PEDESTRIAN EFFECT ON AT-GRADE INTERSECTION VEHICULAR FLOW

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The basic objective of this study was to identify variables that are significant to the pedestrian effect on vehicle flow through at-grade intersections. Data were collected and analyzed to determine if a statistical relationship existed between the selected variables and the vehicle-seconds of delay being caused by pedestrian-vehicle frictions as a result of both vehicular and pedestrian movements at the study intersections. The multiple-regression analysis of the data produced three regression models that should give accurate estimates of the vehicle-seconds of delay. The first model included the data for all 6 study intersections, 3 with all one-way streets intersecting and 3 with 1 one-way street and 1 two-way street connecting. The second model was applied to 3 intersections with one-way streets intersecting. The third model was derived from the data on 3 intersections with 2 one-way street legs and 2 two-way street legs. A definite statistical relationship was found to explain the pedestrian effects on vehicle delay at typical urban intersections.

• URBAN traffic engineers have been dealing with the problems of safe, efficient pedestrian movements for a long time, but the possible effect of pedestrian movement on vehicular flow through at-grade intersections has had relatively little attention, and the attempts to use various concepts of the three E's approach (engineering, enforcement, and education) have not met with a very high degree of success. However, many engineering ideas that have been applied to pedestrian safety problems for intersections may also be used to accomplish smooth, coordinated pedestrian and vehicular flow.

The complex system of pedestrian-vehicle movement at intersections consists of four elements: the vehicle, the road, the driver, and the pedestrian. Various factors such as increasing vehicle registration and numbers of pedestrians, high-speed vehicles, and the right-of-way conflict between drivers and pedestrians are adding to the complexity of the system. The problems generated by this increased complexity have not always received a satisfactory solution through application of conventional systems of approach. In fact, pedestrians are equally as responsible as drivers for highway safety and smooth, efficient operations, and they should be held equally liable for accidents and smooth traffic flow.

A very large majority of urban intersections are still at-grade crossings and must be considered in any study of the pedestrian effect on intersection vehicle flow. One method that may be considered as a solution to many problems of pedestrian-vehicle friction is the "scatter" pedestrian phase in the signal cycle. This approach, however, has a disadvantage because a uniform reduction in available green time for vehicle traffic is experienced regardless of the pedestrian volume through the intersection. Another possibility is the grade separation of vehicles and pedestrians at intersections; this approach has been recognized as the ideal solution to reduce interference between

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pedestrians and vehicle flow. However, the capital investment as well as the physical restrictions involved limit the use of this type of system. Therefore, pedestrian tunnels and overpasses have been used only at locations of very high pedestrian and vehicular volumes, such as schools, factories, sports arenas, and freeway locations.

The primary consideration for the pedestrian at intersections is safety, but the possible effect of pedestrian movement on vehicle flow should also be considered seriously. Pedestrian effect on vehicle flow has not been studied adequately in the past; in fact, this effect was not included as a factor affecting intersection capacity in the Highway Capacity Manual (8).

This study attempted to determine the effects of pedestrians on vehicular flow, in terms of vehicle delay, through at-grade intersections by identifying some of the relevant variables that may affect both the pedestrians and the vehicular flow. The variables selected are quantifiable factors for which the data are relatively easy to collect. These factors were used to form a statistical relationship among variables by multiple-regression analysis. The independent variables that most significantly affected pedestrian-vehicle friction were included in the regression models for the different types of intersection operations. From these models a reasonably accurate estimate of the actual vehicle delays due to pedestrian-vehicle friction at the selected types of intersections can be derived.

LITERATURE REVIEW

The coordinated movement of both pedestrians and vehicles through at-grade intersections has not been the subject of many studies; therefore, the number of techniques that have been used to develop a statistical relationship among relevant variables appears to be very limited. This section reviews some of the work previously done in the field of coordinated pedestrian-vehicular flow through at-grade crossings.

The factors affecting vehicular flow at an at-grade intersection are broken into four general categories (8): (a) physical and operating conditions, (b) environmental conditions, (c) traffic characteristics, and (d) control measures.

The pedestrian is a physical element of the intersection and must be given the same consideration as any other factor of the physical and operating conditions. Miller (11) states that "supervising, controlling, guiding, or planning any phase of the traffic problem means dealing with human beings, and no one is perfect. Errors occasionally do occur. Striving always to be broadminded, sincere, tolerant and to consider the other person's viewpoint and problems will promote efficiency and good relations. Valuable time will be saved, life will be more pleasant, and, most important, we shall go farther toward accomplishing our goal—the prevention of congestion, accident, injuries, and death on our streets and highways."

The pedestrian reactions at the curb must be considered along with all other environmental factors for the intersection. A study by DiPietro and King (5) showed that the number of pedestrians waiting at curbside has a significant effect on the near-side gap as well as the near-side plus far-side gap accepted by an individual pedestrian within the group. Statistically, it was also found that volume of traffic enters into the pedestrian crossing decision. Group crossing speeds were found to be slower than individual crossing speeds and groups of pedestrians accepted shorter gaps than individual pedestrians.

Some traffic characteristics of the intersection must also be given serious consideration. Wegmann (18) has shown that the acceptable gap or degree of chance that a pedestrian is willing to take is a function of (a) speed of approaching vehicles, (b) average number of waiting pedestrians, (c) average delay of waiting pedestrians, (d) sight distance of intersection, (e) characteristic of pedestrians, (f) environmental conditions, and (g) width of roadway to be crossed.

A study by Hoel (9) showed that the mean walking speed of pedestrians was approximately 4.80 fps. The mean speed for men was 4.93 fps and for women 4.63 fps. The speeds vary depending on the trip purpose, e.g., 4.92 fps for 8:00 to 9:00 a.m. work-oriented trips and 4.45 fps for 1:00 to 2:00 p.m. shopping and business purposes. The walking speed of the pedestrian has a significant effect on the exposure time or time that he is apt to cause a vehicle delay.

The control measures are probably the most important factors when considering pedestrian-vehicle friction. Generally, crosswalks should be marked in all areas to delineate clearly where pedestrians should cross the roadway (2). The marking should conform to the Manual on Uniform Traffic Control Devices (14).

A study by Welke (17) pointed out that a multiphase operation gives rise to unacceptable delays. A "share-the-green" system reduced cycle length by 50 percent over the "scatter" system. Since adjustments were made in the signal system, traffic moves freely in the study area without backing up and without racing pedestrians.

A study in Toronto by Rotman (13) showed that the use of the pedestrian crossing gave a much more efficient operation (less delay) than either pedestrian-actuated signals or a pre-timed pedestrian phase in the signal cycle. The accident records also reflected that there were fewer accidents where the pedestrian crossing was used than at signalized locations. The pedestrian crossing system used in Toronto was composed of lines on the roadway, signs over the roadway, no signal, and warning signs in advance. This operation was set up with distinctive pedestrian laws that were backed by enforcement. A comprehensive education program was conducted prior to putting this system into operation, and a public opinion poll conducted for the system showed that 88 percent of the population had favorable opinions. This was a very flexible system that utilized cooperation between pedestrians and drivers and created minimum delays.

Box and Alroth (4) showed that the separate pedestrian phase in the signal cycle, if used for minimum delay and maximum efficiency, would frequently operate only during absolute peak periods such as for employees leaving industrial plants and office buildings. In the absence of a better controller system, the "time-clock-controlled fixed-time" controller appears preferable. In most cases, pedestrian fixed-time signals of the continuously operating type should not be used. The "scatter" pedestrian phase gives a uniform vehicle delay regardless of the pedestrian volume through the intersection.

Concerning the capacity of a street network, intersections are usually capacity bottlenecks. The most common method of attempting to increase the capacity of a network has been to make a change in the signal cycle or in the widening of the arterial streets. Vuchic (16) has shown that the vehicular capacity of signalized intersections with a separate pedestrian phase increases with street width at a decreasing rate, reaches an absolute maximum around 110 ft, and then begins to decrease. Because street width is directly related to pedestrian crossing time, it is a very important factor in the vehicular capacity of at-grade intersections. Consequently, the traffic engineer must view the pedestrian at at-grade intersections as an element of the traffic stream in order to provide an optimal solution. One possible improvement for the wide-street situation is the use of pedestrian refuge islands in the center of multilane divided arterials.

ANALYSIS OF RELEVANT VARIABLES

From the review of previous studies concerning vehicular flow at signalized intersections, it was found that a model-building technique has been most successful in explaining the relationship among independent variables. For example, the CEIR multiple-regression models (19) that used some of the same data used for the Highway Capacity Manual intersection capacity factors analysis were used as a guideline in this study. Before the development of a multiple-regression model can proceed, one of the first and most important considerations is the identification of significant variables that affect pedestrian-vehicle friction.

In this study two criteria were used to select variables: those factors for intersection capacity that had been shown in previous studies to affect significantly pedestrian-vehicle friction and other variables that may have a significant effect on pedestrian-vehicle friction. The following variables were considered to have possible effects on the vehicular traffic flow where the pedestrian-vehicle conflict occurs. These variables are grouped into three categories—pedestrian, driver, and environment—as follows:

1. Pedestrian—understanding of the traffic control system; familiarity with roadway geometry; trip purpose and length; defects in sight or hearing; psychological condition and possible blood alcohol content; attitude toward vehicular traffic; and age and sex.

2. Driver—attitude toward pedestrians; psychological condition; age and sex; familiarity with pedestrian traffic regulations; defects in sight; desirable vehicle speed; and vehicle performance capability.

3. Environment—enforcement campaign; educational campaign; clarity and uniformity of traffic control systems; ambient conditions; physical layout of intersection; pedestrian and vehicle volumes; parking conditions, loading zones, and bus stops; percent of turning movements; total cycle length or maximum red interval; location within metropolitan area; and adequacy of roadway lighting.

After consideration was given to the possible variables for this problem, nine that were considered to be quantifiable and most significant to the pedestrian-vehicle friction effect on vehicular flow were selected for the final analysis. These nine variables and the reasons for their selection are as follows:

1. Number of pedestrians involved (X_1)—The greater the number of pedestrians involved in the pedestrian-vehicle friction the higher is the probability of a larger vehicle delay due to the increase in pedestrian-vehicle friction. This variable represents the number of pedestrians that actually cause delays.

2. Pedestrian violations (X_2)—The greater the number of pedestrian violations the higher is the probability of a possible vehicular delay as a result of increased exposure. For example, a pedestrian is considered to be in violation if he departs the curb on a green signal for the street that he is crossing or on a yellow signal for the connecting street.

3. Parking conditions (X_3)—Parking near the intersection could reduce exposure time by reducing the effective street width, which may reduce possible vehicle delays. This variable may be quantified by the number of sides of the legs of the intersection on which parking is permissible. Loading zones should be counted as parking areas, but corner bus stops should not be considered parking areas.

4. Vehicle volume (X_4)—Increased vehicle volume may increase the probability of a vehicle delay due to a possible increase in exposure. This value is the total vehicle volume on all legs of the intersection for a given interval.

5. Pedestrian volume (X_5)—An increase in pedestrian volume may also increase the probability of a vehicle delay due to a possible decrease in length of gap acceptance. This variable value is the total pedestrian count for all pedestrian movements through the intersection in a given interval.

6. Percentage of left turns (X_6)—The probability is high that a substantial increase in vehicle-pedestrian friction may occur with an increased percentage of left-turning movements as a result of the increase in exposure.

7. Percentage of right turns (X_7)—The same high probability of increased pedestrian-vehicle friction can occur during right-turning movements as occurs during left-turning movements.

8. Maximum red interval (X_8)—Maximum red interval was considered to be of possible importance because a longer red interval may reduce gap acceptance that could have an effect on the vehicle-pedestrian friction. The length of the cycle was found to have significant correlation in the Washington, D.C., intersection traffic flow studies (17).

9. Street width (X_9)—Street width determines the length of time or distance that is subject to pedestrian-vehicle friction. This distance was measured from curb to curb on all intersection legs.

Vehicle seconds of delay (Y), the product of the number of cars in the queue and the time that they were delayed, was used as the dependent variable for this analysis. This value can be a measure of the loss in vehicle flow through an intersection. Therefore, in this study it will cover only the vehicle delay that was caused directly by pedestrians interfering with the vehicle traffic stream.

Many other factors were also considered as being important in the determination of the pedestrian-vehicle friction effect on the vehicular flow through the intersection but were deleted from this analysis as a result of some peculiarity in the data collection procedure for the study intersections. Some of these are as follows:

1. Bus stops—Four of the six intersections had one bus stop, one intersection had two bus stops, and one of the six did not involve any bus stops.
2. Total cycle length—All six of the signals had 70-sec cycle lengths.
3. Location within metropolitan area—All intersections have central business district characteristics; therefore, no attempt was made to include an adjustment factor for location in the metropolitan area.
4. Metropolitan area population—All data were collected in the same city; therefore, the metropolitan population for all samples would be in the 500,000 population range.
5. Crosswalk marking—All sample locations except one had the crosswalk markings in place. Visual inspection of the data did not show any significant difference at the one location.
6. Types of signalization—All signal systems at the study locations were "share-the-green" systems with turning movements being permitted while the pedestrians were crossing the intersecting street.

DATA COLLECTION

After reviewing the intersection capacity section of the Highway Capacity Manual (8) and other previous work in the field of intersection vehicular flow, the decision was made to select six study intersections in Richmond, Virginia. This decision was based on the larger population of the metropolitan area, the dense vehicular traffic, the dense pedestrian movement, and the large central business district.

The primary limitations affecting the data would be relative to the metropolitan area population and the central business district of the city. Serious limitations were not imposed because Richmond has a metropolitan population of approximately 500,000 and has a relatively typical CBD. This problem is not considered serious because vehicle-pedestrian friction does not become a significant problem until the metropolitan population becomes rather large and then it should not change significantly relative to an increase in population.

Sample Intersections

Three of the six intersections selected consist of all one-way street legs. These three intersections are 8th and Marshall, 8th and Main, and 5th and Grace. Main and Grace Streets are high-volume westbound traffic arterials. Marshall carries a relatively high volume of eastbound traffic. Both 5th and 8th Streets are one-way cross streets (north-south) that carry a relatively high vehicle volume and produce a high frequency of turning movements.

The other three intersections selected are junctions of 1 one-way street and 1 two-way street. These three are the intersections of 9th and Main, 11th and Marshall, and Harrison and Franklin. A typical study intersection is shown in Figure 1. As stated previously, Marshall and Main are high-volume eastbound and westbound arterials respectively. Franklin Street is also a high-volume eastbound arterial. Harrison, 9th, and 11th are two-way cross streets (north-south) that produce a high frequency of turning movements. The fluctuations at a typical study intersection are shown in Figure 2.

Collection Procedure

The data collection phase of this study was conducted by three persons at the two locations on Marshall Street and the one location on Franklin Street. The equipment used was two 12-key counter boards; one to record the vehicular volume and turning movements and the other to record the pedestrian movements. The third person used a watch to determine the vehicle-seconds of delay caused by the pedestrian-vehicle friction.

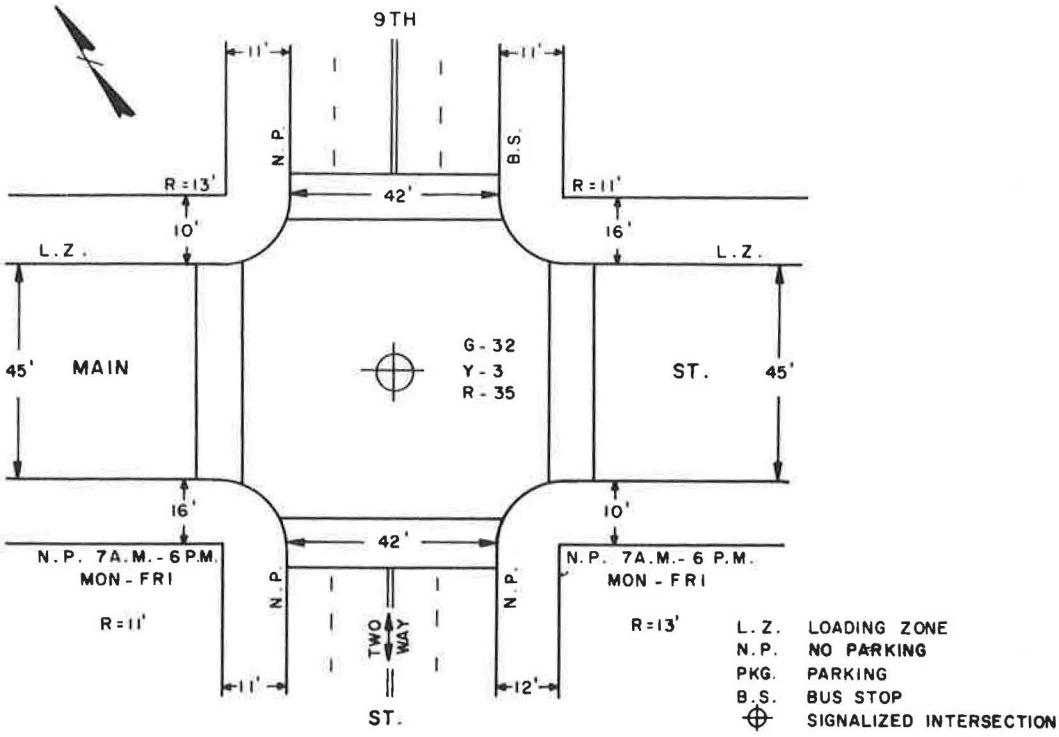

Figure 1. Typical study intersection, 9th and Main Streets.

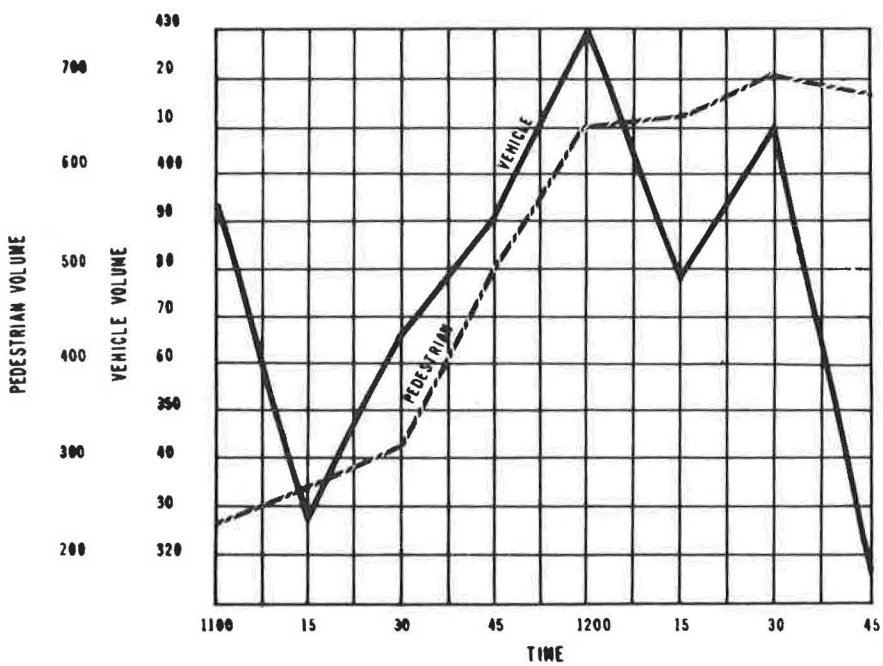

Figure 2. Vehicular and pedestrian volumes per 15-min interval, intersection of 9th and Main Streets.

In the data collection phase of the two Main Street locations and the one intersection of Grace Street an additional observer was involved because of the relatively high pedestrian volume. Three persons used 12-key counter boards, and one used a watch to determine the vehicle delays. The counter boards were used in the following manner: One was used to determine vehicular volumes and turning movements, and two were used to determine the pedestrian movements, each being used for half of the intersection by breaking the workload down to pedestrian departures from each of two street corners.

Data were collected for all variables simultaneously from 11:00 a.m. to 1:00 p.m. on Tuesday, Wednesday, and Thursday. This period was chosen because a preliminary field observation showed that pedestrian movement and vehicle traffic flow were both high during this time giving a high potential for pedestrian-vehicle conflict.

MODEL DEVELOPMENT

After the relevant variables had been identified and the data on these variables had been effectively collected, a statistical method, the multiple-regression technique, was used to formulate a relationship that would, to some extent, describe the effect of pedestrian movements on the vehicle traffic flow at the study intersections. It is hoped that the resulting relationship is meaningful both in the general case where the data from all test intersections are included and in the specific case where the data input is limited to similar types of intersection operations.

Modeling Techniques

Two regression analysis programs developed by the Health Sciences Computing Facility of the University of California (6) were used for the computer analysis.

The BMDO2R, a stepwise regression program, was first used to determine the most significant of the nine variables that were considered. This program computed a sequence of multiple linear regression equations in a stepwise manner. At each step one variable is either added or deleted from the regression equation. The variable added is the one that makes the largest reduction in the error sum of the squares and residual sum of the squares and has the highest partial correlation coefficient with the dependent variable partialed on the included variables, and the variable that if added would have the highest F value. Variables are automatically removed if their F values become too low.

The criteria used in this analysis were an F-level of significance of 0.10 for an independent variable to enter the model and an F-level of significance of 0.05 for any independent variable in the model to remain.

After the stepwise regression program was used to determine the independent variables to be included in the model, BMDO3R, a multiple regression with case combinations program in which the variables in the model must be specified, was then used to analyze the data again. This program gives the correlation coefficients for all of the variables in the model and a table of residuals for the dependent variable in the model.

Model Formulation

Three models were developed in this study. Model 1 used the data from all six intersections. Model 2 was derived from the data of the three intersections with all one-way operations. Model 3 was applied to the intersections of one-way with two-way streets. The resulting models from this analysis are as follows:

$$Y = -87.10 + 2.48\,X_1 + 0.25\,X_4 - 0.05\,X_5 + 2.67\,X_7 \qquad (1)$$

$$(R = 0.941,\ E_S = 37.40)$$

$$Y = -3715.58 + 2.63\,X_1 - 0.28\,X_4 - 0.19\,X_5 + 12.70\,X_6 + 90.49\,X_9 \qquad (2)$$

$$(R = 0.931,\ E_S = 34.65)$$

$$Y = -164.65 + 2.19\,X_1 + 0.30\,X_4 + 1.78\,X_6 + 5.46\,X_7 \qquad (3)$$

$$(R = 0.961,\ E_S = 37.47)$$

The procedures of the stepwise regression analysis for developing the models are given in the Appendix.

The multiple correlation coefficient (R) indicates the degree of association between the independent variables and the dependent variable in the model. The higher the value of R, the greater is the reliability of the association.

The standard error of estimate (E_S) indicates the degree of variation of the data about the regression line. This is a measure of the error to be expected in predicting the dependent variable from the independent variables in the model.

Model Evaluation

In the evaluation of a statistical model developed by multiple-regression analysis, one of the more important considerations is the relationship between the dependent variable and the independent variables in the model. The variables X_1, pedestrians involved, and X_4, vehicle volume, appear in all three models. The number of pedestrians involved in the delay resulting from pedestrian-vehicle friction is obviously an important factor in the vehicle delay value. The greater the number of pedestrians involved, the greater is the delay time. The vehicle volume through the intersection will also have a significant effect on the vehicle delay time because the greater the vehicle volume, the greater is the exposure rate or probability of a delay.

The percentage of left turns, X_6, is also significant in determination of the vehicle delay time. Past studies have shown that turning movements increase the pedestrian-vehicle friction, which contributes to the delay time to be expected. This variable could have appeared in all three models but was not included in the combined type of intersection model because it did not give a significant enough increase in the R value to justify its inclusion. Also, four independent variables appeared to give a sufficiently stable model.

Average street width, X_9, appears in both models for the specific type of intersection. This can be expected because an increase in street width increases the exposure time or probability of friction between vehicle and pedestrian traffic.

The pedestrian volume, X_5, appears in both the combined type of intersection model and the one-way-only intersection model. This again is a case where increased exposure or probability of a conflict occurs with the increased pedestrian volume. Past studies (5) have also shown that a pedestrian in a group will take a greater risk than an individual pedestrian waiting on the curb. An increase in pedestrian volume gives a greater probability that a group situation exists; however, the data for this study do not reflect group size.

The percentage of right turns, X_7, appears in both the combined type of intersection models and in the one-way-with-two-way intersection model. Again, this is a case confirmed by past studies (1) that indicate that turning movement increases the pedestrian-vehicle conflict, which increases the vehicle delay time.

Model Application

The data collection for the application of these models can utilize a much less sophisticated collection procedure than was utilized in the research without any loss of quality in the results. The vehicle volume that appears in all of the models can easily be collected with a 15-min recording counter on each leg of the intersection. The pedestrian volumes as measured by both X_1 and X_5 as well as the number of turning vehicles will still need to be counted manually.

The substitution of these data into the appropriate model would give the range of delays that was being experienced at each intersection. From a study of these delays better traffic engineering judgment can be derived. The enhanced judgment could then be used in taking the necessary correctional measures to provide for safe intersections that also yield maximum efficiency.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This study was initiated to determine the statistical relationship between the significant independent variables presented in this study and the vehicle-seconds of delay caused by pedestrian-vehicle friction at at-grade intersections with "share-the-green" type signalization. A significant relationship was found, and the three models developed in this study are the result of the multiple-regression analysis of data on the relevant variables.

The three models developed in this study have high R values and have independent variables that have passed F-tests at 0.10 significance. Statisticians have shown that high R values do not necessarily mean a good regression model if the independent variables that are used have little or no effect on the dependent variable; it is thought that this is not the case in this study because previous studies have also identified the same significant variables.

Further research is needed in the field of vehicle delays resulting from pedestrian-vehicle friction so that better guidelines can be developed for coordinated, smooth pedestrian and vehicle movement through at-grade intersections. The following specific recommendations for further research are made:

1. Each of these three models should be field-tested under much more extensive conditions. The 48 observations at the six study intersections were considered sufficient for statistical validity, but a more extensive test may show any shortcomings in the models.
2. Serious consideration should be given to the possibility of including a pedestrian-effect factor in at-grade intersection analyses. At present this type of factor is nonexistent; as this study has shown, however, there is a definite effect resulting from pedestrian-vehicle friction.

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Appendix

STEPWISE REGRESSION ANALYSIS FOR MODELS

TABLE I

Model 1

Stepwise Regression Equations

Model	R	E_s	F
$Y = 19.15 + 2.36\ X_1$	0.917	42.54	244
$Y = -40.65 + 2.16\ X_1 + 0.23\ X_4$	0.934	38.68	153
$Y = -26.79 + 2.42\ X_1 + 0.20\ X_4 - 0.05\ X_5$	0.937	38.05	106
$Y = -87.10 + 2.48\ X_1 + 0.25\ X_4 - 0.05\ X_5 + 2.67\ X_7$ *	0.941	37.40	83
$Y = -160.60 + 2.19\ X_1 + 0.35\ X_4 - 0.03\ X_5 + 2.86\ X_6 + 4.17\ X_7$	0.943	37.26	67

*Final Model

TABLE II

Model 2

Stepwise Regression Equations

Model	R	E_s	F
$Y = 13.40 + 2.42\ X_1$	0.862	43.60	63.6
$Y = -97.85 + 1.52\ X_1 + 0.52\ X_4$	0.891	39.89	40.6
$Y + -161.43 + 1.39\ X_1 + 0.43\ X_4 + 14.52\ X_6$	0.906	38.18	30.5
$Y = 120.56 + 1.88\ X_1 + 0.35\ X_4 - 0.06\ X_5 + 12.62\ X_6$	0.914	37.53	24.1
$Y = -3715.58 + 2.63\ X_1 - 0.28\ X_4 - 0.19\ X_5 + 12.70\ X_6 + 90.49\ X_9$*	0.931	34.65	23.5
$Y = -4783.47 + 2.35\ X_1 + 20.67\ X_3 - 0.54\ X_4 - 0.16\ X_5 + 14.33\ X_6 + 115.85\ X_9$	0.935	34.78	19.6

*Final Model

TABLE III

Model 3

Stepwise Regression Equations

Model	R	E_s	F
$Y = 24.73 + 2.32\ X_1$	0.940	42.93	166.9
$Y = -36.62 + 2.23\ X_1 + 0.21\ X_4$	0.955	38.10	109.3
$Y = -119.91 + 2.32\ X_1 + 0.24\ X_4 + 4.68\ X_7$	0.960	36.81	78.9
$Y = -164.67 + 2.19\ X_1 + 0.30\ X_4 + 1.78\ X_6 + 5.46\ X_7$*	0.961	37.47	57.2
$Y = 12.81 + 2.21\ X_1 + 0.31\ X_4 + 5.00\ X_6 + 5.96\ X_7 - 5.56\ X_9$	0.963	37.52	45.8

*Final Model