The Effects of Street Geometrics and Signalization On Travel Time and Their Relationships to Traffic Operations Evaluation

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The effects of street geometrics and signalization are discussed in terms of travel time, which is defined as the time of travel through a street section averaged over all drivers and all specified time periods within a prescribed class. This is the key factor in the evaluation of traffic operations. Travel time is shown to be significantly and reliably related to volume, given specific street section characteristics.

An extensive sample of urban arterial street field survey data collected through a collaborative effort of state and local agencies, is employed to study the dependence of the travel time-volume relationship to the geometrics and traffic control factors. The principal variance-producing factors in the study sample are identified. A major result of the study is the determination of a set of general prediction curves by means of which the travel time-volume relationship can be estimated from knowledge of the characteristics of given specific streets. The application of the travel time results to the evaluation of traffic operations is indicated.

•THE need for a means for objectively, reliably, and practically evaluating traffic operations on streets and highways has been generally recognized by transportation and traffic engineering circles. The availability of soundly based evaluation procedures would permit traffic engineers and administrators to make rational judgments on the performance of streets and highways. They would be able to weigh the benefits of, say, widening a street, changing the signalization, or controlling parking. They would be able to estimate the effects of variations in the volume of traffic. The operational performance of streets and highways could be predicted with respect to future traffic demands. All such estimates and predictions should be made on the basis of simple measurements made by field personnel in order to be operationally acceptable.

We have performed a research study (1) that is directed toward this problem. We have developed a traffic operations evaluation procedure, which we feel is objective, reliable, and, what is considered to be extremely important, practicable. Our attention has been focused on the class of arterial streets, since they have a greater number of factors affecting performance and since they carry the great bulk of traffic.

The determination of the operational performance of any operational situation requires the utilization of an appropriate measure. Such a measure, in this particular case, should reflect the true operational performance of streets and highways. And, to be efficient, such a measure should be capable of providing consistent, unbiased, and sensitive estimates of the street operational performance. Driver satisfaction has formed the keynote for the study, and hence the measure is postulated to contain the most significant individual contributions to the streets' performance which bear on driver satisfaction. Further, the measure must not only reflect the differences among

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streets, characterized by such factors as geometrics and signalization, but also must be directly sensitive to the traffic experienced. Certainly, the performance of a street will depend on the volume of traffic.

METHODOLOGY

The Measure of Traffic Performance

The measure of traffic performance postulated in this study is structured in terms of the significant driver dissatisfaction factors, and for a given length of street takes the form:

$$M = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 \tag{1}$$

where

x_1 = travel time,
x_2 = driver discomfort,
x_3 = driving hazards, and
x_4 = direct vehicle running costs.

Each of the driver dissatisfaction factors is required to have an operational indicator, i.e., a measurable traffic variable that will allow the convenient estimation of the factors. Traffic volume has been selected as the common measurable traffic variable to employ for the four factors.

It was initially hypothesized that the expected value (conditional on traffic volume) for each driver dissatisfaction factor for an individual vehicle would be given by:

$$y_i = a_i + b_i v \qquad i = 1, 2, 3, 4 \tag{2}$$

where v represents directional (say, 15-min) volume, and a_i and b_i are constants corresponding to the physical characteristics of a given street section type. Experimental observations subsequently showed, through a statistical analysis, that Eq. 2 adequately represents the relationship between the individual driver dissatisfaction factors and traffic volume for at least one of the factors (travel time) for the range of volumes that span roughly the time period between 7 a.m. and 7 p.m. The observation periods thus excluded the very low-traffic hours.

Since it is of interest to estimate the net loss of benefits for the population of drivers using a given street, it is necessary to weight the y_i by the corresponding volumes. The average of these weighted values, with respect to the volume distribution is then given by:

$$x_i = E\{v y_i(v)\} \qquad i = 1, 2, 3, 4 \tag{3}$$

The x's (cf. Eq. 1) thus represent the statistical average, over the relevant distribution of traffic volumes, of the driver dissatisfaction factors corresponding to the population of drivers that use the street in the time period over which the volume was measured (say, 15 min). The α's in Eq. 1 are the unit costs or values associated with each of the driver dissatisfaction factors.

The performance measure, M, thus provides a direct operational indication of actual driver satisfaction (or dissatisfaction). It is emphasized that M employs explicitly the important factors that traffic engineers normally use in gaging street performance, plus others that research has determined to have significant value. The four component factors in M were researched in this study to different degrees. However, the most comprehensive investigation was performed on travel time. The results presented subsequently will be confined to this factor.

Equation 2 can be illustrated (Fig. 1) for the travel time factor. This relationship is basic to the study. Eq. 2 demonstrates the effect of volume on the driver dissatisfaction factors (e.g., travel time) on a facility with given street characteristics (e.g., given geometrics and signalization).

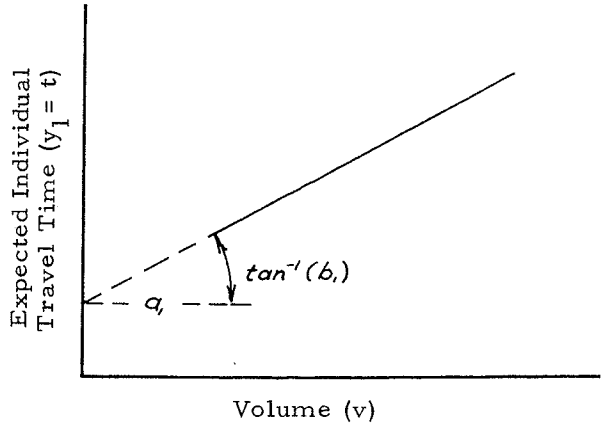

Figure 1. Typical factor relationship.

The Basis for Practical Procedures

The form of the forestated equations (e.g., Eq. 2) suggests that the effect of geometrics and traffic control will enter through the coefficients a_i and b_i. The effect of volume, of course, will enter through the variable v. Ideally, in an evaluation situation, given the significant street characteristics for a specific street section, the corresponding coefficients a_i and b_i would be selected from a predetermined set. And, subsequently, given the traffic volume distribution for the street section, the performance measure M would then be obtained.

The problem of developing an adequate evaluation basis and procedure then resolves to that of determining a way of simply and reliably relating the coefficients a_i and b_i to the significant street characteristics for sufficiently broad classes of streets. The set of such relationships would form the basis for evaluation. It is crucial, however, for the reliable determination of street operational performance that the relationships y_i (or equivalently the a_i and b_i) be consistently estimated for given street sections, once the geometrics and traffic control characteristics for the given street are identified. Thus, two different street sections with the same street characteristics would be expected to have the same slope b_i and the same intercept a_i. On the other hand, two street sections with widely different characteristics would be expected to have significantly different slopes and intercepts.

Accounting for the Variation

Many factors affect the variation of operational performance (characterized, for example, by travel time). This has led many to believe that the problem of obtaining reliable general estimating relationships is an impossible task. However, it is reasonable to expect that some factors will have a much greater effect on the variations than others. An initial problem then was the identification of these more influential factors. The approach for determining a set of general prediction relationships for the coefficients required the implementation of the following steps:

1. The identification of the significant variance-producing geometrics and traffic control factors.
2. The classification and structuring of streets with respect to the most significant factors.
3. The validation of the hypothesis that representative correspondence relationships can be obtained for street classes.
4. The determination of the general prediction relationships (coefficients vs street characteristics) for each of the driver satisfaction factors.

A statistical investigation is implicit in these four steps. Adequately comprehensive and adequately measured data corresponding to the individual driver satisfaction factors had to be employed. It is recalled that the evaluation measure (Eq. 1) is in terms of four driver satisfaction factors of which the most important is believed to be travel time.

THE TRAVEL TIME FACTOR

Travel time received the major effort from the overall program and has provided some of the more interesting results, some of which are believed to be directly applicable to the suboptimal evaluation of streets which fall within the scope of the study sample. The discussion of the travel time factor will also serve to illustrate the manner in which the other driver satisfaction factors could be treated.

The detailed investigation of the proposed methodology required comprehensive sets of travel time, volume, and street inventory data. A search conducted among various agencies early in the study yielded only two existing sets of data which were felt to be adequate for the study. One of these was from the Chicago Area Transportation Study. The other was from the Pennsylvania Department of Highways. The analysis of these preliminary sets of data established the feasibility of identifying the significant variance-producing factors, thereby obtaining reliable travel time and volume relationships. However, the results obtained were based on samples of data which were limited in size as well as limited geographically. But after the favorable results obtained from these initial studies, the way appeared to be clear for a more extensive investigation using more comprehensive data purposely gathered for this study.

The Data Set

A quite extensive set of travel time, volume, and street inventory data was subsequently collected in a planned survey through a substantial collaborative effort of several local and state traffic engineering and planning agencies. The collaborating agencies who participated in this research study are given in the Appendix. The data were collected following the preparation of careful experimental plans after extensive and intensive discussion with staff personnel of the various localities. The careful preparation served to guarantee a more efficient payoff with respect to the effort expended. Further, close coordination was maintained with the agencies throughout the conduct of the field surveys.

The overall set of data is composed of seven basic subsets which correspond to the following plans: Albany area street plan, Baltimore street plan, Buffalo street plan, Dallas street plan, Detroit street plan, Pittsburgh street plan, and San Diego street plan. Urban arterial street sections were selected for each plan which carried relatively heavy volumes and which were relatively homogeneous throughout the length of the test section. The total sample is composed of 158 street sections. Each section has an average of 40 to 50 paired observations of travel time and volume per direction. Travel time was measured by an adaptation of the floating-car method. Volumes were measured over 15-min intervals for each street section.

There are four general types of signal system types which describe the street sections in the data sample. These are: (a) pre-timed coordinated, (b) progressive, (c) traffic-actuated, and (d) pre-timed non-interrelated. The technical nature of these signal systems is distinct enough so that it was expected that different response relationships would hold for each of these types.

Methodology of Analysis

The response (or analysis variable) used for the study was the paired set of observations (slope, intercept) for the travel time-volume relationship for each street section. As indicated earlier, these two coefficients were hypothesized to be a function of the street factors, such as geometrics and signalization. Several specific factors had been initially indicated to significantly affect the variation of travel in urban areas. Among the most prominent of these were: (a) traffic volume (v), (b) pavement width

(w), (c) signal density (s), and (d) speed zoning (z). Travel time (per mile) is then related to all these factors in terms of the equation:

$$t = a + bv \tag{4}$$

where

$a = a(w, s, z, \ldots.)$
$b = b(w, s, z, \ldots.)$

that is, a linear relationship between t and v, where the regression coefficients are functions of the factors. For each street section (in each direction of flow) the 50 odd points (t, v) were then fitted with the best fitting line.

Significantly, it was found that the intercept could be well estimated by the speed zoning or speed of progression factors in most cases. In the remainder of the cases, such as streets with non-interconnected signals, it could be estimated by the lowest valued travel time observations. This finding enabled a sharpening of the analysis, since it implied that the slope coefficient is the variable primarily affected by the remaining street factors. The subsequent analyses are then based on the relationship between the slope b and the street factors. The variance of the observations around the regression lines is also investigated.

ANALYSES AND RESULTS

The mathematical analysis of the travel time data was performed in three steps after the identification of an initial set of potential variance-producing factors: (a) the analysis of variance of the factors, (b) test of homogeneity of the street sections classified according to the factors, and (c) determination of the general relationships that hold for broad street classes.

Analysis of Variance—Albany Area Data

An analysis of variance was performed on two factorial experimental designs that employed the Albany area data. The objective was to determine which factors were significant as well as the degree of significance. The analysis of one of these designs (which is representative of the other), a ¼ replicate of a six-factor experimental design, is given in Table 1 for:

Factors	Criterion Points
A. Number of lanes	3
B. Moving lane width (ft)	11
C. Signals per mile	3.5
D. Percent green time	50
E. Intersections per mile	10
F. Parking	one side

Each factor is taken at two levels. The criterion points indicating the levels of the factors are shown in parentheses after each factor. Values of the individual factors greater than the criterion point constitute one level, and values less than the criterion point constitute the second level. The factor interactions indicated by "e" in the analysis of variance table have been employed as the estimate of the error.

The fractional replicate given in Table 1 was designed in such a way that the indicated interactions could be estimated with little likelihood of confounding by other factor effects. The analysis of variance of this six-factor experiment indicates that all of the main effects are significant at least at the 10 percent level, with the exception of factor E, intersection density. In fact, signal density C is significant at the 0.1 percent level, which may be instrumental in the significance of the interactions AC and ACF.

TABLE 1

ANALYSIS OF VARIANCE FOR QUARTER REPLICATE DESIGN FOR SIX FACTORS, ALBANY AREA DATA

Section No.	Effect Estimated	Factor Values						Ratio of Mean Squares (F)
		A	B	C	D	E	F	
14	T	3	6.7	21.05	41	10.53	2	-
37	A	4	10.3	6.45	46	6.45	1	7.42[b]
20	B	2	11.0	3.51	53	15.79	2	5.17[a]
31	AB + CE	4	11.3	3.13	50	14.06	1	e
75	C	2	10.0	0.88	50	6.61	0	48.69[d]
33	AC	4	11.3	0	0	15.63	1	19.83[c]
69	AE	2	12.0	0	0	11.54	0	16.85[c]
41	E	4	11.3	3.45	42	6.90	1	NS
42	D	2	13.3	3.70	51	16.67	1	12.77[b]
25	AD + BF	4	10.0	4.08	59	7.14	2	e
22	BD + AF	2	11.0	13.33	56	10.00	2	4.92[a]
46	F	4	11.0	3.45	59	10.34	0	8.54[b]
76	CD	2	10.0	0.56	60	6.18	0	e
27	ACD	4	9.0	1.05	60	4.71	0	e
62	ACF + BCD	2	12.0	1.32	60	10.60	2	19.71[c]
77	DE + CF	4	13.5	1.80	58	7.21	0	e

Defining Contrasts: {I, ABCE, ABDF, CDEF} (2)

Slopes normalized to a per-lane basis for compatible comparisons.

[a]Significant at 10 percent level.
[b]Significant at 5 percent level.
[c]Significant at 1 percent level.
[d]Significant at 0.1 percent level.

The results of the analyses of variance of these two factorial designs suggest that signal density has a very significant effect on the variation. To a lesser degree, road width (or, equivalently, number of lanes and lane width), percent green time, and parking also have an effect. The effect of intersection density seems dubious. The weak effect indicated for parking may be partly due to the fact that it was not possible to identify from the data which street side had parking for those that allowed parking on only one side.

Factorial Design Analysis—Detroit Data

Of further interest is the analysis of the significance of the factor effects in the full-factorial experimental design for three factors, which employs the Detroit set of data. This set of data, it is recalled, is derived from a set of sections of a high type of arterial with a progressively phased signal system (Detroit street plan). The three factors considered for this study are street section, signal split, and number of lanes.

The analysis of variance of this factorial design is summarized in Table 2. The analysis was performed on both the slopes and on the standard errors. Furthermore, each of these was analyzed for both the favored direction of flow (signal-wise) and for the counter-favored direction. Thus, four analyses are shown in the table. The analysis shows that there is no significant difference in slopes between the two sections (factor A) in the favored direction. Going from a 50 to 30 split to a 45 to 35 split produced an increase in the slope which is significant at the 15 percent level. An increase in the slope, significant at the 5 percent level, was produced by going from 4 lanes to 3 lanes. In the counter-favored direction, all the main effects for the slopes become significant.

The analysis of variance on the standard error shows that signal split is significant at the 1 percent level along the favored direction. No other factor is significant for both the favored and counter-favored directions. Number of lanes and signal split are shown to produce a significant effect, whereas the difference between sections is not significant.

TABLE 2

ANALYSIS OF VARIANCE OF FULL FACTORIAL EXPERIMENTAL DESIGN FOR THREE FACTORS, DETROIT DATA[a]

Section No.	Effect Est.	Slopes (min/veh-mi)				Standard Error (min/mi)			
		$b \times 10^5$	Avg. Effect	Mean Square	F	$\sigma \times 10^3$	Avg. Effect	Mean Square	F
(a) Favored Direction									
8	T	107	-	-	-	349	-	-	-
6	A	167	20.5	841	0.57	394	11.3	253	0.05
4	B	104	-29.0	1,682	1.14	297	-103.8	21,528	5.2[c]
2	AB	125	-17.0	578	e	297	-31.8	2,016	e
7	C	85	-51.0	5,202	2.85[b]	347	-33.3	2,211	0.54
5	AC	100	-20.0	800	e	388	-11.3	253	e
3	BC	64	-6.5	85	e	255	-29.3	1,711	e
1	ABC	50	2.5	13	e	214	-9.3	171	e
(b) Counter Favored Direction									
8	T	211	-	-	-	363	-	-	-
6	A	335	118	27,613	3.66[b]	329	-8.3	136	0.05
4	B	184	-105	21,841	2.90[b]	304	-14.3	406	0.16
2	AB	270	-7	98	e	330	31.8	2,016	e
7	C	358	89	15,842	2.10[b]	312	-29.8	1,770	0.71
5	AC	483	13	313	e	291	-4.3	36	e
3	BC	190	-59	6,845	e	279	14.8	435	e
1	ABC	325	12	288	e	325	1.8	6	e

[a]The two directions have been pooled together (they have been indicated to be homogeneous).
[b]Significant at 5 percent level.
[c]Significant at 1 percent level.

Multiple Regression Analyses of Factors

Four multiple regression analyses were performed on the Albany area set of data. Two of these analyses were performed on the two sets of streets sections which constitute the two aforementioned factorial designs. The other two multiple regression analyses were made for: (a) the set of 2-moving-lane streets and (b) the set of 4-moving-lane streets, after first removing from consideration all those streets where the responses were significantly different (at the 1 percent level) between directions. In each case, the slope responses were regressed on the indicated independent variable.

Table 3 summarizes the results of these analyses. Signal density can be seen to be the most significant factor. Road width is also indicated to have a strong effect. Intersection density and parking are indicated to have a possible effect. These analyses reinforce the significance of the signal density factor and the road-width factor. The parking factor is once again indicated to have a possible effect.

Analyses of covariance were performed on the four sets of data after first arbitrarily dividing each set into two subsets for comparison purposes. The hypothesis that the two multiple regression equations for each pair are essentially the same could not be rejected, at about the 10 percent level of significance, which suggests that the employed factors may be explaining most of the variation. However, this may be partially because the observational sets have a large amount of variation. As a consequence, care would have to be taken in applying the multiple regression equations for prediction purposes.

Tests for Homogeneity

The analyses of variance discussed in the foregoing pages have singled out the factors that are most likely to introduce significant variation. Signal density appears to have an overwhelming effect on the variation. Pavement width and parking are also significant, but to a lesser degree. Strong contrasts are obtained between directions on the progressively signalized street sample. On the basis of the significant factors, which includes type of signalization, the street sections from the various samples were aggregated into groups which were considered to be relatively similar. These

TABLE 3

MULTIPLE REGRESSION ANALYSES OF GEOMETRIC AND CONTROL FACTORS, ALBANY AREA DATA

Variables	Coefficient	Standard Error	t-value	Mean Value
(a) First Factorial				
Half-width	-529	257	-2.06[a]	20.7
Signal density	1279	390	3.28[a]	4.6
Percent green	24	98	0.24	61.2
Intersection density	917	352	2.61[a]	9.0
(b) Second Factorial				
Number of lanes	-2821	947	-2.98[b]	3.1
Lane width	813	763	1.07	10.9
Signal density	1478	258	5.73[b]	4.3
Percent green	-6	65	0.09	59.0
Intersection density	231	317	0.73	10.0
Parking	519	1436	0.36	0.9
(c) 4-Lane Set				
Half-width	248	422	0.59	26.0
Signal density	-113	534	-0.21	3.8
Percent green	-89	79	-1.13	60.0
Intersection density	-47	391	-0.12	7.7
Parking	3642	2106	1.73	0.9
(d) 2-Lane Set				
Half-width	-476	417	-1.14	17.0
Signal density	1528	498	3.07[b]	4.3
Percent green	-131	102	-1.29	52.5
Intersection density	601	317	1.90[a]	10.7
Parking	2618	2536	1.03	1.3

[a]Significant at 5 percent level.
[b]Significant at 1 percent level.

groups, which have similar geometrics and traffic control characteristics, were conjectured to have similar responses. At the same time, some control groups were aggregated which were expected to have dissimilar responses.

Analyses of covariance (ANOCOV) were then performed on this large set of groups to test whether the responses for each group were similar (or dissimilar as the case may be). Generally, the results strongly confirm the hypothesis that uniform responses are obtained, once the street sections for each group are selected with similar factor characteristics. Furthermore, street sections aggregated with dissimilar characteristics give nonuniform responses. These findings strongly suggest that no significant factors have been overlooked, and all other factors are likely to have a minor effect.

The results of these analyses of covariance thus tend to strongly confirm that the major variance-introducing factors have been identified. The way now appeared to be prepared for the final and key step, which was to determine the actual effect of the factor levels on the responses. Of course, this would lead to general prediction relationships. The development of these relationships is presented in the sections that follow. But, first, the effect of signal density on the standard error is discussed.

SIGNAL EFFECT ON THE STANDARD ERROR

Signal density has been strongly indicated to have a significant effect on the slope responses. Hence, from the quantitative findings, as well as from theoretical considerations, a significant relationship would be expected between the standard error and the factor of signals per mile. This conjecture is confirmed by a plot of these two variables performed for the Albany area data (Fig. 2). Each point on the figure represents one street section. In particular, it is of interest to examine the relationship between the standard error and signals per mile for the arterial streets within the Albany area data set. Therefore, the mean line is determined for the points corresponding to arterial streets.

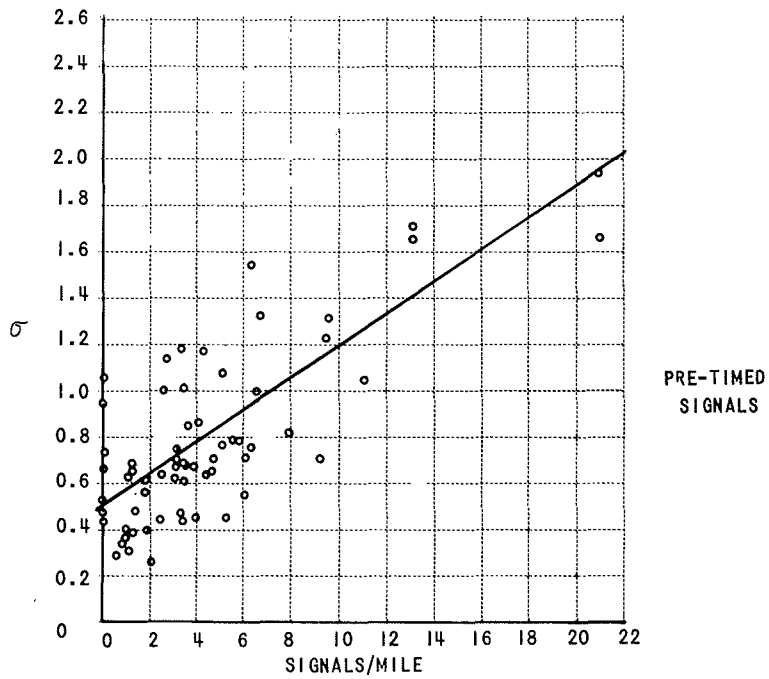

Figure 2. Relationship between standard error and signal density, Albany area data.

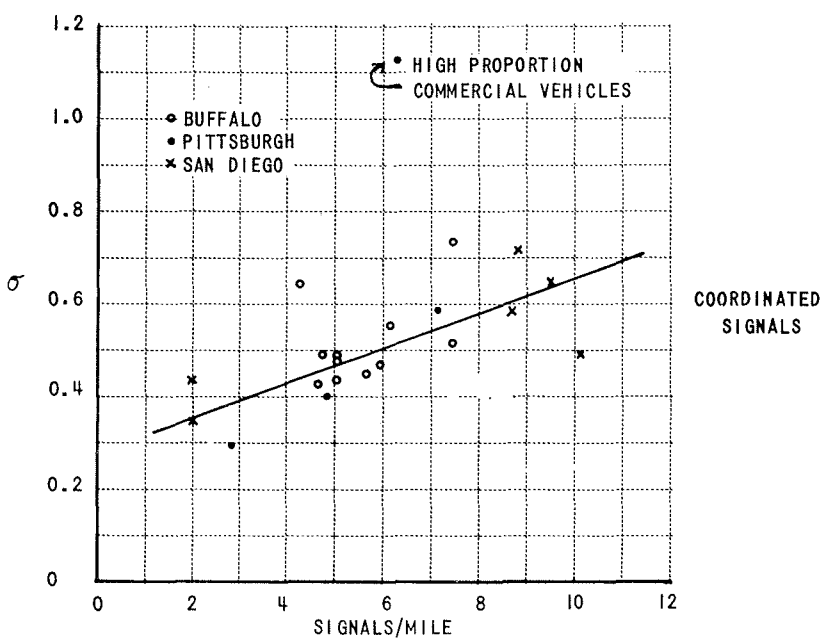

Figure 3. Relationship between standard error and signal density, pre-timed signals.

A comparable set of streets was selected from the data corresponding to the other localities; i.e., the selected streets were required to have pre-timed signal systems. The relationship corresponding to this set is shown in Figure 3. Here, again, the effect of signal density on the standard error is demonstrated. More significant is the fact that the points corresponding to the various localities are consistently distributed, with low variance, around the mean line (with the exception of one Pittsburgh section which had a large standard error attributable to a high proportion of commercial vehicles). This suggests stability in the measurement procedures.

Relationship Between Slope and Signal Density for Pre-timed Coordinated Signals

Streets with noncoordinated signal systems exhibit considerable variation in their responses. The traffic control factors peculiar to these systems, in combination with

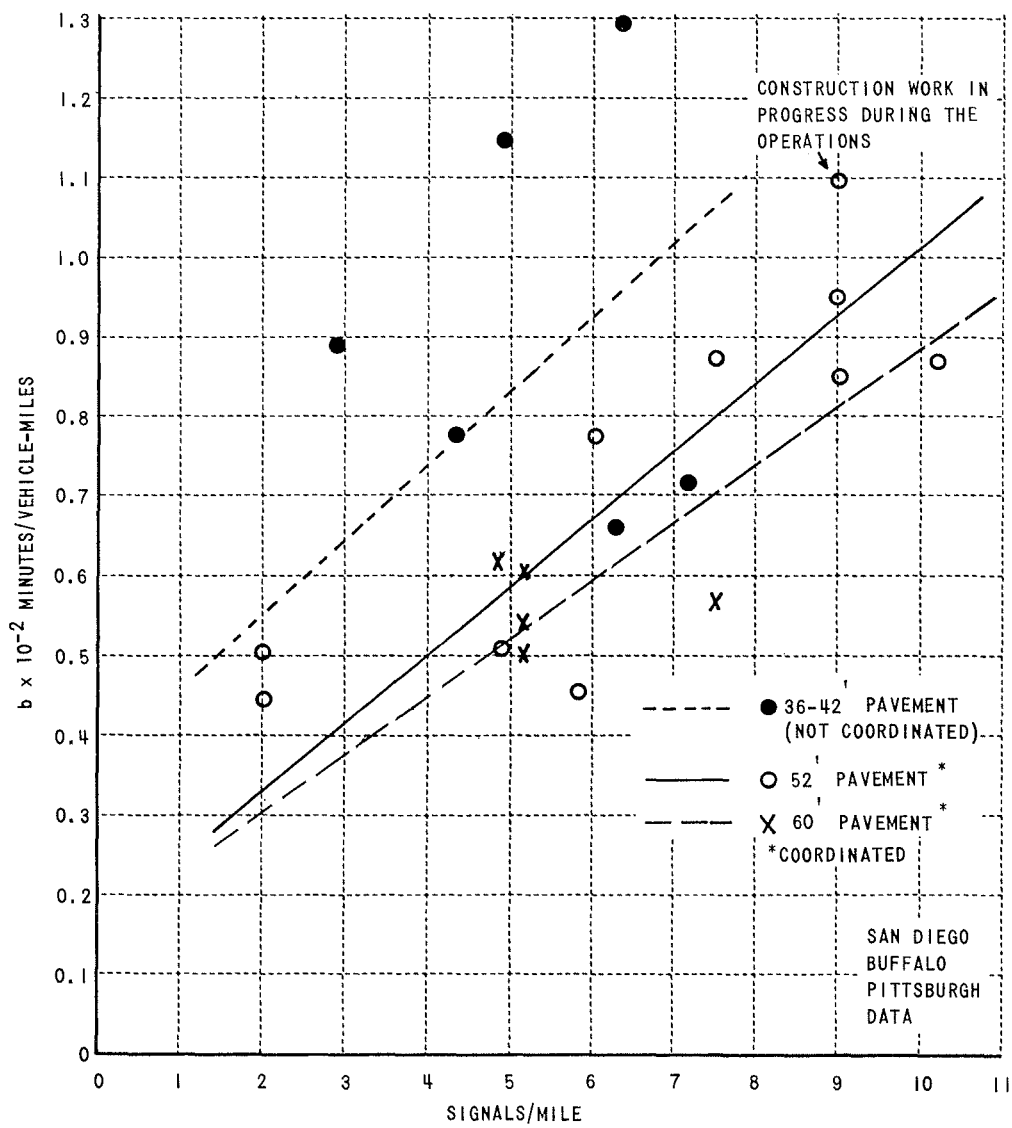

Figure 4. Relationship of slope to signal density.

the geometrics, tend to produce a significant effect on the responses. This variation compounds the problem of obtaining reliable estimates of the response through the use of street characteristics. Once the signals are coordinated, stable and predictable responses are then more likely to be obtained. Since signal density was found to be a very significant factor in the preliminary analyses, it was felt that an intensive exploitation of this factor would explain much of the variation and go a long way towards obtaining general prediction relationships.

The relationship between the slope coefficients and signal density has been examined for the set of streets with pre-timed signals from the Buffalo, Pittsburgh, and San Diego data. The data points (each point represents one street section) corresponding to these sets are shown in Figure 4. There are three groups of streets, corresponding to three pavement widths. The mean lines have been drawn through the corresponding sets of points for the 42-ft and the 52-ft pavement street sections. The 52-ft pavement set of points, the largest group, has a very significant relationship. It appears that most of the variation is explained by the signal density factor. The distribution of points for the 60-ft pavement set is indicated to fall slightly below the spread for the 52-ft pavement set (in particular, the centroid of the 60-ft set of points is located below the mean line for the 52-ft set). Since the observations for the 60-ft pavement set are clustered over a small range of signal densities, and since the mean line for this group is expected to be no worse than that for the 52-ft pavement set, the line through this set of points was obtained by hinging the line at the y intercept of the 52-ft pavement line. The data for the 36- to 42-ft pavement streets indicate that the corresponding line is translated upward at a steeper slope. This is to be expected since the number of moving lanes has been reduced from four to two. Considerably greater variation is also evident for this latter group, which is explained by the fact that the streets in this set did not have coordinated signal systems, in contradistinction with the other sets. A general relationship is thus evident between the slopes and signal density for streets with pre-timed, coordinated signals.

Further Confirmation From Another Set of Data

The relationship between the slopes and signal density has been further examined against the set of Baltimore data and the progressively phased streets from the San

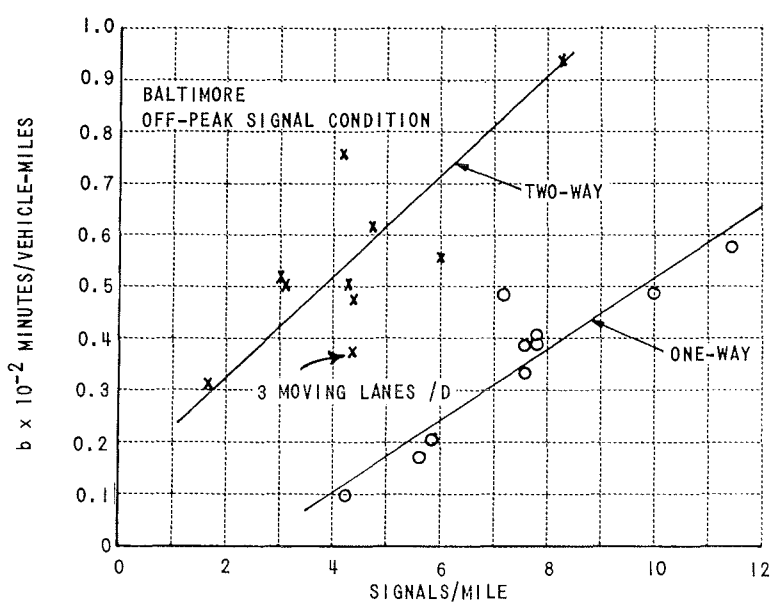

Figure 5. Relationship between slope and signal density, Baltimore—off-peak.

Diego set. The City of Baltimore has a traffic-adjusted signal system, where the progression and the cycle lengths are prescribed by the traffic conditions on strategic arterials. The signal parameters may thus vary throughout the day, which could imply difficulty of analysis.

An early inspection of the Baltimore raw data, however, revealed that the signal parameters, for most cases, can be blocked out into three distinct conditions that correspond to: a.m. peak (7a.m.-9 a.m.); off peak (9 a.m.-4 p.m.); and p.m. peak (4 p.m.-6 p.m.). During the a.m. peak, the signal progression favors the inbound traffic to the downtown area. During the p.m. peak, the signal progression favors the outbound traffic from the downtown area. The counter-favored direction suffers during the peak periods. During the off-peak period, average progression is employed where both inbound and outbound traffic have equal priority. The cycle lengths during the peak periods are typically 90 to 110 sec. For the off-peak period, the cycle lengths are typically 70 to 75 sec. By blocking out the data in the way indicated, the inferences for Baltimore are made comparable with those locations with pre-timed systems. However, this is not to say that the traffic-adjusted systems perform equivalently with the pre-timed systems. The traffic-adjusted system still has the advantages of flexibility and adaptability, which allow it to cope with variations in the traffic volume distributions.

The slope relationships were examined for the peak and for the off-peak conditions. The two peak periods (in the appropriate directions) were pooled into one group, since they constitute a symmetrical set. Further, since 1, 2, and 3-moving-lane streets were studied, the slopes were normalized in terms of 2-moving-lane streets. Figure 5 shows the relationship between the slope and signal density for two-way streets and one-way streets for the off-peak signal condition. Highly significant relationships are once again obtained, with a sharp distinction between the two sets. The distribution of points, corresponding to the two-way streets, can be superimposed right over the distribution already obtained for pre-timed signals. The mean line for the Baltimore set

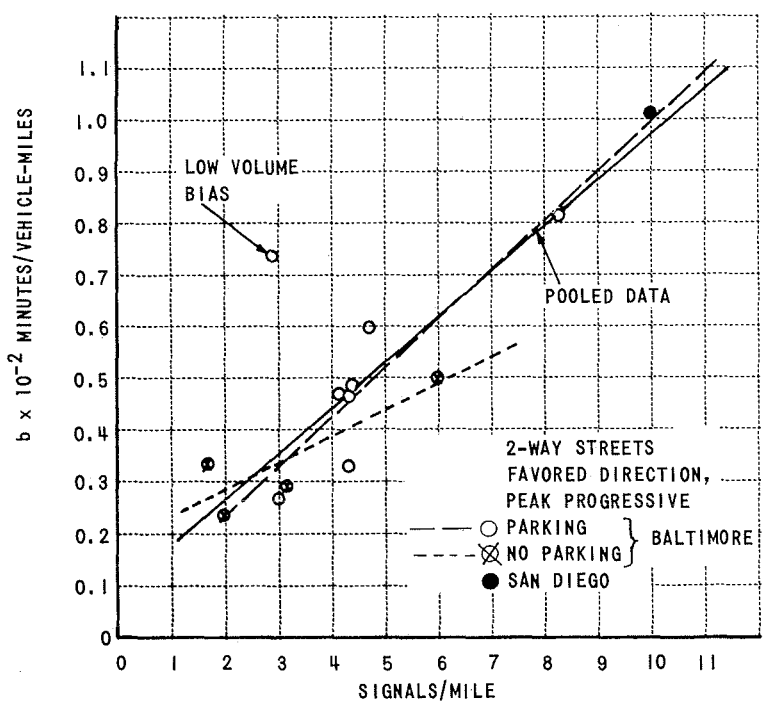

Figure 6. Relationship between slope and signal density, two-way streets.

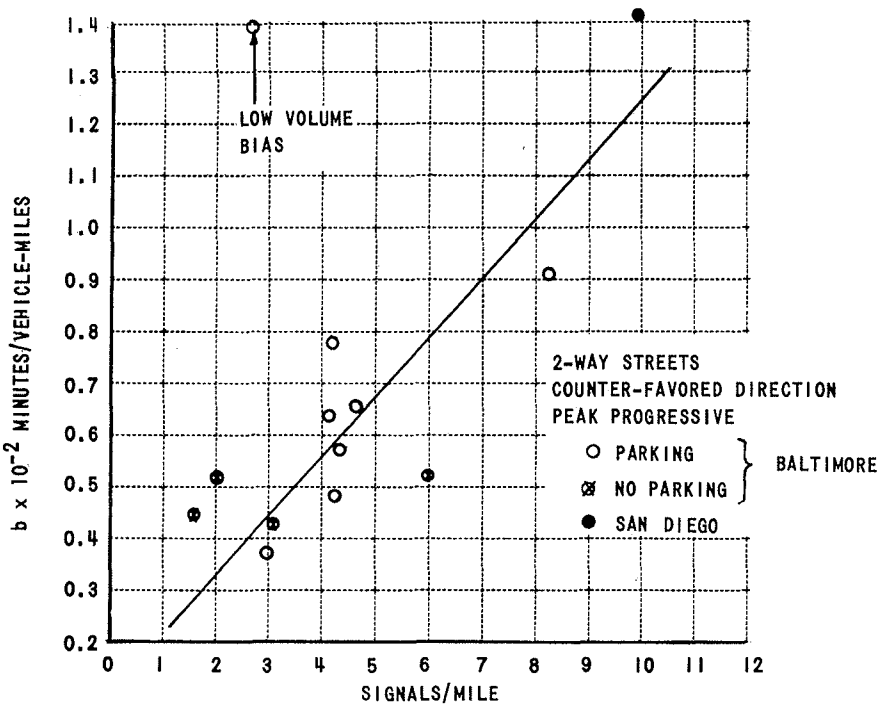

Figure 7. Relationship between slope and signal density, two-way streets.

coincides almost exactly with the mean line for the group of streets with pre-timed signals. Furthermore, the dispersion of the points around the mean line is also comparable for both sets.

The set of one-way streets (for the off-peak condition) is indicated to have very low dispersion around the mean line. The slope of the mean line through this set of points appears to be about the same as the two-way street set, but the intercept at the b-axis is considerably lower.

The relationships for the two-way streets for peak signal conditions are shown in Figures 6 and 7. Figure 6 shows the relationship along the favored direction of flow. Streets with parking or standing restrictions have been distinguished from those which do not have such restrictions, and a difference in the slope relationships is indicated. The relationship for the counter-favored direction is shown in Figure 7. Greater dispersion is evident for this direction and the mean line is displaced upward, as expected.

The relationships for the one-way streets for the peak signal conditions are shown in Figure 8. The slopes for the relationships are displaced downward from that for the two-way streets. The favored direction is shown to have a steeper slope than that for the counter-favored direction. Here, again, the data from the two different localities (Baltimore and San Diego) are consistent within the general relationship.

These results show strong relationships obtained between the slope coefficients for each street and signal density, for coordinated signal systems. The analyses have demonstrated that signal density has an overwhelming effect on the variation. Reliable relationships are obtainable once this factor is accounted for. The effect of locality has been shown to be not significant. Consistent relationships were obtained after pooling data from different cities. Pavement width (or, rather, lane width) and parking have been indicated to have an effect; however, the effect introduced by these factors is secondary. Cycle length and signal split are also secondary factors.

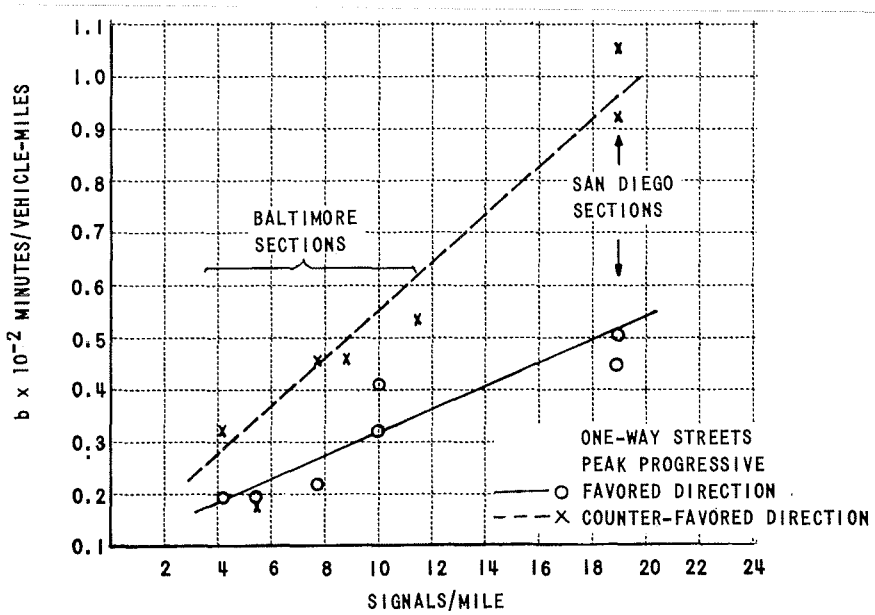

Figure 8. Relationship between slope and signal density, Baltimore and San Diego one-way streets.

The Effect of Signal Split

The Detroit street sections have been shown to have slope coefficients which are appreciably lower than those for the other streets considered. This appears to be due to the larger number of moving lanes (four in each direction during the peak periods), larger average lane width (10 ft), and the presence of a left-turning lane, besides the fact that a progressive signal system is employed.

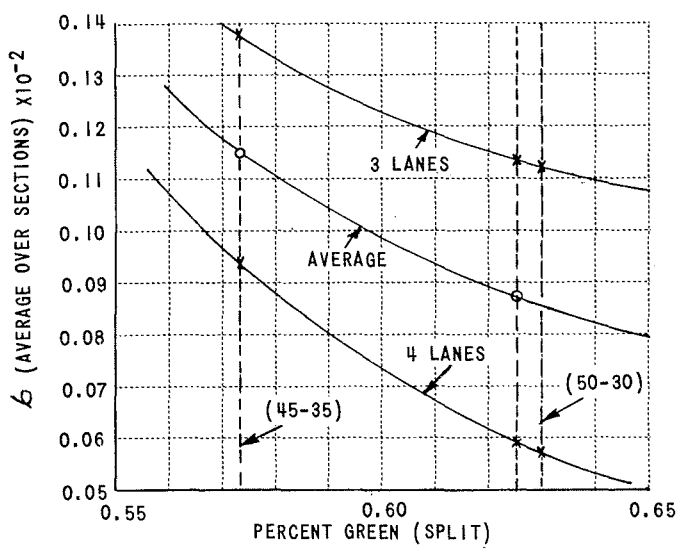

Figure 9. Relationship between slope and split, Detroit data—favored direction.

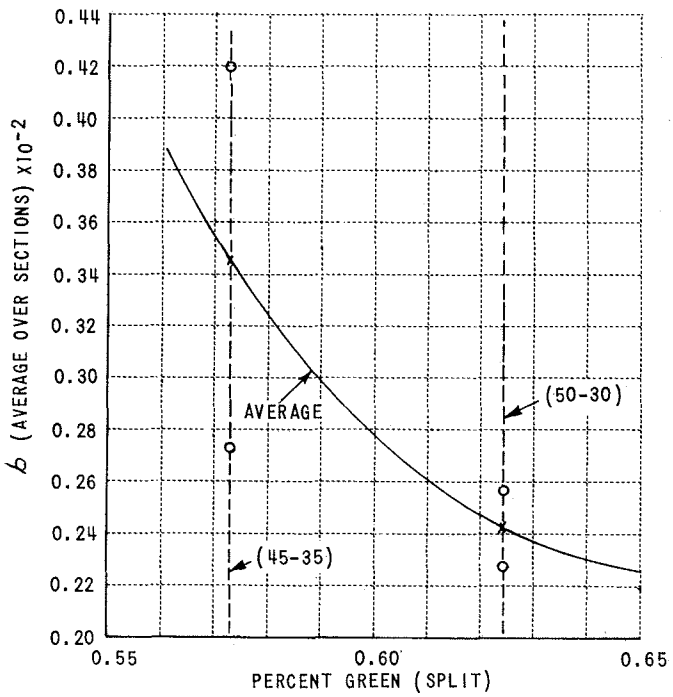

Figure 10. Relationship between slope and split, Detroit data—counter-favored direction.

For this set of streets, it was possible to conveniently and reliably investigate the effect of signal split. This effect is shown in Figures 9 and 10. The relationship between the slope b and signal split is expected to be a curve which is concave upward, since b can be seen to tend to infinity as percent green approaches zero, b can be seen to tend to some fixed lower bound as percent green tends to 100 percent, and the curve is expected to be continuous between the two extremes. It is noted for the favored direction case shown in Figure 9, that the 4-lane curve for the slope is indicated to be significantly lower than the 3-lane case. Further, the effect of signal split is evident. The relatively low volumes that are characteristic of the counter-favored direction do not allow a significant comparison between the 4-lane and 3-lane cases. The average curve through the pooled counter-favored set of points is shown in Figure 10.

In both the favored and counter-favored cases, signal split is shown to have a significant effect. A general relationship is indicated between the slopes and signal split. The favored direction curves appear to have a higher confidence relationship. The curves also show that the travel time loss in the counter-favored direction tends to increase more rapidly than along the favored direction as the signal split (percent green) is reduced.

Effect of Commercial Vehicles

The effect of the proportion of commercial vehicles has also been tested. Commercial vehicles are believed to introduce an effect on the dispersion of the travel time observations and consequently of the slope of the mean line. It is expected that as the proportion of commercial vehicles (dual-tired vehicles) increases, the standard error will increase. The hypothesis on this effect by commercial vehicles has been confirmed with the Pittsburgh data (Fig. 11). The Pittsburgh data were selected for this demonstration since the sections of this set had large contrasts in the number of commercial vehicles. A line is drawn through the set of points that correspond to the two

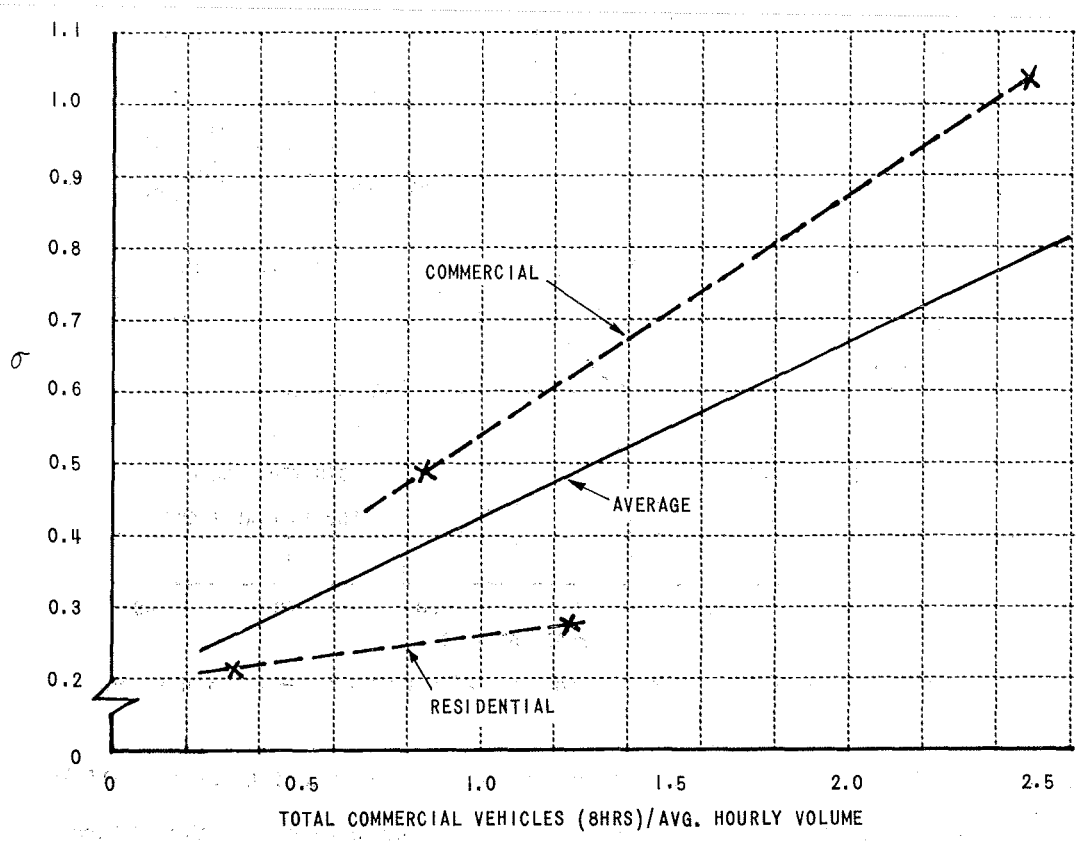

Figure 11. Relationship between standard error and commercial vehicles, Pittsburgh data.

residential street sections. A second line is drawn through the set that corresponds to the two commercial street sections. A third line is drawn through the pooled set of points.

The Slope Relationships for Traffic-Actuated Signal Systems

The factors that affect the responses of streets with traffic-actuated signal systems were expected to differ from those for streets with pre-timed signal systems. In fact, from the nature of traffic-actuated systems, it was expected that the greatest effect on the variation would come from the cross-traffic volume at the signalized intersections. The higher the volume on the cross streets, the greater the likelihood of having traffic-induced interruptions. Consequently, on the average, the delays on the through street would increase as the cross traffic increased.

This hypothesis was tested and confirmed against the set of Dallas data. All the street sections in the Dallas group have fully actuated signals and are all similar in their geometric characteristics. Average daily traffic (ADT) for the pertinent cross streets was obtained from the 1964 Dallas ADT map. The independent variable was selected to be the sum of the ADT's from all the cross streets that corresponded to the signalized intersections on each sample street section.

Figure 12 shows the relationship obtained between the slope and cross-ADT, when the directions are pooled together. Low dispersion is evident for this group. However, Sections 4 and 7 appear as outliers, which appears to be because traffic in both directions carries approximately the same volume even during the peak periods; no one direction is able to dominate the progression of flow. Also shown in Figure 12 are the indicated differences between streets with parking and streets with no parking permitted.

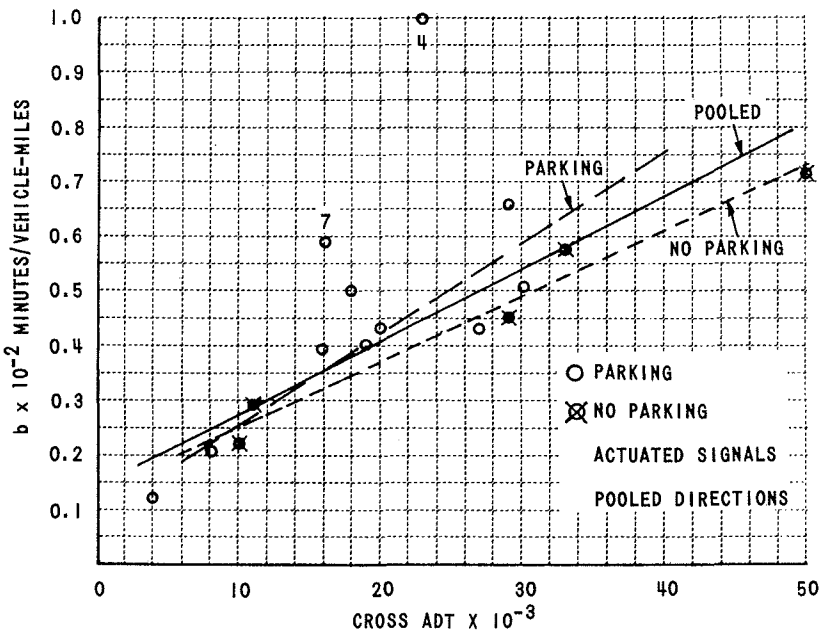

Figure 12. Relationship between slope and cross-ADT, Dallas data—pooled direction.

Highly significant relationships are evident between the slope and the cross-ADT for these data groups.

Figure 13 shows the relationship corresponding to the favored direction of flow (heaviest volume) during the peak periods. The slope relationship for the off-peak periods is shown in Figure 14. Greater dispersion is evident for these relatively

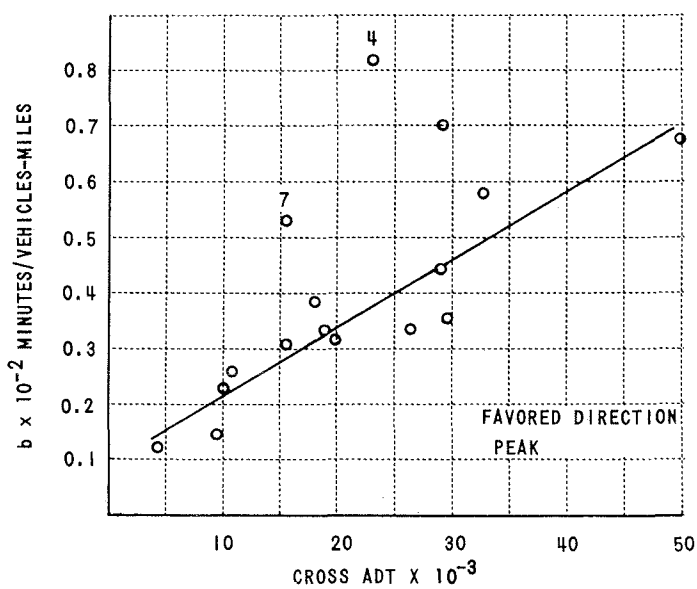

Figure 13. Relationship between slope and cross-ADT, Dallas data—peak.

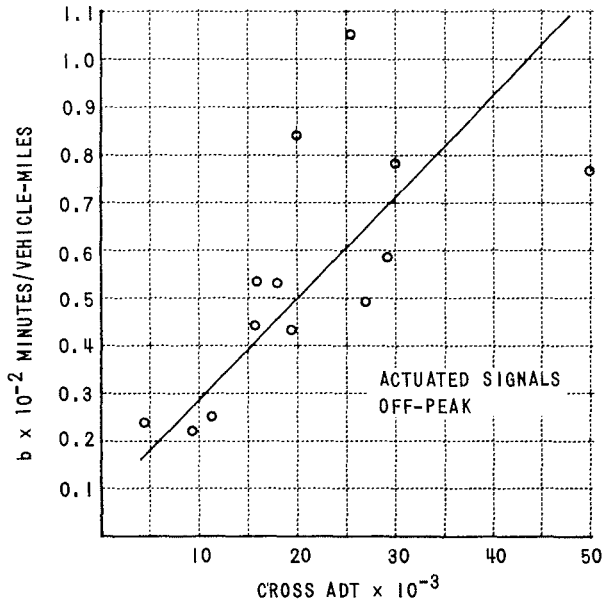

Figure 14. Relationship between slope and cross-ADT, Dallas data—off peak.

low-volume conditions, which was expected beforehand. The classification according to peak favored and off peak has thus also yielded highly significant relationships.

Slope Relationships for Traffic-Supervised Systems

The traffic-supervised, semiactuated set of streets from the San Diego sample was also expected to be principally affected by the cross-ADT. In order to obtain a stable

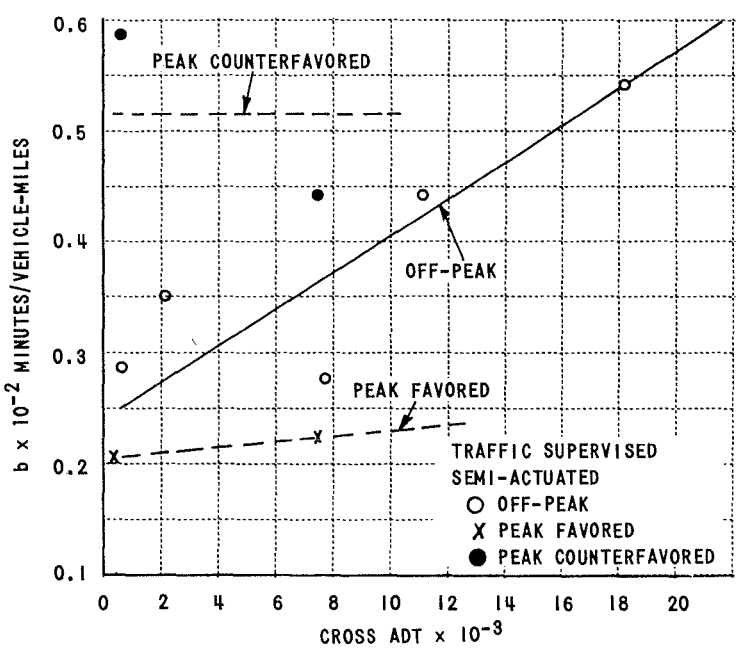

Figure 15. Relationship between slope and cross-ADT, San Diego data.

set of data that would not be confounded by extraneous variables, the signal system conditions were held fixed at either the peak settings or the off-peak settings during each set of experimental runs. Thus, the flexible features of the traffic-supervised system were not tested. Once again, since semiactuated signals are employed, the likelihood of traffic interruptions would increase as the volume on the signalized cross streets increases. This suggested the cross-ADT as the principal variance-introducing factor.

The relationships obtained for this type of system are shown in Figure 15. The off-peak condition shows a significant relationship. It is further noted that a comparison of this data with the data for the actuated signal systems (Dallas) reveals that the data sets roughly overlap at the low cross-ADT region, suggesting quite similar relationships.

CONCLUSIONS

A measure of traffic operational performance was proposed which is expressed in terms of four driver satisfaction factors: travel time, driver discomfort, driving hazards, and direct vehicle running costs. Travel time was discussed in great detail. An extensive investigation was performed on this factor, based on the slope relationship between travel time and volume. By accounting for the effect of volume variation in this way, it was possible to perform a more efficient investigation of the effects of the other geometrics and signalization factors. This led to the demonstration of the operational effects of the most significant street characteristics.

Signal density was shown to have a highly significant effect on the variation of travel time through analyses of variance and multiple regression analyses performed on several factorial experimental designs (Tables 1, 2 and 3). Road width (lane width), percent green time, and parking had a lesser effect. Analysis of covariance confirmed the conclusion that the major variance-producing factors had been identified, and that, consequently, consistent general relationships could be obtained between the slopes and the geometrics and signalization factors. With the satisfactory results obtained from these preliminary steps, the way was then clear for the final and key step—the determination of general prediction relationships between the geometrics and signalization factors and the slopes.

The strong effect of signal density in coordinated signal systems was shown in Figures 4 to 8. Lane width and parking were indicated to have a secondary effect. Attention was called to the relatively low dispersion of the observations around the mean line for each homogeneous group. Also, the effect of locality was shown to be not significant. Consistent relationships were obtained after pooling the observations from different cities.

The effect of signal split and number of lanes was shown in Figures 9 and 10; the effect of commercial vehicles was shown in Figure 11.

The significant factor in traffic-actuated and traffic-supervised systems was found to be the relative number of signalized intersections, weighted by the cross-ADT at those intersections. Figures 12 to 15 show these relationships. A contrast was observed between peak and off-peak operations. Parking, once again, was found to have a secondary effect.

The figures in the foregoing discussion provide a set of general estimating relationships for the travel time factor that covers large classes of arterial streets. Consistent and reliable estimates of the travel time slopes can be obtained for specific street sections, given the geometrics and traffic control characteristics. These estimates can then be applied to the traffic evaluation problem, given the volume distribution.

Although it is believed that the most reliable estimates of the operational performance of streets should also make use of the other three driver satisfaction factors, first order estimates of street performance can be obtained through the use of travel time. Travel time is recognized as the major factor from the drivers' viewpoint. The performance, in terms of the one factor, would be obtained by making use of the first term in Eq. 1, thus

$$
\begin{aligned}
M &= E\{vt\} \\
&= E\{v(a + bv)\} \\
&= aE\{v\} + b\,E\{v^2\} \\
&= aE\{v\} + b\,[\mathrm{Var}\{v\} + E^2\{v\}]
\end{aligned}
$$

Hence, given a street section whose slope relationships have been predetermined, and knowing the street characteristics of the section, such as type of signalization, signal density, number of moving lanes, etc., . . . , the slope b could then be obtained. This would be done, for example, through the application of the figures presented in this paper. And, given the speed zoning or speed of progression of the street, the coefficient a would be determined. The volume distribution would give E{v} and Var {v}. Finally, the determination of the performance measure, M, would be a simple arithmetical computation involving the quantities noted.

To illustrate an application of the results presented in this paper, a sample problem is discussed. Say that it has been proposed that a certain one-mile section of an arterial street have two additional intersections signalized in order to assist the cross traffic which has increased in the two corresponding cross streets. This would raise the number of signalized intersections over the section from an initial four to six. The street section is further characterized as having a 52-ft pavement width, a pre-timed coordinated signal system, and it is zoned for a 30-mph speed. It is desired to know how this signalization change will affect the through traffic on the arterial section.

To make the evaluation, the directional volume characteristics E {v} and Var {v} are required. These two parameters are obtained from a sample directional volume (say, 15-min volumes) distribution for the section. The first parameter is simply

$$E\{v\} = \frac{\mathrm{ADT}}{(2)(4)(24)}$$

Assuming now that the street section under study has the following volume parameters:

$$E\{v\} = \frac{16{,}000}{(2)(4)(24)} = 83.5 \text{ vehicles/15 min}$$

$$\mathrm{Var}\{v\} = 3480$$

then all the necessary information is now available for performing the evaluation.

The expected, or average, travel time per 15-min period is determined for each of the two signal conditions. It is recalled that the equation for M will be used. First, it is observed that, since the section is zoned for 30 mph, then

$$a = \frac{60}{30} = 2.0 \qquad \text{(min/mi)}$$

Further, since the section has a pre-timed coordinated signal system with a 52-ft pavement, the solid line in Figure 4 is to be employed. For the first signal density condition, we enter the graph in the abscissa at the value of 4 signals per mile and read out the slope $\beta = 0.5 \times 10^{-2}$. For the second (the proposed) signal condition, the slope of $\beta = 0.67 \times 10^{-2}$ is obtained.

Letting M_1 be the expected travel time for the street with signal density of 4, and M_2 for the street with signal density of 6, we then obtain

$$M_1 = (2)(83.5) + (0.005)[3480 + (83.5)^2]$$

$$M_2 = (2)(83.5) + (0.0067)[3480 + (83.5)^2]$$

Hence

$$M_2 - M_1 = (0.0017)\,[3480 + (83.5)^2]$$

$$= 17.8 \text{ min per directional mile per 15-min period}$$

This represents the increase in travel time per mile for the drivers using the street section in one direction over a 15-min period. Dividing this number by the average 15-min volume, we obtain

$$\frac{17.8}{83.5} = 0.213 \text{ min} = 12.8 \text{ sec/mi/veh}$$

Thus, by increasing the number of signalized intersections from four to six, the travel time per vehicle is increased by 12.8 sec while traveling over the one-mile section.

Concluding Comment

Our research has included the other three driver dissatisfaction factors; each has been investigated to a lesser degree than the travel time factor. The preliminary findings on these other three factors suggest that they can be treated in a similar fashion to the travel time factor. Further research, however, is required to establish the relationships between these factors and volume. We believe that the use of this overall methodology will result in objective and rational judgments of traffic operational performance. And, it is stressed, the suggested procedure is practicable.

ACKNOWLEDGMENTS

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2. Davis, O. L. Design and Analysis of Experiments. Hafner, 1960.

Appendix

COLLABORATING AGENCIES ON TRAVEL TIME TASK

Agency	Contact
New York State Department of Public Works, Subdivision of Transportation Planning and Programming	Roger L. Creighton, Director
Baltimore Department of Transit and Traffic	James L. Foley, Commissioner
Dallas Department of Traffic Control	Winston H. Carsten, Director
Detroit Department of Streets and Traffic	Alger F. Malo, Director
Pittsburgh Bureau of Traffic Planning	Anthony F. Miscimarra, Traffic Engineer
San Diego Division of Transportation and Traffic Engineering	Martin J. Bouman, Transportation and Traffic Engineer
Buffalo Division of Safety	Henry W. Osborne, Traffic Engineer
Erie County Department of Public Works	H. Dale Bossert, Commissioner
Buffalo Department of Police	William H. Schneider, Commissioner
Town of Amherst Highway Department	George Austin, Superintendent