Statistical Modeling of Travel Speeds and Delays on a High-Volume Highway

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•VEHICULAR travel has increased at a tremendous rate in recent years, and the construction of new highways and the improvement of existing facilities have failed to keep pace with the growth of motor-vehicle travel. The problem is especially acute in urban areas where major arterial highways lack needed capacity for handling large movements of intracity travel. Inadequate planning and improvement of these facilities have resulted in congestion and delays which are costly and irritable to the road users.

Limited-access freeways are being constructed in large urban areas to accommodate major flows of through and intracity travel. Existing arterial highways continue to play an important role in the movement of traffic, however, and they serve as collectors and distributors for the new expressways. The improvement of these arterial facilities is necessary for the efficient and safe functions of the complete urban area transportation system. As a result of the emphasis placed on the construction of new roads, the continuing renovation of existing highways has been largely neglected.

This project was undertaken by the Joint Highway Research Project of Purdue University, the Indiana State Highway Commission, and the U.S. Bureau of Public Roads to evaluate the effectiveness of traffic engineering as applied to the improvement of a congested urban arterial highway. The purpose of this research investigation, as a portion of that project, was a detailed analysis of travel speeds and delays. The specific objectives of this study were (a) to determine the significant factors and variables which influence travel speeds and delays; and (b) to develop statistical models using these significant variables to predict travel speeds and delays.

The various statistical models developed to express travel speeds and delays as functions of factors and variables that are descriptive of the roadway and its environment afforded an insight into the characteristics of traffic flow on the study route. The relationships permitted the determination and evaluation of appropriate improvements in the existing roadway and in traffic control devices to minimize travel delays. The planning and design of new facilities are also benefited by the development of estimating equations to predict travel speeds and delays.

REVIEW OF LITERATURE

Travel-time studies have been performed for various purposes, all of which are related to the evaluation of the level of service afforded by a highway section. Because the driver often considers total time in reaching his destination as the criterion for selecting a certain route, travel times are given consideration in the evaluation of a highway system (4).

Previous investigations have been performed to determine those variables that have significant effects on travel speed. These variables are generally classified in the categories of traffic stream, roadway geometry, roadside development, and traffic controls.

Overall travel speed appears to be related closely to traffic volume. W. P. Walker found that for a highway section on which all variables were controlled except volume,

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the average speed of traffic decreased with an increase in volume. In rural areas, a straight-line relationship occurred between volume and average travel speed when the critical density of the highway was not exceeded. Beyond this density, speed continued to decrease but volume also decreased because of congestion (13). In the Chicago area, travel speeds were observed to decrease continually with increasing volumes without a break signifying the critical density (7).

The characteristics of the traffic stream have important effects on travel speed, but these influences have not been conclusively substantiated by field investigations (13). The character of traffic includes such items as through traffic, local traffic, driver residence, trip purpose, and trip destination. In one study, the percentage of commercial vehicles had a negligible influence on travel speed (2).

Little information is available concerning the relationship of overall travel speed with highway geometry. A linear correlation of travel time with street width was made by R. R. Coleman. The width alone did not affect travel time significantly (2).

The effects of various types of impedances on the average overall speeds of test vehicles were studied in North Carolina. Many of these impedances were related to commercial development. They included various types of turning movements, slow-moving vehicles, marginal friction such as parked cars and pedestrians, and vehicles passing in the opposing direction. The presence of slow-moving vehicles had the most significant influence in reducing speeds. Left and right turns from the direction of travel of the test car were also important causes of speed reductions. The remaining impedances examined in the study were both individually and collectively insignificant (3).

Investigations have been made to evaluate and compare the performance of different types of traffic signals and their relationships to travel speeds and delays. W. N. Volk reported that stopped-time delays to vehicles which were required to stop were much greater at fixed-time signals than for traffic-actuated signals and for two-way and four-way stopped-controlled intersections. In the same study, intersections exhibiting similar relationships between delays and volumes were grouped together. Simple linear regression equations were developed to predict delay from traffic volume with an acceptable degree of reliability (12).

A straight-line relationship between mean travel time and signal density was established for urban areas in Pennsylvania. Regression equations developed for various volume-to-capacity ratios were reasonably precise for uncongested conditions. Travel times for test sections with coordinated signals were compared with times for a series of non-coordinated signals. The sections with coordinated signals had reduced travel times, but the difference was not statistically significant (2).

PROCEDURE

The highway analyzed in this investigation was the U.S. 52 Bypass at Lafayette, Indiana. A variety of traffic functions served by this two-lane facility include the following:

1. Through traffic between Indianapolis, Chicago, and intermediate points;
2. Terminal traffic from throughout Tippecanoe County to Lafayette, an industrial center and the county seat, and to Purdue University in adjoining West Lafayette; and
3. Local traffic to commercial and industrial establishments abutting the bypass.

Study Design

The bypass was divided into 18 homogeneous study sections by considering geometry, speed limit, roadside development, and location of traffic signals (Fig. 1). Signalized intersections were separated from the other sections of this route. These intersections, which were categorized as "interrupted flow," represented a special condition where traffic was required to stop for a red signal. A distance of 500 ft on each side of the center of the intersection was established to define the zone of influence of the traffic signal. Sections 3, 8, 11, 13, and 15 were classified in this category of interrupted flow. The traffic signal in section 3 was semi-actuated, and the other four signals had fixed-time cycles. The remaining portion of the two-lane bypass was

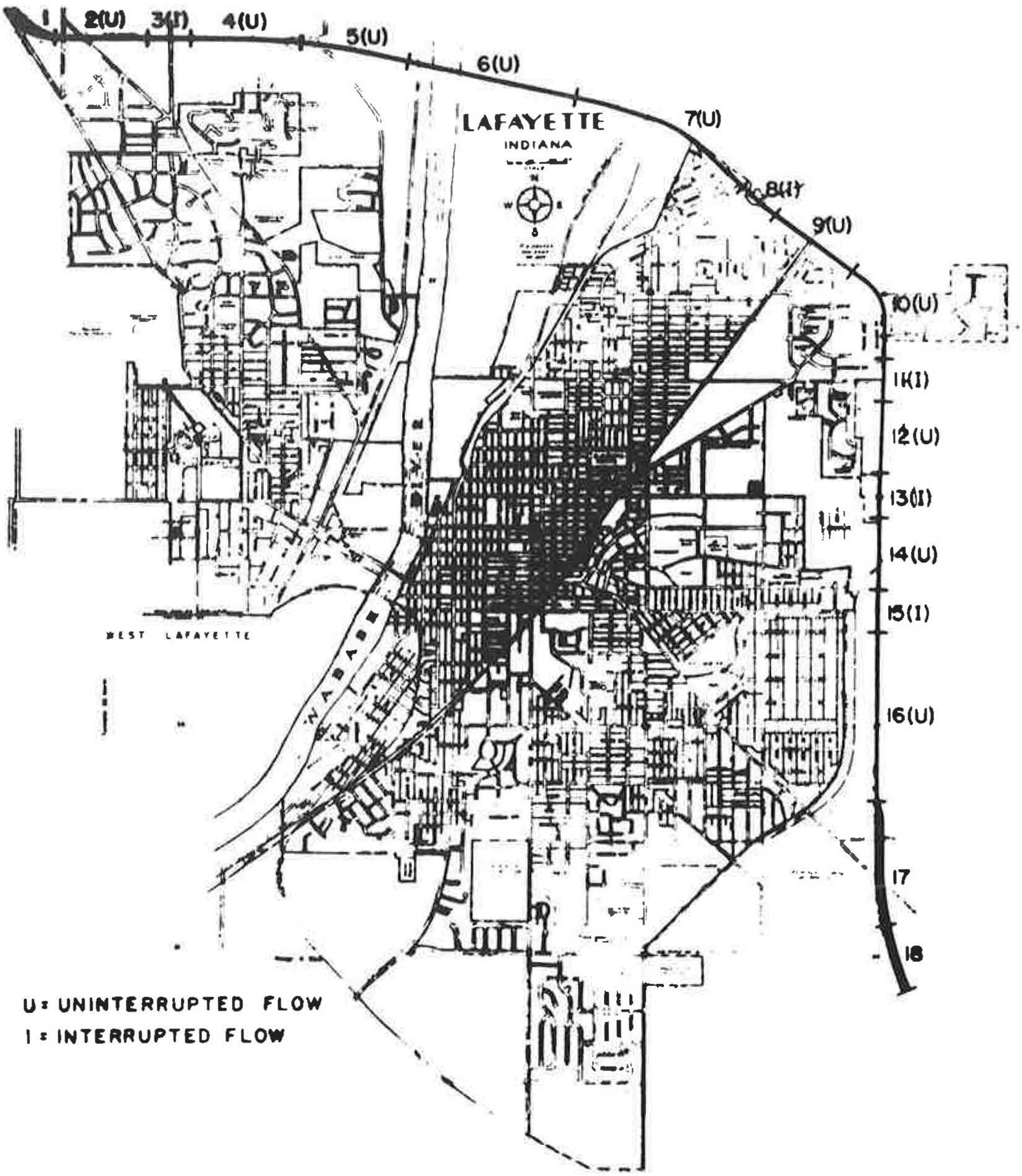

Figure 1. Test sections of U.S. 52 Bypass.

designated and analyzed as "uninterrupted flow." This category included sections 2, 4, 5, 6, 7, 9, 10, 12, 14, and 16.

Three sections of the bypass were not considered in the multivariate analysis of the interrupted and the uninterrupted flows. Sections 1 and 17 included transitions from a four-lane divided highway to a two-lane roadway; section 18 was entirely a four-lane facility.

The selection of the variables to be included in the multivariate analyses was dependent on an examination of those variables considered in previous investigations and on the availability and ease of collecting data. The following variables were included in the analysis of uninterrupted flow by direction of travel:

1. Intersecting streets on the right, number per mile;
2. Intersecting streets on the left, number per mile;
3. Intersecting streets on both sides, number per mile;
4. Access drives on the right, number per mile;
5. Access drives on the left, number per mile;
6. Access drives on both sides, number per mile;
7. Commercial establishments on the right, number per mile;
8. Commercial establishments on the left, number per mile;
9. Commercial establishments on both sides, number per mile;
10. Posted speed limit, mph;
11. Average shoulder width on the right, ft;
12. Average shoulder width on the left, ft;
13. Portion of section length where passing was not permitted, percent;
14. Average absolute grade, percent;
15. Average algebraic grade, signed percent;
16. Average curvature, deg;
17. Geometric modulus—based on gradient, lane width, sight distance, and curvature—(11);
18. Average safe stopping sight distance, ft;
19. Practical capacity, vph;
20. Possible capacity, vph;
21. Advertising signs, number per mile;
22. Warning signs, number per mile;
23. Information signs, number per mile;
24. Regulatory signs, number per mile;
25. Presence of a truck climbing lane (0 if no, 1 if yes);
26. Presence of a signal in the next section (0 if no, 1 if yes);
27. Presence of a signal in the preceding section (0 if no, 1 if yes);
28. Monday (0 if no, 1 if yes);
29. Tuesday (0 if no, 1 if yes);
30. Wednesday (0 if no, 1 if yes);
31. Thursday (0 if no, 1 if yes);
32. Friday (0 if no, 1 if yes);
33. 8:00 a.m. to 10:00 a.m. (0 if no, 1 if yes);
34. 10:01 a.m. to 12:00 n. (0 if no, 1 if yes);
35. 12:01 p.m. to 3:00 p.m. (0 if no, 1 if yes);
36. 3:01 p.m. to 6:00 p.m. (0 if no, 1 if yes);
37. Traffic volume in direction of travel, vehicles per 15 min;
38. Traffic volume in the opposing direction of travel, vehicles per 15 min;
39. Commercial vehicles (larger than a pickup truck), percent;
40. Southeast direction of travel (0 if no, 1 if yes);
41. Northwest direction of travel (0 if no, 1 if yes);
42. Total traffic volume, vehicles per 15 min;
43. Volume to practical capacity ratio;
44. Volume to possible capacity ratio; and
45. Overall travel speed, mph.

The remaining variables, included in the analysis of interrupted flow, are as follows:

46. Presence of a semi-actuated signal (0 if no, 1 if yes);
47. Presence of a signal indication for left-turn movement (0 if no, 1 if yes);
48. Presence of a right-turn lane (0 if no, 1 if yes);
49. Length of approach to turning lane, ft;
50. Length of exit for merging lane, ft;
51. Average algebraic grade of approach, percent;
52. Average algebraic grade of exit, percent;
53. Intersecting streets, excluding that street with the signal, on the right, number;
54. Intersecting streets, excluding that street with the signal, on the left, number;
55. Intersecting streets, excluding those streets with the signal, on both sides, number;

56. Access drives on the right, number;
57. Access drives on the left, number;
58. Access drives on both sides, number;
59. Commercial establishments on the right, number;
60. Commercial establishments on the left, number;
61. Commercial establishments on both sides, number;
62. Cycle length of traffic signal, sec per cycle;
63. Green time in direction of flow, sec per cycle;
64. Practical approach capacity, vph;
65. Advertising signs, number;
66. Warning signs, number;
67. Information signs, number;
68. Regulatory signs, number;
69. Southeast direction of flow (0 if no, 1 if yes);
70. Northwest direction of flow (0 if no, 1 if yes);
71. Vehicles making left turns from the direction of travel, percent;
72. Vehicles making right turns from the direction of travel, percent;
73. Vehicles making left turns from the opposing direction of travel, percent;
74. Average shoulder width on the right, ft;
75. Average shoulder width on the left, ft;
76. Monday (0 if no, 1 if yes);
77. Tuesday (0 if no, 1 if yes);
78. Wednesday (0 if no, 1 if yes);
79. Thursday (0 if no, 1 if yes);
80. Friday (0 if no, 1 if yes);
81. 8:00 a.m. to 10:00 a.m. (0 if no, 1 if yes);
82. 10:01 a.m. to 12:00 n. (0 if no, 1 if yes);
83. 12:01 p.m. to 3:00 p.m. (0 if no, 1 if yes);
84. 3:01 p.m. to 6:00 p.m. (0 if no, 1 if yes);
85. Traffic volume approaching the intersection in the direction of travel, vehicles per 15 min;
86. Traffic volume approaching the intersection in the opposing direction of travel, vehicles per 15 min;
87. Total traffic volume entering the intersection on all approaches, vehicles per 15 min;
88. Commercial vehicles (larger than a pickup truck), percent;
89. Green time to cycle length ratio;
90. Approach volume to total volume entering intersection ratio;
91. Approach volume to practical capacity ratio;
92. Overall travel speed, mph; and
93. Delay (total delay for the test vehicle traveling through the intersection), sec.

Variables comprising street, access drive, and commercial densities were expressed in a "per-mile" form for the uninterrupted flow sections because of the variation in section lengths. The lengths of the interrupted flow sections were uniform, and similar variables for this analysis were retained as an absolute value. Because all traffic lanes of the bypass were 11 ft wide, lane width was not included as a variable.

Collection of Data

An inventory of the physical characteristics for the bypass was made from construction plans and aerial photographs. In some cases, actual measurements were performed in the field. Section lengths measured by a fifth-wheel odometer were checked with the control points located on the construction plans.

Possible and practical capacities were computed in accordance with methods described in the "Highway Capacity Manual" (6). Volumes were recorded simultaneously with the measurement of travel times. Counts were taken at four points along the test route for 15-min intervals. The control stations, located in sections 2, 6, 10, and 16, were used to expand the volumes by hour and by direction for the remaining sections. All volumes were obtained with recording counters actuated by pneumatic hoses.

The result of a traffic composition analysis at representative sections was that the percentage of vehicles larger than a small two-axle pickup truck was constant for all sections of the bypass. Hourly fluctuations did occur, and ratios were established for different periods of the day. The percentages of vehicles turning right and left at a given signalized intersection did not vary significantly for different periods of the day. Average values for turning movements were established for each intersection.

Travel times were measured by the average-car technique. The driver operated the test car at a speed which in his opinion was representative of the average speed of the traffic stream. During periods when the test car was not influenced by other vehicles, the driver observed the speed limit. Travel times at the section boundaries were recorded with a stop watch by an observer in the car. Whenever the vehicle was forced to stop, the duration of this stop was measured with a second stop watch.

Forty runs were made in each direction to assure a good estimate of the mean travel speed for each section (1, 10). This procedure provided a sample size of 800 observations for the ten sections representing uninterrupted flow. Five sections provided a sample size of 400 observations for the analysis of interrupted flow.

All test runs were made over the entire length of the bypass. The test vehicle entered the traffic stream about 0.5 mile before the first section and continued for approximately the same distance after the last section. The data collections were made on weekdays between 8:00 a.m. and 6:00 p.m., and during clear, dry weather conditions. Trips were made during peak and off-peak hours to insure a variation in traffic volumes.

Analysis of Data

The data were first processed and summarized before the multivariate analyses were initiated. Travel times for each run and section were converted to overall travel speeds as follows:

$$S = \frac{L(3600)}{T} \tag{1}$$

where

S = overall travel speed—mph,
L = length of test section—miles, and
T = travel time—sec.

The mean travel speed and stop time for each section and direction were calculated.

The travel delay for each run at signalized intersections was computed as follows:

$$D = T - \left[\frac{L\,(3600)}{0.5\,(\bar{S}_B + \bar{S}_A)}\right] \tag{2}$$

where

D = travel delay—sec,

T = travel time—sec,

L = length of section—miles,

$\bar{S}_B$ = average overall travel speed of adjacent section before intersection—mph, and

$\bar{S}_A$ = average overall travel speed of adjacent section after intersection—mph.

The term in the brackets in Eq. 2 was considered as the hypothetical travel time if the intersection had not existed. In a few cases where the computed delay was a negative value, these delays were assumed to be zero. The delays were averaged for each intersection by direction.

The average delay per vehicle for each signalized intersection was again calculated by a theoretical method which depends on the red interval of the cycle, the average arrival headway in the traffic stream, and the starting performance of the queue. The average delay per vehicle is

$$\bar{d} = \frac{A}{C}\left[nR - \frac{n^2A}{2} + \frac{2.1(n)(n+1)}{2} + 3.7n - Q\right] \quad (3)$$

where

$\bar{d}$ = average delay per vehicle—sec,
A = average arrival headway—sec,
C = cycle length—sec,
n = total number of vehicles stopped in R,
R = length of stop time in cycle—sec, and
Q = constant (depending on the value of n).

Complete details of this derivation are presented in the textbook, "Traffic Engineering" (8).

The first step in each multivariate analysis was the calculation of a correlation matrix for the study variables. Both factor analysis and multiple linear regression techniques were utilized in this statistical modeling of travel speeds and delays on a high-volume highway. Before the factor analysis was performed, the dependent variables were deleted from the correlation matrix. This procedure permitted later correlations between the dependent variables and the generated factors.

Orthogonal factors were generated so that a maximum contribution to the residual communality was provided. The generation of the factors was terminated when the eigenvalue became less than 1.00. The factor matrix was then rotated with the varimax method to aid interpretation of each factor. An examination of the rotated-factor matrix resulted in the identification of the generated factors.

Coefficients were developed to express each factor in terms of the original variables. Thus, the factors were evaluated from the values of the variables that were significantly related to each factor. The final step in the factor analysis was the correlation of the generated factors with the dependent variables. The resulting multiple linear regression equation expressed the dependent variable as a function of the significant factors (9).

A build-up regression analysis was then performed on the study variables (5). The following criteria were used in rating the variables for inclusion in the final multiple linear regression equations:

1. Each significant factor was represented by at least one closely related variable;
2. The final model involved a minimum of computations with readily obtainable data; and
3. The multiple coefficient of determination did not increase significantly by including additional variables.

RESULTS

The results of the multivariate analyses of travel speeds and delays are discussed in this section. The data were first summarized by computing mean travel speeds and delays for each study section. A factor analysis was performed to gain an insight into the relationships among the study variables. Multiple linear regression equations were developed to predict mean travel speeds and delays in terms of the factors and the variables. The results of these analyses were then applied in recommending improvements to minimize delays on the bypass location. All variables are identified by the numbers which are listed in the discussion of the experimental design. Each factor is labeled with a letter in the evaluation of the results of the factor analysis.

Uninterrupted Flow

The overall travel speeds for each test section in the analysis of uninterrupted flow were averaged for both directional flows and the combined flows. These mean travel

TABLE 1

AVERAGE OVERALL TRAVEL SPEEDS, UNINTERRUPTED FLOW

Section	Average Overall Travel Speed, mph		
	SE Flow	NW Flow	Combined Flows
2	41.4	40.6	41.0
4	42.0	47.7	44.9
5	51.0	52.5	51.8
6	52.8	53.9	53.4
7	45.1	45.2	45.2
9	40.3	42.0	41.2
10	40.8	42.6	41.7
12	34.4	39.3	36.9
14	30.4	33.5	32.0
16	35.3	35.3	35.3

speeds are given in Table 1. The highest speeds occurred in sections 5, 6, and 7 where the commercial roadside development was sparse. In sections 12, 14, 16, where heavy commercial strip development occurred, the lowest speeds were recorded.

Factor Analysis

A correlation matrix was calculated for variables 1 to 45. Variables 2, 5, 8, and 38 were deleted from the matrix to avoid singularities. Variables 40 and 41, which identified the directional flows, and variable 45, overall travel speed, were also removed. The speed variable was later correlated with the generated factors. The revised correlation matrix was factorized with unities inserted in the main diagonal of the matrix. The 38 variables were reduced to 13 factors which accounted for 88 percent of the total variance of the variables.

The 13 factors were then rotated to aid in their identification. The signed factor coefficients indicate the relative importance of each variable in the explanation of the generated factors. The plus and minus signs are indicative, respectively, of the increasing or decreasing presence of the variables in the composition of the factors. Each factor, along with its major component variables and their respective coefficients, is included in the following list.

Commercial Development—This factor includes a concentration of commercial establishments, access drives, and related conditions indicating a high degree of commercial development:

6. Access drives on both sides, +0.9294;
9. Commercial establishments on both sides, +0.9287;
10. Speed limit, -0.4930;
11. Shoulder width on right, +0.2341;
12. Shoulder width on left, +0.5259;
26. Signal in next section, +0.4114; and
27. Signal in preceding section, +0.5888.

Horizontal Resistance—Horizontal roadway features influencing traffic movement are included in this group:

13. No-passing zone, +0.9244;
16. Average curvature, +0.7644;
17. Geometric modulus, -0.8693;
18. Stopping sight distance, -0.7443;
19. Practical capacity, -0.7638; and
20. Possible capacity, -0.7556.

Evening Shopping Travel—This category describes late afternoon shopping trips on the evenings when local stores are open:

28. Monday, +0.3523;
31. Thursday, -0.6170;
32. Friday, +0.4392;
33. 8:00 to 10:00, -0.2464;
34. 10:01 to 12:00, -0.7637; and
36. 3:01 to 6:00, +0.8724.

Flat Topography—A level roadway alignment is reflected in this factor:

15. Algebraic grade, -0.9151; and
25. Truck climbing lane, -0.6860.

Time Variations—This factor, which is not completely defined, expresses variations in the time periods and the days when the data were collected:

30. Wednesday, -0.7612; and
35. 12:01 to 3:00, -0.8616.

Urban Development—This category indicates that the highway is located in an urban area:

3. Intersecting streets on both sides, +0.7510;
10. Speed limit, -0.4368; and
24. Regulatory signs, +0.4697.

Driver Distractions—This group includes items which distract the driver's attention from the highway:

21. Advertising signs, +0.7895;
26. Signal in next section, +0.5416; and
27. Signal in preceding section, -0.4861.

Further Time Variations—Additional variations in times are reflected in this undefined factor:

31. Thursday, -0.4723;
33. 8:00 to 10:00, -0.8820; and
34. 10:01 to 12:00, +0.4830.

Outbound Traffic—Traffic heading away from the urban area is described by this factor:

23. Information signs, -0.8789;
24. Regulatory signs, -0.5969; and
37. Volume in direction of travel, -0.2154.

Day-of-Week Variations—This factor, generated by daily variations, is not completely discernible:

28. Monday, +0.8559;
30. Wednesday, -0.2779; and
32. Friday, -0.6026.

Rural Development—This group of variables describes a rural-type highway with little roadside development:

3. Intersecting streets on both sides, -0.2194;
9. Commercial establishments on both sides, -0.2030;
11. Shoulder width on right, -0.9113; and
26. Signal in next section, -0.2891.

Stream Friction—Conditions which cause congestion within the traffic stream ar indicated by this factor:

20. Possible capacity, -0.5313;
25. Truck climbing lane, -0.5902;
26. Signal in next section, +0.4616;
37. Volume in direction of travel, +0.3986; and
44. Volume to possible capacity ratio, +0.4952.

Additional Day-of-Week Variations—This undefined facto for different days of the week:

28. Monday, -0.2780;
29. Tuesday, +0.9610; and
32. Friday, -0.3467.

The factors were readily identified e day-of-week characteristics. Th different days and time perio

The next execution in the factor-analysis procedure was the computation of the factor-score matrix. The coefficients in this matrix permit the factors to be evaluated as functions of the original variables which are expressed in terms of multiple linear regression equations. Examples of these equations are presented later in the results.

The final step was the correlation of each factor with the mean overall travel speed to determine those factors which significantly accounted for the variation in travel speeds (Table 2). The four dominant factors were, in their order of importance, commercial development, stream friction, urban development, and rural development. The following multiple linear regression equation was evolved to predict mean travel speeds from the significant factors:

$$S_1 = 42.30 + 9.185\,(-0.5507F_A - 0.1874F_F + 0.1744F_K - 0.2674F_L) \tag{4}$$

where

S_1 = mean travel speed, mph;
F_A = commercial development;
F_F = urban development;
F_K = rural development; and
F_L = stream friction.

The multiple correlation coefficient of this expression was 0.664. Approximately 44 percent of the total variation in travel speeds was explained by the four factors. The precision of the estimate was measured by the standard error of estimate of 6.87 mph. The factors of commercial development, urban development, and stream friction were negatively related to travel speed, whereas the remaining factor of rural development was positively associated with travel speed. Eq. 4 is most useful in an explanatory sense rather than for actual computations.

Multiple linear regression equations were developed to evaluate the significant factors in terms of those variables which predominantly explained each factor. The following equations were written from the coefficients in the factor-score matrix:

$$F_A = -0.1070Z_3 + 0.2498Z_4 + 0.2064Z_6 + 0.2438Z_7 + 0.2068Z_9 + 0.1930Z_{27} \tag{5}$$

$$F_F = 0.3878Z_1 + 0.2954Z_3 - 0.1012Z_9 - 0.1190Z_{10} + 0.2558Z_{12} - 0.1444Z_{22} - 0.1214Z_{23} + 0.2535Z_{24} - 0.1106Z_{26} - 0.1049Z_{43} \tag{6}$$

$$F_K = +\,0.1134Z_1 + 0.1870Z_4 + 0.1688Z_7 + 0.1179Z_{10} - 0.5580Z_{11} + 0.1456Z_{15} + 0.1800Z_{18} - 0.1575Z_{19} - 0.1256Z_{20} - 0.2860Z_{22} - 0.1460Z_{26} + 0.1384Z_{43} \tag{7}$$

$$F_L = -0.1102Z_1 - 0.1193Z_{10} - 0.3897Z_{15} + 0.1130Z_{15} - 0.2064Z_{16} + 0.1564Z_{17} - 0.2553Z_{20} - 0.1513Z_{21} - 0.2502Z_{25} + 0.2362Z_{26} - 0.2523Z_{27} + 0.1135Z_{37} + 0.1144Z_{42} + 0.1719Z_{44} \tag{8}$$

where

F_i = common factor, and
Z_i = standard score of variable.

The values of the dependent and independent variables in these equations are expressed standard-score form. Standard scores are computed by the following relationship:

$$Z_i = \frac{X_i - \overline{X}_i}{s_i} \tag{9}$$

TABLE 2

CORRELATION OF MEAN TRAVEL SPEED WITH FACTORS, UNINTERRUPTED FLOW

Factor	Correlation Coefficient
A	-0.5507[a]
B	-0.0525
C	-0.0928
D	+0.0049
E	-0.0659
F	-0.1874[a]
G	+0.0956
H	-0.0920
I	+0.0535
J	+0.0289
K	+0.1744[a]
L	-0.2674[a]
M	-0.0400

[a]Significant at the 5 percent level.

where

Z_i = standard score of variable,
X_i = observed value of variable,
$\bar{X}_i$ = grand mean of variable, and
s_i = standard deviation of variable.

Multiple Linear Regression and Correlation Analysis

The second phase of the multivariate analysis of uninterrupted-flow conditions was the development of a multiple linear regression equation to predict mean travel speed from the significant variables. The 38 variables in the revised correlation matrix were included in a build-up regression technique.

The following multiple linear regression equation was selected as the most valid functional relationship for the estimation of overall travel speed:

$$S_2 = 68.60 - 0.4541X_3 - 0.1775X_9 - 0.1007X_{13} - 0.0150X_{19} - 0.0301X_{42} \quad (10)$$

where

S_2 = mean travel speed, mph;
X_3 = intersecting streets on both sides, number per mile;
X_9 = commercial establishments on both sides, number per mile;
X_{13} = portion of section length where passing was not permitted, percent;
X_{19} = practical capacity, vph; and
X_{42} = total traffic volume, vehicles per 15 min.

The various statistics of this regression equation are given in Table 3. The measure of correlation was expressed by a multiple correlation coefficient of 0.704. The variables of intersecting streets, commercial establishments, no-passing zone, practical capacity, and total volume accounted for 50 percent of the total variation in overall travel speeds for the uninterrupted flow sections of the bypass. These five variables were negatively related to travel speed. The standard error of estimate of 6.55 mph was a measure of the precision of the equation.

A significant portion of the unexplained variation in overall travel speeds was probably caused by individual driver behavior. Variations were evident in the driving habits of vehicle operators as the test-car driver attempted to relate his speed to the average speed of the traffic stream. In addition, variations occurred within the test driver in his reactions to the many conditions influencing his speed.

TABLE 3

MULTIPLE LINEAR REGRESSION AND CORRELATION ANALYSIS, UNINTERRUPTED FLOW[a]

Variable	Net Regression Coefficient	Standard Error
3	-0.4541	0.1214
9	-0.1775	0.0211
13	-0.1007	0.0135
19	-0.0150	0.0022
42	-0.0301	0.0044

[a]Dependent variable: travel speed; intercept = 68.60 mph; multiple correlation coefficient = 0.704; and standard error of estimate = 6.55 mph.

Interrupted Flow

The analysis of interrupted flow followed the same pattern as the investigation of uninterrupted flow. Mean overall travel speeds and mean running speeds were computed for directional flows and for the combined flows in each section (Table 4).

TABLE 4

AVERAGE TRAVEL SPEEDS, INTERRUPTED FLOW

Section	Average Travel Speed, mph					
	SE Flow		NW Flow		Combined Flows	
	Overall Speed	Running Speed	Overall Speed	Running Speed	Overall Speed	Running Speed
1[a]	26.8	29.5	42.4	42.4	34.6	36.0
3	30.1	31.9	29.3	32.2	29.7	32.1
8	21.7	26.4	24.1	28.2	22.9	27.3
11	19.9	25.3	27.4	30.0	23.7	27.7
13	23.6	25.9	24.8	27.8	24.2	26.9
15	19.7	23.5	21.1	25.7	20.4	24.6
17[a]	35.0	38.0	32.0	35.7	33.5	36.9
18[a]	29.2	32.9	24.1	31.9	26.7	32.4

[a]Not included in the multivariate analysis.

The overall speed equaled the running speed in the northwest flow of section 1 because no stop was required in this direction. The mean speeds in sections 17 and 18 were higher than for the other sections; these sections were longer and the delays caused by the signal were distributed over a greater distance. Of the five sections included in the multivariate analysis, section 3, which had a semi-actuated traffic signal for the traffic on the road crossing the bypass, had the highest overall travel speeds.

The stopped times for each section were summarized by computing the mean stopped time of each run, the mean duration of the stop, and the percent of the runs when stops occurred. These results are given in Table 5. Because a stop sign existed in the southeast flow of section 1, the test vehicle was always forced to stop. The stopped times were less at section 3 with the semi-actuated signal than at any other signal. In section 11 the test vehicle encountered fewer stopped times in the northwest flow, because there was a 10-sec advance green time for left turns and through movements in that direction.

The average delays per vehicle for both bypass approaches to each intersection included in the multivariate analysis were computed by the two methods described. These total delays, including both stopped and running delays, are given in Table 6. The delays computed were very similar. A hypothesis test was performed to determine whether the mean of the differences of the computed and the theoretical mean delays at each

TABLE 5

AVERAGE STOPPED TIMES, INTERRUPTED FLOW

Section	SE Flow			NW Flow		
	Avg. Stopped Time per Run (sec)	Avg. Length of Stop (sec)	Percent of Runs When Stops Occurred	Avg. Stopped Time per Run (sec)	Avg. Length of Stop (sec)	Percent of Runs When Stops Occurred
1[a]	5.3	5.3	100.0	—	—	—
3	3.7	12.4	30.0	4.1	15.3	27.5
8	10.0	16.6	60.0	8.1	15.0	52.5
11	12.1	18.7	65.0	4.2	10.5	40.0
13	4.8	11.4	42.5	5.7	12.8	45.0
15	9.2	17.5	52.5	8.6	16.5	55.0
17[a]	5.3	16.4	32.5	8.0	16.3	60.0
18[a]	8.8	17.6	50.0	15.8	19.6	72.5

[a]Not included in the multivariate analysis.

TABLE 6

AVERAGE DELAYS, INTERRUPTED FLOW

Section	Avg. Delay per Vehicle (sec)			
	SE Flow		NW Flow	
	Calculated	Theoretical	Calculated	Theoretical
3	7.0	6.4	7.4	7.9
8	11.0	15.7	15.1	12.9
11	15.5	16.4	8.3	8.5
13	8.3	7.9	10.6	8.9
15	13.5	14.2	13.0	12.7

approach was equal to zero. The hypothesis was accepted at a 5 percent level of significance. Therefore, the results of the two computational methods did not differ significantly for each intersection.

Factor Analysis

The correlation matrix including variables 46 to 93 was computed and examined. Variables 53, 57, 59, 69, and 70 and the dependent variables 92 and 93 were deleted, and the resultant matrix was factorized by the principal-axes method. The factor analysis reduced the 41 variables to 11 factors which accounted for 90 percent of the total variance of the variables.

An examination of the rotated-factor matrix permitted the identification of each factor. The following identified factors are listed with their important component variables and respective coefficients.

High Through Volume on Major Street—This factor describes a signal designed to handle a predominantly through movement of traffic for the major direction of flow:

55. Intersecting streets on both sides, -0.9117;
62. Cycle length, +0.6592;
63. Green time per cycle, +0.8961;
64. Practical approach capacity, +0.8350; and
89. Green to cycle ratio, +0.7013.

Off-Peak Period—This condition indicates an off-peak volume period of the day:

79. Thursday, +0.5827;
80. Friday, -0.4199;
81. 8:00 to 10:00, +0.5865;
84. 3:01 to 6:00, -0.7629;
85. Approach volume, -0.8230;
86. Opposing volume, -0.7167;
87. Total intersection volume, -0.8031; and
91. Approach volume to capacity ratio, -0.8525.

Flat Topography—This factor describes a level type of topography:

51. Approach grade, -0.6335; and
52. Exit grade, -0.3926.

Commercial Development—A high degree of commercial development adjacent to the intersection is indicated by this grouping of variables:

58. Access drives on both sides, +0.7022;
61. Commercial establishments on both sides, +0.7244; and
68. Regulatory signs, +0.5504.

Low Minor-Street Traffic—This factor describes an intersection with a relatively minor street intersecting the major traffic flow:

46. Semi-actuated signal, +0.8646;
62. Cycle length, -0.6240;
87. Total intersection volume, -0.2913; and
90. Approach to total volume ratio, +0.4257.

Concentrated Turning Movements—This factor indicates a large percentage of turning movements from both streams of the major traffic flow to the right side of the direction of travel of the test vehicle:

71. Left turns from directional travel, -0.7392;
72. Right turns from directional travel, +0.8801; and
73. Left turns from opposing travel, +0.8243.

Time Variations—Variations in the times and days when the data were recorded are reflected in this factor, which is not completely defined:

78. Wednesday, -0.8220;
79. Thursday, +0.5977;
81. 8:00 to 10:00, +0.4812; and
83. 12:01 to 3:00, -0.7767.

Vertical Resistance—This group describes the vertical alignment affecting the traffic flow:

50. Length of exit merge lane, +0.7288;
51. Approach grade, +0.6978; and
52. Exit grade, +0.7365.

Long-Distance Travel—Through traffic traversing the entire length of the bypass is reflected in this factor.

81. 8:00 to 10:00, -0.3519;
82. 10:01 to 12:00, +0.8699;
84. 3:01 to 6:00, -0.4207;
88. Commercial vehicles, +0.4160; and
90. Approach to total volume ratio, +0.3943.

Day-of-Week Variations—The variation in days for which travel times were obtained contribute to this partially defined factor:

76. Monday, +0.8456;
78. Wednesday, -0.2492; and
80. Friday, -0.6065.

Other Day-of-Week Variations—Further variations within the week are evident in this group:

77. Tuesday, -0.9226;
79. Thursday, +0.2653; and
80. Friday, +0.3217.

After the factor-score matrix was computed, the factors were correlated with both mean travel speed and mean delay (Table 7). The same three factors were significant in accounting for the variations of both dependent variables. These factors, which were off-peak period, flat topography, and low minor-street traffic, were associated with increased speeds and decreased delays. Multiple linear regression equations were developed to predict travel speed and delay from these significant factors. The following relationship was derived to estimate travel speed for interrupted flow:

$$S_3 = 24.16 + 10.186\ (0.2022F_0 + 0.1404F_P + 0.2626F_R) \qquad (11)$$

where

S_3 = mean travel speed, mph;
F_0 = off-peak period;

TABLE 7

CORRELATION OF MEAN TRAVEL SPEED AND DELAY WITH FACTORS, INTERRUPTED FLOW

Factor	Correlation Coefficient	
	Travel Speed	Delay
N	-0.0278	-0.0646
O	+0.2022[a]	-0.1455
P	+0.1404[a]	-0.1778[a]
Q	-0.0703	+0.0470
R	+0.2626[a]	-0.2044[a]
S	-0.0194	+0.0399
T	+0.0137	+0.0120
U	-0.0540	+0.0224
V	-0.0413	+0.0164
W	+0.0567	-0.0636
X	+0.0388	-0.0583

[a]Significant at the 5 percent level.

F_P = flat topography; and
F_R = low minor-street traffic.

The degree of correlation of this equation was expressed by a multiple correlation coefficient of 0.360. Approximately 12 percent of the total variation in travel speed was reflected in the three significant factors. The standard error of estimate was 9.49 mph.

Delay was related to the significant factors by the following:

$$D_1 = 16.49 + 14.23 (-0.1455F_0 -0.1778F_P -0.2044F_R) \quad (12)$$

where

D_1 = mean delay, sec;
F_0 = off-peak period;
F_P = flat topography; and
F_R = low minor-street traffic.

The multiple correlation coefficient of 0.307 measured the degree of linear association between delay and the three significant factors. The three factors explained only 9 percent of the total variation in delays. An index of precision was provided by the standard error of estimate of 13.54 sec.

The significant factors were evaluated in terms of the original study variables. The following multiple linear regression equations were developed in standard-score form to express these factors:

$$F_0 = 0.1177Z_{79} - 0.1225Z_{80} + 0.1969Z_{81} - 0.1390Z_{84} - 0.1907Z_{85} - 0.1200Z_{86} - 0.1416Z_{87} + 0.1514Z_{88} - 0.2080Z_{91} \quad (13)$$

$$F_P = -0.1765Z_{48} - 0.1406Z_{49} - 0.1765Z_{66} - 0.1690Z_{75} \quad (14)$$

$$F_R = 0.2790Z_{46} + 0.1080Z_{60} - 0.1904Z_{62} + 0.1265Z_{64} - 0.2305Z_{67} + 0.1071Z_{68} - 0.1234Z_{71} + 0.1608Z_{89} + 0.1694Z_{90} \quad (15)$$

where

F_j = common factor, and
Z_i = standard score of variable.

The standard scores of each variable are computed from Eq. 9.

Multiple Linear Regression and Correlation Analysis

Multiple linear regression equations were developed to estimate travel speeds and delays for interrupted flow as functions of the significant variables. The techniques for deriving these relationships were similar to the standards followed in the uninterrupted flow analysis.

The multiple linear equations expressing overall travel speed and delay as functions of the significant variables are given in Table 8. The speed relationship has the following form:

$$S_4 = 28.595 - 0.4165X_{51} - 0.2118X_{62} - 0.0120X_{85} - 0.0170X_{87} + 29.4800X_{89} \quad (16)$$

where

S_4 = mean travel speed, mph;

TABLE 8

MULTIPLE LINEAR REGRESSION AND CORRELATION ANALYSIS, INTERRUPTED FLOW

Variable	Net Regression Coefficient	Standard Error
	Part I[a]	
51	-0.4165	0.3235
62	-0.2118	0.0587
85	-0.0120	0.0280
87	-0.0170	0.0104
89	+29.4800	7.4789
	Part II[b]	
49	+0.0052	0.0024
62	+0.2299	0.0833
85	+0.0135	0.0401
87	+0.0168	0.0154
89	-35.7935	12.7107

[a]Dependent variable: travel speed; intercept = 28.59 mph; multiple correlation coefficient = 0.368; and standard error of estimate = 9.53 mph.
[b]Dependent variable: travel delay; intercept = 11.95 sec; multiple correlation coefficient = 0.326; standard error of estimate = 13.544 sec.

X_{51} = average algebraic grade of approach, percent;
X_{62} = cycle length of traffic signal, sec;
X_{85} = traffic volume approaching the intersection in the direction of travel, vehicles per 15 min;
X_{87} = total traffic volume entering the intersection on all four approaches, vehicles per 15 min; and
X_{89} = green time to cycle length ratio.

The degree of linear correlation was indicated by a multiple correlation coefficient of 0.368. The significant variables (approach grade, cycle length, approach volume, total intersection volume, and green-to-cycle ratio) accounted for 14 percent of the variation in travel speeds. All variables except green time to cycle length ratio were negatively related to travel speeds. The reliability of the estimate was expressed by a standard error of 9.53 mph.

The following multiple linear regression equation for travel delay was evolved:

$$D_2 = 11.951 + 0.0052X_{49} + 0.2299X_{62} + 0.0135X_{85} + 0.0168X_{87} - 35.7935X_{89} \quad (17)$$

where

D_2 = mean travel delay, sec;
X_{49} = length of approach to special turning lane, ft;
X_{62} = cycle length of traffic signal, sec;
X_{85} = traffic volume approaching the intersection in the direction of travel, vehicles per 15 min;
X_{87} = total traffic volume entering the intersection on all four approaches, vehicles per 15 min; and
X_{89} = green time to cycle length ratio.

The correlation coefficient of 0.326 measured the degree of the functional relationship of the variables. Approximately 11 percent of the variability in delay was explained by the independent variables. The variables of length of approach to turning lane, cycle length, approach volume, and total intersection volume were correlated with delay in a positive manner, while the green time to cycle length ratio had a negative relationship. The standard error of estimate was 13.54 mph. The sign of the regression coefficient of the length of approach to turning lane variable was contrary to expectation. The plus sign indicated that delay increased as the length of the approach increased in combination with the other variables in the model. The length of the approach, however, was interrelated with a high-volume intersection and with a relatively high number of turning movements. These conditions contributed to the increased delays.

The multiple correlation coefficients of these two regression equations were lower for the analysis of the interrupted flow vs those for the uninterrupted flow. Overall travel speeds and delays at signalized intersections depended greatly on whether or not the vehicle was required to stop. This condition of chance was not accounted for in the analysis. In addition, those variables which were significant in the final models exhibited little variation among the study intersections. The unexplained variability with individual drivers was again evident in the analysis.

SUMMARY OF RESULTS AND CONCLUSIONS

The following conclusions were derived from the results of the multivariate analyses of overall travel speeds and delays on the U.S. 52 Bypass located in Lafayette, Indiana. The movements of traffic on the bypass were classified into two categories. Uninterrupted flow was distinguished from interrupted flow at signalized intersections where traffic was required to stop for a red signal. These conclusions are valid only for the flow of traffic on the bypass, but the findings also serve as generalizations of the significant determinants of travel speeds and delays on similar type facilities.

1. The overall travel speeds of the uninterrupted-flow portions of the bypass were influenced by four significant factors. Commercial development, urban development, and stream friction were negatively related to speed; the remaining factor, rural development, was associated with travel speed in a positive manner. Commercial development accounted for 30 percent of the variation in travel speed.
2. Five variables were significant in the prediction of mean overall travel speeds for the uninterrupted flow sections. These variables, which were total number of street intersections per mile, total number of commercial establishments per mile, percent of section where passing was not permitted, practical capacity, and total volume, were all negatively related with travel speed.
3. For the interrupted-flow portions the factors which significantly explained both overall travel speeds and delays were off-peak period, flat topography, and low minor-street traffic. These three factors were associated with increased travel speeds and decreased delays.
4. The variables of cycle length, traffic volume approaching the intersection in the direction of travel, and total intersection volume contributed to decreased speeds and increased delays. The green time to cycle length ratio accounted for significant variations in travel speeds and delays in a positive and negative manner, respectively. The approach grade of the intersection was negatively related to speed, and the length of the approach to the turning lane was positively associated with delay.
5. Multiple linear regression equations were developed to estimate mean travel speeds and delays from the significant factors and variables for both flows. Approximately 50 percent of the variation in speed of uninterrupted flow was explained and 10 to 15 percent of the variation in travel speeds and delays at signalized intersections was accounted for. The reliability of these relationships was limited by the unknown effects of driver behavior which was not included in the analysis. In addition, delays at traffic signals were largely dependent on whether or not a stop occurred.

REFERENCES

1. Berry, D. S. Evaluation of Techniques for Determining Over-All Travel Time. HRB Proc., Vol. 31, pp. 429-440, 1952.
2. Coleman, R. R. A Study of Urban Travel Times in Pennsylvania Cities. HRB Bull. 303, pp. 62-75, 1961.
3. Cribbins, P. D., Horn, J. W., and Vick, C. E. Development and Use of Maximum-Car Techniques for Measuring Travel Time. HRB Bull. 303, pp. 94-102, 1961.
4. Determining Travel Time. Procedure Manual 3B, National Committee on Urban Transportation, 1958.
5. Dixon, W. J. Biomedical Computer Programs. Health Sciences Computing Facility, Univ. of Calif., Los Angeles, pp. 169-184, 233-257, Jan. 1, 1964.
6. Highway Capacity Manual. U.S. Bureau of Public Roads, Washington, pp. 35-102, 1950.
7. Keefer, L. E. The Relation Between Speed and Volume on Urban Streets. Chicago Area Transportation Study, 1958 (unpublished).
8. Matson, T. M., Smith, W. S., and Hurd, F. W. Traffic Engineering. McGraw-Hill Book Company, Inc., New York, pp. 327-334, 1955.
9. Oppenlander, J. C. Multivariate Analysis of Vehicular Speeds. Highway Research Record 35, pp. 41-77, 1963.

10. Oppenlander, J. C., Bunte, W. F., and Kadakia, P. L. Sample Size Requirements for Vehicular Speed Studies. HRB Bull. 281, pp. 68-86, 1961.
11. Oppenlander, J. C., and Dawson, R. F. Criteria for Balanced Geometric Design of Two-Lane, Rural Highways. Highway Research Record 83, pp. 1-28, 1965.
12. Volk, W. M. Effect of Type of Control on Intersection Delay. HRB Proc., Vol. 35, pp. 523-533, 1956.
13. Walker, W. P. Speed and Travel Time Measurement in Urban Areas. HRB Bull. 156, pp. 27-44, 1957.