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Effect of Traffic Mix, Volume, and Geometrics on the Trip Time of Passenger Cars and Trucks on Urban Freeways

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The objective of this paper is to investigate and quantify the relation between the average travel time per unit distance experienced by passenger cars, trucks, and other vehicles and the prevailing volumes of passenger cars and trucks on urban freeway sections. This macroscopic relation is examined for freeway sections exhibiting four types of geometric and operational characteristics (pipe, diverge, merge, and weave sections). The models are calibrated for each type of section using the FHWA 1982 data set on urban truck freeway characteristics, thereby providing the basis for the systematic testing of (a) the effect of geometrics on the relative effects of passenger cars and trucks on freeway performance, and (b) the relative sensitivity of the service quality experienced by passenger cars and trucks to the components of the traffic stream. These questions are of current practical interest to agencies contemplating truck-related highway improvements. The results indicate that the coefficients of the respective volume components vary significantly across section types, yielding volume effect truck passenger car equivalents (pces), in terms of impact on average travel time, which differ markedly from one type to another. This suggests that the undifferentiated treatment of pces for certain geometric and operational conditions may not be appropriate.

The effect of trucks on traffic flow characteristics has long been a subject of interest to traffic and transportation engineers. The principal mechanism for capturing the effect of trucks relative to that of passenger cars has been the concept of passenger car equivalents (pces), which is widely adopted and consistent with the *Highway Capacity Manual* (HCM) *(1)*. Nevertheless, the

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effect of trucks on freeway traffic performance remains the subject of considerable debate in the research community, ranging from the definition of pce and its applicability in various situations to questions over the specific numbers recommended by standard references, such as the HCM (1). Recent reviews of these issues are given by Roess and Messer (2), and Van Aerde and Yagar (3). Two questions are of particular interest to this work:

1. Are pce values defined for capacity analysis purposes necessarily appropriate for the study of the effect of trucks on other aspects of a facility's performance, particularly the effects of trucks and heavy vehicles on average travel time and speed through the facility?

2. How does the effect of trucks vary with the characteristics of the facility under consideration? The HCM recognizes factors such as grade and terrain, but not other geometric features, such as those encountered in sections for merging or diverging.

The objective of this paper is to investigate and quantify the effect of traffic volume on the average travel time per unit distance on urban freeway sections, with specific attention given to the composition of the traffic stream (trucks and passenger car volumes). The effect of truck volume is examined for freeway sections with different geometric characteristics (pipe, diverge, merge, and weave sections). In addition, the operational characteristics of passenger cars and trucks are ascertained and compared across these different geometric features.

In addition to their intrinsic interest, the aforementioned questions are of particular practical concern in light of increasing truck volumes in the traffic stream, and the accompanying size and weight trends. Many highway and transportation agencies are considering a variety of strategies, including both physical and operational improvements, to mitigate the impacts of truck traffic. The present study's focus on travel time performance is predicated on the initial motivation for this work because results will ultimately be used for planning purposes in the context of link performance functions for network traffic assignment (4).

The methodological approach followed in this study is similar to that used by Van Aerde and Yagar (3, 5, 6) in their analysis of the volume effects on speeds for two-lane highways, although, in addition to the obvious difference in problem context, the former focuses on average trip time per unit distance rather than speed as the principal performance measure. Essentially, multivariate regression analyses are conducted to explain the observed variability in average travel time in terms of the prevailing traffic volume and traffic mix. The principal research questions are then addressed through systematic hypothesis testing with the calibrated models. The approach is a macroscopic one, where relations are sought among average quantities taken of vehicles over given observation periods. The data used for analysis come from the FHWA-sponsored data set on *Urban Freeway Truck Characteristics* (7), which contains information in the form of individual vehicle trajectories at 11 locations.

In the following sections, the development of the data needed for analysis from the original data base is presented. Next, the travel time–volume relationships are developed for passenger cars and trucks separately for a range of traffic

volumes up to 1,300 vehicles per hour (vph) per lane, followed by statistical testing of the effect of geometry on these relationships. Finally, concluding comments and implications are discussed.

DATA SET DEVELOPMENT

The data used in this study were developed from a large data base on *Urban Freeway Truck Characteristics* (7), collected for FHWA in 1981–1982 on 11 different freeway facilities in four major metropolitan areas: Atlanta, Dallas, Detroit, and Houston. The facilities selected exhibit four different geometries: merge, diverge, weave, and basic (pipe) freeway sections. All of these sections are characterized by essentially level terrain in order to avoid grade-induced complications. The distribution of the 11 sections into the four geometric types is given in Table 1, along with their respective geometric characteristics. Data collection was limited to clear and dry weather conditions on normal weekdays.

The data base consists of over one-half million individual vehicle trajectories, collected using the FHWA Traffic Evaluator System, which is a high-precision multichannel event recorder. Each of its 60 channels accepts and records pulses activated by the passage of a vehicle's tire over low-profile tapeswitches affixed to the road surface. The system keeps track of the activated channel and the corresponding time of activation (to the nearest 1/16th of a millisecond). The tapeswitches were configured in standard traps within the travel lanes and consisted of a parallel pair of 6- to 10-ft tapeswitches normally placed 4 ft apart [see Sequin (7)] for further information]. The passage time of each vehicle at each trap is thus available for the duration of the observation period, which ranges in duration from 1 to over 16 hr at the various locations, resulting in grand totals of 561,227 individual vehicle traces observed over 240 hr. Using that information, the average travel time per unit distance of a vehicle could be obtained by subtracting the time at which the entry trap is activated from the time at the exit trap, and dividing the resulting value by the known distance between the entry and exit traps.

The data needed for the purpose of this analysis are in aggregate form, consisting of averages taken over specified observation periods (or time slices) of equal duration. As noted in the previous section, the intent is not to explain the considerable variation in individual vehicle performance, nor to predict the minute-by-minute dynamics of traffic flow in the facility, but to characterize the effect of the prevailing average volume level and traffic mix on the average travel time experienced by users of the facility. In particular, the dependent variables of interest are the average trip time per unit distance experienced by vehicles using the facility over each observation period. As noted earlier, this average trip time is the reciprocal of the space mean speed of the vehicles traversing the section during the observation period. The average trip time per unit distance is calculated separately for passenger cars and trucks, as well as over all vehicles, because one of the objectives of the analysis is to examine differences in operating characteristics of passenger cars versus trucks on urban freeways, and the dependence of each on the prevailing passenger car and truck volumes. The average volume on the link corresponding to a

TABLE 1 GEOMETRIC CHARACTERISTICS OF SITES

Sites[a]	Identification	Area	Type	Lane Width (ft)	No. of Lanes	Shoulder Width (ft)	Median Width (ft)
KP	Kingery	Chicago	Pipe	12	3	10	7
LP	LaPorte	Houston	Pipe	12	3	10	10
ED	Edens	Chicago	Diverge	12	3	12	7
LD	Linfield	Dallas	Diverge	12	3	_b	_b
BM	Bryant	Atlanta	Merge	12	3	3	_b
LM	Linfield	Dallas	Merge	12	3	6–11	_b
RM	Richey	Houston	Merge	12	3	9	3.5–10.5
AW	Clark–Howell	Atlanta	Weave	12	2	_b	_b
CW	Calumet	Chicago	Weave	12	3	12	5
DASH	Dairy–Ashford	Houston	Weave	12	3	6	9
DW	Arapaho	Dallas	Weave	11.5	2	_b	_b

[a]All sites are on level terrain and have no curvature.
[b]Shoulder or median widths are considered adequate.

particular aggregation period is defined as the number of vehicles passing a certain point on the link (typically the entry or exit points) during that period, divided by the length of that period.

The analysis presented in this paper is based on observations aggregated over 10-min sampling intervals, though different sampling lengths were also tested. The selection of the length of the aggregation period is not straightforward: on one hand, long time intervals provide a better approximation of steady-state conditions (8), and avoid dealing with the accompanying dynamic phenomena. On the other hand, if the sampling interval is too long, averaging may be over distinctly different operating conditions; furthermore, longer intervals might result in fewer observations for the estimation of the parameters of the underlying relation.

Plots of the average travel time per unit distance versus the total vehicular volume (in vehicles per hour per lane) for all observations available at the various test locations conformed

to the well-known pattern of initial low sensitivity of travel time to traffic volume, followed by a rapid nonlinear increasing pattern for volumes above a certain level. An illustrative example taken over all pipe sections in the data is shown in Figure 1; additional plots can be found elsewhere (9). Based on these plots, volumes up to 1,300 (total) vph per lane appeared to define that initial range (referred to hereafter as the linear range) for the sections under consideration. It also became apparent that relatively few observations were available in the remaining nonlinear range, and only at a few of the sites, and thus could not adequately support the desired testing of the influence of geometrics on the effects of trucks on freeway travel times in that volume range. Moreover, traffic conditions in that range are essentially unstable. Thus the primary focus of the analysis presented in this paper is placed on the linear range, for which observations were adequate. In addition, note that because of the lack of sufficient nighttime data, the analysis is based primarily on data for daytime conditions, except for a comparison with the available night data.
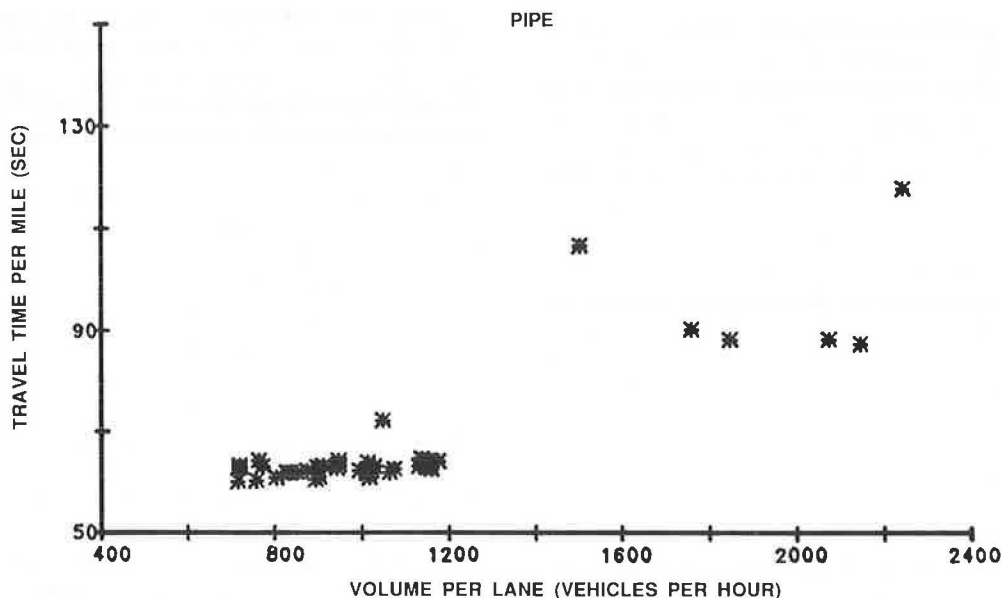

FIGURE 1 Plot of travel time–volume relationship for pipe sections.

ESTIMATION OF LINEAR MODELS

The development and calibration of a linear relationship between average travel time per unit distance (dependent variable) and the respective volumes of passenger cars and trucks in the traffic stream within a total volume range extending up to 1,300 vph per lane are discussed. Using several multivariate linear regression models, the travel time–volume relationships obtained for the various sections with different geometric features are compared in order to identify patterns in freeway operational characteristics. Separate relations are developed for (average) truck and passenger car travel time per unit distance, and are compared to a model for average vehicular travel time (per unit distance). This analysis addresses four questions: (a) the extent to which respective passenger car and truck volumes contribute to the observed variation in average travel time; (b) the magnitude of volume-effect pces for trucks under various conditions; (c) the differential effect on car versus truck travel time, examined through the estimation of separate regression equations; and (d) the variation of the preceding effect across locations with different geometric characteristics.

The principal model form used in this analysis is linear (in parameters, as well as in variables) with both car and truck volumes as the independent variables, as follows:

$$T_i = T_0 + C_1 V_{1i} + C_2 V_{2i} + \varepsilon_i \qquad (1)$$

where

$$
\begin{aligned}
T_i &= \text{average travel time per unit distance (in} \\
&\quad \text{seconds per mile), for the } i\text{th} \\
&\quad \text{observation;} \\
V_{1i} \text{ and } V_{2i} &= \text{respective volumes of passenger cars} \\
&\quad \text{and trucks (in vehicles per hour per} \\
&\quad \text{lane), for the } i\text{th observation;} \\
T_0 &= \text{travel time per unit distance under free} \\
&\quad \text{flowing conditions, that is, the} \\
&\quad \text{reciprocal of the free mean speed, and} \\
&\quad \text{is a parameter to be estimated;} \\
C_1 \text{ and } C_2 &= \text{parameters to be estimated; and} \\
\varepsilon_i &= \text{random disturbance term, assumed, as} \\
&\quad \text{usual, to be normally distributed with} \\
&\quad \text{zero mean.}
\end{aligned}
$$

Model calibration is performed by pooling the data from all sites within each of the four types of geometric characteristics. The least squares estimates of the coefficients of the average vehicular travel time model are given in Table 2 for each geometric type, as well as for all types combined. The coefficients obtained for relationships estimated separately for passenger car travel time and truck travel time are reported in Tables 3 and 4, respectively. In all of the preceding cases, all parameters are statistically significant (different from zero) at any reasonable level of confidence, as are the overall regressions. In the aforementioned tables, T_0, which corresponds to the mean free travel time per unit distance (that is, reciprocal of the mean free speed), is expressed in seconds per mile; taking the inverse of the estimated values and converting to miles per hour yields respective values in the range of 58 to 63.5 mph, which is what would be expected for U.S. urban freeways.

Note that the volume-effect coefficients C_1 and C_2 are expressed in seconds per mile per 100 passenger cars or trucks,

respectively, that is, they capture the expected changes in travel time with a change of link volume by 100 passenger cars or trucks per lane. In interpreting the estimation results, several statistical tests are performed of hypotheses regarding the following: (a) differences between the respective effects of passenger cars and trucks on average travel time, (b) differences across the four geometric types, and (c) day versus night effects.

TABLE 2 RESULTS OF PARAMETER ESTIMATION FOR AVERAGE VEHICULAR TRAVEL TIME MODEL (range: $V \leq 1,300$ vph per lane)

Section Type	$T_0{}^a$	$C_1{}^b$	$C_2{}^c$	No. of Observations
Pipe	56.86	0.322	1.16	132
Diverge	58.93	0.205	2.84	146
Merge	60.20	0.314	0.764	174
Weave	61.93	0.173	1.13	236
All sections	61.46	0.236	0.551	688

$^a T_0$ is expressed in seconds per mile.
^{b} The coefficient C_1 is expressed in seconds per mile per 100 cars.
^{c} The coefficient C_2 is expressed in seconds per mile per 100 trucks.

TABLE 3 RESULTS OF PARAMETER ESTIMATION FOR AVERAGE CAR TRAVEL TIME MODEL (range: $V \leq 1,300$ vph per lane)

Section Type	$T_0{}^a$	$C_1{}^b$	$C_2{}^c$	No. of Observations
Pipe	56.69	0.330	1.22	132
Diverge	59.02	0.173	3.06	146
Merge	60.24	0.312	0.732	174
Weave	62.11	0.162	1.08	236
All sections	61.57	0.226	0.536	688

$^a T_0$ is expressed in seconds per mile.
^{b} The coefficient C_1 is expressed in seconds per mile per 100 cars.
^{c} The coefficient C_2 is expressed in seconds per mile per 100 trucks.

TABLE 4 RESULTS OF PARAMETER ESTIMATION FOR AVERAGE TRUCK TRAVEL TIME MODEL (range: $V \leq 1,300$ vph per lane)

Section Type	$T_0{}^a$	$C_1{}^b$	$C_2{}^c$	No. of Observations
Pipe	57.21	0.286	1.09	132
Diverge	58.52	0.304	2.35	146
Merge	59.86	0.335	1.01	174
Weave	60.78	0.193	1.74	236
All sections	61.08	0.263	0.666	688

$^a T_0$ is expressed in seconds per mile.
^{b} The coefficient C_1 is expressed in seconds per mile per 100 cars.
^{c} The coefficient C_2 is expressed in seconds per mile per 100 trucks.

Test of Passenger Car Versus Truck Volume Effects

To formally establish what the numerical values of the coefficient estimates strongly suggest, namely that cars and trucks have different effects on average travel time, the hypothesis that $C_1 = C_2$ is tested separately for each facility type, as well as for the "all types" model. The tests are performed for the average travel time models (Table 2), using the general F-test for linear models (10). To perform this test, the hypothesis that $C_1 = C_2$ is viewed as a restriction on the model parameters, relative to the unconstrained case in which C_1 and C_2 are allowed to assume different values. The test then becomes one of whether the hypothesized restriction is true (or valid) for the data at hand. The test procedure consists of estimating the parameters of the restricted model (that is, with $C_1 = C_2$), yielding the sum of squared errors Q^R; similarly, the sum of squared errors for the unrestricted model, already estimated, is denoted by Q^U. The test statistic is then calculated as $F^* = [(Q^R - Q^U)/r]/[Q^U/(n - k)]$, where n is the number of observations; k is the number of parameters to be estimated in the unrestricted model (in this case, $k = 3$), and r is the number of restrictions (in this case, $r = 1$). Under the null hypothesis that the restriction is true, this statistic is F-distributed with $(r, n - k)$ degrees of freedom (10).

The results of this test for the various section types are summarized in Table 5. The null hypothesis is clearly rejected, with better than 95 percent confidence, for pipe, diverge, and weave sections, implying the existence of differences between the respective effects of passenger cars and truck volumes on average travel time for these three types of geometries. In addition, the null hypothesis can be rejected for all section types combined with better than 90 percent confidence. However, such a conclusion cannot be reached for merge sections, despite the fact that the numerical value of C_2 is more than twice that of C_1. The reason for this conclusion of the statistical test is that the standard error for the regression model calibrated for merge sections is substantially higher than that of the other section types, reflecting greater variability in the observations for those sections, and the poor ability of the model of Equation 1 to explain this variability. Given the preceding conclusion, it is safe to assume that, in general, truck volume effect on travel time is significantly different from that of passenger cars.

Of course, C_1 is considerably smaller in magnitude than C_2. The ratio of the estimates of C_2/C_1 may be interpreted as a volume-effect pce of trucks in the traffic stream in the volume range under consideration. Note however that this pce definition, which is the relevant one from the standpoint of predicting the effect of truck traffic on travel times (or speeds), and subsequently on user costs, is not altogether consistent with that used to obtain the HCM values (2). In particular, values of 3.6, 13.9, and 6.5 are obtained for this ratio for the pipe, diverge, and weave sections, respectively; a value of 2.4 is obtained for the merge sections, though not particularly reliable, and 2.3 for all sections combined (including the influence of merge sections). This indicates considerable variation of this volume-effect pce across geometric types; the value that does not recognize these differences, namely the 2.3 for all sections, is actually the closest to the 1.7 suggested by the 1985 HCM for these types of facilities (1), and is used in current traffic engineering practice. The significance of the apparent variation of the respective passenger car and truck volume effects across geometric types is formally established next.

Significance Tests of Variation Across Geometric Types

The hypothesis that the four subgroups of sections (geometric types) share the same underlying parameters is examined. Formally, the null hypothesis can be stated as $T_{0P} = T_{0D} = T_{0M} = T_{0W}$ and $C_{1P} = C_{1D} = C_{1M} = C_{1W}$ and $C_{2P} = C_{2D} = C_{2M} = C_{2W}$, where C_{1P}, C_{1D}, C_{1M}, and C_{1W}, respectively, denote the true values of the passenger car volume coefficients for pipe, diverge, merge, and weave sections; the corresponding constants (T_0) and coefficients of the truck volume (C_2) are similarly defined. The same F-statistic used above is also applicable here, with the number of restrictions $r = (G - 1)k$, where G is the number of subgroups (in this case, $G = 4$ and $r = 9$). In this test, Q^R is the sum of squared errors for the pooled (all sections) model, while Q^U is obtained by taking the summation, over the four section types, of the corresponding sum of squared errors (11).

This test has been applied separately to the models calibrated for the average travel time for passenger cars, trucks, and all vehicles. The results are presented in Table 6. For all three models, the null hypothesis is overwhelmingly rejected, thereby strongly supporting the claim that the parameters of the volume–travel time relation vary with different geometric features. Actually, this conclusion is to be expected given the results of the previous test regarding the relative effect of passenger car and truck volume at merge sections. For this reason, the aforementioned test is repeated for the other three geometric types, excluding merge sections. The results are summarized in Table 7, and clearly support the earlier conclusion that the parameters describing the effect of passenger car and truck volume on average travel time are significantly different across freeway sections exhibiting different geometric characteristics. Looking at the relative magnitudes of the estimated coefficients, it appears that the volume effect coefficients generally tend to be lower for merge and weave sections than for pipe and diverge sections, whereas the corresponding values of T_0 are higher.

TABLE 5 RESULTS OF SIGNIFICANCE TESTS OF THE DIFFERENCE BETWEEN PASSENGER CAR AND TRUCK VOLUME EFFECTS OF TRAVEL TIME ($C_1 = C_2$)

Site Type	$n - k$	r	Q^{Ra}	Q^{Ub}	F^{*c}	$F_{(0.05, r, n-k)}{}^d$
Pipe	129	1	241.8	233.8	4.41	3.90
Diverge	143	1	235.0	205.0	20.9	3.90
Merge	171	1	1,241.1	1,237.9	0.44	3.90
Weave	233	1	991.6	835.3	43.6	3.90
All sections type	685	1	4,798.3	4,775.8	3.23	3.84^e

$^a Q^R$ is the sum of squared errors for restricted model.
$^b Q^U$ is the sum of squared errors for unrestricted model.
$^c F^*$ is the calculated value for F-test statistic.
$^d F_{(0.05, r, n-k)}$ is the theoretical value for F-distributed statistic with r, d, f for numerator and $n-k$ d, f for denominator at the 5 percent significance level.
^{e} The corresponding $F(0.10, r, n-k) = 2.71$.

TABLE 6 RESULTS OF SIGNIFICANCE TESTS OF THE EFFECT OF LINK GEOMETRY TYPE ON MODEL PARAMETERS

Dependent Variable[a]	$n - k$	r	Q^{Rb}	Q^{Uc}	$F^{\cdot d}$	$F_{(0.05,r,n-k)}{}^{e}$
T (all vehicles)	685	9	4,775.8	2,512.0	68.6	1.88
T_c (passenger cars)	685	9	4,831.1	2,520.9	69.8	1.88
T_t (trucks)	685	9	6,060.0	3,600.7	52.0	1.88

[a]T, T_c, and T_t denote the average travel time per unit distance for all vehicles, passenger cars, and trucks, respectively.
[b]Q^R is the sum of squared errors for restricted model.
[c]Q^U is the sum of squared errors for unrestricted model.
[d]$F^{\cdot}$ is the calculated value for F-test statistic.
[e]$F_{(0.05,r,n-k)}$ is the theoretical value for F-distributed statistic with r, d, f for numerator and $n-k$ d, f for denominator at the 5 percent significance level.

TABLE 7 RESULTS OF SIGNIFICANCE TESTS OF THE EFFECT OF LINK GEOMETRY TYPE ON MODEL PARAMETERS (excluding merge sections)

Dependent Variable[a]	$n - k$	r	Q^{Rb}	Q^{Uc}	$F^{\cdot d}$	$F_{(0.05,r,n-k)}{}^{e}$
T (all vehicles)	511	6	3,448.7	1,274.0	145.4	2.1
T_c (passenger cars)	511	6	3,440.3	1,307.9	138.9	2.1
T_t (trucks)	511	6	4,107.0	1,724.7	117.6	2.1

[a]T, T_c, and T_t denote the average travel time per unit distance for all vehicles, passenger cars, and trucks, respectively.
[b]Q^R is the sum of squared errors for restricted model.
[c]Q^U is the sum of squared errors for unrestricted model.
[d]$F^{\cdot}$ is the calculated value for F-test statistic.
[e]$F_{(0.05,r,n-k)}$ is the theoretical value for F-distributed statistic with r, d, f for numerator and $n-k$ d, f for denominator at the 5 percent significance level.

Continuing the interpretation of the parameter estimation results, comparison of the relative magnitudes of the estimates obtained for the passenger car and truck travel time models (in Tables 3 and 4) yields insights into the relative sensitivity of the quality of traffic service experienced by passenger cars and trucks to the corresponding volumes of each vehicle class. Using only the results of the models calibrated for the pooled (all section types) data would seem to indicate that the respective passenger car and truck volume effects on truck travel time are higher than those for passenger car travel time; this would suggest that truck travel time is more sensitive to volume changes than passenger car travel time, that is, truck travel time worsens at a faster rate than that of passenger cars with increasing volume (regardless of traffic mix). However, such a conclusion is not appropriate in a general sense, given that significant differences in the travel time–volume relations have already been clearly established across the different geometric configurations. Moreover, the all-sections data set consists of a nonrepresentative mixture of the four section types. Therefore, differences (across geometric types) between the relative sensitivity of passenger car and truck travel times to respective passenger car and truck volumes must not be ruled out.

Such differences are indeed present, according to the estimated coefficients for each section type in Tables 3 and 4. For

instance, both C_1 and C_2 are higher for passenger cars than they are for trucks on pipe sections, indicating that, on basic freeway sections, the travel time of passenger cars is more sensitive than that of trucks to increases in either passenger car or truck volume, which is the opposite of the conclusion that would have been reached on the basis of the combined data. On the other hand, the results for merge and weave sections are in agreement with the all-sections conclusion (which they undoubtedly influenced given the disproportionate number of observations from these two types of sections). The conclusion for diverge sections is yet again different, and perhaps the most interesting: insofar as truck travel time seems to be more sensitive than passenger car travel time to passenger car volume (0.304 versus 0.173 sec per mile per 100 passenger cars) the reverse is true with regard to sensitivity to truck volume (2.35 versus 3.06 sec per mile per 100 trucks). Indeed, it is particularly noteworthy that not only do the quantitative aspects of the travel time–traffic volume and mix relation vary with geometric features, but so do its qualitative aspects.

Furthermore, as noted earlier, the relative magnitudes of the estimated values of C_1 and C_2 and of the ratio C_2/C_1, interpreted as a volume effect pce, are significantly different across geometric types, exhibiting a rather wide range of variation. This is shown in Table 8, which summarizes these ratios for the passenger car, truck, and all-vehicles travel time models by geometric section type. For all three travel time variables, the value closest to the HCM pce for the conditions under consideration is that which corresponds to the all-sections model. This underscores an important implication, namely that the HCM values would be appropriate primarily for coarse-level planning purposes, although their use for other purposes, such as geometric design or traffic control, could be quite misleading, particularly in locations with special geometric features (such as diverge and weave sections).

Test of Night Versus Day Differences

As noted earlier, most of the available data are for daytime conditions. Nevertheless, the very limited nighttime data points present in the data set are used to explore whether the volume effect on travel time at night is the same as during daytime conditions. The same F-test procedure is also used here for the null hypothesis (restriction) that the model parameters are the same for nighttime and daytime conditions, for each section type (with the exception of diverge sections, for which no meaningful nighttime data were available). There are two subgroups, night and day, for each test; the restricted model is estimated for the pooled data from both subgroups. The test results are summarized in Table 9, clearly indicating that the

TABLE 8 VOLUME EFFECT TRUCK pce-VALUES BY GEOMETRIC SECTION TYPE

	Pipe	Diverge	Merge	Weave	All Sections
Passenger car travel time	3.7	17.7	2.4	6.7	2.4
Truck travel time	3.8	7.7	3.0	9.0	2.3
All vehicles	3.6	13.9	2.4	6.5	2.3

TABLE 9 RESULTS OF SIGNIFICANCE TESTS OF NIGHT VERSUS DAY EFFECT ON MODEL PARAMETERS

Section Type	$n - k$	r	Q^{Ra}	Q^{Ub}	F^{*c}	$F_{(0.05, r, n-k)}{}^d$
Pipe	199	3	619.4	505.3	15.0	2.7
Merge	144	3	1,718.7	1,276.1	16.6	2.7
Weave	330	3	1,133.5	1,082.2	5.2	2.7
All section types	874	3	6,306.0	5,561.9	39.0	2.6

$^a Q^R$ is the sum of squared errors for restricted model.
$^b Q^U$ is the sum of squared errors for unrestricted model.
$^c F^*$ is the calculated value for F-test statistics.
$^d F_{(0.05, r, n-k)}$ is the theoretical value for F-distributed statistic with r, d, f for numerator and $n-k\,d, f$ for denominator at the 5 percent significance level.

hypothesized restriction can be rejected. Therefore, the effects of passenger car and truck volumes on average travel time differ during the day from what they are at night. Although the data on which this conclusion is based are rather limited, the corresponding confidence level is evidently quite high.

VOLUME-DEPENDENT pce MODEL

Naturally, several alternative functional specifications have been considered and estimated for the given set of observations during the course of this analysis. In particular, specifications including power terms of the two principal independent variables, as well as multiplicative interaction terms, were tested. In general, these specifications were inferior to the simple linear model presented earlier. Although it would not be particularly useful to present the estimation results for all the poor model specifications attempted in the search for the best-fitting plausible equation, it is worthwhile to comment on the results of one such specification where the squared value of the truck volume is used as follows:

$$T_i = T_0 + C_1 V_{1i} + C_2 (V_{2i})^2 + \varepsilon_i \qquad (2)$$

where all terms are as defined previously.

A summary is given in Tables 10, 11, and 12 of the parameter estimation results, by section type, for the average all-vehicles, passenger car, and truck travel times, respectively. The results for the all-sections combined data are not included

TABLE 10 RESULTS OF PARAMETER ESTIMATION FOR AVERAGE TRAVEL TIME MODEL (volume-dependent pce model)

Section Type	$T_0{}^a$	$C_1{}^b$	$C_2{}^c$	No. of Observations
Pipe	58.38	0.315	0.212	132
Diverge	59.77	0.184	2.14	146
Merge	60.61	0.323	0.245	174
Weave	62.57	0.169	0.481	236

$^a T_0$ is expressed in seconds per mile.
^{b} The coefficient C_1 is expressed in seconds per mile per 100 cars.
^{c} The coefficient C_2 is expressed in seconds per mile per 100 trucks.

TABLE 11 RESULTS OF PARAMETER ESTIMATION FOR PASSENGER CAR TRAVEL TIME MODEL (volume-dependent pce model)

Section Type	$T_0{}^a$	$C_1{}^b$	$C_2{}^c$	No. of Observations
Pipe	58.27	0.323	0.224	132
Diverge	59.93	0.157	2.23	146
Merge	60.64	0.321	0.228	174
Weave	62.72	0.158	0.462	236

$^a T_0$ is expressed in seconds per mile.
^{b} The coefficient C_1 is expressed in seconds per mile per 100 cars.
^{c} The coefficient C_2 is expressed in seconds per mile per 100 trucks.

TABLE 12 RESULTS OF PARAMETER ESTIMATION FOR TRUCK TRAVEL TIME MODEL (volume-dependent pce model)

Section Type	$T_0{}^a$	$C_1{}^b$	$C_2{}^c$	No. of Observations
Pipe	58.66	0.278	0.194	132
Diverge	59.20	0.269	1.97	146
Merge	60.38	0.347	0.364	174
Weave	61.87	0.179	0.699	236

$^a T_0$ is expressed in seconds per mile.
^{b} The coefficient C_1 is expressed in seconds per mile per 100 cars.
^{c} The coefficient C_2 is expressed in seconds per mile per 100 trucks.

because the model's performance was particularly poor when differences in geometry were not taken into account. Although the reported model results passed the usual statistical tests of significance, overall, as well as for individual parameters, the model did not, in general, exhibit a discernible improvement in terms of overall statistical performance relative to the earlier linear version (slight improvement for diverse sections, but inferior performance for pipe data). However, the implications seem intuitively plausible and worthy of further examination given their potential significance for practice.

Although the values of T_0 and C_1 are directly comparable to those obtained with the previous model (Equation 1), the interpretation of C_2 is not as straightforward. The underlying assumption here is that the marginal effect of truck volume is proportional to the prevailing volume of trucks, with $\partial T / \partial V_2 = 2 C_2 V_2$. Other similar assumptions—but with truck effect proportional to passenger car or total volumes—were also considered but did not perform satisfactorily. The values reported in Tables 10–12 indicate that the volume-effect pce of trucks (now given by $2 C_2 V_2 / C_1$) can vary over a rather wide range. For example, when truck volume is 100 vph per lane, the ratio of the (marginal) truck effect to that of passenger cars, based on the all-vehicles travel time model, is 1.3 for pipe, 23.3 for diverge, 1.5 for merge, and 5.7 for weave sections, respectively.

The dependence of the pce-value on truck volume implied in the estimation results, based on the all-vehicles, passenger car, and truck travel time models, respectively, is shown clearly in Figures 2–4. Each figure presents the pce plots corresponding to the different section types. Note that in Figures 2 and 3, only one line is plotted for both pipe and merge sections; this is
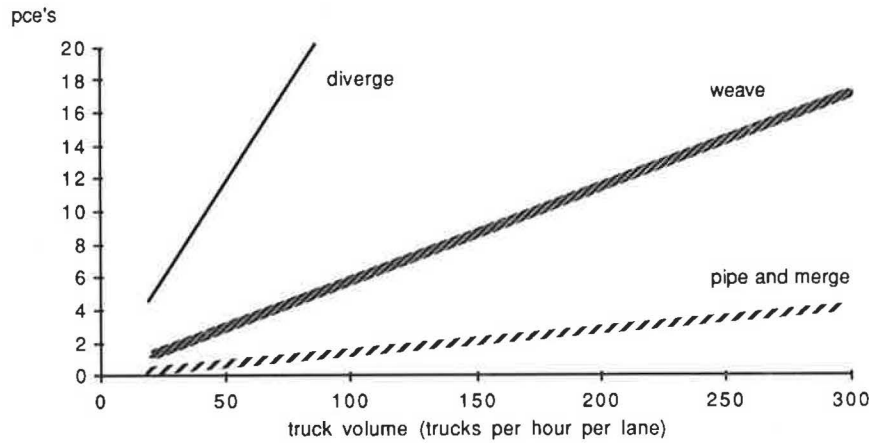
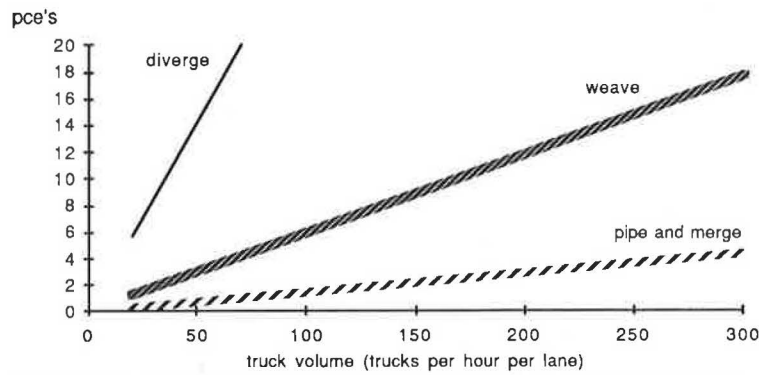**FIGURE 2   Volume-dependent truck pce based on effect on average travel time of all vehicles.**

FIGURE 3   Volume-dependent truck pce based on effect on average travel time of passenger cars.
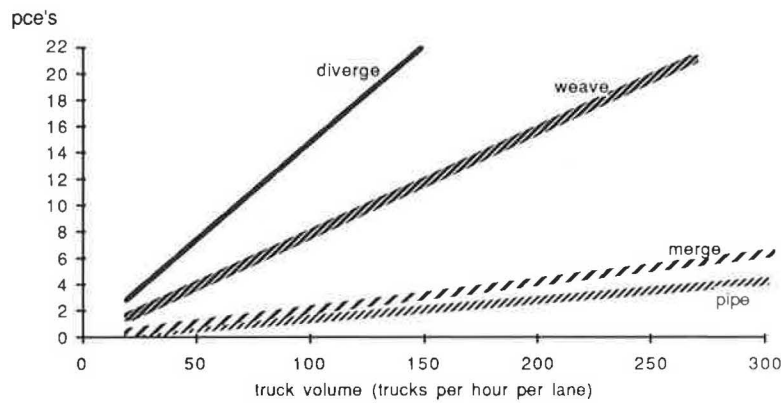

FIGURE 4   Volume-dependent truck pce based on effect on average travel time of trucks.

because the two lines are virtually confounded. In general, the relative magnitudes of the estimated coefficients lead to conclusions that are qualitatively in agreement with those obtained with the linear model discussed earlier, with regard to the relative sensitivity of passenger car and truck travel times to the prevailing volumes, and the variation across section types. Note that these figures are presented primarily for illustrative purposes, and are not intended for use as definitive values. Caution must naturally be exercised in extrapolating these results into the higher volume range, particularly for diverge

sections. Unfortunately, the limited nature of the data precludes more definitive conclusions but suggests, at the very least, that truck effect on freeway performance may not be captured very well by the HCM values for certain geometric features.

CONCLUDING COMMENTS

The results of an empirical analysis of the relationship between the average travel time per unit distance (experienced by pas-

senger cars, trucks, and all vehicles, respectively) and the prevailing volumes of passenger cars and trucks on urban freeway sections have been discussed in this paper. Using simple multivariate regression models, separate relations were developed for freeway sections exhibiting four types of geometric and operational characteristics. The calibrated relations then provided a mechanism for the systematic testing of (a) the effect of geometrics on the relative effects of passenger cars and trucks on freeway performance and (b) the relative sensitivity of the service quality (in terms of average trip time per unit distance) experienced by passenger cars and trucks to the components of the traffic stream. These questions are essential to the understanding of the performance of freeway facilities, and are of considerable practical interest in the context of the design and evaluation of truck-related highway improvements.

The results of the analysis presented in this paper revealed that the coefficients of the respective volume components varied significantly across section types, yielding volume-effect truck pces (in terms of impact on average travel time) that differed markedly from one type to another. These pces varied across geometric section types from approximately 2 up to over 15, and were different depending on whether they were based on the volume effect on passenger car, truck, or all-vehicles travel time. The values closest to the HCM-specified pce for the conditions under consideration were obtained when all observations were pooled together, thereby masking the statistically significant differences across section types. The results strongly suggest that the undifferentiated treatment of pces under different geometric conditions is not appropriate.

It should be kept in mind that the analysis presented here is primarily exploratory in nature, and is not intended to provide definitive generalizable values, especially given its reliance on less than ideal secondary data initially developed for the microscopic analysis of certain aspects of truck traffic in freeways. Nevertheless, the insights obtained regarding the relative effects of truck and passenger car volumes on freeway performance are worthy of further exploration. In this study, no differentiation could be made among truck types; however better understanding of the effect of various truck types, such as doubles and triples, needs to be developed in order to address the complex set of operational issues created by these vehicles on urban traffic facilities. Given the practical importance of these questions, experimental approaches under controlled conditions may be warranted, in conjunction with direct observation of existing conditions, in order to develop a sound understanding of the interaction between passenger cars and trucks in the shared use of highway facilities.

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