	2	2.3	1.0	27	2	1.6	1.0	29	2	1.6	1.0
	4.8	22	2	2.3	1.0	29	2	1.6	1.0	31	2	1.6	1.0
	6.4	23	2	2.3	1.0	31	2	1.6	1.0	32	2	1.6	1.0
4	0.4	7	2	2.3	1.0	6	2	1.6	1.0	3	2	1.6	1.0
	0.8	16	2	2.3	1.0	20	2	1.6	1.0	20	2	1.6	1.0
	1.2	22	2	2.3	1.0	30	2	1.6	1.0	32	2	1.6	1.0
	1.6	26	2	2.3	1.0	35	2	1.6	1.0	39	2	1.6	1.0
	2.4	28	2	2.3	1.0	39	2	1.6	1.0	44	2	1.6	1.0
	3.2	30	2	2.3	1.0	42	2	1.6	1.0	47	2	1.6	1.0
	4.8	31	2	2.3	1.0	44	2	1.6	1.0	50	2	1.6	1.0
	6.4	32	2	2.3	1.0	46	2	1.6	1.0	52	2	1.6	1.0
5	0.4	10	4	2.3	1.0	10	3	1.6	1.0	7	2	1.6	1.0
	0.8	24	4	2.7	1.0	33	3	1.6	1.0	37	2	1.6	1.0
	1.2	29	4	2.9	1.0	42	3	1.6	1.0	47	2	1.6	1.0
	1.6	33	4	3.0	1.0	47	3	1.6	1.0	54	2	1.6	1.0
	2.4	35	4	3.2	1.0	51	3	1.6	1.0	59	2	1.6	1.0
	3.2	37	4	3.3	1.0	54	3	1.6	1.0	63	2	1.6	1.0
	4.8	39	4	3.5	1.0	56	3	1.6	1.0	66	2	1.6	1.0
	6.4	40	4	3.6	1.0	57	3	1.9	1.0	68	2	1.6	1.0
6	0.4	14	7	2.9	1.0	17	6	1.6	1.0	16	4	1.6	1.0
	0.8	33	7	3.6	1.0	47	6	2.0	1.0	54	4	1.6	1.0
	1.2	39	7	4.3	1.0	56	6	2.3	1.0	65	4	1.6	1.0
	1.6	41	7	4.4	1.0	59	6	2.5	1.0	70	4	1.6	1.0
	2.4	44	7	4.8	1.0	62	6	2.9	1.0	75	4	1.6	1.0
	3.2	46	7	4.9	1.0	65	6	3.0	1.0	80	4	1.6	1.0
	4.8	48	7	4.9	1.0	68	6	3.0	1.0	84	4	1.6	1.0
	6.4	50	7	5.0	1.0	71	6	3.1	1.0	87	4	1.6	1.0
7	0.4	22	12	3.3	1.2	32	12	2.2	1.0	35	10	1.6	1.0
	0.8	44	12	3.7	1.4	63	12	2.6	1.0	75	10	1.6	1.0
	1.2	50	12	4.6	1.5	71	12	2.7	1.0	84	10	1.6	1.0
	1.6	53	12	4.8	1.6	74	12	2.8	1.0	90	10	1.6	1.0
	2.4	56	12	4.8	1.7	79	12	2.9	1.0	95	10	1.6	1.0
	3.2	58	12	4.9	1.8	82	12	3.0	1.0	100	10	1.6	1.0
	4.8	60	12	4.9	1.9	85	12	3.0	1.0	104	10	1.6	1.0
	6.4	62	12	5.0	1.9	87	12	3.1	1.0	108	10	1.6	1.0

Note: 1 km = 0.6 mile.
[a]Values are from Highway Capacity Manual (1, Table 10.10, p. 305).
[b]Values are from Highway Capacity Manual (1, Table 10.11, p. 306).
[c]Recreational vehicles.
[d]Passenger vehicles.

Table 2. Average generalized passenger car equivalents of trucks, buses, recreational vehicles, and passenger cars on two-lane highways by terrain.

Vehicle	Level of Service	Equivalent by Terrain[a]		
		Level	Rolling	Mountainous
Truck	A	2.0	4.0	7.0
	B and C	2.2	5.0	10.0
	D and E	2.0	5.0	12.0
Bus	A	1.8	3.0	5.7
	B and C	2.0	3.4	6.0
	D and E	1.6	2.9	6.5
Recreational vehicle	A	2.2	3.2	5.0
	B and C	2.5	3.9	5.2
	D and E	1.6	3.3	5.2
Passenger vehicle	A	1.0	1.3	2.3
	B and C	1.0	1.0	2.5
	D and E	1.0	1.0	1.0

[a]Some of the values for trucks and buses have been readjusted from those given in the Highway Capacity Manual (1, Table 10.9a, p. 304).

Table 3. Relation of maximum grades to design speed on main highways.

Terrain	Design Speed (km/h)							
	50	65	80	100	105	110	120	130
Level	6	5	4	3	3	3	3	3
Rolling	7	6	5	4	4	4	4	4
Mountainous	9	8	7	6	6	5	—	—

Note: 1 km = 0.6 mile.

PASSENGER CAR EQUIVALENCIES FOR TRUCKS, BUSES, AND RECREATIONAL VEHICLES FOR USE IN HIGHWAY CAPACITY CALCULATIONS

Performance of recreational vehicles can be predicted with reasonable accuracy by a linear equation whose coefficients are related to vehicle characteristics. The vehicle characteristics considered include maximum acceleration capability, maximum speed, power, weight, rear axle and transmission gear ratios, drag coefficient, frontal area, and air-mass density. A vehicle simulation model, developed by A. D. St. John of the Midwest Research Institute and incorporating various equations, was used along with Newton's basic laws of motion to derive average speeds on grades (3). The results for two-lane rural highways are shown in Figure 3. Figure 2 and Figure 3 can be used to determine the PCEs of recreational vehicles at various speeds.

Table 1 gives PCEs of recreational vehicles, trucks, and buses on two-lane highways on specific individual subsections or grades. Table 2 gives average generalized PCEs of trucks, buses, and recreational vehicles on two-lane highways over extended section lengths. The following rationale was used in preparing Table 2:

1. The average speed of trucks, buses, and recreational vehicles (and even to an extent passenger vehicles) decreases as they move from level terrain to rolling and then to mountainous terrain;
2. The average speed of all types of vehicles de-

creases as they move from level of service A to level of service E (capacity); and

3. The speeds were selected for various vehicles for level of service A for the different terrains based on spot speed studies and on experience and judgment regarding the performance of trucks, buses, and recreational vehicles relative to each other.

PCEs may be determined for passenger cars because field studies demonstrated that passenger cars are also susceptible to speed reductions on steep grades. However, the use of PCEs in highway capacity computations is not included because, by accepted definitions of levels of service, which incorporate speed, the values are meaningless.

The procedure given in the HCM for computing the service volume for a two-lane highway is

$$SV = 2000\,(V/C)\,W_L\,T_C\,B_C \qquad (5)$$

where

SV = service volume,
V/C = volume to capacity ratio,
W_L = adjustment factor for lane width and lateral clearance at a given level of service,
T_c = truck adjustment factor, and
B_c = bus adjustment factor.

Equation 5 may be modified to account for the effect of recreational vehicles as follows:

$$SV = 2000\,(V/C)\,W_L\,T_C\,B_C\,R_C \qquad (6)$$

where R_c = recreational vehicle adjustment factor.

Equation 6, however, can introduce errors in capacity and service volume calculations. Rather than consider the adjustment factors separately to convert from the base volume into a mixed volume, equation 7 suggests a procedure that considers trucks, buses, and recreational vehicles in combination instead of separately.

$$C_c = 100/(100 - P_t - P_b - P_r + P_tE_t + P_bE_b + P_rE_r) \qquad (7)$$

where

C_c = combined adjustment factor,
P_t = percentage of trucks
P_b = percentage of buses,
P_r = percentage of recreational vehicles,
E_t, E_b, and E_r = PCEs for trucks, buses, and recreational vehicles respectively.

The importance of combining the adjustment factors as shown in equation 7 was tested, and the percentage of error introduced in capacity and service volume calculations by considering the factors separately could range as high as 10 to 20 percent for mountainous terrain. In general when the adjustment factors are considered separately the following errors result:

1. As the PCEs increase, the resulting error increases;
2. As the percentage of vehicles other than passenger cars increases, the resulting error increases; and
3. As the number of variables increases, the resulting error increases.

Conditions on the Canadian transmountain two-lane highway system cause high PCEs. These conditions include steep grades and a high percentage of vehicles other than passenger cars. Thus, equation 6 may be written as follows:

$$SV = 2000\,(V/C)\,W_L\,C_c \qquad (8)$$

SOME BASIC PROBLEMS IN DETERMINATION OF EQUIVALENCIES AND USE OF HIGHWAY CAPACITY EQUATION

In performing highway capacity (service volume) calculations over extended section lengths, one should correctly classify the highway section under consideration. Table 3 provides a guideline to correct classification. However, in many cases classifying the site according to terrain still remains difficult. Therefore to test the sensitivity of the effect of incorrect road classification, and also the manner in which recreational vehicles can be handled, computations were performed for a section of two-lane highway with the following characteristics:

Speed limit, 100 km/h (60 mph)
Travel lanes, 3.75 m (12 ft)
Shoulders, 3.0 m (10 ft)
Passing sight distance, 80 percent
Traffic composition—trucks 2 percent, buses 1 percent, recreational vehicles 19 percent

The results of the calculations are given in Table 4. A wide range of values results when recreational vehicles are considered as passenger cars, trucks, buses, or recreational vehicles. The table also illustrates the values for various terrains.

SENSITIVITY ANALYSIS

PCEs for trucks, buses, or recreational vehicles at the slower speeds, i.e., less than 50 km/h (30 mph), increase rapidly as speed decreases; the PCE varies greatly for a small change in speed. Sensitivity testing was conducted on the simulation model developed for recreational vehicles; the results are given in Table 5. In summary, power, mass, rear axle ratio, and altitude are highly sensitive variables in the model. Frontal area and coefficient of drag are not so sensitive.

Because the variables mass and power cause large changes in speed, the testing was continued to include highway capacity calculations. For the 9 percent grade under consideration with 80 percent passing-sight distance, traffic composition was assumed to be 80 percent passenger cars and 20 percent recreational vehicles with no buses or trucks. The results are given in Table 6. The two variables tested (power and mass) were reduced 10 percent, and the capacity at level of service E was changed from 1080 to 560 vehicles/h and 1080 to 1780 vehicles/h—changes of 51.8 percent and 64.8 percent respectively. These values appear very unrealistic, particularly the capacity value of 560 vehicles/h for the power variable at a speed of 39.3 km/h (24.4 mph), which is near the speed of a roadway running at or near capacity. Such values cause the PCE-speed curves to be suspect and suggest that the equivalencies are obviously too high at the slower speeds.

To further substantiate this hypothesis, another approach was taken. The maximum capacity of 2000 passenger cars/h/lane was arrived at by observing the minimum headways of passenger cars at various speeds (Figure 4, 1) and then applying the relationship.

$$\text{Volume} = \text{speed/spacing} \qquad (9)$$

A familiar bell-shaped volume-speed curve (Figure 4) results from the above relationship.

In the headway study of recreational vehicles, the PCE for recreational vehicles was approximately 1.6

for 1000-vehicles/h flow for the lane studied. Assuming that the space occupied by a recreational vehicle is 1.6 times that of a passenger car, a volume-speed curve for recreational vehicles can be derived by applying equation 8 (Figure 5). Because the new curve depicts 100 percent recreational vehicles, PCEs can be derived by applying equations 7 and 8. The resulting PCE-speed curve at capacity is shown in Figure 6.

The location of the new PCE-speed curve exhibits a drastic shift to the left with a great discrepancy in values

Figure 4. Distance headway-speed relationship for passenger cars.

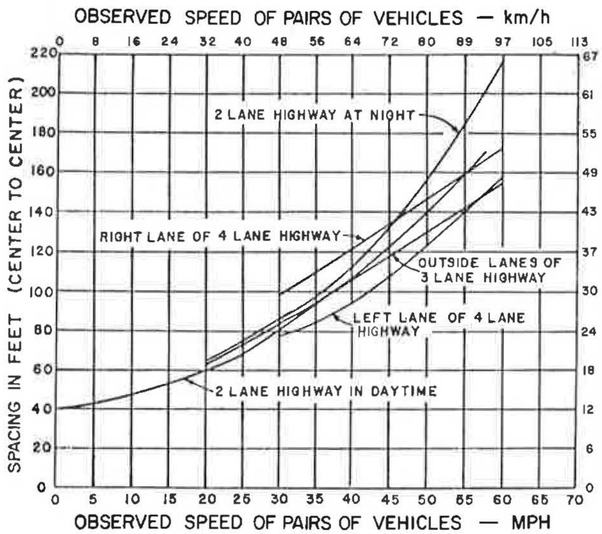


Figure 5. Daytime passenger car-recreational vehicle speed-volume relationship based on minimum headway spacing for two-lane highway.

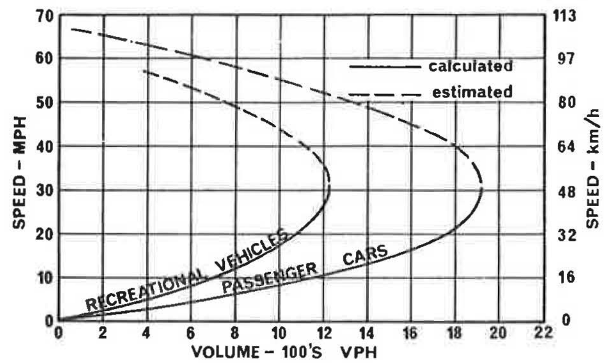


Table 4. Capacity of two-lane highway based on terrain, level of service, and recreational vehicle equivalent.

Terrain	Level of Service B	C	D	E	Recreation Vehicle Equivalent
Level	677	1180	1579	1949	Passenger car
	531	925	1421	1754	Recreational vehicle
	572	997	1421	1754	Bus
	555	967	1328	1639	Truck
Rolling	634	1105	1474	1820	Passenger car
	423	737	1055	1302	Recreational vehicle
	449	782	1110	1370	Bus
	376	655	871	1076	Truck
Mountainous	556	968	1271	1564	Passenger car
	345	602	781	965	Recreational vehicle
	321	560	698	862	Bus
	238	415	481	594	Truck

Note: All calculations are based on procedure used for combined adjustment factor (C_c) and PCEs given in Table 2.

Table 5. Sensitivity of variables in simulation model for vehicle performance on 9 percent grade.

Variable				Absolute Speed After 40 s (m/s)			Absolute Speed At 9.66 km (m/s)			Average Speed (m/s)			Average Speed Over 9.66 km (m/s)		
Name	From	To	Change (%)	From	To	Change (%)	From	To	Change (%)	From	To	Change (%)	From	To	Change (%)
Time, s	1.00	0.75	25.0	10.1002	10.0977	0.03	9.3130	9.3130	0.00	12.8246	12.8413	0.13	9.4684	9.4601	0.09
	1.00	1.25	25.0	10.1002	10.0446	0.55	9.3130	9.3130	0.00	12.8246	12.7900	0.27	9.4684	9.4659	0.03
	1.00	2.00	100.0	10.1002	9.9255	1.73	9.3130	9.3130	0.00	12.8246	12.6860	1.08	9.4684	9.4588	0.10
	1.00	3.00	300.0	10.1002	9.9710	1.28	9.3130	9.3130	0.00	12.8246	12.6934	1.02	9.4684	9.4595	0.09
	1.00	5.00	500.0	10.1002	9.9500	1.49	9.3130	9.3130	0.00	12.8246	12.6307	1.51	9.4684	9.4558	0.13
	1.00	8.00	800.0	10.1002	9.3562	7.37	9.3130	9.3130	0.00	12.8246	12.1189	5.50	9.4684	9.4226	0.48
Drag coefficient	0.60	0.65	8.33	10.1002	9.9055	1.92	9.3130	9.1288	1.98	12.8246	12.7011	0.96	9.4684	9.2832	1.96
Rear axle ratio	3.00	3.30	10.00	10.1002	10.9564	8.48	9.3130	10.8712	16.73	12.8246	13.2170	3.06	9.4684	10.9799	15.96
Frontal area, m^2	4.18	4.65	11.11	10.1002	9.9418	1.57	9.3130	0.0708	2.60	12.8246	12.7330	0.71	9.4684	9.2298	2.52
Power, kW	187.69	168.90	10.00	10.1002	8.8351	12.53	9.3130	7.2517	22.13	12.8246	12.2129	4.77	9.4684	7.4346	21.48
Mass, kg	3725.92	3316.59	10.00	10.1002	11.1208	10.10	9.3130	11.0869	19.05	12.8246	13.3084	3.77	9.4684	11.1908	18.19
Altitude, m	1890	1372	27.41	10.1002	10.9974	8.88	9.3130	10.8904	16.94	12.8246	13.2622	3.41	9.4684	11.0011	16.19
		Sea level[a]		10.1002	12.1281	20.07	9.3130	12.2544	31.58	12.8246	13.9886	9.08	9.4684	12.4990	32.00

Note: 1 m/s = 3.281 ft/s; 1 kg = 2.205 lb; 1 kW = 1341 hp; 1 m = 3.281 ft; 1 m^2 = 10.764 ft^2.

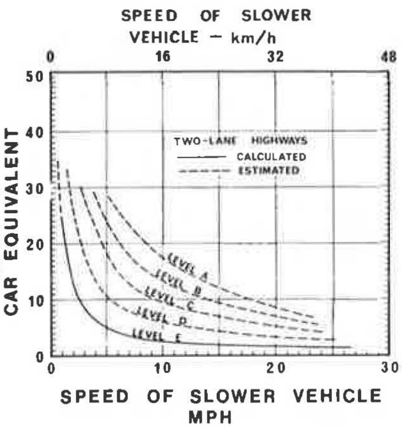
[a]At sea level, vehicle was subject to cyclic gear changes; therefore, absolute speeds are not too meaningful.

Table 6. Effect of varying power and mass of recreational vehicles on passenger car equivalents and service volumes on 9 percent grade using 80 percent passenger cars and 20 percent recreational vehicles.

Item	Power: From 187.7 kW	To 168.9 kW	-10.0% Change	Mass: From 3725.9 kg	To 3316.6 kg	-10.0% Change
Speed, km/h						
Avg over 10 km	50.1	39.3	-21.5	50.1	59.1	+18.2
Levels of service B and C	6.8	12.0	+76.5	6.8	4.0	-41.2
Levels of service D and E	5.2	15.3	+194.2	5.2	1.6	-225.0
Vehicles per hour						
Service level B	322.0	217.0	-32.6	322.0	434.0	+34.8
Service level C	561.00	378.0	-31.7	561.0	756.0	+34.8
Service level D	875.00	454.0	-51.9	875.0	1441.0	+65.8
Service level E	1080.00	560.0	-51.8	1080.0	1780.0	+64.8

Note: 1 km = 0.6 mile; 1 kg = 2.20 lb; 1 kW = 1.341 hp.

Figure 6. Estimated placement of passenger car equivalent speed curves for two-lane highways.



at very slow speeds and, to a lesser extent, at higher speeds. Similar curves may exist for other levels of service as shown by the dotted lines in Figure 6.

FUTURE WORK

During our investigation several questions became evident; we present them here in the form of suggestions for further research.

1. A more precise definition of terrain is required to correctly classify extended highway subsections. Perhaps the British terms "hilliness" and "bendiness" might be applied to North America. Hilliness is defined as the total rise and fall per unit of distance, and bendiness, the total change of direction per unit of distance.
2. The present concept of level-of-service measures is primarily based on the idea that speed should be reevaluated. Reevaluation is necessary because many agencies are adopting the 88-km/h (55-mph) speed limit and the volume/capacity ratios for the different speeds are felt to be no longer valid. By the speed definition level of service A no longer exists.
3. The methods for determining PCEs of slower vehicles need to be reviewed. The validity of the PCE for vehicles at very slow speeds is doubtful.

CONCLUSIONS

The research project was able to uncover the underlying methods for generating PCEs and replicate the PCE-speed curves contained in the HCM. By applying the same principles with a vehicle simulation model, adjustment factors for recreational vehicles were derived. However, subsequent work in applying the new adjustment factors to a field site and in carrying out sensitivity testing in highway capacity computations produced strong evidence that the new adjustment factors and those for trucks and buses contained in the HCM may not be valid and may require further refinement. There is a need for further research for the determination of PCEs of larger and slower moving vehicles for two-lane rural highways.

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Discussion

Arthur A. Carter, Office of Traffic Operations, Federal Highway Administration

The authors should be commended for undertaking this research. The increasing presence of recreational vehicles in the traffic stream in Canada is, of course, equally evident in the United States, and the findings, therefore, are equally needed here. I am familiar with the work, having corresponded with Werner on several occasions regarding it and having reviewed the complete report on which this paper is based.

Two particular factors distinguish the recreational vehicle problem from the overall problem of slow-moving vehicles in the traffic stream. First, the largest concentrations of recreational vehicles are likely to be found on those very highways least appropriate for expansion to multilane design because of environmental considerations—highways in or near parks or other scenic attractions. Second, some recreational vehicle drivers are relatively unfamiliar with their vehicles, as compared to typical truck and bus drivers, and drive hesitantly, erratically, and sometimes carelessly. The problem, then, is a real one not subject to easy correction. It needs to be included in highway capacity criteria. The authors' contribution to development of an understanding of it is therefore welcome. The fact that their work was based on detailed studies of actual traffic flows in western Canada lends credibility to the findings.

Particularly welcome is their reporting of results in a format directly supplementing the tables in the 1965 HCM. Anyone familiar with HCM procedures can immediately apply the new findings.

In this connection, the authors express concern regarding the "error" presumably introduced by using three separate adjustment factors for trucks, buses, and recreational vehicles individually as multipliers, as would be done if the HCM procedures are followed. They suggest substitution of an overall combined adjustment factor, particularly where many vehicles other than passenger cars are in the traffic stream, and equivalencies are

large as in mountainous terrain. This discrepancy between the two methods was recognized in the past, but rarely was it a problem. Seldom were bus volumes large enough to warrant an adjustment separate from that for trucks. At the time that the current procedures were completed, simplicity of use of separate multipliers, given the limited precision of the overall method, overshadowed any potential refinement of a combined factor. Now, with allowance necessary for large volumes of recreational vehicles as well as significant volumes of tour buses on the same recreational routes, the authors are fully justified in again suggesting a refined procedure.

The authors refer to the Walker method for deriving vehicle equivalencies as having been the basis for much of their work on performance on grades. The method, which appears somewhat complex as summarized briefly here, is the procedure that was used in development of equivalencies reported by Schwender, Norman, and Granum (6). The detailed procedures were never formally published, but W. P. Walker of the then Bureau of Public Roads retained them in his files. In the mid-1960s they were applied to develop the equivalencies for all levels of service on two-lane, two-way highways, which appear in chapters 5 and 10 of the 1965 HCM, and several researchers have recently applied them in Europe and elsewhere.

Questions have since been raised regarding the validity of the resulting equivalencies and about the method itself. In particular, the logic of the relationships between comparable values at the several levels of service has been debated, since the values contradict in some respects the original values appearing in the Schwender, Norman, and Granum paper (6), which represented three levels of operation at and near current level of service B. Further questions could be raised regarding the present-day validity of the data to which the method was applied in the 1950s and the 1960s. But the authors appear to have found the basic concept of the methods acceptable. Further, their Figure 2 generally confirms the relationships between levels of service as shown in Figure 5.6 in chapter 5 of the HCM, if not the absolute values. By using the concept, they have produced results consistent with the HCM.

Interestingly the curves for lower speeds shown in Figure 5, which the authors derived partially on speculation by using headway concepts and equations developed by A. D. St. John of Midwest Research Institute, have relationships contradicting Figure 2. That is, the order of the family of curves is reversed. The logic of this reversal is questionable. The figure did not appear in earlier work on which this summary paper was based, but that work did include discussion of the differing equivalencies obtained by the "passing" versus the "headway" methods. The larger of the two equivalencies was preferred, but the reversal problem was not mentioned.

The authors have gradually changed their viewpoint, as they have further analyzed their work, and now see increasing validity in the headway-derived values, which produce lower equivalencies. This whole topic is open to question. Historically, the headway approach has proved subject to pitfalls. The widely varying results shown in Figure 1 of the original 1950 HCM graphically illustrate this point. In particular, wide errors have occurred in predicting overall hourly traffic performance from the performance of one-directional platoons of vehicles on two-lane, two-way highways.

Capacities and flow rates on such highways must be quoted as totals for both directions because of the shared use of lanes for basic flows and opposing-direction passing. "By-lane" flow rates have proved to be misleading and usually excessive, unless carefully interpreted. (St. John of Midwest Research Institute is contending with this problem and has recently developed some interesting views.)

The point that the authors raise regarding passenger car performance deterioration on long steep grades is well taken. Policy of the American Association of State Highway Officials indicates that most passenger cars can negotiate grades up to 7 or 8 percent without appreciable speed loss. The HCM is slightly more conservative and states that capacity is seldom affected by passenger car performance on such grades; that is, they can almost always maintain the 48.27 to 56.32-km/h (30 to 35-mph) speeds at which capacity occurs. The latter appears to be more likely today; the better levels of service, requiring higher speeds, are being increasingly influenced by the reduced performance found in many modern cars.

In a related matter, the authors recommend that the entire level of service-speed scale be reevaluated in the light of the national 88.5-km/h (55-mph) speed limit. This would seem to be premature. Admittedly, level A performance is not now permitted, but the scales are based on driver desire, not performance. Until and unless drivers come to accept 88 km/h (55 mph) more fully than they do now, labeling this speed as level A seems incorrect.

In summary, the authors have provided a much-needed, practical, immediately useful addition to the state of the art in their expansion of the Walker, or passing, method to cover recreational vehicles. Their findings with respect to the headway method appear more speculative.

I hope that this research can be used with other recent relevant studies (particularly those under the National Cooperative Highway Research Program by St. John, who, incidentally, used the authors' field data) for eventual development of updated equivalency procedures suitable for replacement of the current HCM procedures.

Authors' Closure

We wish to comment briefly on some of the important points stressed by Carter. We agree that our viewpoint has changed during the course of our recreational vehicle project and now see increasing validity in the headway-derived values. However, as correctly stated by Carter, the entire topic is open to question. Our recommendation that the entire level of service-speed scale be reevaluated still stands. In the mountainous regions of British Columbia, where the speed limit is 88.5 km/h (55 mph), two-lane highways wind along cliffs, and a high percentage of trips are highly recreational, drivers may not experience level of service A performance as defined in the HCM. However, under these circumstances this speed may well be their desire. We agree that the next stage of research should be in conjunction with the recent work of St. John.