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Capacity, Speed, and Platooning Vehicle Equivalents for Two-Lane Rural Highways

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ABSTRACT

Passenger car equivalents (pce's), derived for purposes of capacity, speed, and platooning analyses, are examined using literature sources and traffic data analyzed for 37 different two-lane rural highway sites in Ontario. Speed pce's for trucks and recreational vehicles were found to be considerably higher than those presently used for most types of standard capacity analyses. Truck pce values were found to be 11.4, 6.1, and 3.8 for the 10th, 50th, and 90th percentile speeds, respectively. Corresponding pce values for recreational vehicles were determined as 3.9, 3.7, and 2.6, and the opposing direction pce was found to be 0.5 for all percentiles. The relative effects of trucks and recreational vehicles, in terms of the creation of platoon followers, were found to be much smaller than the corresponding equivalents for speed. Platoon follower pce's for trucks, recreational vehicles, and opposing direction vehicles were 1.23, 1.23, and 0.06 for low traffic volumes and 1.20, 1.07, and 0.07 for high traffic volumes. Platoon leader pce's were 1.55 for recreational vehicles, and 2.0 and 1.35 for trucks on recreational and commuter routes, respectively.

Volumes of different vehicle types and different directions of travel affect the operational characteristics of two-lane two-way rural highways in different ways and to different extents. The analysis of a nonhomogeneous stream of vehicles is therefore often simplified if the relative effect of each vehicle type can be expressed in terms of passenger car equivalent (pce) units. Passenger car equivalents have been quoted for different vehicle types, terrains, levels of service, and rural and urban settings because they can vary with these factors.

Past and current use of vehicle equivalents for trucks, recreational, and opposing direction vehicles on rural two-lane highways on relatively level terrain is reviewed. Specifically, the current practice and literature on pce's are surveyed and these findings are compared with pce values derived from a comprehensive data collection project in Ontario. Because pce's differ for capacity, speed, and platooning analyses, pce values are examined separately for each of these measures. Some of the reasons for these discrepancies are examined.

CURRENT PRACTICE AND LITERATURE ON PCE VALUES

A variety of pce derivations based on capacity analysis are found in the literature, and others pertain to service volumes, speed reduction, or platooning. Separate literature reviews were carried out for each, and the most relevant and significant of these findings are summarized in this section. A comparison of literature estimates and those found in Ontario is provided at the end of the paper.

Capacity-Based Vehicle Equivalents

Vehicle equivalents have most commonly been used for analyses of capacity and level of service. Capacity-based pce estimates have been made by the Highway Capacity Manual (1), the Organization for Economic Co-operation and Development (OECD) (2), Werner et al. (3), Werner and Morrall (4), Walton and Lee (5), Cunagin and Messer (6), Yagar (7), and Krumins (8).

The Highway Capacity Manual (HCM) (1) assumes that both the level of service and capacity of a two-lane rural highway are directly related to the combined two-way volume, regardless of directional split. This implies a vehicle equivalent of 1 for opposing direction traffic. The HCM also provides estimates of truck and bus equivalents for different grade and level of service considerations. However, an OECD report (2) indicates that several countries, including the United States, Denmark, and the Federal Republic of Germany, have evidence that many of the equivalents given in the HCM may be too high.

Werner et al. (3) determined that, for rolling or mountainous terrain, recreational vehicles had a greater impact on capacity than passenger cars but a smaller impact than trucks. Werner and Morrall (4) also found average passenger car equivalents for trucks, buses, and recreational vehicles for two-lane Alberta highways on level terrain. Walton and Lee (5) explained the reduction in estimates of truck equivalency factors in terms of changes in truck engine performance and typical truck weight-to-power ratios. Cunagin and Messer (6) determined pce's for flat terrain, two-lane rural highways based on a combination of the Walker spacial headway and equivalent delay methods. They found truck equivalents to range from 1.5 to 1.7, for 5 percent trucks, and from 1.5 to 2.0, for 25 percent trucks. The ranges indicate the variability due to differences in volume levels from levels of service A to E.

Because of a universal shortage of data, little quantitative research has been done on vehicle equivalents at ultimate capacity. Two-lane highways are seldom allowed to reach their ultimate two-way capacity, and data are therefore very difficult to obtain.

Curves 1-3 in Figure 1 show the capacity relationships that have been proposed by the HCM (1), Krumins (8), and Yagar (7), respectively. The HCM curve considers a constant opposing direction vehicle equivalent of 1.0, regardless of directional split, and Krumins (8) and Yagar (7) propose much smaller magnitudes of opposing volume impacts. The relationship proposed by Krumins (8) implies an increasing marginal impact as opposing volumes increase, and the Yagar (7) curve suggests that opposing direction pce values decrease in a continuous fashion toward zero as opposing volume increases, indicating that high volumes can be achieved simultaneously in both directions. This is supported by traffic volume data from Australia and Canada, which are plotted in Figure 1. Note that the characteristics of the Canadian highway on which the lower volumes in Figure 1 were recorded were far from ideal, with one-way capacity considerably fewer than 2,000 vehicles per hour. Thus both data points suggest very low capacity pce's for opposing volumes as the directional split approaches 50 percent.

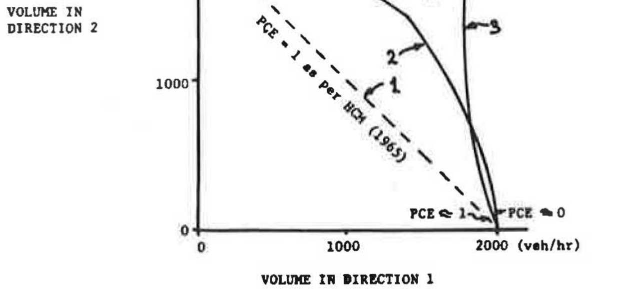

FIGURE 1 Comparison of opposing direction pce's for an ideal two-lane highway.

Speed Reduction-Based Equivalents

Passenger car vehicle equivalents have also been estimated from the relative sizes of the speed reductions caused by equal volumes of each vehicle type. Passenger car equivalent estimates, based on ratios of speed reduction coefficients for different vehicle types and different directions of travel, have been made by Normann (9), Duncan (10), Craus et al. (11), and Krumins (8).

In a study of highway capacity in 1934-1935, Normann (9) found a ratio of opposing direction to main direction speed reduction coefficients of about 0.7. Duncan (10) carried out a similar investigation of speed-volume relationships, in terms of light and heavy vehicles in the main and opposing directions, for 17 two-lane roads. The ratio of the average speed-reduction coefficients indicated a heavy vehicle pce of 15, and an average of coefficient ratios produced a pce ratio of 7.5. The ratio of the opposing-to-main-line effect was about 2:3. In Canada, Krumins (8) used a linear regression model to predict main-line speeds and estimated these speeds to be about seven times more sensitive to main-line volumes than to opposing direction traffic volumes, which differs markedly from the findings of Normann and Duncan.

Craus et al. (11) reviewed current approaches to pce determination and suggested a revised method based on the ratio of delay caused by one truck to the delay caused by one passenger car. They found the main tendencies and fluctuations of pce's, as a function of level of service and truck speed, to be similar to those in the HCM (1).

Because of the difficulty in setting up a controlled experiment on the highway, computer simulation techniques have been used to estimate the effects of different vehicle types and to establish speed pce values. The most significant contributions in this area have been made by Taylor et al. (12), Stock and May (13), St. John (14), and St. John and Kobett (15).

Taylor, Miller, and Ogden (12) suggest, based on simulation techniques, that the proportion of trucks in the flow does not significantly affect speeds for gradients below 3 percent. They also suggest an upper limit for the proportion of trucks in the traffic flow above which the effect of an increasing proportion of trucks is not as great. This critical proportion was found to lie between 0.05 and 0.08, the higher value corresponding to higher gradients.

Using the simulation model SIMTOL, Stock and May (13) also found that the HCM may overestimate the detrimental effect of trucks on steeper grades. Using a microscopic simulation model, A.D. St. John (14) proposed that the truck factor, currently of linear form, should be nonlinear. He reasoned that each incremental addition of slow vehicles to the traffic flow affects the speed less than the former one, because speeds have already been somewhat depressed. St. John and Kobett (15) found that the current form of the truck factor neglects nonlinear effects and inaccurately estimates the effects of heterogeneous truck populations.

Platooning-Related Equivalents

Although platooning and platoon follower equivalents are not quoted specifically in the literature, some vehicle-type effects on platooning can be derived from studies of overtaking or passing behavior.

Troutbeck (16) conducted an extensive study of overtaking behavior on Australian rural highways and found that large vehicles are more difficult to pass than small ones and are therefore more likely to become platoon leaders. He found mean overtaking times to increase with the length of the overtaken vehicle but concluded that further differences in overtaking behavior could not be attributed to either the height or the configuration of heavy vehicles of a given length. Morrall and Werner (17) studied the opposing traffic flow effect on platooning and suggested that not only the magnitude of the opposing volume but also its spacing was critical. They indicated that an opposing hourly volume of only 200 vehicles could prevent all safe overtaking if all vehicles traveled at uniform headways of 18 sec.

Summary of Literature Review

There have been a number of efforts to determine pce values for various conditions, but most of these efforts have focused on recalibrating or slightly modifying the methods outlined in the HCM (1), which in turn go back to Normann (9) and Wardrop (18). This strict adherence to the HCM procedure has resulted in most findings being inadequate in two major areas:

1. Passenger car equivalents have generally been assumed to be similar for capacity, speed, platooning, and other types of analysis. This notion appears to be incorrect and is perhaps one of the main sources of discrepancies among the various pce studies.
2. Capacity, level of service, and pce analyses have been based on combined two-way volume counts. However, recent findings (7,8,19,20) have shown the operational characteristics of two-lane rural highways to be mainly a function of directional volumes, suggesting the need for a re-evaluation of all pce's on a directional basis.

ESTIMATING PCEs FOR TWO-LANE RURAL HIGHWAYS IN ONTARIO

The literature indicated there is no universal pce equivalent that can be used for all purposes. Rather, each analysis should be based on the pce's determined for that particular application. This is illustrated by estimating the respective types of pce's for Ontario's two-lane rural highways. Because there were not enough data available for estimating capacity pce's, the Ontario analyses, which are described, consider only speed and platooning pce's. These are compared with the various values obtained from the literature at the end of the paper. The data used for this purpose, and the details of the analyses, are described.

Data Collection

A total of 267,536 passenger cars, 14,021 trucks, 10,804 recreational vehicles, and 3,035 other vehicles were monitored on two-lane highways in Ontario between July 1 and October 8, 1980, using the radar-platoon technique. At 37 different sites a total of 441 hours of data were obtained for a total of 5,292 5-min time slices of speed-volume information. The data and the data collection sites are described in detail by Van Aerde and Yagar (21).

All data were collected using the radar-platoon technique (22), which records the speed of each platoon traveling in the main direction along with the vehicle types of the platoon leader and all of the followers in the platoon. Given that all vehicle speeds in a platoon are equal, this procedure yields a 100 percent sample of traffic volumes, and corresponding speed and platooning data. Data were collected in this manner in a series of 5-min time slice records, which also contained corresponding 5-min counts of vehicles traveling in the opposing direction.

ESTIMATING VEHICLE EQUIVALENTS IN TERMS OF SPEED REDUCTION

Passenger car equivalents are determined in this section based on the relative rates of speed reduction for each type of vehicle traveling in the main direction and for all vehicles combined traveling in the opposing direction.

Speed-volume relationships were compared for various study sections to establish patterns, special trends, and recurring general shapes. This analysis identified a general speed-volume curve shape consisting of two distinct parts: a linear section, which represents the normal operating conditions, and a nonlinear section, which represents a transition to a breakdown in flow as capacity is approached. This general shape is shown in Figure 2 using data for a typical site, Location 400S1.

Because the nearly linear section of the speed-volume curve represents the entire range of practical operating volumes, further study was focused on it. A linear approximation was found to fit the data at each of the locations that were studied, and was quantified by Van Aerde and Yagar (19) for each of the 10th, 50th, and 90th speed percentiles.

For purposes of analysis, a multiple linear regression model was structured as follows:

$$\begin{aligned}\text{Percentile speed} = \text{Free speed} &+ (C1 \cdot \text{Number of cars})\\ &+ (C2 \cdot \text{Number of trucks})\\ &+ (C3 \cdot \text{Number of recreational vehicles})\\ &+ (C4 \cdot \text{Number of other vehicles})\\ &+ (C5 \cdot \text{Number of opposing vehicles})\end{aligned}$$

to estimate the free speed and the speed-reduction coefficients C1-C5. Coefficients C1-C5 indicate the relative sizes of speed reductions for each vehicle type (or direction of travel) and permit pce values to be determined as follows:

$$\text{PCE for vehicle type } n = Cn/C1$$

However, the lack of large volume counts for some vehicle types at certain locations renders the estimates of some of these coefficients insignificant or unstable or both. Speed-reduction coefficients were therefore aggregated across all sites to obtain more significant and stable average results.

A simple average over all sites for a speed-reduction coefficient would include several insignificant values, and averaging only the statistically significant values would produce an estimate that is biased in favor of the more extreme positive values. Therefore, the variability in levels of significance

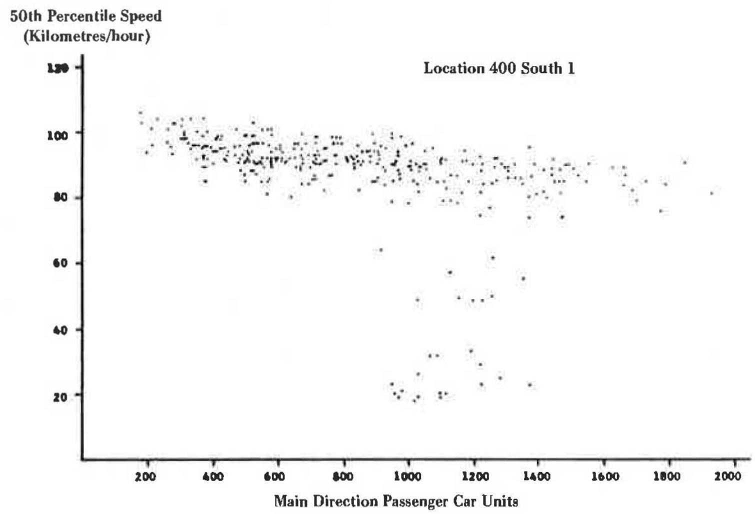

FIGURE 2 Generalized speed-volume relationship.

of the speed-reduction coefficients was incorporated in the analysis through the use of a weighted average, where each speed-reduction coefficient was weighted inversely proportional to its variance. The results of this aggregation are given in Table 1, with a free speed intercept and set of speed-reduction coefficients quoted for each percentile speed. In each case, the average estimate is provided along with an estimate of its standard error. Also, the calculated pce's (Cn/Cl) are quoted for trucks, recreational vehicles, and other vehicles in the direction being monitored and the total number of vehicles in the opposing direction.

Table 2 gives recommended pce values that were derived from Table 1 after accounting for statistical errors. Equivalents for trucks and recreational vehicles were left unchanged, and the equivalent for other vehicles was arbitrarily set to a default value of 1 (i.e., equal to cars) because there were insufficient data to estimate any significant value different from the 1.0 used for cars. Because there was only a slight variation of opposing direction pce's, they were set to 0.5 for all percentiles.

TABLE 1 Estimated Speed-Reduction Coefficients Aggregated Across All Sites

		Percentile Speeds		
		10th	50th	90th
Free speed intercept	Estimate	81.3	90.1	101.7
	Std. error	0.3	0.2	0.3
Speed reduction coefficients				
Main line				
Passenger Car	Estimate	-3.2	-5.2	-8.4
	Std. error	0.4	0.3	0.3
Trucks	Estimate	-36.4	-31.5	-30.7
	Std. error	0.4	2.9	3.2
	Equivalent	11.4	6.1	3.6
Recreational vehicles	Estimate	-12.4	-19.1	-22.1
	Std. error	3.6	2.7	2.9
	Equivalent	3.9	3.7	2.6
Other vehicles	Estimate	-3.6	5.6	7.7
	Std. error	7.5	5.4	5.7
	Equivalent	1.1	-1.1	-0.9
Opposing				
Total count	Estimate	-1.6	-2.4	-3.7
	Std. error	0.8	0.5	0.6
	Equivalent	0.5	0.5	0.4

TABLE 2 Estimated pce's for Speed Reduction Based on Ontario Data

		Percentile Speeds		
Direction	Vehicle Type	10th	50th	90th
Main line	Trucks	11.4	6.1	3.8
	Recreational	3.9	3.7	2.6
	Other	1.0	1.0	1.0
Opposing	All types	0.5	0.5	0.5

ESTIMATING VEHICLE EQUIVALENTS IN TERMS OF PLATOON LEADERS AND FOLLOWERS

In general, platooning is caused by fast vehicles catching up with slower vehicles and not being able to pass. Trucks, recreational vehicles, and buses often have lower desired speeds and poorer acceleration capabilities than standard passenger cars and are therefore more likely to be caught by faster vehicles than are passenger cars. In addition, once caught, the larger vehicles are more difficult to pass because their height, width, or length impairs the follower's sight and necessitates longer passing distances.

Traffic in the opposing direction also influences platooning on two-lane highways because any main-line passing maneuvers require acceptable gaps in the opposing traffic stream. Such acceptable gaps decrease, but at a decreasing rate, as vehicles are added to the opposing traffic stream. Platooning is also dependent on the distribution of the opposing traffic, which in turn depends on with-flow volumes. Platooning is therefore a function of an interaction term of the volumes in the two directions.

The following analysis will examine the impact on the extent of platooning in the main direction of different vehicle-type flows in the main direction and the total opposing direction vehicle flow. Although there can be several measures of the extent of platooning, the impact of each vehicle type is examined here in terms of platoon leaders and platoon followers.

The investigation of platoon leaders estimates the propensity of a vehicle type to become a platoon leader, and the number of followers provides a measure of how many vehicles are held up in platoons by the presence of such a vehicle in the traffic stream.

Platoon Creation

Large vehicles, such as trucks, buses, and recreational vehicles, have a higher individual propensity to become platoon leaders than do passenger cars. These leader propensities are analyzed using the ratio of percent leads, by vehicle type, to percent of total main-line traffic count, by vehicle type. Table 3 gives a summary of these ratios and then lists them normalized with respect to the original ratio for passenger cars to obtain pce's in terms of platoon leadership.

The summary in Table 3 indicates that trucks and recreational vehicles are, respectively, about 1.8 and 1.5 times as likely to be leaders as passenger cars, whereas other vehicles are not significantly different from passenger cars in this regard. The normalized ratios, which represent a form of pce's, were calculated for each location and are plotted separately for trucks and recreational vehicles in Figures 3(a) and 3(b), respectively.

Figure 3(a) shows the truck ratios clustered in two groups. For the upper group, which represents significant locations on commuter routes (7 and 85), trucks are 1.35 times as likely to lead as are passenger cars. For the second group, which represents the recreational routes (400 and 35), the truck ratio is nearly 2.0. This difference may be attributed to differences in drivers on these routes, to a decreasing marginal effect of trucks as the percentage of trucks in the traffic stream increases, or to a larger average size of trucks on the recreational highways, which tend to carry longer trips.

Estimates of generalized recreational vehicle ratios are made only for recreational routes because the percentage of recreational vehicles on commuter roads is too small to provide statistically significant results. Figure 3(b) indicates that, on recreational routes, recreational vehicles are more likely to lead than passenger cars by a factor of approximately 1.55.

TABLE 3 Platoon Leader Ratios by Vehicle Type

	Ratios	
Vehicle Type	Original[a]	Normalized[b]
Total vehicles	1.000	1.056
Passenger cars	0.946	1.000
Trucks	1.716	1.813
Recreational	1.386	1.464
Other	1.023	1.082

[a]Original ratio = percentage of leads by vehicle type divided by percentage of total count by vehicle type.

[b]Normalized ratio = original ratio for vehicle type divided by original ratio for passenger cars.

Follower Creation

Although platoons are identified by their leaders, leaders experience little frustration or reduction in safety as a result of being in a platoon. They are generally not delayed and, except for some pressure from the following vehicles, experience virtually perfect service. It is principally the followers who suffer the largest reduction in service; they may be delayed, frustrated, and even caused to attempt unsafe passing maneuvers.

The increase in the number of followers as a function of main-line traffic volume is shown in Figure 4 for two different locations. Because the relationship in nearly linear, except for a slight curvature at a volume of approximately 650 veh/hr, the number of followers can be modeled using piecewise linear functions with separate linear models fitted for the low- and high-volume regions. This is discussed in detail elsewhere (20,23). Based on a "knee" (change in slope) in the relationship at a volume of approximately 650 veh/hr (in the main-line direction) the number of followers was modeled using separate multiple linear models for traffic volumes between 100 and 650 veh/hr (low-volume range) and 650 to 2,000 veh/hr (high-volume range) as follows:

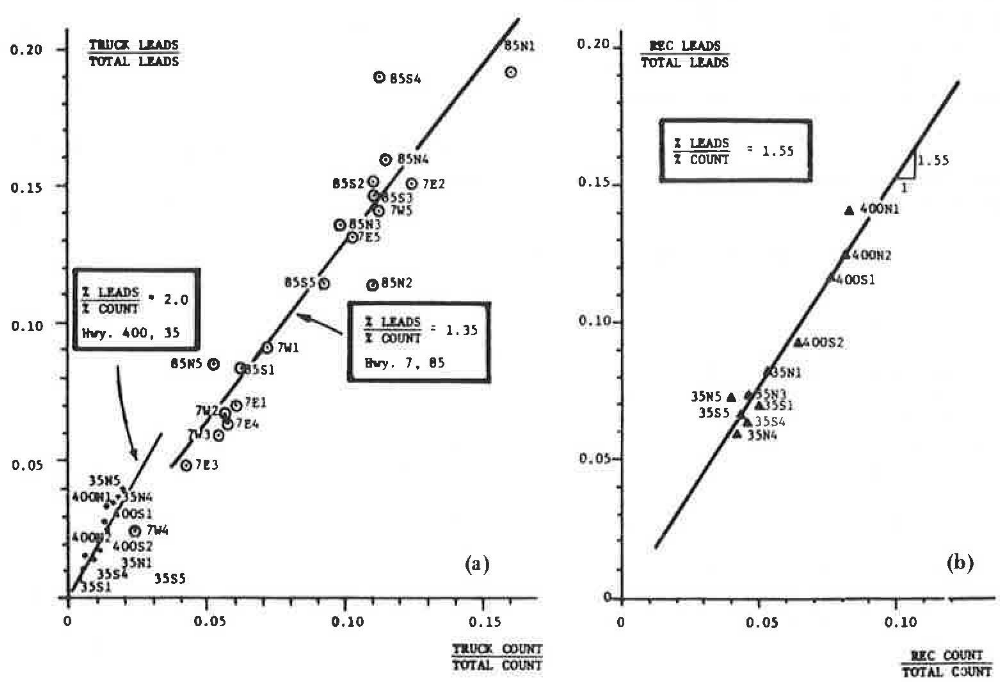

FIGURE 3 Ratios of platoon leaders to traffic volume: (a) trucks on commuter and recreational routes, (b) recreational vehicles on recreational routes.

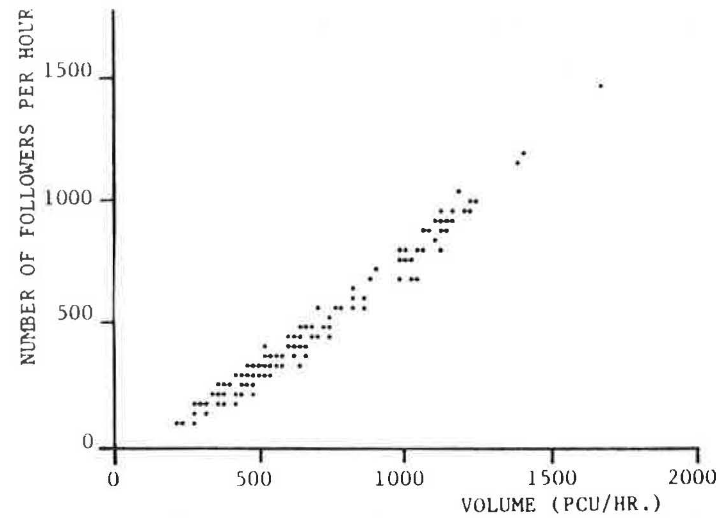

FIGURE 4 Typical relationship between number of followers and main-line volume.

Number of followers = A1 + B1 • Cars
+ B2 • Trucks
+ B3 • Recreational vehicles
+ B4 • Other vehicles
+ B5 • Opposing vehicles • main-line vehicles

In the models, coefficients B1-B5 estimate the rate at which the number of followers increases for each traffic volume component. Main-line vehicle-type coefficient (B1-B4) represent the number of additional followers produced per vehicle, and the opposing volume coefficient (B5) is quoted as the number of follower produced per opposing vehicle at a main-line volume of 1,000 veh/hr. The interaction term for opposing direction traffic volumes makes any opposing volume effect proportional to the total main-line volume. Therefore, the follower production due to traffic in the opposing direction is larger or smaller than the quoted coefficient when the main-line traffic volumes are larger or smaller, respectively, than 1,000 veh/hr.

Table 4 gives average vehicle-type follower coefficients and normalized follower production rates (i.e., quoted with respect to the car rate of 1.0) for the high- and low-volume region. Because the relative size of these rates represents the relative effect of different vehicles on platooning, the normalized ratios can be considered estimates of platooning pce's. For the low-volume region, pce's were calibrated using data from all two-lane highway sites, and those for the high-volume region were calibrated based on data from the mainly recreational routes (most of Ontario's commuter roads are upgraded before very high traffic volumes are reached).

In the low-volume range, trucks or recreational vehicles produce about 0.91 followers compared with cars, which produce only 0.74. This results in a pce of 1.23 (i.e., 0.91/0.74) and indicates that trucks and recreational vehicles produce, on the average, approximately 23 percent more followers than do passenger cars under the same conditions.

Follower production rates were higher in the high-volume region for all vehicle types and both directions of travel. The estimated truck pce decreased slightly, and standard error increased significantly, due mainly to the much smaller representation of trucks on the high-volume recreational routes. The recreational vehicle pce decreased from 1.23 to 1.07, but its standard error remained virtually the same. The smaller pce might be due to the increased representation of recreational vehicles on high-volume recreational routes, whereby they become an integral part of the traffic stream and have a significantly reduced marginal impact. Other vehicles also appear to have a larger pce in the high-volume region, although their estimate is based on fewer data than those for cars, trucks, recreational vehicles, or opposing flows.

The opposing direction coefficients indicate that opposing volume affects main-line platooning for all ranges of main-line traffic by merging a number of smaller platoons into fewer, but larger, platoons. Specifically, the presence of 1,000 opposing direction vehicles is estimated to increase the number of followers by approximately 35, 70, and 135 veh/hr for main-line traffic volumes of 500, 1,000, and 1,500, respectively.

TABLE 4 Passenger Car Equivalents in Terms of Number of Followers Produced

		Low-Volume Range		High-Volume Range	
Direction	Parameter	Avg Value	pce	Avg Value	pce
Main line	A Intercept	-81.1		-246.8	
	B1 Car	0.74	1.00	1.01	1.00
	B2 Truck	0.91	1.23	1.21	1.20
	B3 Recreational	0.91	1.23	1.08	1.07
	B4 Other	0.72	0.98	1.14	1.13
Opposing	B5 Total count	0.042	0.06	0.066	0.07

Note: Low-volume range, 100-650 veh/hr in main-line direction; high-volume range, 650-2,000 veh/hr in main-line direction.

COMPARISON OF ONTARIO'S RESULTS WITH PCEs FROM THE LITERATURE

The findings of this study for speeds were found to agree with some sources but were drastically different from others. Findings from the literature for capacity and speed analyses are given in Table 5, and Table 6 gives percentile speed, platoon follower, and platoon leader pce's estimated for Ontario's two-lane rural highways. Note that the speed percentiles in Table 6 do not correspond with levels

TABLE 5 Average Generalized pce's Found in the Literature

pce and Vehicle Type	Levels of Service A	B	C	D	E	Avg	Source
Capacity							
Truck	3.0	2.5	2.5	2.0	2.0		HCM (1)
	2.0	2.2	2.2	2.0	2.0	2.1	Werner and Morrall (4)
	1.5	1.6	1.6	1.6	1.7	1.6	Cunagin and Messer (6)
Bus	2.0	2.0	2.0	2.0	2.0	2.0	HCM (1)
	1.8	2.0	2.0	1.6	1.6	1.8	Werner and Morrall (4)
Recreational vehicle	2.2	2.5	2.5	1.6	1.6	2.1	Werner and Morrall (4)
Opposing vehicles						1.0	HCM (1)
	1±				0+		Yagar (7)
Speed							
Truck						15.0	Duncan (10)
Opposing vehicles						1.00	HCM (1)
						0.7	Normann (9)
						0.66	Duncan (10)
						0.14	Krumins (8)

TABLE 6 Average Generalized pce's for Ontario's Two-Lane Highways

	Speed Equivalents (speed percentile)			Platooning Equivalents			
				Followers		Leaders	
Vehicle Type	10th	50th	90th	Low Vol.	High Vol.	Recreation	Commuter
Truck	11.4	6.1	3.8	1.23	1.20	2.00	1.35
Recreational vehicles	3.9	3.7	2.6	1.23	1.07	1.55	
Other	1.0	1.0	1.0	0.98	1.13	1.464	
Opposing vehicles	0.5	0.5	0.5	0.06	0.07		

Note: Low volume = main direction traffic volumes of 100-650 veh/hr; high volume = main direction traffic of 650-2,000 veh/hr.

of service, as drivers choose their own percentiles within the available level of service.

Speed Prediction Equivalents

Speed prediction vehicle equivalents for trucks and recreational vehicles traveling in the main-line direction were found to decrease for higher speed percentiles. The absolute magnitude of the opposing volume effect was larger for higher speed percentiles, but corresponding increases in the main-line speed reduction coefficients resulted in a constant opposing direction vehicle equivalent.

In Ontario, trucks were found to have a speed-reduction coefficient of approximately 30 km/hr per 1,000 trucks/hr. This compares with Duncan (10), who determined an average speed reduction due to heavy vehicles of 62 km/hr, assuming a composition of 15 percent heavy vehicles. The Ontario truck equivalents of 11.4, 6.1, and 3.8 for the 10th, 50th, and 90th percentile speeds, respectively, are much higher than truck pce's (Table 6) but lower than Duncan's (10). He found that the ratio of average speed-reduction coefficients indicated a heavy vehicle pce of 15, whereas an average of coefficient ratios produced a pce ratio of 7.5.

Ontario speed pce's for recreational vehicles ranged from 3.9 to 2.6, compared with truck pce's that ranged from 11.4 to 3.8. Werner, Morrall, and Halls (3) determined that the effect of recreational vehicles on service volumes was more than that of standard passenger cars but less than that of trucks.

The speed pce for vehicles traveling in the opposite direction was consistently found to be 0.5 for all speed percentiles. This compares with Normann (9) and Duncan (10), who estimated this effect as 0.7 and 2/3 of main line, respectively. In contrast, the HCM (1) uses a default of 1.0, and Krumins (8) found an opposing volume equivalent of 1/7.

Platooning Equivalents

Platooning pce's were determined in terms of both platoon leadership and follower creation. However, comparisons with other sources are difficult because there are no other quantitative estimates of vehicle-type impacts on platooning in the literature. Therefore, platooning pce's are compared with estimates for speed and capacity.

Main-line platoon follower pce estimates are generally lower than comparable estimates for speed and capacity. As the data in Tables 5 and 6 indicate, capacity pce's for trucks generally range from about 1.5 to 3.0, and speed pce's can vary from 3.8 to 15.0. These values are generally larger than the Ontario platoon leadership values of 2.00 for recreational roads and 1.35 for commuter roads or the follower creation values between 1.20 and 1.23. Similarly, recreational vehicle pce's range from 1.6 to 2.5 for capacity and from 2.6 to 3.9 for speed, but they were only 1.55 for platoon leadership and between 1.07 and 1.23 for follower creation.

Follower creation pce estimates for traffic in the opposing direction were 0.06 and 0.07 for the low- and high-volume ranges, respectively. Although these numbers are small, they represent additional followers without adding main direction vehicles (i.e., opposing traffic causes platoons to merge).

The effect of opposing direction platooning on main-line platooning was not examined, although the extent of platooning in the opposing direction affects main-line platooning. The marginal effect that is not explained by the opposing volume was not considered to be commensurate with the effort required to examine it.

CONCLUSIONS

The relative effect of trucks on the lower percentile drivers is particularly pronounced. The truck pce ranged from 3.8 for 90th percentile speed to 11.4 for 10th percentile speed in Ontario. The recreational vehicle pce ranged from 2.6 to 3.9. The speed pce for vehicles traveling in the opposite direction was consistently 0.5 for all speed percentiles.

Passenger car equivalent values for platooning are lower than corresponding equivalents for speed. Follower creation pce's for trucks and recreational vehicles averaged 1.22 and 1.15, respectively, in Ontario, and corresponding platoon leader pce's averaged 1.8 and 1.4, respectively. The follower creation pce of traffic in the opposite direction averaged 0.065 for Ontario.

Although the various types of vehicle equivalents are related, pce's are not interchangeable, and only the appropriate pce's should be used in any application.

Discussion

Myung-Soon Chang*

Van Aerde and Yagar have made a good hypothesis that passenger car equivalents may be different for various criteria such as capacity, speed, platooning, and directional volume on two-lane rural highways. However, their data collection and analysis overlooked important considerations that should be recognized.

DATA COLLECTION

Van Aerde and Yagar collected platoon data using the radar-platoon technique (22). However, this method is very sensitive to the definition of what headway separation constitutes a different platoon. The first criterion in studying platooning would be the discrimination of platoon formation, and this varies among researchers. Miller, for example, separated platoons if the headway was longer than 8 sec (24). Edie et al. defined a vehicle as platooning if its headway was less than 4 to 5 sec, depending on its speed (25). Keller considered a vehicle as platooning if its headway was less than 2 sec (26).

If platooning involves a headway criterion, the radar-platoon technique Van Aerde and Yagar used is not sufficient and consequently needs more sophisticated data collection procedures and equipment. It should be recognized that their data collection method is subjective, depending on the perception of the observer, although it has an advantage of not requiring sophisticated equipment.

ANALYSIS

The authors used a multiple linear regression model to define pce values for different vehicle types. They defined pce for vehicle type n as the coefficient of vehicle type n (C_n) over coefficient of passenger car (C). However, this approach is only valid when no intercorrelation between the pair of independent variables (i.e., pair of vehicle types) exists. The coefficients given in Table 1 make it evident that there is intercorrelation or multicollinearity (i.e., high correlation between independent variables) between independent variables. Some of the algebraic signs are reversed, resulting in the negative value of pce's.

When there is multicollinearity between independent variables, not only will the sign often be reversed but the coefficients are also changed by the introduction and deletion of one or the other variable (27,28). When independent variables are correlated, the regression coefficient of any independent variable depends on which other independent variables are included in the model. Thus, a regression coefficient does not reflect any inherent effect of the particular independent variable on the dependent variable but has only a marginal or partial effect, given whatever other correlated independent variables are included in the model.

In short, the estimates of individual regression coefficients are very unreliable (28) when independent variables are intercorrelated among themselves.

CONCLUSIONS

Although the authors explored a potential use of regression models for deriving pce values, the suggested values should be modified using the approaches (28) that can eliminate intercorrelation or multicollinearity between independent variables.

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Authors' Closure

First we would like to thank Myung-Soon Chang for providing us with the opportunity to discuss some of the theoretical problems involved in applying multiple linear regression, which we had adopted as the only real choice for analyses of this type. This selection was based on an exhaustive consideration of the various statistical techniques for analyses of this nature. Chang suggested that we had overlooked these theoretical issues in the paper, but we had thought that a discussion of such theoretical issues was really peripheral to the central theme of our work. Theoretical issues are treated in the appropriate statistical literature. However, because the issues have been raised they are addressed. Because Chang's discussion has addressed data collection and analysis separately, we shall respond in these corresponding categories, so that the reader can relate our responses to Chang's respective questions.

First, we shall provide the reasons for selecting the manual radar-platoon data collection technique used for identifying and quantifying platoons. We will then address Chang's questions and concerns regarding the effect of possible multicollinearity on our multiple linear regression analysis.

DATA COLLECTION

Because the entire radar-platoon data collection procedure is presented in detail in the earlier literature, we have limited our response to specifically addressing Chang's concerns regarding our selection of a platoon discrimination procedure.

An exact quantitative definition of a platoon would involve a complex and even stochastic combination of relative positions, speeds, and accelerations of a potentially large number of vehicles, rather than simply the relative positions and speeds of only two vehicles. Therefore we thought it impractical to even attempt to fit a function for our purpose. Those who have attempted to automate this process have generally had to simplify their definition of a platoon to consider only successive pairs of vehicles. Also, platoon characteristics will vary among different highway types and situations. It is therefore not surprising that Miller (24), Edie et al. (25), Keller (26), and others have found different critical headways for defining limits for platoons under their very different sets of conditions, which Chang may have unfortunately confused as representive of the same process. For example, Keller's extreme headway of less than 2 sec was not intended as a critical headway for two-lane rural highways, which our paper addresses exclusively. We had measured an average headway for platooned vehicles on a two-lane rural highway of 2.0 sec, which is even greater than the low critical value that Chang attributes to Keller. This average value is not to be confused with a follower discrimination criterion as Chang has apparently done in Keller's case.

With these considerations in mind, we thought that the traffic could best be divided into platoons by a trained observer, who would have the benefit of observing long traffic streams as they approached. Being concerned about the subjectivity of the process, we had a number of people observe the same traffic: a physicist, a politician, a student, and a traffic engineer. There was consistently virtually unanimous agreement about where the platoons started and ended. This indicated that the error due to subjective selection of platoons referred to by Chang was less than that due to differences among researchers. Our results are not dependent on any mathematical descriptions of platoons that different researchers might speculate on or even find. Because we were interested only in sorting the traffic into platoons and not in finding a model for describing this process, the human observer method served our needs better than any mathematical model we could find or create.

ANALYSIS

Criticism of our statistical analysis centered around multicollinearity and reversed algebraic signs. We are well aware of the problems of multicollinearity, but cannot apologize for our use of multilinear regression (MLR). After careful consideration of the nature of our data and the available analysis techniques we believed that we could live with the implications of MLR. We are satisfied with our "ball park" estimates, and feel that they have supported our main hypothesis that pce's are different for capacity, speed, and platooning, respectively. We have also quoted levels of statistical significance, and only draw conclusions concerning the types of vehicles that were represented in sufficient sample size to allow meaningful statistical inference. Chang suggested that he can alter our findings by eliminating multicollinearity. However, a closer examination of our paper would show that this has already been done, as we shall discuss. It is also noted that the models and data used for estimating respective pce's for speed, capacity, and platooning were consistent. This, along with the statistical significance obtained in estimating these different types of pce's, indicates that they are reasonably accurate, subject only to their statistical significance, represented by the ratio of their relative magnitudes and errors of estimation given in Table 1. In each case, a ratio of about 2 or more represents reasonable statistical significance.

Chang referred to Mullet (27) who discusses the causes of coefficients having the wrong sign, quoting the following four reasons:

1. Range of independent variable not fully covered by data,
2. Exclusion or omission of important predictor variables,
3. Multicollinearity between independent variables, and
4. Computational error.

We respond to each of these as follows:

1. It should be noted that the entire range of traffic volumes, up to and including capacity, was covered by our data. The mix of locations included recreational, commuter, and combined highway types, providing mixtures that included both high and low volumes of trucks in combination with a similar range of recreational vehicle volumes. This therefore includes virtually the entire possible range of traffic condition variables that were of interest to our study.
2. The MLR analysis drew on all the component traffic volumes present in the traffic stream and was therefore comprehensive without being overspecified. Because the counts for all vehicles were included, no important predictor variables were excluded and no variable types were redundant.
3. Issues of multicollinearity are treated specifically by Mason et al. (28), and are therefore addressed in detail hereafter.
4. Finally, computational error in the estimate of our regression coefficients was minimized through the use of the SAS statistical analysis program. SAS is one of the most widely applied and therefore tested mainframe statistical analysis packages. Its results were verified using an independent regression package.

Chang referred to Mason et al. (28) who discuss issues of multicollinearity in great detail and suggest methods to be used to eliminate or to allow for its presence. Specifically, they suggest three solutions:

1. To reduce or eliminate collinearity, they recommend that the data be augmented with additional data. Having monitored nearly half a million vehicles, we believe that it would be impractical to increase the size of the sample, which is, if anything, larger than necessary.
2. As an alternative they suggest that the regression should be attempted subject to restrictions on some of the independent variables. Such restrictions were explored and are documented by Van Aerde and Yagar (21) as Model II. Briefly, these restricted regressions fixed the relative sizes of the vehicle type speed reduction coefficients such that the regression was forced to focus on the relative sizes of the main-line and opposing direction speed effects. The resulting reduction in degrees of freedom provides more stable and often more reliable results.
3. The final recommendation involves selection of variables. They suggest that no important predictor variable should be omitted and that no two variables should be included if they represent virtually the same thing. This issue is similar to item 2 from Mullet and the same arguments apply here.

These discussions should satisfy any skeptic that we have not only carefully avoided multicollinearity problems to the extent possible, but also have followed the appropriate remedial measures. It is therefore not necessary to modify our values as suggested by Chang.

It should be noted that in Table 1 our average regression coefficients were quoted with corresponding measures of statistical significance. All significant coefficients, which usually correspond to vehicle types with a large count, are of the correct sign and order of magnitude. Only the coefficients that had a larger variance associated with them ended up with a wrong sign or an incorrect magnitude, and in this case we explicitly stated that we do not recommend their use.

CONCLUSIONS

We believe that the data bank that we used for our analyses was more than adequate. Although we could easily have lived with a smaller sample, a sample of this size was made possible by the use of the efficient radar-platoon data collection technique. This technique is especially useful in providing data for analysis of platoons, because it provides data in terms of platoons.

Any automated platoon discrimination technique will have to be calibrated with the use of human observers, who were used in the radar-platoon technique. It is therefore not possible to develop an automated technique that can provide better platoon discrimination than competent, trained human observers.

Multiple linear regression analysis was found to be the best analysis approach because it permitted a similar model structure for the various platoon and speed measures that were explored. We have taken the necessary precautions to avoid collinearities or minimize their effects, and are confident about the reliability of our results.

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