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16. Abstract

Several different control designs can be utilized to serve the vehicular and pedestrian traffic at signalized intersections. These range from traffic signals only to traffic signals with pedestrian-actuated signals and detectors. Virtually all of these are commonly used by traffic engineers in the United States; however, there is less than complete agreement regarding the conditions under which each is most appropriate.

This research study developed guidelines for pedestrian-actuated signal installation based upon dual consideration of operational and behavioral characteristics. Operational criteria address three (sometimes conflicting) design objectives, which are maximization of pedestrian safety and minimization of pedestrian and traffic delay. Key variables employed in the criteria include the magnitudes of vehicular delay and volumes, number of lanes, and pedestrian volume, walk speed and behavior. These key variables were employed in delay, behavioral, and arrival rate analyses.

Delay savings offered by pedestrian-actuated signals compared to fixed-time pedestrian signals are presented, and guides are shown for determining the impact of pedestrian presence at intersections. Guides for determining pedestrian volume without retracting to costly pedestrian counts are also shown. These tools aid in analyzing pedestrian impacts for various intersection conditions.

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PEDESTRIAN SIGNALS: WARRANTS AND EFFECTIVENESS

by

Stephanie C. Otis
Hani S. Mahmassani
Randy B. Machemehl
Srinivas Palamarthy

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Pedestrian Signals: Warrants and Effectiveness

conducted for the

Texas Department of Transportation

in cooperation with the

U.S. Department of Transportation
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by the

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Bureau of Engineering Research
The University of Texas at Austin

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IMPLEMENTATION

The guidelines for use of pedestrian-actuated signals contained within this report will provide a rational basis for installation of pedestrian signals. Since the guidelines are based on operational as well as behavior criteria, their implementation offers the potential of improved traffic operational efficiency.

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Prepared in cooperation with the Texas Department of Transportation
and the U.S. Department of Transportation, Federal Highway Administration

DISCLAIMERS

Randy B. Machemehl, P.E. (Texas No. 41921)
Research Supervisor

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SUMMARY

This study, which addresses various aspects of pedestrian behavior and compliance at signalized intersections, proposes guidelines for pedestrian actuation. The results of the study's five objectives are summarized as follows:

OBJECTIVE 1. *Summarize and evaluate existing guidelines or warrants for pedestrian signals, including pedestrian signals with fully actuated signal controllers.*

There appears to have been no comprehensive critical study of pedestrian-actuated signals' warrant. However, Zegeer et al [Ref 5] have surveyed traffic engineers on related pedestrian warrants for traffic signals and found that even with good judgment, traffic engineers have great difficulty using pedestrian signal warrants. That study stated that because of intensive data requirements and lack of flexibility, pedestrian warrants have a low acceptability level.

The Texas Manual on Uniform Traffic Control Devices guidelines in the traffic and pedestrian warrant sections either are not specific or contain vague wording. In the traffic section, Warrant #3 (Minimum Pedestrian Volume) has been criticized as being unreasonable, too data-intensive, and non-flexible. Traffic Warrant #4 (School Crossing) has received mixed reviews [Ref 5]. In addition, Warrants #3 and #4 have been criticized as being too permissive, lacking detail, and in need of modification. In fact, most practicing engineers do not rely on these warrants to signify traffic signalization need.

Section 4C-12 (Pedestrian-Actuated Control) discusses the conditions for which pedestrian signals are not warranted, but may be considered. The guidelines in this section are vague and undefined, making effective use very difficult. The phrases "occasional pedestrian movement," "undue delay," and "adequate crossing time" are not defined.

OBJECTIVE 2. *Evaluate the ability of pedestrians to understand pedestrian signal indications, as well as signing, and their willingness to comply.*

Through literature review, it was found that compliance rates with all pedestrian controls at signalized intersections are higher than those at non-signalized intersections. However, the installation of these signals has not always proved effective. Lack of understanding and of uniformity of these signals could be one reason for their ineffectiveness; one study reported that 64 percent of the elderly lacked adequate signal phase understanding.

Signal timing also has an impact on compliance; a study reported that when too much green was given to the vehicular traffic in relation to its volume, pedestrian violations increased. Also reported is that (i) at low volumes, pedestrians are likely to ignore signal indications and (ii) pedestrian clearance intervals increase compliance rates, though long intervals lead to violations. Studies on young pedestrians show

that they exhibit very unsafe attitudes concerning street-crossing. As with people who are not familiar with pedestrian signals, children need to be provided with safe-crossing information.

Several studies have shown variability in walking rates among pedestrian classes. An extensive study by Hoel [Ref 21] has reported that in downtown areas, the pedestrian travel rate varies between 0.91-2.13 m/sec (3 and 7 ft/sec), with the average at 1.44 m/sec (4.72 ft/sec).

At signalized intersections data collected in this study indicate greater pedestrian compliance. In particular, compliance by male pedestrians is increased when signalization is present. In general, among all age groups and races, signalization increased compliance rates.

Push-button compliance at signalized intersections is at most 50 percent based either on age, on gender, or on race. The results show that the push-button is not effective. However, the gratifying result is that the percentage of pedestrians who push the button and wait for "walk" is quite satisfactory (over 70%) at low pedestrian volumes.

Walk rates (for walking mode only) were observed for pedestrian crossings at signalized intersections only. As expected, males have a higher walking rate, but it is not statistically significantly higher. Also, the variation across groups is not statistically significant. The mean walk rate for the population is 1.70 m/sec (5.57 ft/sec) with a standard deviation of 0.38 m/sec (1.25 ft/sec). The average start-up time is 1.55 seconds with a standard deviation of 2.97. Young adults react more quickly than members of other age groups.

Using gap acceptance theory in multinomial probit (MNP) analyses, further pedestrian behavior investigations were made. At wide intersections, longer crossing times create higher risks. Pedestrians may not always see turning vehicles, or they may be less alert during turn phases. Pedestrians are also less vigilant with respect to vehicles in the far traffic streams. Medians encourage lane-by-lane crossing, but also provide a safe refuge. Analyses establish that pedestrians, by nature, are not inclined to use push-button signal actuation devices. At wide or busy intersections, push-buttons seem to be of some assistance. Lastly, the MNP Model results indicate that group interactions are not negligible and cannot be ignored.

OBJECTIVE 3. *Evaluate the benefits of pedestrian signalization and the costs due to hardware, operation, and vehicular delay.*

The analysis in Chapter 5 quantifies the pedestrian-induced vehicular delay, based on Newell's work [Ref 42], and calculates the minimum vehicular flows over which pedestrian green time requirements do not govern the traffic signal operations. In cases where pedestrian green requirements exceed the vehicular traffic requirements, pedestrian-actuated signals provide substantial savings, especially at lower pedestrian flows. In particular, it has been found that with a higher number of lanes and lower vehicular flows, pedestrian-actuated signals show vehicular delay savings potential.

The provision of pedestrian phasing allows pedestrians to reduce their waiting time when traffic green times do not permit crossing. The costs of hardware and operation (Table 5.3) are approximately $2800/year per intersection.

Conditions under which pedestrian signals offer special benefits are described. Also, since it was found that pedestrians are less cautious during turn phases, it is recommended that the "walk" time should not be scheduled during the left-turn phases. As for right-turn-on-red, there have been mixed results regarding the technology used to warn pedestrians and/or drivers. Particular problems should be assessed on an intersection basis. Given that low pedestrian volumes do not pose significant difficulty on turn phases/vehicles (as opposed to high pedestrian volumes), pedestrian-actuated signals can be used (when minimum volume is met) to clear the pedestrian from the roadway.

OBJECTIVE 4. *Develop guidelines reflecting the above costs and benefits.*

The guideline is presented in Table 8.1 and Figure 8.2. It incorporates the delay savings concept with the pedestrian generation rate determination. Step-by-step, it guides the engineer in determining whether or not a pedestrian-actuated signal is needed.

OBJECTIVE 5. *Develop guidelines identifying the conditions under which pedestrian crosswalk pavement markings should be installed.*

At signalized intersections, more pedestrians are likely to cross within the crosswalk. Therefore, signalization in conjunction with crosswalk markings may encourage more pedestrians to cross at the intersection. This finding is supported by Smith et al [Ref 50].

In addition to the above objectives, a method of determining pedestrian arrival rates was developed. Based on the cost/benefit analysis, it appears that intersections located in the residential 1.609-km (1-mile) radius might not need signals, particularly those with residential or minor retail in the 0.402-km (quarter-mile) radius.

CHAPTER 1. INTRODUCTION

1.1 Motivation

Pedestrianism is becoming more popular owing to growing concerns for energy-efficient transportation and environmental pollution. However, traffic control system design is based upon vehicular traffic and may not provide adequate pedestrian guidance and control [Refs 1,2]. Part of the safety problem can be attributed to pedestrian behavioral indifference towards traffic control systems. Pedestrian signals assign right-of-way, but pedestrians frequently ignore "walk" as well as "don't walk" indications. Even though demand-responsive systems such as push-buttons are provided, it appears they are rarely trusted, and used only by a small segment of the pedestrian population. One study [Ref 3] found that installation of pedestrian signals and crosswalk markings has, in a few cases, created a false sense of safety. Currently, the major criteria for installing pedestrian signals are based on vehicle volumes, pedestrian volumes, and engineering judgment [Ref 4]. As the question of an equitable distribution of delay between pedestrian and vehicular traffic remains unresolved, the operation of pedestrian signals, especially the timing issue, is governed primarily by vehicular traffic. Compliance with these signals is, however, dependent on pedestrian behavior.

To determine pedestrian-induced vehicular delay at signalized intersections, one must know pedestrian volumes. Time-consuming pedestrian counts are usually needed at each candidate pedestrian signal installation site. A less costly method would utilize land use as a predictor of pedestrian volumes, similar to vehicular trip generation methods. However, very few studies have examined pedestrian arrival rates; most studies have been performed in downtown areas because of the high pedestrian volumes. A method of quantifying a threshold pedestrian volume recommended for signalization would be a useful contribution to existing practice.

Pedestrian accidents are a rare occurrence. However, the severe loss inflicted by these accidents is a compelling reason to study their cause and develop solution techniques. The characterization and understanding of pedestrian behavior at intersections, signalized and unsignalized, can enable more effective signal operation, and allows further development and evaluation of pedestrian control strategies. Therefore, there is a need to better understand the interaction between pedestrian behavior and the traffic control system.

1.2 Scope and Objectives of the Study

The specific objectives of this research effort are described as follows:

1. Summarize and evaluate existing guidelines or warrants for pedestrian signals, including pedestrian signals with fully actuated signal controllers.
2. Evaluate the ability of pedestrians to understand pedestrian signal indications, as well as signing, and their willingness to comply.
3. Evaluate the benefits of pedestrian signalization and the costs due to hardware, operation, and vehicular delay.

4. Develop guidelines reflecting the above costs and benefits.
5. Develop guidelines identifying the conditions under which pedestrian crosswalk pavement markings should be installed.

1.3 Study Overview

A literature review is presented in the following chapter. The background and limitation of pedestrian warrants in the Texas Manual of Uniform Control Devices are described. Following this is a synthesis and discussion of various published pedestrian studies. There are few quantitative investigations of pedestrian crossing behavior at intersections and its implications for traffic signal operations. Most studies focus on single behavioral issues such as gap analysis, safety, or signal operations. An overview of these studies is given in the chapter.

In Chapter 3, a conceptual basis for the factors that should be integrated into an installation guideline is described. An integrated model with three major components including vehicular delay, pedestrian behavior, and pedestrian arrival rates is presented. Data collection requirements and further model development are outlined.

Chapter 4 focuses on data collection. As no prior data were available for model calibration, on-site surveys are conducted using observer and video recording. A survey methodology is developed using a stratified random sampling approach with land use as the exogenous variable. The procedure is applied to selected intersections, primarily in the city of Austin, with one additional location in Fort Worth. The video tape data reduction process is described and an inter-scorer reliability check is performed to ensure data accuracy.

Development of the pedestrian-induced vehicular delay model is presented in Chapter 5. The theory behind this model is derived from Newell's vehicular delay theory. The formulation and results of the calculations are presented as well.

In Chapter 6, pedestrian behavior analysis is presented in the framework of gap-acceptance models. Several gap-acceptance models are proposed, along with group and push-button behavior. After preliminary analysis of gap sizes, model specifications and estimation results are described. Following these results, behavioral implications are presented.

In Chapter 7, the analysis of pedestrian arrival rates and arrival rates generated by each land use type is described. Regression analysis that relates pedestrian arrival rates and predictor variables is presented. Independent predictor variables include land use, transit availability, and census information.

The combined results of vehicular delay, pedestrian behavior, and pedestrian arrival rates are presented in Chapter 8. Implications of the combination of these issues are explained, and suggested guidelines are presented.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Researchers have taken different approaches to analyze the various aspects of pedestrianism. They have devised means of quantifying safety, delay, and behavior based on traditional engineering analyses. The literature reviewed can be grouped under six headings:

i) Pedestrian Warrants of TMUTCD
ii) Safety
iii) Behavior
iv) Vehicular Delay
v) Pedestrian Arrival Rates
vi) Robertson's Warrant for Fixed Pedestrian Signals

While many descriptive pedestrian studies have been performed, few fundamentally quantitative investigations are available. Furthermore, most studies focus on single behavior, safety, or signal operations issues rather than on a comprehensive assessment. This section presents a general overview of these studies.

2.2 Pedestrian Warrants of TMUTCD

Review and evaluation of the Texas Manual on Uniform Traffic Control Devices reveals that several guidelines in the traffic and pedestrian warrant sections either are not specific or contain vague wording.

In the traffic section, Warrant #3 (Minimum Pedestrian Volume) has been criticized as being unreasonable, too data-intensive, and non-flexible. Traffic Warrant #4 (School Crossing) has received mixed reviews [Red 5]. In addition, Warrants #3 and #4 have been criticized as being too permissive, lacking detail, and in need of modification. In fact, most practicing engineers do not use these warrants to signify traffic signalization need.

Section 4C-12 (Pedestrian-Actuated Control) discusses the conditions under which pedestrian signals are not warranted, but may be considered. The guidelines in this section are vague and undefined, making effective use very difficult. The phrases "occasional pedestrian movement," "undue delay," and "adequate crossing time" are not defined.

The pedestrian warrant section describes basic pedestrian signal indication functions. However, there are no specific guidelines for determining when to install pedestrian detectors, which pedestrian signal intervals to use, or how long the pedestrian phase interval should be.

Provisions for crosswalks also contain vague wording. The phrases "substantial conflict" and "appropriate points of pedestrian concentration" are not defined.

In general, the Texas MUTCD lacks specificity and must be supplemented by considerable judgment. The MUTCD has always attempted to maintain an "appropriate" balance between specificity and judgment, but pedestrian signal sections lean heavily upon user judgment.

2.3 Safety

Accident frequency is a measure of safety problems, and it can be used to identify accident causes. One often-quoted study using pedestrian accident data to study safety impacts of pedestrian signals was made by Fleig and Duffy [Ref 6]. However, their limited sample size did not allow conclusive statistical analysis. Robertson and Carter [Ref 7] used existing state data bases and found that approximately one of every five vehicles involved in an intersection accident was turning, with left-turning vehicles being more numerous. Also, they found that the young and the elderly are more accident-susceptible. In addition, Robertson [Ref 8] found that left turns are almost three times more hazardous to pedestrians than through movements, and he quoted other studies findings that, after implementation of Right-Turn-on-Red, pedestrian accidents increased. Another study [Ref 3] provided evidence from accident data showing that pedestrian signalized intersections are no safer than unsignalized intersections. Witkowski [Ref 9] studied the relationship between land-use type and accident rates. He concluded that intersection-related accidents occur more often in areas of commercial or financial land use, and that residential land use is more frequently associated with mid-block accidents. Zaidel and Hocherman [Ref 10] used accident rates to compare performance of pedestrian crossing arrangements. A general drawback of accident analysis is that accidents are rare phenomena, and not all are reported. They occur under various circumstances, making identification of generic causes difficult. Development of site-specific remedies is much easier and is the usual practice.

Since accidents are rare and available databases are not extensive, researchers have attempted to substitute conflict data for accident data. A conflict occurs when pedestrians and vehicles "nearly" come into contact with each other, causing one and/or the other to change a course of action [Refs 11,12]. Conflicts can be obtained from roadside observations. Cynecki [Ref 11] identified thirteen different types of conflicts and defined a conflict severity index to reflect the degree of hazard at the intersection. The index is obtained for different sites, and these indices compared to identify risky intersections. This approach requires observers to undergo rigorous training so that an acceptable degree of observational uniformity can be obtained. Garder [Ref 13] also used this technique to relate conflict and accident data.

The conflict technique is more effective than accident analysis for developing intersection-specific remedies. The disadvantage of this method is that site-specific deficiencies, such as sight distance, tend to have greater influence; and, therefore, identification of general causes may not be possible. The behavior of pedestrians and drivers, which is the primary cause of an accident or a conflict, is not directly addressed.

Another method for predicting accident rates is the use of exposure measures (indicators of pedestrian and vehicle volume). Knolblauch [Ref 14] has shown that exposure measures yield high hazard scores for certain groups such as the young and the elderly, as well as those running, crossing against the red, outside the intersection area, and/or where buses and motorcycles exist. This same study also pointed out that there is considerably less hazard with left- or right-turning vehicles except in the case of right-turn-on-red. Unfortunately, the conflict and exposure theories have shown mixed results when tested against accident rates.

2.4 Behavior Analysis

Pedestrian signals are installed to increase safety. Mortimer [Ref 15] compared compliance rates at intersections with and without pedestrian signals, and concluded that signalized intersections experience higher compliance. However, the installation of these signals has not always proved effective. Zegeer et al [Ref 3] found that there was no difference in accident frequency between pre-timed intersections with and without pedestrian signals. Lack of understanding and uniformity of these signals could be one reason for their ineffectiveness. One study on the elderly [Ref 16] reports that 64 percent of the respondents lacked adequate signal phase understanding. Also, most avoided crossing during peak hours and at low visibility periods.

Signal timing also has an impact on compliance. A study by Robertson and Carter [Ref 7] reports that, when too much green was given to the vehicular traffic relative to its volume, pedestrian violations increased. Also, the researchers found that longer pedestrian clearance time increased the number of violations. Rouphail [Ref 17] conducted a user preference survey to document the behavior of pedestrians at mid-block crosswalks with and without signals. He found that pedestrians and motorists preferred unsignalized mid-block crosswalks. Khasnabis et al [Ref 18], in their review of behavior studies, observed that (i) at low volumes, pedestrians are likely to ignore signal indications, (ii) compliance rate for steady "walk" is higher than that for flashing "walk," and (iii) pedestrian clearance intervals increase compliance rates. Hill [Ref 19] studied the behavior of school children regarding route choice, walking speeds, trip lengths, and route complexity. He found group walking speeds to be much higher than those for adult groups: 1.68 m/sec versus 1.43 m/sec (5.5 ft/s versus 4.7 ft/s). Most children were found to run rather than walk. Studies of young pedestrians show that they have very unsafe attitudes concerning street crossing [Ref 20]. As with people who are not familiar with pedestrian signals, children need to be provided with safe-crossing information.

Other studies on walk rates have shown that variation among different classes of pedestrians do exist. Hoel [Ref 21] has shown that in downtown areas, the pedestrian travel rate varies between 3 and 7 ft/sec (0.91 - 2.13 m/sec), with the average at 1.44 m/sec (4.72 ft/sec). He also showed that pedestrians walk more slowly in warmer weather and during the 1-2 pm hour. Virkler et al [Ref 22] showed that in groups, the first pedestrians cross at a rate of 1.37 m/sec (4.5 ft/sec) and the following pedestrians cross at a rate of 6.7 22. sec/ped*meter (sec/pedestrian*ft)[1]. Two studies [Refs 23,24] have shown that walking speed varies considerably among different countries; for example, average walking speeds in Saudi Arabia and Pittsburgh are 1.08 m/sec (3.55 ft/sec) and 1.47 m/sec (4.81 ft/sec), respectively. Such differences warrant a second look at walking speed variation.

Driver gap-acceptance studies have been conducted in the past to study delay and capacity at intersections, as well as merging and passing maneuvers. In the case of pedestrians, capacity at non-downtown intersections is not an issue, as more than one pedestrian can cross simultaneously. These studies have also been used in assessing the accident risk at the intersections. In the current study, gap-acceptance situations arise when a non-compliant pedestrian attempting to cross on a "don't walk" phase looks for traffic stream gaps. A gap is accepted if it exceeds a minimum gap, referred to as the critical gap, and rejected otherwise. The probability of acceptance is given by a distribution function, referred to as the gap-acceptance function. Different functions can either be obtained at the individual level or aggregated for the population level by assuming different critical gap distributions. In the literature, three different types of behavioral models have been proposed:

i) Constant critical gap model: In this model, it is assumed that the critical gap is a constant and is the same for the entire population. When the available gap is greater than the critical gap, it is always accepted; otherwise it is rejected. This concept was first introduced by Adams [Ref 25]. Tanner [Ref 26] also adopted this assumption in deriving the mean delay and other queue statistics for the pedestrian waiting to cross a road. However, this model is not realistic because there are both systematic and random variations in behavior within and across subjects.

ii) Consistent behavior model: This model differs from the first in that the critical gap is assumed constant for an individual but distributed over the population. The across-subject variation may be attributed to the existence of both cautious and aggressive people. This assumption has prevailed for many years and is reflected in models studied by Miller [Ref 27], Maze [Ref 28], and Radwan and Sinha [Ref 29].

iii) Inconsistent behavior model: Several authors have shown the existence of within-subject variability in gap acceptance behavior in both test-track and actual field data. In this case, the critical gap is no longer treated as a constant, but rather as a random variable distributed across both individuals and decision instances [Refs 27,30,31,32]. One source of within-subject variability (impatience) was captured in the systematic (or observed) component of the critical by Mahmassani and Sheffi [Ref 33].

Different approaches have been designed to estimate the critical gap from empirical data. Only a few of them consider all the presented gaps. Miller [Ref 27] compared nine different methods using simulated data and concluded that the maximum likelihood method is most reliable. Apart from gap size, the maximum likelihood method has the flexibility to incorporate other factors such as waiting time, number of gaps rejected, and socio-economic variables in the estimation process. This estimation procedure has been implemented by Miller [Ref 27], Mahmassani and Sheffi [Ref 33], and Daganzo [Ref 34].

2.5 Vehicular Delay

Although researchers have studied both vehicular and pedestrian delay, more emphasis has been given to vehicular delay. Robertson [Ref 7] studied pedestrian and vehicle delay at signalized intersections; this delay is a function of signal timing, pedestrian and vehicle volumes, and roadway width. Usually overlooked, pedestrian compliance with the signal can have a significant effect on pedestrian delay. Pedestrian compliance is usually greater when vehicle volumes are high. When vehicle volumes are low, or when too much green is given to vehicles, pedestrians tend not to comply. Those who trust their own judgments and cross before their own time usually decrease their own delay.

King [Ref 35] used pedestrian delay as a principal criterion in traffic signal warrants, primarily for traffic conditions under which adequate gaps may never occur. The rationale for the pedestrian warrant was that it should be based on an acceptable level of average pedestrian delay, a tolerable level of maximum delay, and an equitable allocation of total delay. King's study found that at vehicular saturation rates, the average pedestrian delay without signals was higher than the average vehicular delay with signals. The delay equity criterion was ultimately dropped because pedestrians are less comfortable standing than drivers (and passengers) sitting inside vehicles.

A major study [Refs 36,37,38,39] completed on pedestrian and vehicular delay, used observations of 215,000 vehicles and 75,000 pedestrians to develop a simulation program. A mathematical model was developed using simple queuing relationships. Vehicular delay described in this model is in the form of total delay per vehicle as pedestrian (and vehicle) volumes increase, not in terms of the increase due to pedestrian impact.

Abrams and Smith [Refs 40,41] discussed the practicality of using phasing schemes other than the combined pedestrian-vehicle interval. Three alternatives studied were early release, late release, and scramble timing. They were evaluated in terms of pedestrian and vehicle delay and safety. The data collection included vehicle delay, pedestrian arrival rates, pedestrian delay, and pedestrian compliance. Vehicle delay was defined as the difference between time required for right-turning vehicles with and without pedestrians.

Compared to standard timing, early release timing caused no additional pedestrian delay for higher pedestrian volumes. Higher vehicular delay occurred at lower pedestrian volumes and higher vehicle volumes. This phasing will always result in additional total person-delay.

Compared to standard timing, late release timing causes more pedestrian delay if pedestrian volume is high. For high vehicle volumes, more vehicular delay occurred, and for concurrently high pedestrian levels, the vehicular delay results were mixed. Compared to standard timing, scramble timing causes the pedestrian delays to increase for both parallel and diagonal crosswalks. In most cases, standard pedestrian phasing minimizes total intersection delay. This appears to be particularly true for low pedestrian volumes.

Newell's [Ref 42] examination of traffic signal settings includes extensive discussions on vehicular delay and includes occasional discussions on the effect of pedestrians on vehicular delay. Most discussions dealing with pedestrians are qualitative rather than quantitative. Newell's approach is extended in Chapter 5 to evaluate pedestrian-induced vehicular delay and examine trade-offs underlying different signal operation strategies.

2.6 Pedestrian Arrival Rates

Previous pedestrian volume studies have been concentrated in CBD areas. Some studies have developed expressions for pedestrian volume characteristics based on short volume counts without respect to other variables [Ref 43,44,45]. A similar study in Israel examined CBD and residential areas [Ref 46]. These authors have stated that the developed models could only be used with similar sites, and that additional counts would need to be performed in order to transfer the results to other areas. Sandrock [Ref 42] mentioned that perhaps land use should be considered.

Another CBD study attempted to explain pedestrian volumes by using land-use space as predictor variables [Ref 47]; however, the results of this study are not transferable because geographic characteristics were not taken into account. A more detailed CBD study related walking distance, trip generation rates, and volume variation to available walkway space and building space (Pushkarev et al, 1971). About 0.536 km (one-third mile) was the average walking distance, and half of all pedestrians walked less than 305 m (1,000 feet).

A study in Washington, D.C., used land use as the principal site selection criterion [Ref 48]. Mathematical models which use short volume counts as predictor variables were developed, and the authors claimed that the models worked well, although they wondered about transferability. A major limitation of this study is that only sites with "significant pedestrian volumes" were chosen and all were in well developed areas of Washington, D.C.

2.7 Robertson's Warrant for Fixed Pedestrian Signals

A study that recognized the deficiency of pedestrian signal warrants was done by Robertson on fixed pedestrian signals. In this study, many elements were considered, including the number of pedestrians required to install fixed pedestrian signals. In conjunction with the minimum volume requirements, other "deficient" conditions must coexist in order for the signals to be installed. In Robertson's scheme, pedestrian signal indications at traffic-signalized intersections are warranted if:

1. The number of pedestrians crossing at the intersection per hour for an average day is:
   100 or more for each of any 4 hours or,
   140 or more for each of any 2 hours or,
   170 or more during the peak hour,

   and one or more of the following conditions exist:

2. An exclusive interval or phase is provided for pedestrian movement.

3. Vehicular indications are not visible to pedestrians such as on one-way streets and at "T" intersections.

4. Multi-phase indications are confusing to pedestrians guided only by vehicle signal indications.

5. The pedestrian's sight distance to an approaching vehicle is impaired or is less than the average stopping sight distance of the vehicle.

6. The pedestrian clearance interval exceeds the corresponding vehicle clearance interval, or, pedestrians can cross only part of a street during a particular interval.

7. Of the pedestrians crossing at the intersection, the proportion of pedestrians under the age of 15 is more than one standard deviation above the mean proportion of young pedestrians in the control base.

8. Of the pedestrians crossing at the intersection, the proportion of elderly and/or handicapped pedestrians is more than one standard deviation above the mean proportion of elderly/handicapped pedestrians in the control base.

9. A significant improvement in operational efficiency will result.

By requiring two conditions to coexist, the warrant does not allow indiscriminate pedestrian signal installation based on minimum volume or safety conditions alone.

2.8 Summary

The above findings reveal somewhat conflicting evidence regarding the effectiveness of signals in providing for pedestrian flow and safety. The findings warn against indiscriminate use of pedestrian signals. To maintain the credibility of these devices, efforts should be directed at identifying scenarios where these are most appropriate.

This chapter discussed the literature relevant to pedestrian safety and behavior, vehicular delay, and pedestrian arrival rates. In addition, this chapter presented a study done by Robertson, who developed a warrant on fixed pedestrian signals which depended on more than one simultaneous criterion. The next chapter focuses on multiple criteria for conceptual and methodological approaches in the present study to address these concerns.

CHAPTER 3. STUDY CONCEPTUAL DEVELOPMENT

3.1 Introduction

The major focus of this research is quantification of the minimum numbers of pedestrians that should justify pedestrian detectors. The Texas Manual on Uniform Traffic Control Devices does not have clear guidelines for installation of pedestrian indications. Paragraph 4C-12 of the current version states "when pedestrian signals are not warranted in conjunction with a traffic actuated signal installation but where occasional pedestrian movement exists and there is inadequate opportunity to cross without undue delay, pedestrian detectors shall be installed and operated as prescribed in sections 4D-6 and 7." It is understood that this wording will be changed in the next revision of the TMUTCD to "where minimum numbers of pedestrian movements regularly occur."

There appears to have been no comprehensive study regarding the criticisms of the pedestrian-actuated signals warrant. However, Zegeer et al [Ref 5] have surveyed traffic engineers concerning related pedestrian warrants for traffic signals in 1978 MUTCD and have found that, even with good judgment, traffic engineers have great difficulty using a pedestrian warrant for traffic signals. This low level of acceptance has been attributed to intensive data requirements and lack of flexibility. The pedestrian volume warrant requires counts of 8 hours of pedestrian volumes. Some cities conduct 24-hour pedestrian volume studies, others 1-3 hours, and many cities collect little or no pedestrian volume data. With limited personnel, it is unrealistic to expect cities to perform long-duration pedestrian volume counts.

Installation guidelines should be appropriate, simple to use, non-data-intensive, flexible, and acceptable to practicing traffic engineers.

3.2 Conceptual Model Development

Traffic control strategies are usually implemented with hopes of producing several benefits. One major potential benefit is accident reduction and, of course, delay of all users should be reduced to a minimum.

The benefits vary as a result of many factors including geometrics, control type, human behavior, traffic volumes, and environmental elements. Robertson et al [Ref 7] list many factors that influence pedestrian signals benefits, and some of these are described, indicating the complexity of designing installation guidelines.

Geometric factors include median islands, lighting, parking, street width, and sight distance. Median islands vary in width from 0.91 meter (3 feet) to more than 6.10 meters (20 feet) (which is difficult to classify as a median). Lighting can become an issue for those who have sight impairments, such as the elderly. Parking is often a critical visibility issue for children, who cannot see above parked cars, and a parking lane adds roadway width. Sight distance is often blocked by shrubbery, sometimes obscured by roadway geometrics, and made difficult with certain signal placements.

Control factors include vehicle signals, pedestrian signals, pedestrian push buttons, phasing, and timing. Vehicle signals include fixed-time, actuated, and coordinated, each of which may produce different effects upon pedestrians in terms of delays and predictability. Pedestrian signals include fixed-time and pedestrian-actuated. Fixed-time signals have cyclically occurring pedestrian phases, whereas pedestrian-actuated signals display pedestrian indications only when called, potentially reducing vehicular delay. Both signal types have different behavioral consequences under many different situations. Pedestrian push buttons allow pedestrians to declare their need for a pedestrian phase; however, people have different reactions toward this little device. The phasing (of vehicles) can be difficult in the sense that pedestrians may not be able to predict the phase sequence and/or understand the phasing indications. In addition, the phase timing may be too short (or too long) for different pedestrians. Although not listed, crosswalks have been used for pedestrians, albeit with questionable results.

Human factors include age, gender, physical disability, walking speed, compliance, risk-taking, gap acceptance, group behavior, erratic behavior, understanding, and accidents. The young (under 14) and the elderly (over 60) may have difficulty understanding the rules and technology of traffic signals. Gender may be an issue if, in certain geographic areas, gender can be correlated with traits such as vigilance or aggressiveness, or with level of education. Physical disability is often a concern in three areas: the blind, the deaf, and the mobility-impaired. Audible signals are under intense debate among the visually impaired community and among experts and advocacy groups concerned with blindness issues. The deaf may not hear vehicles approaching or stopping. The mobility-impaired not only would have difficulty in crossing at a normal pace, but might have difficulty getting on and off sidewalks that do not comply with ADA requirements. Walking speeds vary greatly, especially for the elderly, young, and mobility-impaired. Compliance rates usually vary with vehicle volumes and other site characteristics; if pedestrians do not comply with the signal indications, then the benefits of signalization are questionable. Risk-taking and erratic behavior are usually exhibited by younger pedestrians, uneducated pedestrians, and rushed pedestrians. Gap acceptance is the process by which pedestrians decide to cross between passing vehicles, and it varies with gender, age, and other factors. Group dynamics may influence difficult crossing behavior; for instance, if one person crosses the street prematurely, others may follow without fully assessing the situation. Young pedestrians, rural pedestrians (who may not be familiar with urban traffic control), and elderly pedestrians may lack traffic signal knowledge.

Traffic factors include vehicle volume, pedestrian volume, vehicle speed, vehicle mix, vehicle directional split, vehicle delay, pedestrian delay, vehicle arrivals, pedestrian arrivals, and gap distribution. Higher vehicle and pedestrian volumes, as well as vehicle speed and mix, usually increase accident probabilities. Vehicle directional split may confuse pedestrians. Pedestrian delays influence signal compliance rates. Vehicle arrival patterns may influence pedestrian signal phasing, and pedestrian arrival patterns could dictate the type of pedestrian signal. If there are large pedestrian groups, but few groups, then pedestrian-actuated signals may be very beneficial.

Environmental factors include weather, time of day, pollution, and energy considerations. In storm conditions, vision may be impaired, and vehicular movements may be more erratic, leading to more hazards. Also, snow conditions may prevent pedestrians from crossing in a timely manner. Nighttime conditions may make it more difficult for vehicle drivers to detect pedestrians. Also, those with vision problems may find nighttime more difficult.

An installation guideline which considers all factors would be nearly incomprehensible. Therefore, only those factors that have great importance and/or that can be controlled should be considered.

Hence, for normal[1] conditions, nine factors have been selected, including vehicle delay, volumes, and saturation flow rates; number of approach lanes; and pedestrian delay, volumes, walk speed, start-up time, and compliance.

In this research, these nine factors are the prime focus for developing a pedestrian-actuated signal guideline. Three primary subareas form the integrated model components, and these are pedestrian-induced vehicular delay, pedestrian behavior, and pedestrian arrival rates.

A model to calculate pedestrian-induced vehicular delay is developed in Chapter 5, along with pedestrian delay savings associated with both fixed and actuated pedestrian signals. The results are applicable for both pre-timed and vehicle-actuated signal installations. The model considers the impact of pedestrian and vehicle volumes, and the number of lanes, on vehicle delay for both fixed pedestrian and pedestrian-actuated signals. The delay estimates form the basis of an economic evaluation framework that captures the trade-offs between induced vehicular delay, pedestrian delay savings, and the installation and operation of pedestrian signalization. The analysis, developed on an hourly basis, is extended to recognize low variation over a 24-hour period. Unfortunately, the requisite pedestrian volume data are not readily available. It must be obtained through on-site counting (which is expensive) or through predictive modeling, for use in analysis such as that presented in Chapter 7.

The compliance of pedestrians with fixed pedestrian signals—pedestrian-actuated signals as well as no pedestrian signals—is analyzed in Chapter 6. The analysis uses the concept of gap-acceptance behavior as exhibited by pedestrians. Pedestrian behavior is also examined with respect to group behavior and push-button use.

The source of information for the predictive pedestrian arrival rate model and behavior analyses is gathered through on-site observation and video recording. The site selection criteria and data collection efforts are described primarily in Chapter 4. Preliminary statistics such as pedestrian walk rates are also presented. The aggregate data for each are described in Chapter 7.

In Chapter 8, a summary of the effects of these nine factors in terms of delay versus behavior is restated, and the various effects are compared. The results of the analyses presented in the preceding chapters are integrated into specific and understandable guidelines for application.

3.3 Summary

In this chapter, nine primary factors were identified for use in developing the integrated model. The next chapter describes primary data collection efforts for behavioral and pedestrian arrival rate analyses. The following chapters will describe the integrated model subcomponents.

CHAPTER 4. DATA COLLECTION METHODOLOGY

4.1 Introduction

An essential element of behavioral modeling is observation of the actual user-system interaction. For the current study, no such documentation was available. A data collection methodology was therefore designed using a stratified random sampling technique. A stratification based on land use was adopted. This approach serves a dual purpose, for the following reasons. One objective of the data collection was to obtain pedestrian arrival rate information, and land use is a strong explanatory variable of the arrival process. Also, land use is a factor exogenous to behavior, and would thus allow the unbiased estimation of behavioral models. Furthermore, pedestrian crossing behavior is dependent on trip purpose, and land use around the intersection is, in general, a good determinant of the pedestrian's trip purpose.

All traffic-signalized intersections can be grouped into three categories:

a) Intersections with no pedestrian signals,
b) Intersections with pre-timed signals, and
c) Intersections with pedestrian-actuated signals.

Signals in the first and third categories may be pre-timed for vehicles or vehicle-actuated. Signals in the second category are pre-timed for both vehicles and pedestrians. Each signal type is associated with specific characteristics producing both systematic and random behavior variation. The sampling strategy allows for a comparison study by not precluding intersections from any specific category. The following sections discuss the development and application of the procedure.

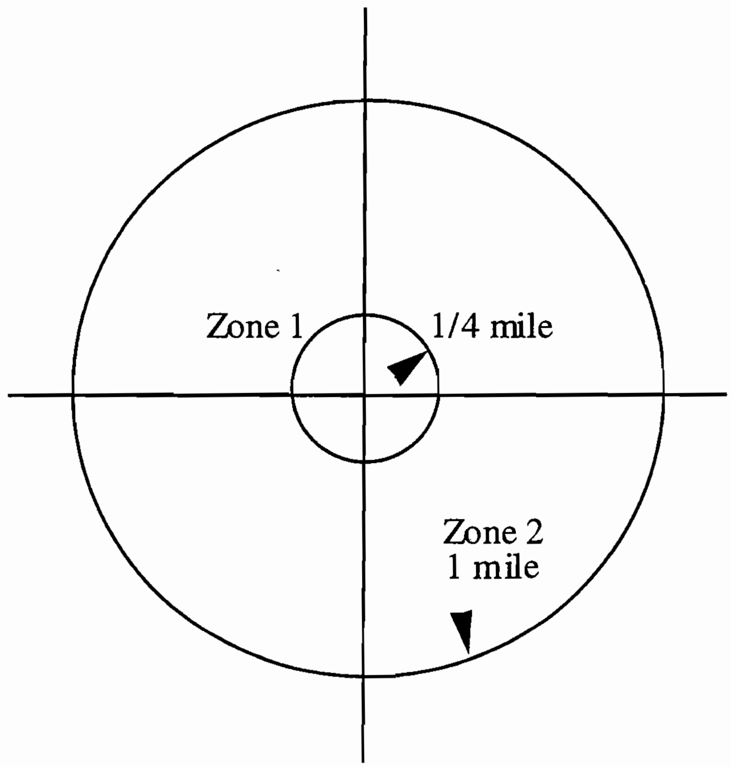
4.2 Procedure

The land use surrounding a candidate intersection was divided into two concentric zones as shown in Figure 4.1 on the following page. The first zone is defined by a circle of 0.402-km (0.25-mile) radius, which is the typical pedestrian walking distance. The second zone is a circle of 1.609 km (1 mile) radius, not including the first zone. It is used to account for any inter-zonal trips which could generate pedestrian trips at the intersection. As most sites have a mixture of land use, the dominant pedestrian activity intensity generating land use type was used to classify the intersections. Five land-use types for the 0.402 km (0.25mile) zone and four for the 1.609 km (1 mile) zone are identified as shown in Table 4.1. They are listed in ascending order of prevalence.

TABLE 4.1 LAND USE TYPE FOR ZONES 1 AND 2

0.402 km (0.25 mile) Zone	1.609 km (1 mile) Zone
Residential	Residential
Minor-Retail	Commercial
Major-Retail	Institutional
Institutional	Recreational
Recreational	

The above classification gives rise to twenty combinations. The land uses are defined as follows. Within the 0.402 km (0.25 mile) zone, buildings for residential and other living purposes, as well as vacant land, are identified under residential land use. A minor-retail land use is a combination of residential land use with small commercial centers such as convenience stores and fast-food centers. Major-retail land use is identified with shopping malls, major grocery stores, and businesses. Institutional land use is comprised of hospitals, schools, universities, and major multi-floor office buildings where large numbers of pedestrians are generated. Recreational land use includes major parks and recreational centers which are accessed by large numbers of people on foot.



Note: 1 mile = 1.609 km; 1/4 mile = 0.402 km

Figure 4.1 Zonal demarcation of land use at the intersection.

For the 1.609 km (1 mile) zone, residential land use is a combination of both residential and minor-retail land uses defined earlier. The commercial land use is equivalent to the major-retail land use and the remaining two land uses have the same definitions as those for the 0.402 km (0.25 mile) zone.

If the intersection under study is in a sparsely populated area, as in rural areas, the 1.609 km (1 mile) land use zone will most likely fall into the residential land use category.

4.3 Application

In order to test the robustness of the procedure, the above methodology was applied to the intersections in the city of Austin, Texas. The city has approximately 500 traffic-signalized intersections, of which about 200 were selected. They were then classified based on a prior knowledge, with the aid of a map, and, in some cases, on a visit to the intersection. On a Rand-McNally map of the city, most of the major commercial centers, institutions, and recreational facilities are clearly marked and could be identified with ease. The distribution of the intersections, using this design procedure, is shown in Table 4.2. For purposes of the survey, a site from each subset was randomly selected. The intersections selected for this study are listed in Table 4.3. Since the object of this data collection was also to obtain information on the distribution of pedestrian arrivals over time, each site was surveyed for a duration of five to six hours.

TABLE 4.2 DISTRIBUTION OF INTERSECTIONS BY LAND USE

LAND USE		INTERSECTIONS	
1 mile zone	1/4 mile zone	#	(%)
Residential [55] (28.65%)	Residential	10	(5.21)
	Minor retail	18	(9.38)
	Major retail	10	(5.21)
	Institutional	16	(8.33)
	Recreational	1	(0.52)
Commercial [57] (29.69%)	Residential	10	(5.21)
	Minor retail	17	(8.85)
	Major retail	23	(11.98)
	Institutional	4	(2.08)
	Recreational	3	(1.56)
Institutional [57] (29.69%)	Residential	12	(6.25)
	Minor retail	19	(9.90)
	Major retail	7	(3.65)
	Institutional	15	(7.81)
	Recreational	4	(2.08)
Recreational [23] (11.98%)	Residential	7	(3.65)
	Minor retail	4	(2.08)
	Major retail	2	(1.04)
	Institutional	1	(0.52)
	Recreational	9	(4.69)

Note: 1 mile = 1.609 km; 1/4 mile = 0.402 km

A video recording technique was used to obtain information on pedestrian behavior. The advantage of using video is that information could be reviewed repeatedly, thus assuring a higher credibility to the data collected. A Sony camcorder, CCD 410 FX model, was used for this purpose. The video equipment was set up at one corner of the intersection. It was operated only when there was a pedestrian crossing. The tapes were replayed to obtain information on a large set of variables, and those relevant to this study are listed in Appendix B.

Inter-vehicular gaps were measured using a continuous time-event recorder. With this instrument, gaps could be measured to an accuracy of 0.01 seconds. When the pedestrian arrives at the intersection, or when a vehicle passes the crosswalk, a button is pushed to mark the event. The instrument automatically records the time between events. It has the capacity to store up to thirty gaps. Waiting time was also recorded using this instrument.

The task of decoding information from the video tapes was shared by two scorers. In order to ensure consistent interpretation of variable definitions, an inter-scorer reliability check was also performed. The flow chart in Figure 4.2 illustrates the procedure.

TABLE 4.3 INTERSECTIONS BY LAND USE SELECTED FOR THE STUDY

LAND USE			INTERSECTION
1 mile zone	1/4 mile zone	Signal Type	
Residential	Residential	Fully Actuated	Bull Creek & 45th
	Minor retail	Fully Actuated	W. Cannon & Brush County
	Major retail	Fully Actuated	W. Cannon & W. Gate
	Institutional	Fully Actuated	W. Cannon & Brodie
	Recreational	Pretimed	Oak Springs & Springdale
Commercial	Residential	Pretimed	Airport & 12th
	Minor retail	Pretimed	Lamar & Justin
	Major retail	Semi-Actuated	Anderson & Shoal Creek
	Institutional	Fully Actuated	Cameron & St. John
	Recreational	Fully Actuated	Guadalupe & 51st
Institutional	Residential	Pretimed	Duval & 38th
	Minor retail	Pretimed	Lamar & 34th
	Major retail	Pretimed	Ben White & 1st
	Institutional	Semi-Actuated	Main & Magnolia*
	Recreational	Pretimed	Guadalupe & 45th
Recreational	Residential	Pretimed	I-35 & Riverside
	Minor retail	Pretimed	Lamar & Oltorf
	Major retail	Pretimed	Lamar & Barton Springs
	Institutional	Semi-Actuated	Riverside & Congress
	Recreational	Semi-Actuated	Barton Springs & R.E. Lee

* Fort Worth location

Note: 1 mile = 1.609 km; 1/4 mile = 0.402 km

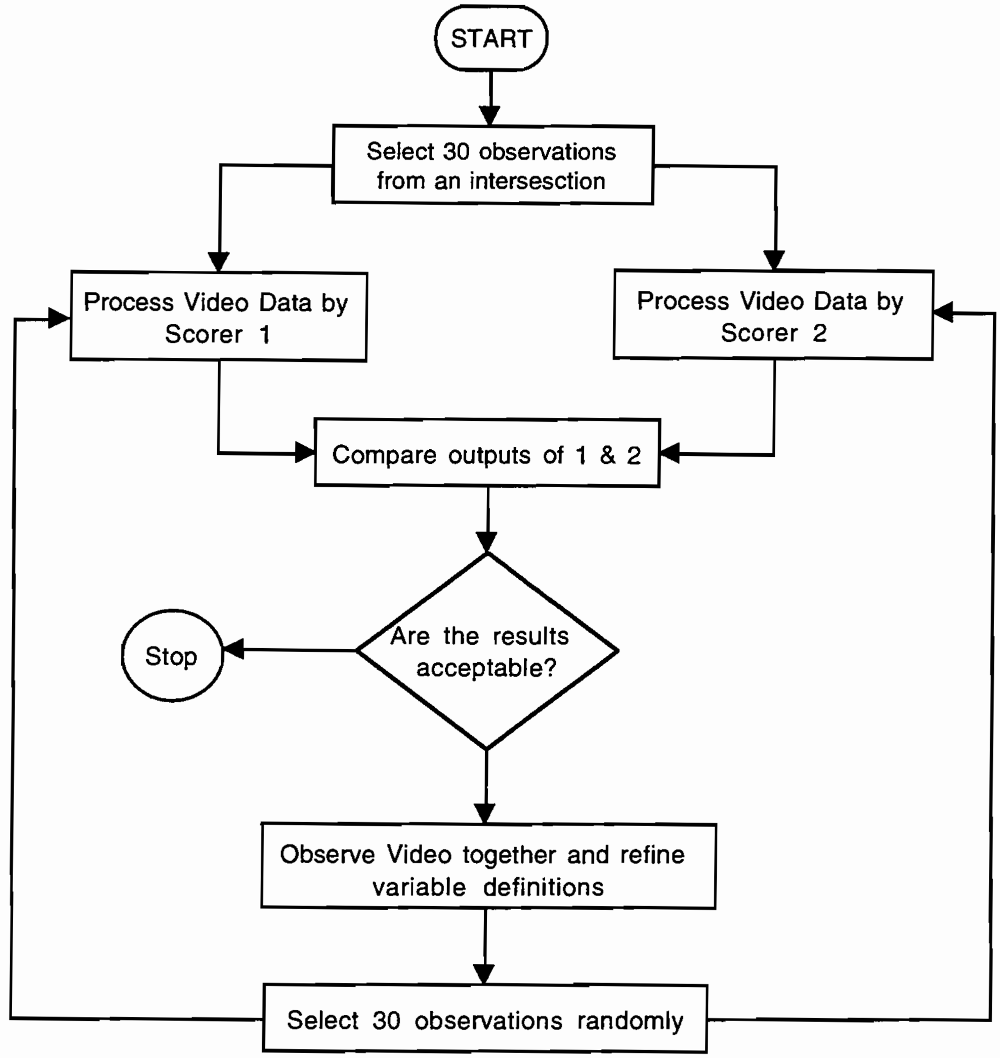


Figure 4.2 Inter-scorer data reliability procedure

4.4 Behavior and Compliance Characteristics

A descriptive analysis was conducted to study the behavior and compliance characteristics of the pedestrians. The analysis is performed separately for intersections with and without pedestrian signals. This approach is likely to provide some evidence on the benefits of signalization, if any, and also to help in assessing the impacts of pedestrian signal on crossing behavior. Since behavior is person-specific, the behavior and compliance characteristics are studied with respect to individual attributes, namely gender, age, and ethnicity. Pedestrians are segmented into five groups based on age and into four groups based on ethnicity, as follows:

Age	= 0, if age < 9	Ethnicity	= 1, if White
	= 1, if 9 ≤ age ≤ 18		= 2, if Black
	= 2, if 18 < age ≤ 39		= 3, if Hispanic
	= 3, if 39 < age ≤ 59		= 4, otherwise
	= 4, if age > 59		

An a priori hypothesis is that there are no significant variations among pedestrians within the group. The following variables are considered in the analysis: signal compliance, push-button compliance, crosswalk compliance, walk rates, start-up times, and crossing mode (walk, run, etc.). Henceforth, a signalized intersection refers to an intersection with pedestrian signals, and an unsignalized intersection is one with no pedestrian signals.

Data from different intersections are pooled depending on the presence or absence of a pedestrian signal. A total of 712 and 231 intersection crossings were observed at signalized and unsignalized intersections, respectively. The numbers of arrivals and crossings on each signal indication are reported in Table 4.4. The percentage of pedestrians making an illegal crossing, i.e., crossing on Steady Don't Walk (SDW) or RED, is less at signalized compared to unsignalized intersections. Also, most pedestrians arriving on a flashing "don't walk" cross immediately, and only a small fraction wait for a "walk" indication.

TABLE 4.4 ARRIVALS AND CROSSINGS AT SIGNALIZED AND UNSIGNALIZED INTERSECTIONS

Signalized Intersections				
	Arrival on			
Crossing on	Walk	Flashing DW	Steady DW	Total
Walk	88 (96)	7 (9)	327 (61)	422
Flashing DW	3 (3)	59 (74)	23 (4)	85
Steady DW	1 (1)	14 (17)	190 (35)	205
Total	92	80	540	712

Unsignalized Intersections			
	Arrival on		
Crossing on	Green	Red	Total
Green	78 (96)	77 (51)	155
Red	3 (4)	73 (49)	76
Total	81	150	231

Numbers in brackets denote percentages; the sum may be different from 100 due to rounding.

W - WALK; FDW - Flashing DON'T WALK; SDW - Steady DON'T WALK

4.4.1 Pedestrian Signal Compliance

The first aspect studied with respect to pedestrian characteristics is signal compliance. Table 4.5 compares the signal compliance at signalized and unsignalized intersections, i.e., for arrivals on SDW and red, respectively. Once again, the signalized intersections have higher compliance. It can be seen that at signalized intersections, the compliance is not much different for male and for female pedestrians. However, at unsignalized intersections, the compliance is much better for female pedestrians, implying that the male pedestrians may be less observant. Therefore, it is likely that signalization increases compliance by male pedestrians. Pedestrians of age ≤ 8 are more likely to be accompanied by adults, and therefore their behavior is closer to that of their attendants. There is no significant difference between age groups 2 and 3 at signalized intersections. Because of insufficient data, it is not possible to make any definitive comments on behavioral variation with age. From a comparison of the percentages of compliance based on race, it appears that the second group pays less regard to the signal indications. Again, it can be seen that signals produce better compliance.

TABLE 4.5 SIGNAL COMPLIANCE AT SIGNALIZED AND UNSIGNALIZED INTERSECTIONS

Percentage crossing during walk (W), flashing don't walk (FDW), and steady don't walk (SDW), or during green (G) and red (R)

Crossing Indication		Signalized Intersection			Unsignalized Intersection	
Attributes		% W	% FDW	% SDW	% G	% R
Gender	M	59	5	36	47	53
	F	63	3	34	60	40
Age	0	55*	18*	27*	52	48
	1	58*	17*	25*	0*	100*
	2	60	5	35	47	53
	3	61	2	37	71*	29*
	4	60*	1*	39*	40*	60*
Ethnicity	1	63	4	33	53	47
	2	50	7	43	39	61
	3	57	4	39	59	41
	4	75*	0*	25*	100*	0*

* Percentage based on fewer than 30 observations.

4.4.2 *Push-Button Compliance*

The second aspect is push-button compliance. Two issues to be considered are: fraction of pedestrians (with a push-button option) using the push button, and, of those who use, fraction waiting for "walk" indication, i.e., those who crossed on "walk" or a flashing "don't walk." Both of these are again studied with respect to gender, age, and ethnicity. The compliance percentages are shown in Table 4.6. Push-button compliance at signalized intersections is at most 50 percent based either on age, on gender, or on ethnicity. At unsignalized intersections, because of smaller sample size, no study is possible. The results show that the push button is not effective. However, the gratifying result is that the percentage of pedestrians who push the button and wait for "walk" is quite satisfactory (over 70%) at low pedestrian volumes. The appearance of a safe gap is likely to encourage a pedestrian to cross on "don't walk."

TABLE 4.6 PUSH-BUTTON COMPLIANCE AT SIGNALIZED AND UNSIGNALIZED INTERSECTIONS

Push-Button Attributes		Signalized Intersection		Unsignalized Intersection	
		% YES	% NO	% YES	% NO
Gender	M	46 (80)	54	29*	71*
	F	44 (74)	56	22*	78*
Age	0	0* (0)	100*	0*	0*
	1	36* (100)	64*	0*	100*
	2	50 (78)	50	57*	43*
	3	37 (72)	63	0*	100*
	4	0* (0)	100*	0*	100*
Ethnicity	1	50 (84)	50	25*	75*
	2	33* (88)	67*	0*	0*
	3	38 (60)	62	0*	0*
	4	0* (0)	0*	0*	0*

*Percentage based on fewer than 30 observations.

The values in parentheses denote the percentage of pedestrians who used the push button and waited for "walk"

4.4.3 *Crosswalk Compliance*

The next aspect to be considered is crosswalk compliance. Throughout the crossing maneuver, a pedestrian may be entirely within the crosswalk, partially inside and partially outside the crosswalk, or totally outside the crosswalk. If pedestrian compliance with crosswalk markings is poor, then crosswalks represent a futile investment of both time and money. The compliance rates by gender, age, and ethnicity are shown in Table 4.7. The percentages are quite high, especially the sum of those inside or partially inside the crosswalk, even at unsignalized crossings. At signalized intersections, more pedestrians are likely to cross within the crosswalk. Therefore, signalization in conjunction with crosswalk markings may entice pedestrians to cross at the intersection.

TABLE 4.7 CROSSWALK COMPLIANCE AT SIGNALIZED AND UNSIGNALIZED INTERSECTIONS

Crosswalk Attributes		Signalized Intersection			Unsignalized Intersection		
		Within Crosswalk	Partially Inside	Totally Outside	Within Crosswalk	Partially Inside	Totally Outside
Gender	M	72	25	3	70	25	5
	F	81	17	2	52	41	7
Age	0	62*	38*	0*	71	25	4
	1	90*	10*	0*	67*	33*	0*
	2	77	20	3	54	37	8
	3	69	20	12	73	24	3
	4	82*	9*	9*	33*	67*	0*
Ethnicity	1	75	22	3	69	24	7
	2	80	19	1	52	41	7
	3	72	26	2	65	33	2
	4	67*	33*	0*	60*	40*	0*

* Percentage based on fewer than 30 observations.

4.4.4 Walk Rates

Knowledge of pedestrian walk rates is critical in evaluating the duration of the flashing "don't walk" phase. Shorter durations are likely to create a problem analogous to the dilemma zone problem (when vehicles are faced with yellow light) and may result in an uncomfortable crossing (running instead of walking). The average walk rates of pedestrians are obtained for the population based on gender, age, and ethnicity, and are shown in Table 4.8. Note that these values are defined for pedestrian crossings at signalized intersections only. Also, only walking mode is to be considered. Other modes (run, jog, wheel chair crossing, etc.) are normally faster than walk mode. As expected, males have a higher walking rate. The hypothesis, male walk rate is equal to female walk rate, cannot be rejected at the 95% level. The older population seems to have a lower walk rate compared to the other age groups. Also, the variation across groups is not statistically significant. Therefore, the mean walk rate for the population can be obtained as 1.70 m/sec (5.57 ft/sec) with a standard deviation of 0.38 m/sec (1.25 ft/sec) by averaging over the entire population.

Also shown in Table 4.8, the average start-up time is 1.55 seconds with a standard deviation of 2.97. It appears that younger adults react more quickly than members of any other age groups.

4.5 Summary

Data collection is an integral part of any behavioral modeling study. A stratified random sampling approach based on land use was developed. Two zones were defined to classify intersections. Using this approach, intersections were selected from the city of Austin, as well as one from Fort Worth. Data were obtained using on-site and video recording techniques. Preliminary data analysis and results on the behavioral processes are discussed in the following chapter.

TABLE 4.8 WALK RATES AND START-UP TIMES AT SIGNALIZED INTERSECTIONS

Signalized Intersection		Walk rate ft/sec (m/sec)	Start-up time (sec)
Gender	M	5.71 (1.25)	1.60 (3.41)
	F	5.32 (1.20)	1.42 (1.67)
Age	0	5.47 (1.50)*	3.74 (3.52)*
	1	5.37 (1.13)*	2.46 (3.01)*
	2	5.68 (1.26)	1.09 (1.48)
	3	5.30 (1.15)	2.67 (5.38)
	4	4.77 (1.30)*	2.38 (1.82)*
Ethnicity	1	5.62 (1.29)	1.58 (3.30)
	2	5.66 (1.18)	0.92 (2.01)
	3	5.24 (1.09)	1.91 (2.14)
	4	6.02 (1.07)*	-

Values in brackets are standard deviations

* Values based on fewer than 30 observations

CHAPTER 5. PEDESTRIAN-INDUCED VEHICULAR DELAY

5.1 Introduction

At certain intersections, pedestrians may require more time to cross than is required to serve vehicle arrivals; therefore, if a pedestrian signal is provided, it may cause vehicular delay. Pedestrian-activation is one strategy for avoiding wasted vehicular green and delay to vehicles. A framework is developed in this chapter to evaluate the trade-offs between the conflicting needs of pedestrians and of vehicular traffic. The framework allows the estimation of pedestrian-induced vehicular delay, as well as assessment of the relative merits of different strategies for accommodating pedestrians.

Delay times for vehicles and pedestrians are examined for the three possible pedestrian signalization conditions. If there are no pedestrian signals, vehicular traffic phase lengths are unaffected by pedestrians (assuming pedestrian requirements are not taken into consideration in setting green times); however, pedestrians may experience delays. Fixed-time or non-actuated (no push buttons) pedestrian signals may, under light vehicle traffic conditions, force longer than optimal cycle lengths causing vehicular delays. Pedestrian-actuated pedestrian signals may also force longer than optimal cycle lengths, but only when a pedestrian phase is called. Effects of these three pedestrian control options upon fixed (pre-timed) or actuated vehicular traffic controllers are examined.

This framework is developed on the basis of Newell's [Ref 42] "Theory of Highway Traffic Signals." Newell's theory addresses vehicular-induced vehicular delay. It is adapted here to the estimation of pedestrian-induced vehicular delay. Next, numerical illustrations for typical situations allow comparisons between signal operation for fixed pedestrian signal and pedestrian-actuated signal operation. Finally, benefit/cost analysis results are presented, including effects of 24-hour vehicle volume variation.

5.2 Newell's Vehicular Delay Theory

Signal operation at an isolated intersection involves conflicting objectives. The desired outcome is minimization of the "signalization cost" incurred by competing vehicular flows. However, this cost has many possible components: travel time, stops, environmental detriments, delay, accidents, etc. Newell considers explicitly two of these objectives, total delay and number of stops, each of which carries different optimal signal setting implications. Delay minimization favors short cycle times because vehicles have less red-time waiting periods. Minimization of the number of vehicular stops favors longer cycles because fewer vehicles have to stop on account of fewer signal changes (and fewer occurrences of lost time at the beginning and end of each phase). Because delay appears to be more sensitive to the cycle time, delay minimization has generally been the primary consideration.

The analysis begins with a description of the processing of vehicles through the intersection. In Figure 5.1, the queue length and associated delay are illustrated. At any time at a traffic signal, some vehicles are stopped while others are moving. At a time t, after the start of the effective green during which the queue is discharging, the associated delay to a vehicle is W(t), and the queue length is Q(t). (The effective green time for vehicles is smaller than the actual signal's green, because vehicles need additional time to begin to move, and there are fewer vehicles moving through the yellow time.)

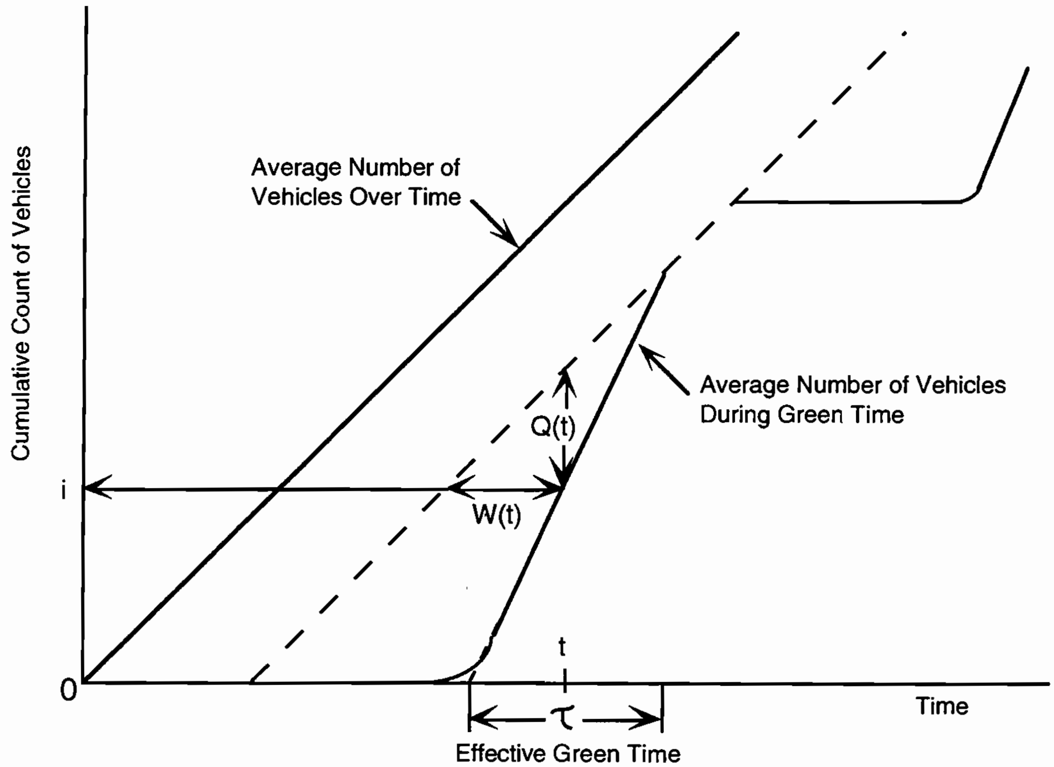


Figure 5.1 (Ref 42): Graphical interpretation of queue length Q(t) and delay W(t)

From this simple deterministic analysis, the fraction of vehicles that are delayed is calculated. The average delay per vehicle that "experiences" delay is taken to be half the red time. Thus, the total average delay for all vehicles is the fraction of those delayed multiplied by the average delay per vehicle. For a four-way intersection, the total delay per unit time is equal to the sum of the number of vehicles multiplied by the average delay per vehicle in each direction.

An additional delay term may be added to take into account the variability in the arrival and departure procedure. This delay term is used to incorporate variability into the signal timings.

Newell provides an expression for the "optimal" cycle time that minimizes a weighted sum of delay and number of stops, and derives expressions for the total vehicular delay per unit time and green time for each approach given the optimal cycle. Therefore, since all the Newell calculations are based on optimized signals, these signals could be either actuated or pre-timed.

In theory, optimized signal operations under fixed traffic demand conditions yield similar performance for both traffic-actuated signals and fixed-time traffic signals. Under variable traffic demand conditions, traffic-actuated signals adjust to changing demand. However, the long-run average timings of ideal traffic-actuated signals would be comparable to continuously optimized timings of fixed traffic signals. Furthermore, minimum and maximum green times of traffic-actuated signals are established using fixed or point estimates of traffic demand. For design or peak hours, timing plans for actuated signals generally cause loss of green through maximum extension ("max out") for most cycles, which causes performance much like that for fixed-time controllers.

5.3 Pedestrian Signalization Effect

When pedestrian constraints are added, it is possible that the cycle will have to be lengthened beyond what is optimal for vehicular flows. The major factors affecting this decision are existing vehicular volumes on the approaches and the pedestrian crossing time requirement (a function of street width).

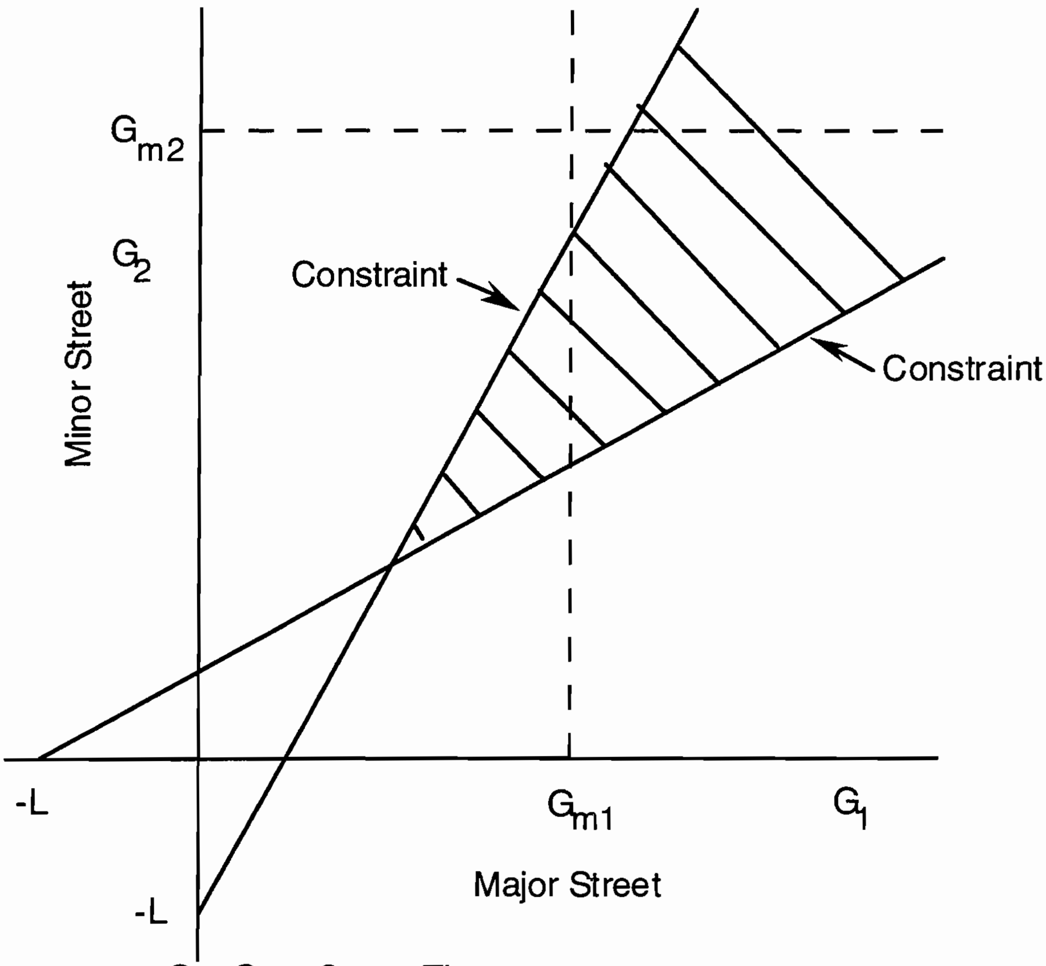
The first factor, traffic volumes, may or may not govern the traffic signal when there is pedestrian signalization. In other words, if the traffic volume is large for both directions, the cycle length required to handle the volumes will be greater than the required pedestrian crossing time.

The second factor, the time required for a pedestrian to cross the street, consists of two parts: reaction time and physical crossing time. From Chapter 4, an average reaction time (start-up time) of 1.6 seconds with a standard deviation of 3.0 seconds was obtained. The reaction time that is widely accepted by traffic engineers is 5 seconds. Although this reaction time seems long, it provides extra time for the elderly and for children. The time required to cross the street depends on the street width and the walk rate. From the data collected, the mean walk rate was 5.6 ft/sec (1.71 m/sec) and the standard deviation was 1.2 ft/sec (0.37 m/sec). At the 15th percentile level, a walk rate of 3.5 ft/sec (1.07 m/sec) is obtained; this number is also used in engineering studies. Similar values were also obtained by Hoel's [Ref 21] extensive walk rate study.

In this analysis, the traffic volume on the major street is always at least as great as that on the minor street. If green time for the minor street is small, the major red will be small, and pedestrians may require more time to cross the major street than that which is provided. In other words, if pedestrian signalization constrains signal operation, frequently the increased cycle length will be induced by increased minor direction green time, G_2. This constraint is seen in Figure 5.2 at the minimum minor-street required green time, G_{m2}. With this increased G_2, a new cycle length is calculated, along with a new corresponding G_1 value. The relationship illustrated in Figure 5.2 ensures that the new G_1 also satisfies the pedestrian minimum G_{m1}. The delay from pedestrian-constrained operations is calculated using the same equations discussed earlier.

5.4 Comparison of Pedestrian-Induced Vehicular Delay Under Different Control Strategies

In order to isolate the effect of pedestrians on vehicular delays, comparisons are performed between optimized (based on vehicular traffic) signal operation with no pedestrian signal phase as the base case, and the following two cases: (1) optimized signal with pre-timed pedestrian signal system and (2) optimized with pedestrian-actuated operation. This comparison helps in assessing the benefits of pedestrian actuation. An overview of the procedure is presented in Figure 5.3.



G_1, G_2 = Green Time
G_{m1}, G_{m2} = Minimum PedestrianGreen Time
L = Lost Time

Figure 5.2 Admissible ranges of green intervals

The following assumptions are made in this comparison. First, on a street with no obstacles other than traffic signals, ideal saturation flow rate is frequently assumed as 1,800 vehicles per hour. However, there are usually several factors which limit this saturation rate (buses, trucks, grades, etc.); hence, a practical value of 1,600 vehicles per hour was assumed. Street widths were calculated on the basis of 12 feet (3.66 meters) per lane; even though many street lanes are narrower than this, there is usually some additional roadway width that pedestrians have to cross, such as parking lanes, shoulders, and/or medians. Second, the variability of the arrival process on major street approaches is assumed to be somewhat greater than on the minor street because of the character of traffic on the major streets and overall higher vehicular volumes.

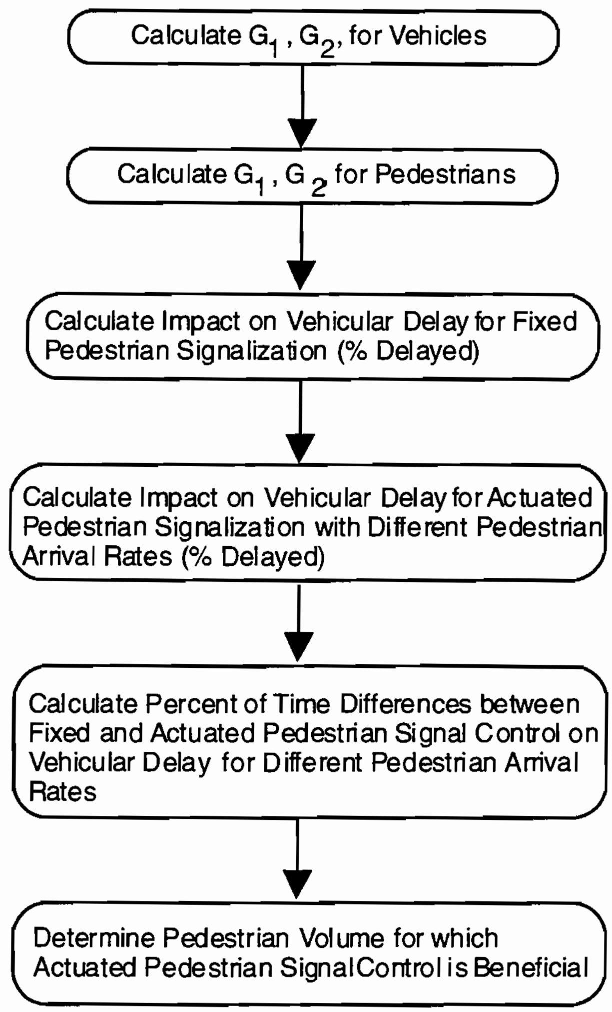
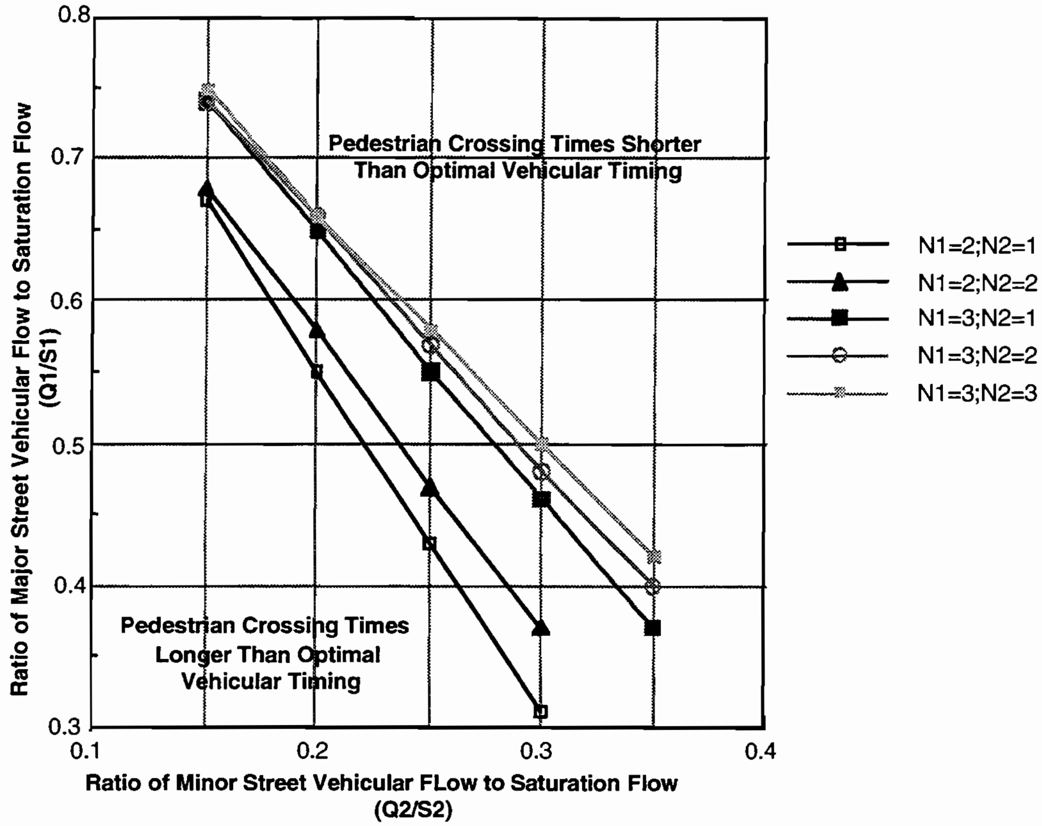


Figure 5.3 Overview of pedestrian-induced vehicular delay model

With these assumptions, the first step in determining the effect of pedestrian constraints is to calculate the values of the critical vehicular flows in excess of which the pedestrian green requirements do not govern the cycle time. This baseline set of results is shown in Figure 5.4.



For S = 1,600

Q/S	Q(vphpl)
0.20	320
0.35	560
0.45	720
0.55	880
0.65	1,040
0.70	1,120

N1 & N2 = number of lanes on major and minor approaches.
Q1 & Q2 = flows on major and minor approaches.
S1 & S2 = saturation flow rates on major and minor approaches.

Usage Note: Locate vertical and horizontal lines representing the minor and major street ratios of flow to saturation flow (Q1/S1 and Q2/S2). If these ratio lines intersect below the line representing numbers of traffic lanes on the two streets, then pedestrian minimum greens force longer than optimal vehicular traffic green intervals.

Figure 5.4 Minimum vehicular flows over which pedestrian green times do not govern

Figure 5.5 illustrates a case for the advantages of pedestrian-actuation over a pre-timed pedestrian signal. Clearly, the benefits are greater for lower pedestrian flow rates (μ). Also, benefits are greater when the number of lanes per approach increases (refer to Tables 5.1 and 5.2 on the following page). The percentage delay increase for pedestrian pre-timed signals compared to phase durations optimized for vehicular traffic, but for few pedestrians, is shown in Table 5.1. The complementary data showing delay savings for the same cases with pedestrian-actuated operation, can be found in Table 5.2. Due to the low pedestrian arrival rate (0.1 pedestrian per minute), most signal phases are not affected by pedestrian arrivals. Therefore Table 5.2 shows delay savings due to pedestrian-actuated operation almost equivalent to delay increases caused by pre-timed pedestrian phases (Table 5.1).

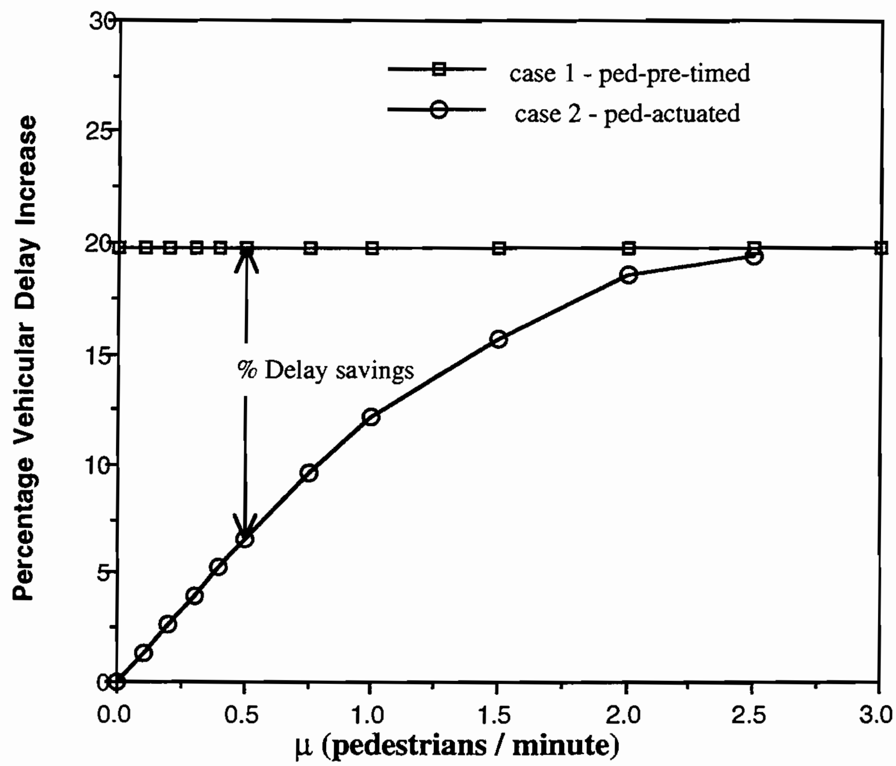


Figure 5.5 Percentage delay savings of pedestrian-actuated compared to pretimed pedestrian signals for a 2 x 2 intersection with: Q1/S1=0.35 Q2/S2=0.15

TABLE 5.1 PERCENTAGE DELAY INCREASE DUE TO PRE-TIMED PEDESTRIAN PHASES COMPARED TO VEHICULAR TRAFFIC OPTIMIZATION (PEDESTRIAN ARRIVAL RATE = 0.1 PED/MINUTE)

Q1/S1	Q2/S2	N1= 1;N2=1	N1= 2;N2=1	N1= 2;N2=2	N1= 3;N2=1	N1= 3;N2=2	N1= 3;N2=3
0.20	0.20	0.0	9.4	16.8	25.4	36.4	45.5
0.35	0.15	0.4	11.9	19.7	29.1	40.1	49.5
0.35	0.25	0.0	1.7	5.2	13.2	20.6	27.0
0.35	0.35	0.0	0.0	0.0	0.5	2.9	5.6
0.45	0.15	0.0	8.9	14.9	25.2	34.0	41.6
0.45	0.25	0.0	0.0	0.5	6.2	10.8	15.0
0.45	0.35	0.0	0.0	0.0	0.0	0.0	0.0
0.55	0.15	0.0	4.8	8.5	19.3	25.3	30.7
0.55	0.25	0.0	0.0	0.0	0.1	0.7	1.8
0.55	0.35	0.0	0.0	0.0	0.0	0.0	0.0
0.65	0.15	0.0	0.3	1.4	10.2	13.3	16.1
0.70	0.15	0.0	0.0	0.0	4.0	5.8	7.5

TABLE 5.2 PERCENTAGE DELAY SAVINGS DUE TO PEDESTRIAN-ACTUATED SIGNALS COMPARED TO PRE-TIMED PEDESTRIAN PHASES (PEDESTRIAN ARRIVAL RATE = 0.1 PED/MINUTE)

Q1/S1	Q2/S2	N1= 1;N2=1	N1= 2;N2=1	N1= 2;N2=2	N1= 3;N2=1	N1= 3;N2=2	N1= 3;N2=3
0.20	0.20	0.0	8.9	15.8	23.9	34.4	43.1
0.35	0.15	0.3	11.1	18.4	27.1	37.4	46.4
0.35	0.25	0.0	1.5	4.8	12.2	19.1	25.1
0.35	0.35	0.0	0.0	0.0	0.5	2.7	5.1
0.45	0.15	0.0	8.1	13.7	23.1	31.3	38.4
0.45	0.25	0.0	0.0	0.4	5.6	9.8	13.6
0.45	0.35	0.0	0.0	0.0	0.0	0.0	0.0
0.55	0.15	0.0	4.3	7.6	17.2	22.7	27.6
0.55	0.25	0.0	0.0	0.0	0.1	0.6	1.6
0.55	0.35	0.0	0.0	0.0	0.0	0.0	0.0
0.65	0.15	0.0	0.3	1.2	8.7	11.4	13.8
0.70	0.15	0.0	0.0	0.0	3.2	4.7	6.1

Figure 5.6 illustrates the variation of percentage delay increase caused by pre-timed pedestrian phases compared to vehicular traffic optimized phases together with the number of lanes.

The wider the street, particularly the major street, the higher the potential for delay savings with pedestrian-actuated signals.

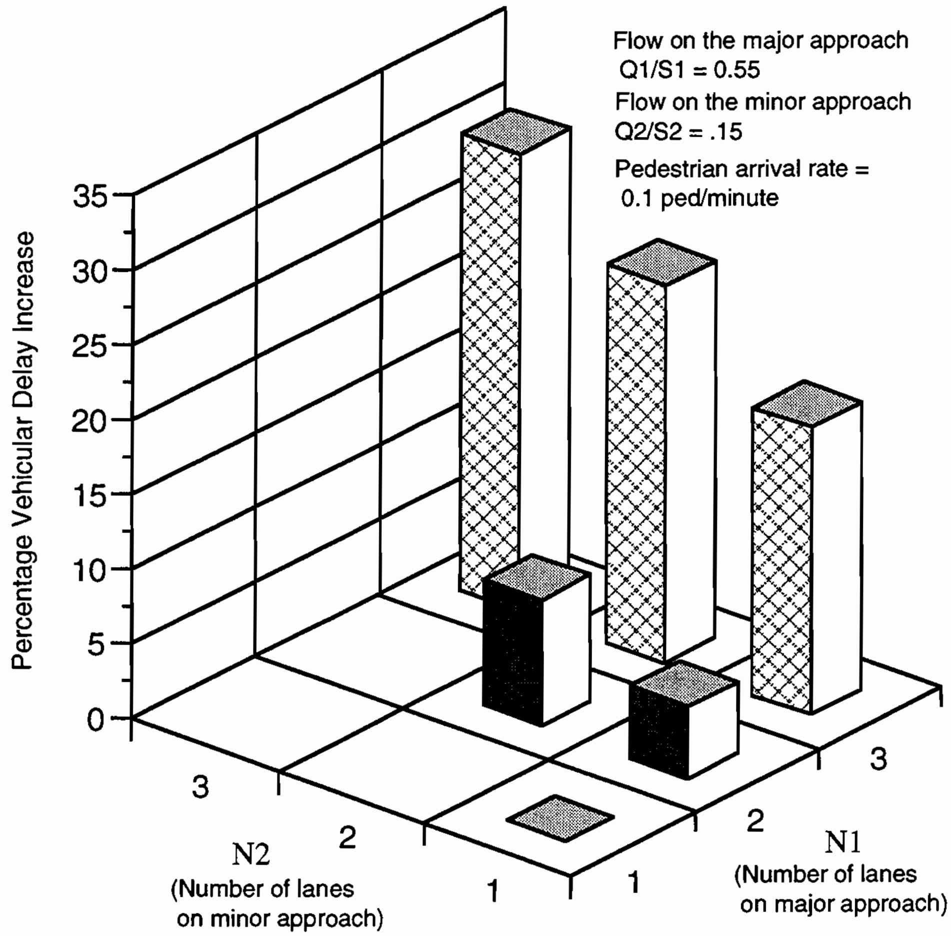


Figure 5.6 Variation of percentage vehicular delay increase with N1 and N2

Figure 5.7 shows vehicular delay increase with the volume-to-capacity ratios of both streets. As the major and minor street flows decrease, the savings with pedestrian-actuated signals increase.

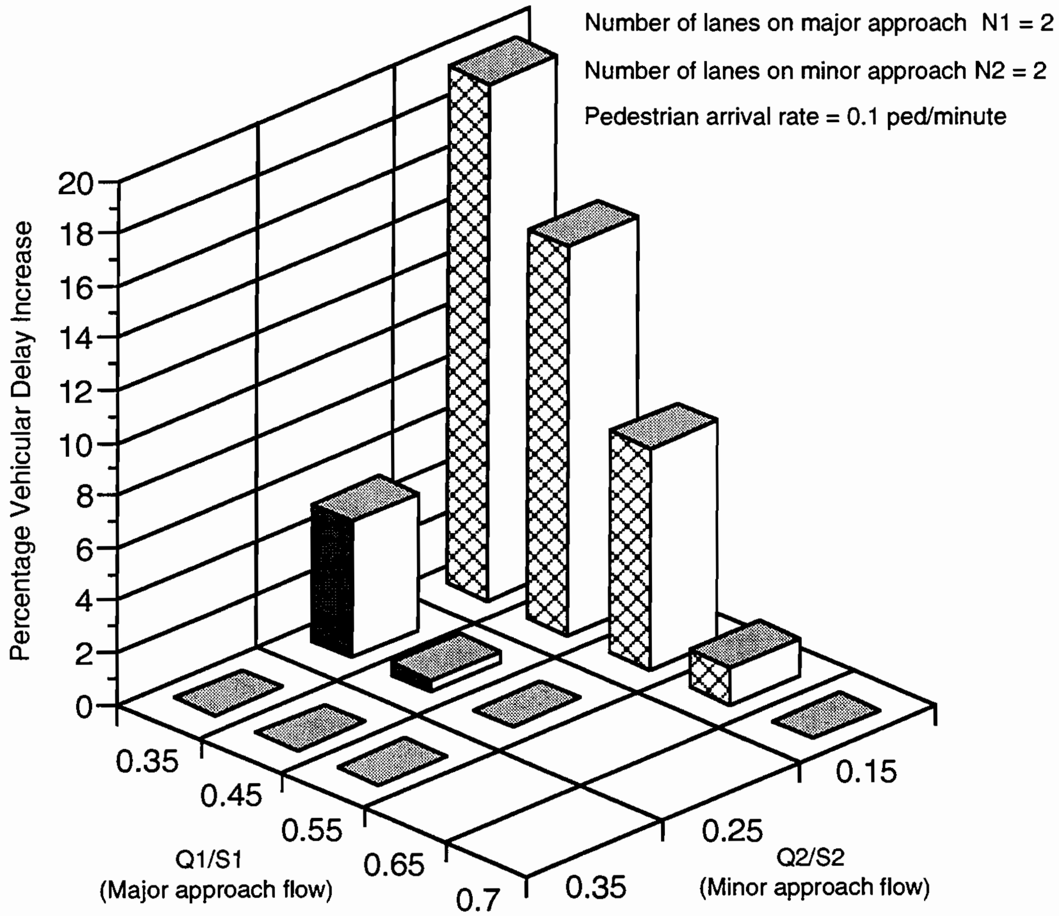


Figure 5.7 Variation of percentage vehicular delay increase with Q1/S1 and Q2/S2

Results of the pedestrian and vehicular delay analyses are summarized in Tables 5.3 through 5.8. Estimated vehicular delay caused by actuated pedestrian phases forcing non-optimal cycle lengths is presented in Tables 5.3 and 5.4. Approximate vehicular delay caused by fixed pedestrian phases (no actuation, no push button) is shown in Tables 5.5 and 5.6. Finally, pedestrian delay associated with pedestrian signalization is presented in Tables 5.7 and 5.8. These pedestrian delays approximate the time lost when no pedestrian signals are provided or the time saved if signals are provided. Minor differences exist between pedestrian time saved under fixed pedestrian phases and actuated pedestrian phases; however, the magnitudes of these differences are small, and therefore separate tables are not presented.

TABLE 5.3 VEHICULAR DELAY DUE TO ACTUATED PEDESTRIAN SIGNALS
(ADDITIONAL OR INCREMENTAL DELAY SECONDS/HOUR COMPARED TO OPTIMAL VEHICULAR SIGNAL TIMING AND NO PEDESTRIAN PHASES)

N1	N2															
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.20	0.20	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	3	4	7	9	10	13	16	20	23	27	30	36	49	59
2	2	1	4	7	11	14	16	20	26	32	38	43	48	58	78	94
3	1	2	6	10	16	20	23	29	37	45	53	60	67	79	104	123
3	2	3	8	14	21	26	31	39	50	61	71	80	89	106	139	164
3	3	3	10	16	25	31	37	46	59	72	84	95	106	125	165	194
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.35	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	1	1	1	1	1	1	2	2	3
2	1	1	3	5	8	10	12	15	19	23	27	30	34	40	53	62
2	2	2	5	9	13	17	20	24	31	38	44	50	56	66	86	102
3	1	2	6	11	17	20	24	29	38	45	52	59	65	76	96	110
3	2	3	9	15	23	28	33	41	52	63	73	82	91	105	134	153
3	3	4	11	18	28	35	41	51	65	78	90	102	112	131	166	189
0.35	0.25															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	1	1	2	2	2	3	4	4	5	6	7	8	11	13
2	2	1	2	3	4	6	7	8	11	13	15	17	19	23	31	37
3	1	1	4	7	10	13	15	18	24	29	34	38	42	50	65	76
3	2	2	6	10	16	19	23	28	36	44	51	58	64	75	98	115
3	3	3	8	13	20	24	29	36	46	56	65	73	81	96	125	146
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.50	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	2	4	5	7	8	10	13	15	18	20	22	26	33	39
2	2	1	4	6	10	12	14	17	22	27	31	35	39	46	59	68
3	1	2	6	9	15	18	21	26	33	39	45	51	56	64	80	89
3	2	3	8	13	20	25	29	36	45	54	63	70	77	89	110	124
3	3	3	10	16	25	31	37	44	57	68	78	87	96	111	137	154
0.50	0.25															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	1	2	3	3	4	5	6	7	8	9	10	12	15	18
3	2	1	2	4	6	7	8	10	13	15	18	20	22	26	33	39
3	3	1	3	5	8	10	12	15	19	24	27	31	34	40	51	59
0.50	0.35															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.65	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	1	1	1	1	1	1	1	2	2	2
2	2	0	1	1	2	2	2	3	4	5	5	6	7	8	10	11
3	1	1	4	6	9	12	14	16	21	25	28	31	34	39	47	51
3	2	2	5	8	13	16	19	23	29	34	39	43	47	53	65	71
3	3	2	6	11	16	20	23	28	36	43	49	54	59	67	82	90
0.70	0.15															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	1	2	3	5	6	6	8	10	12	13	15	16	18	21	23
3	2	1	3	5	7	9	10	12	15	18	21	23	25	28	33	36
3	3	1	4	6	9	12	14	16	21	24	28	31	33	38	45	49

N1 & N2 = Number of lanes on major and minor approaches.
Q1 & Q2 = flows on major and minor approaches.
S1 & S2 = saturation flow rates on major and minor approaches.

TABLE 5.4 ADDITIONAL VEHICULAR DELAY DUE TO ACTUATED PEDESTRIAN SIGNALS
SATURATION FLOW 1600 VPH
(ADDITIONAL OR INCREMENTAL DELAY SECONDS/HOUR COMPARED TO OPTIMAL
VEHICULAR SIGNAL TIMING AND NO PEDESTRIAN PHASES)

N1	N2	Pedestrian Arrival Rate (Pedestrians/Hour)														
Q1 320	Q2 320	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	3	4	7	9	10	13	16	20	23	27	30	36	49	59
2	2	1	4	7	11	14	16	20	26	32	38	43	48	58	78	94
3	1	2	6	10	16	20	23	29	37	45	53	60	67	79	104	123
3	2	3	8	14	21	26	31	39	50	61	71	80	89	106	139	164
3	3	3	10	16	25	31	37	46	59	72	84	95	106	125	165	194
Q1 560	Q2 240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	1	1	1	1	1	1	2	2	3
2	1	1	3	5	8	10	12	15	19	23	27	30	34	40	53	62
2	2	2	5	9	13	17	20	24	31	38	44	50	56	66	86	102
3	1	2	6	11	17	20	24	29	38	45	52	59	65	76	96	110
3	2	3	9	15	23	28	33	41	52	63	73	82	91	105	134	153
3	3	4	11	18	28	35	41	51	65	78	90	102	112	131	166	189
560	400															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	1	1	2	2	2	3	4	4	5	6	7	8	11	13
2	2	1	2	3	4	6	7	8	11	13	15	17	19	23	31	37
3	1	1	4	7	10	13	15	18	24	29	34	38	42	50	65	76
3	2	2	6	10	16	19	23	28	36	44	51	58	64	75	98	115
3	3	3	8	13	20	24	29	36	46	56	65	73	81	96	125	146
Q1 800	Q2 240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	2	4	5	7	8	10	13	15	18	20	22	26	33	39
2	2	1	4	6	10	12	14	17	22	27	31	35	39	46	59	68
3	1	2	6	9	15	18	21	26	33	39	45	51	56	64	80	89
3	2	3	8	13	20	25	29	36	45	54	63	70	77	89	110	124
3	3	3	10	16	25	31	37	44	57	68	78	87	96	111	137	154
800	400															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	1	2	3	3	4	5	6	7	8	9	10	12	15	18
3	2	1	2	4	6	7	8	10	13	15	18	20	22	26	33	39
3	3	1	3	5	8	10	12	15	19	24	27	31	34	40	51	59
800	560															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q1 1040	Q2 240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	1	1	1	1	1	1	1	2	2	2
2	2	0	1	1	2	2	2	3	4	5	5	6	7	8	10	11
3	1	1	4	6	9	12	14	16	21	25	28	31	34	39	47	51
3	2	2	5	8	13	16	19	23	29	34	39	43	47	53	65	71
3	3	2	6	11	16	20	23	28	36	43	49	54	59	67	82	90
1120	240															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	1	2	3	5	6	6	8	10	12	13	15	16	18	21	23
3	2	1	3	5	7	9	10	12	15	18	21	23	25	28	33	36
3	3	1	4	6	9	12	14	16	21	24	28	31	33	38	45	49

N1 & N2 = Number of lanes on major and minor approaches.
Q1 & Q2 = flows on major and minor approaches.

TABLE 5.5 ADDITIONAL VEHICULAR DELAY DUE TO FIXED-TIME PEDESTRIAN SIGNALS
(ADDITIONAL OR INCREMENTAL DELAY SECONDS/HOUR COMPARED TO OPTIMAL VEHICULAR SIGNAL TIMING AND NO PEDESTRIAN PHASES)

		Q1/S1 0.2	Q1/S1 '0.35		Q1/S1 0.5			Q1/S1 0.65	Q1/S1 0.7
N1	N2	Q2/S2 0.15	Q2/S2 0.15	Q2/S2 0.25	Q2/S2 0.15	Q2/S2 0.25	Q2/S2 0.35	Q2/S2 0.15	Q2/S2 0.15
1	1	0	5	0	0	0	0	0	0
2	1	99	88	20	51	0	0	3	0
2	2	158	145	60	89	0	0	13	0
3	1	176	138	104	106	23	0	58	26
3	2	235	192	158	146	50	0	80	40
3	3	278	237	201	183	76	0	101	54

N1 & N2 = Number of lanes on major and minor approaches.

Q1 & Q2 = flows on major and minor approaches.

S1 & S2 = saturation flow rates on major and minor approaches.

TABLE 5.6 ADDITIONAL VEHICULAR DELAY DUE TO FIXED-TIME PEDESTRIAN SIGNALS - SATURATION FLOW 1600 VPH
(ADDITIONAL OR INCREMENTAL DELAY SECONDS/HOUR COMPARED TO OPTIMAL VEHICULAR SIGNAL TIMING AND NO PEDESTRIAN PHASES)

		Q1 320	Q1 '560		Q1 800			Q1 1040	Q1 1120
N1	N2	Q2 320	Q2 240	Q2 400	Q2 240	Q2 400	Q2 560	Q2 320	Q2 320
1	1	0	5	0	0	0	0	0	0
2	1	99	88	20	51	0	0	3	0
2	2	158	145	60	89	0	0	13	0
3	1	176	138	104	106	23	0	58	26
3	2	235	192	158	146	50	0	80	40
3	3	278	237	201	183	76	0	101	54

N1 & N2 = Number of lanes on major and minor approaches.

Q1 & Q2 = flows on major and minor approaches.

TABLE 5.7 CHANGE IN PEDESTRIAN DELAY DUE TO PEDESTRIAN SIGNALS
(PEDESTRIAN TIME SAVINGS, SECONDS PER HOUR, DUE TO PEDESTRIAN SIGNAL INSTALLATION OR APPROXIMATE TIME LOST DUE TO NO PEDESTRIAN SIGNALS)

N1	N2															
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.20	0.20	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	11	32	53	85	106	128	160	213	266	319	373	426	532	799	1065
2	2	33	99	164	263	329	395	493	658	822	987	1151	1315	1644	2466	3288
3	1	10	29	49	79	98	118	147	196	245	295	344	393	491	736	982
3	2	31	93	155	248	309	371	464	619	774	928	1083	1238	1547	2321	3094
3	3	28	83	139	223	278	334	417	556	695	834	973	1113	1391	2086	2781
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.35	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	14	42	71	113	141	169	212	282	353	424	494	565	706	1059	1412
2	1	13	38	64	102	127	153	191	255	319	382	446	510	637	956	1275
2	2	12	37	62	100	125	150	187	249	312	374	436	499	623	935	1246
3	1	12	35	59	94	118	141	177	236	295	354	413	472	589	884	1179
3	2	12	36	60	96	120	144	180	240	300	360	420	480	600	900	1199
3	3	37	111	184	295	369	442	553	737	921	1106	1290	1474	1843	2764	3685
0.35	0.25															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	14	43	72	116	145	174	217	290	362	435	507	579	724	1086	1449
2	2	14	41	69	111	138	166	207	276	346	415	484	553	691	1037	1382
3	1	13	40	67	108	135	162	202	270	337	404	472	539	674	1011	1348
3	2	13	40	67	107	134	160	200	267	334	401	468	534	668	1002	1336
3	3	42	127	212	340	425	510	637	850	1062	1274	1487	1699	2124	3186	4248
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.50	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	18	53	88	140	175	211	263	351	439	526	614	702	877	1316	1754
2	2	17	50	83	133	167	200	250	333	417	500	583	666	833	1250	1666
3	1	16	49	81	130	162	195	243	325	406	487	568	649	812	1217	1623
3	2	16	48	79	127	159	191	238	318	397	477	556	636	795	1192	1590
3	3	16	48	80	128	160	192	240	320	400	480	560	640	800	1200	1600
0.50	0.25															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	21	63	105	168	210	252	315	420	525	630	735	839	1049	1574	2099
3	2	20	61	101	162	202	242	303	404	505	606	707	808	1009	1514	2019
3	3	20	59	99	158	198	237	296	395	494	593	692	790	988	1482	1976
0.50	0.35															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.65	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	30	91	151	242	302	362	453	604	755	906	1057	1208	1510	2265	3020
2	2	28	85	141	225	282	338	423	564	704	845	986	1127	1409	2113	2818
3	1	28	84	140	224	280	336	420	559	699	839	979	1119	1398	2098	2797
3	2	27	80	134	214	267	321	401	534	668	801	935	1068	1336	2003	2671
3	3	26	78	130	207	259	311	389	518	648	778	907	1037	1296	1944	2592
0.70	0.15															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	37	112	186	298	373	447	559	746	932	1119	1305	1492	1865	2797	3729
3	2	35	106	177	284	355	426	532	710	887	1064	1242	1419	1774	2661	3548
3	3	34	103	171	274	342	410	513	684	855	1026	1197	1368	1710	2565	3421

Q1 & Q2 = flows on major and minor approaches.
S1 & S2 = saturation flow rates on major and minor approaches.

TABLE 5.8 CHANGE IN PEDESTRIAN DELAY DUE TO PEDESTRIAN SIGNALS, SATURATION FLOW 1600 VPH

(PEDESTRIAN TIME SAVINGS, SECONDS PER HOUR, DUE TO PEDESTRIAN SIGNAL INSTALLATION OR APPROXIMATE TIME LOST DUE TO NO PEDESTRIAN SIGNALS)

N1	N2															
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
320	320	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	11	32	53	85	106	128	160	213	266	319	373	426	532	799	1065
2	2	33	99	164	263	329	395	493	658	822	987	1151	1315	1644	2466	3288
3	1	10	29	49	79	98	118	147	196	245	295	344	393	491	736	982
3	2	31	93	155	248	309	371	464	619	774	928	1083	1238	1547	2321	3094
3	3	28	83	139	223	278	334	417	556	695	834	973	1113	1391	2086	2781
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
560	240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	14	42	71	113	141	169	212	282	353	424	494	565	706	1059	1412
2	1	13	38	64	102	127	153	191	255	319	382	446	510	637	956	1275
2	2	12	37	62	100	125	150	187	249	312	374	436	499	623	935	1246
3	1	12	35	59	94	118	141	177	236	295	354	413	472	589	884	1179
3	2	12	36	60	96	120	144	180	240	300	360	420	480	600	900	1199
3	3	37	111	184	295	369	442	553	737	921	1106	1290	1474	1843	2764	3685
560	400															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	14	43	72	116	145	174	217	290	362	435	507	579	724	1086	1449
2	2	14	41	69	111	138	166	207	276	346	415	484	553	691	1037	1382
3	1	13	40	67	108	135	162	202	270	337	404	472	539	674	1011	1348
3	2	13	40	67	107	134	160	200	267	334	401	468	534	668	1002	1336
3	3	42	127	212	340	425	510	637	850	1062	1274	1487	1699	2124	3186	4248
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
800	240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	18	53	88	140	175	211	263	351	439	526	614	702	877	1316	1754
2	2	17	50	83	133	167	200	250	333	417	500	583	666	833	1250	1666
3	1	16	49	81	130	162	195	243	325	406	487	568	649	812	1217	1623
3	2	16	48	79	127	159	191	238	318	397	477	556	636	795	1192	1590
3	3	16	48	80	128	160	192	240	320	400	480	560	640	800	1200	1600
800	400															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	21	63	105	168	210	252	315	420	525	630	735	839	1049	1574	2099
3	2	20	61	101	162	202	242	303	404	505	606	707	808	1009	1514	2019
3	3	20	59	99	158	198	237	296	395	494	593	692	790	988	1482	1976
800	560															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
1040	240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	30	91	151	242	302	362	453	604	755	906	1057	1208	1510	2265	3020
2	2	28	85	141	225	282	338	423	564	704	845	986	1127	1409	2113	2818
3	1	28	84	140	224	280	336	420	559	699	839	979	1119	1398	2098	2797
3	2	27	80	134	214	267	321	401	534	668	801	935	1068	1336	2003	2671
3	3	26	78	130	207	259	311	389	518	648	778	907	1037	1296	1944	2592
1120	240															
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	37	112	186	298	373	447	559	746	932	1119	1305	1492	1865	2797	3729
3	2	35	106	177	284	355	426	532	710	887	1064	1242	1419	1774	2661	3548
3	3	34	103	171	274	342	410	513	684	855	1026	1197	1368	1710	2565	3421

N1 & N2 = Number of lanes on major and minor approaches.

Q1 & Q2 = flows on major and minor approaches.

All calculations are based upon vehicular signal timing optimized for each specific vehicular demand condition. As noted earlier, under fixed traffic demands, truly optimized pretimed vehicular traffic controllers and ideal actuated controllers behave very similarly. The signal timing optimization process used here included effects of random vehicle arrivals, which caused somewhat larger optimal cycle lengths. Real actuated controller cycle lengths are constrained by minimum and maximum green times. In summary, incremental vehicular delays shown in Tables 5.3 through 5.6 are reasonably good approximations of actuated vehicular signal controller operations. Since every traffic demand case is based upon optimized cycle lengths, one could enter the table with the 24 different hourly demand conditions of a typical day and determine actuated controller performance during each hour. However, because isolated pretimed controllers generally have one, at most three, different signal timing plans, they cannot continuously optimize timing. Pretimed controllers are generally optimized for one (possibly 3) design hour(s). Since every condition of Tables 5.3 through 5.6 is based on optimized signal timing, the values shown are applicable to the optimized design hour(s) only for the pretimed controller case.

A summary of the applicability and recommended usage of delay tabulations is shown in Figure 5.8. Since twelve different conditions may require analysis, two traffic controller types, two kinds of delay, presence or absence of pedestrian signals and presence or absence of pedestrian activation, the figure is a helpful thought organizer. These data are used in the next section to estimate economic costs and benefits.

PEDESTRIAN SIGNALIZED CASE	**PRETIMED VEHICLE SIGNAL CONTROL**		**ACTUATED VEHICLE SIGNAL CONTROL**	
	Vehicle Delay	Pedestrian Delay	Vehicle Delay	Pedestrian Delay
Actuated Pedestrian Signal	See Table 5.3 or 5.4 (Peak Hour Analysis Only)	See Table 5.7 or 5.8	See Table 5.3 or 5.4	See Table 5.7 or 5.8
Pedestrian Signal **Without** Actuation	See Table 5.5 or 5.6 (Peak Hour Analysis Only)	See Table 5.7 or 5.8	See Table 5.5 or 5.6	See Table 5.7 or 5.8
No Pedestrian Signal	No Effect (Peak Hour Analysis Only)	See Table 5.7 or 5.8	No Effect	See Table 5.7 or 5.8

Figure 5.8 Decision Chart for Pedestrian and Vehicular Delay

5.5 Benefit/Cost Analysis

Costs associated with pedestrian and driver times are similar to wages, or per capita income, as in many transportation studies. In Texas, the per capita income for 1992 was $17,852 [Ref 53]. For 1993, the rate is adjusted to $19,323. The value of time for both pedestrians and drivers is assumed equal. Since there are approximately fifty 40-working-hour-weeks per year, the cost per hour is set at $10.

Table 5.9 displays the estimated cost of actuated pedestrian signals, which is the sum of the fixed pedestrian signal costs from Robertson's study (Ref 8) and the estimated cost of push-buttons. The addition of push-buttons is estimated to be 25% of the equipment cost and 50% of the maintenance cost. The costs of power consumption and push-button installation (when part of the initial installation) are presumed to be negligible.

TABLE 5.9 SUMMARY OF ANNUALIZED COST OF PEDESTRIAN-ACTUATED INDICATIONS (INCANDESCENT-FIBEROPTICS) [REF 8]

ITEM	ANNUAL COST PER SIGNAL*	ANNUAL COST PER INTERSECTION**
Equipment Cost ($225 - $353)	33.53 - 52.61	268.24 - 420.88
Push-Button ($56.25 - $88.25)	8.38 - 13.15	67.06 - 105.22
Power Consumption ***		
(Based on $0.06 per KWH)	70.96 - 23.65	567.65 -189.22
Installation		
(one hour at $20 per hr)	2.98	23.84
Maintenance per Signal		
per year		
(includes parts & labor)	16.88 - 29.81	135.08 - 238.45
Push Button	8.44 - 14.91	67.54 - 119.23
TOTAL ANNUAL COST	141.17 -137.11	1129.41 - 1096.84

* Assume 10 year signal life with a discount rate of 8%
** Includes 8 signals
*** Watts/signal x 24 hours x 365 days x $0.05
Note: All costs have been converted to 1981 dollars;
Robertson has both $0.05, and $0.06 per KWH in his document.

Since costs are quoted in 1981 dollars, a conversion factor of 2.52 was used to convert to 1993 dollars[1]. This rate is very close to the Consumer Price Index for a similar time period. Therefore, the total 1993 annual cost per signal is approximately $350, and, per intersection, $2,800. This cost becomes $0.32 per hour when divided by 8,760 hours per year.

The total cost, or net value, of actuated pedestrian signals will include this $0.32 per hour plus values of vehicular delay time and pedestrian time savings. While the amortized installation and operating cost of $0.32 per hour is fixed, the vehicular delay time cost and pedestrian time savings vary with traffic (vehicular and pedestrian) volumes. Vehicular delay (ddelv) and pedestrian time savings (ddelp) in units of seconds per hour (from Tables 5.3 and 5.7) are presented in Table 5.10 with net hourly economic values. The net values were produced by associating the $10 per hour time values with lost driver and saved pedestrian time and adding the $0.32 amortized operating cost. In Table 5.10 vehicular volumes are presented as ratios of flow to saturation flow (Q/S), while in Table 5.11 saturation flow is assumed to be 1,600 vehicles per hour and flows appear as hourly approach volumes. The net values shown in the tables are sometimes negative, indicating that installation of pedestrian actuated signals would cause a net economic loss for that hourly demand condition. Negative net values are shown shaded.

The tables can be used to determine the desirability of pedestrian signalization. For example, if Q1/S1 = 0.35, Q2/S2 = 0.15, and there are two lane approaches and a pedestrian flow rate of 0.05 pedestrians per minute, then the addition of pedestrian-actuated signals would cause an additional delay of 9 seconds per hour to vehicles, or $0.025 per hour. At the same time, reduced pedestrian delay is 62 seconds per hour, or $0.1722 per hour. (Each total vehicular or pedestrian delay of one second per hour costs $0.00278.) So, the outcome of this scenario is $0.1722 x 1.25^2 - $0.320 - $0.025 = - $0.12975 (rounded to - $0.13), or, the costs exceed the value of saved pedestrian time. If the net value is positive, then, from an economic perspective, the pedestrian-actuated signals should be installed.

In Tables 5.10 and 5.11, many different combinations of major/minor street vehicle volumes, street configurations, and pedestrian volumes were used. However, many more cases were *not* presented, for several reasons. First, with large vehicular traffic volumes, pedestrian green-time requirements do not affect vehicle green-time requirements. Second, high levels of Q1/S1 and Q2/S2 (for which Q1/S1 + Q2/S2 $\geqq$ 0.90) present near- or over-saturated conditions. Third, very low levels of Q1/S1 and Q2/S2 (for which Q1/S1 $\leqq$ 0.15) rarely occur at signalized intersections, except during late-night or early-morning hours. If these conditions should appear, then the net value number is $-0.32 per hour. For other cases that are not represented, the nearest Q1/S1, Q2/S2, and m values should be used.

TABLE 5.10: NET VALUE PER HOUR PEDESTRIAN ACTUATED SIGNALS

Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Minute)														
0.20	0.20	0.01			0.03			0.05			0.08			0.1		
N1	N2	ddelv	ddelp	NET$	ddelv	ddelp	NET$	ddelv	ddelp	NET$	ddelv	ddelp	NET$	ddelv	ddelp	NET$
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	1	11	-0.29	3	32	-0.22	4	53	-0.15	7	85	-0.04	9	106	0.03
2	2	1	33	-0.21	4	99	0.01	7	164	0.23	11	263	0.56	14	329	0.78
3	1	2	10	-0.29	6	29	-0.23	10	49	-0.18	16	79	-0.09	20	98	-0.03
3	2	3	31	-0.22	8	93	-0.02	14	155	0.18	21	248	0.48	26	309	0.68
3	3	3	28	-0.23	10	83	-0.06	16	139	0.12	25	223	0.38	31	278	0.56

Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Minute)														
0.35	0.15	0.01			0.03			0.05			0.08			0.1		
N1	N2	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $
1	1	0	14	-0.27	0	42	-0.17	0	71	-0.08	0	113	0.07	0	141	0.17
2	1	1	13	-0.28	3	38	-0.20	5	64	-0.11	8	102	0.01	10	127	0.09
2	2	2	12	-0.28	5	37	-0.20	9	62	-0.13	13	100	-0.01	17	125	0.07
3	1	2	12	-0.29	6	35	-0.22	11	59	-0.14	17	94	-0.04	20	118	0.03
3	2	3	12	-0.29	9	36	-0.22	15	60	-0.15	23	96	-0.05	28	120	0.02
3	3	4	37	-0.20	11	111	0.03	18	184	0.27	28	295	0.62	35	369	0.86
0.35	0.25															
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	14	-0.27	1	43	-0.17	1	72	-0.07	2	116	0.08	2	145	0.18
2	2	1	14	-0.27	2	41	-0.18	3	69	-0.09	4	111	0.05	6	138	0.14
3	1	1	13	-0.28	4	40	-0.19	7	67	-0.10	10	108	0.03	13	135	0.11
3	2	2	13	-0.28	6	40	-0.20	10	67	-0.12	16	107	0.01	19	134	0.09
3	3	3	42	-0.18	8	127	0.10	13	212	0.38	20	340	0.80	24	425	1.09

Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Minute)														
0.50	0.15	0.01			0.03			0.05			0.08			0.1		
N1	N2	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	1	18	-0.26	2	53	-0.14	4	88	-0.03	5	140	0.15	7	175	0.27
2	2	1	17	-0.27	4	50	-0.16	6	83	-0.05	10	133	0.12	12	167	0.23
3	1	2	16	-0.27	6	49	-0.17	9	81	-0.06	15	130	0.09	18	162	0.19
3	2	3	16	-0.27	8	48	-0.18	13	79	-0.08	20	127	0.07	25	159	0.16
3	3	3	16	-0.27	10	48	-0.18	16	80	-0.09	25	128	0.05	31	160	0.15
0.50	0.25															
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	2	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	1	0	21	-0.25	1	63	-0.10	2	105	0.04	3	168	0.26	3	210	0.40
3	2	1	20	-0.25	2	61	-0.12	4	101	0.02	6	162	0.23	7	202	0.36
3	3	1	20	-0.25	3	59	-0.12	5	99	0.01	8	158	0.21	10	198	0.34
0.50	0.35															
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	2	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	2	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	3	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32

Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Minute)														
0.65	0.15	0.01			0.03			0.05			0.08			0.1		
N1	N2	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	30	-0.22	0	91	-0.01	0	151	0.20	0	242	0.52	0	302	0.73
2	2	0	28	-0.22	1	85	-0.03	1	141	0.17	2	225	0.46	2	282	0.65
3	1	1	28	-0.23	4	84	-0.04	6	140	0.15	9	224	0.43	12	280	0.62
3	2	2	27	-0.23	5	80	-0.06	8	134	0.12	13	214	0.39	16	267	0.56
3	3	2	26	-0.24	6	78	-0.07	11	130	0.10	16	207	0.35	20	259	0.52
0.70	0.15															
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	2	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	1	1	37	-0.19	2	112	0.06	3	186	0.32	5	298	0.70	6	373	0.96
3	2	1	35	-0.20	3	106	0.04	5	177	0.28	7	284	0.65	9	355	0.89
3	3	1	34	-0.20	4	103	0.03	6	171	0.26	9	274	0.60	12	342	0.84

N1 & N2 = Number of lanes on major and minor approaches.
Q1 & Q2 = flows on major and minor approaches.
S1 & S2 = saturation flow rates on major and minor approaches.
ddelv = increased vehicular delay (sec per hour)
ddelp = reduction in pedestrian delay (sec per hour)
NET$=Net value per hour, 1993 dollars, time value=$10/hr

TABLE 5.11 NET VALUE PER HOUR PEDESTRIAN ACTUATED SIGNALS WITH SATURATION FLOW RATE = 1600 VEH/HOUR

Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Minute)														
320	320	0.6			1.8			3.0			4.8			6.0		
N1	N2	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	1	11	-0.29	3	32	-0.22	4	53	-0.15	7	85	-0.04	9	106	0.03
2	2	1	33	-0.21	4	99	0.01	7	164	0.23	11	263	0.56	14	329	0.78
3	1	2	10	-0.29	6	29	-0.23	10	49	-0.18	16	79	-0.09	20	98	-0.03
3	2	3	31	-0.22	8	93	-0.02	14	155	0.18	21	248	0.48	26	309	0.68
3	3	3	28	-0.23	10	83	-0.06	16	139	0.12	25	223	0.38	31	278	0.56
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Minute)														
560	240	0.6			1.8			3.0			4.8			6.0		
N1	N2	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $
1	1	0	14	-0.27	0	42	-0.17	0	71	-0.08	0	113	0.07	0	141	0.17
2	1	1	13	-0.28	3	38	-0.20	5	64	-0.11	8	102	0.01	10	127	0.09
2	2	2	12	-0.28	5	37	-0.20	9	62	-0.13	13	100	-0.01	17	125	0.07
3	1	2	12	-0.29	6	35	-0.22	11	59	-0.14	17	94	-0.04	20	118	0.03
3	2	3	12	-0.29	9	36	-0.22	15	60	-0.15	23	96	-0.05	28	120	0.02
3	3	4	37	-0.20	11	111	0.03	18	184	0.27	28	295	0.62	35	369	0.86
560	400	Pedestrian Arrival Rate (Pedestrians/Minute)														
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	14	-0.27	1	43	-0.17	1	72	-0.07	2	116	0.08	2	145	0.18
2	2	1	14	-0.27	2	41	-0.18	3	69	-0.09	4	111	0.05	6	138	0.14
3	1	1	13	-0.28	4	40	-0.19	7	67	-0.10	10	108	0.03	13	135	0.11
3	2	2	13	-0.28	6	40	-0.20	10	67	-0.12	16	107	0.01	19	134	0.09
3	3	3	42	-0.18	8	127	0.10	13	212	0.38	20	340	0.80	24	425	1.09
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Minute)														
800	240	0.6			1.8			3.0			4.8			6.0		
N1	N2	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	1	18	-0.26	2	53	-0.14	4	88	-0.03	5	140	0.15	7	175	0.27
2	2	1	17	-0.27	4	50	-0.16	6	83	-0.05	10	133	0.12	12	167	0.23
3	1	2	16	-0.27	6	49	-0.17	9	81	-0.06	15	130	0.09	18	162	0.19
3	2	3	16	-0.27	8	48	-0.18	13	79	-0.08	20	127	0.07	25	159	0.16
3	3	3	16	-0.27	10	48	-0.18	16	80	-0.09	25	128	0.05	31	160	0.15
800	400															
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	2	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	1	0	21	-0.25	1	63	-0.10	2	105	0.04	3	168	0.26	3	210	0.40
3	2	1	20	-0.25	2	61	-0.12	4	101	0.02	6	162	0.23	7	202	0.36
3	3	1	20	-0.25	3	59	-0.12	5	99	0.01	8	158	0.21	10	198	0.34
800	560															
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	2	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	2	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	3	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Minute)														
1040	240	0.6			1.8			3.0			4.8			6.0		
N1	N2	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $	ddelv	ddelp	NET $
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	30	-0.22	0	91	-0.01	0	151	0.20	0	242	0.52	0	302	0.73
2	2	0	28	-0.22	1	85	-0.03	1	141	0.17	2	225	0.46	2	282	0.65
3	1	1	28	-0.23	4	84	-0.04	6	140	0.15	9	224	0.43	12	280	0.62
3	2	2	27	-0.23	5	80	-0.06	8	134	0.12	13	214	0.39	16	267	0.56
3	3	2	26	-0.24	6	78	-0.07	11	130	0.10	16	207	0.35	20	259	0.52
1120	240															
1	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	1	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
2	2	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32	0	0	-0.32
3	1	1	37	-0.19	2	112	0.06	3	186	0.32	5	298	0.70	6	373	0.96
3	2	1	35	-0.20	3	106	0.04	5	177	0.28	7	284	0.65	9	355	0.89
3	3	1	34	-0.20	4	103	0.03	6	171	0.26	9	274	0.60	12	342	0.84

N1 & N2 = Number of lanes on major and minor approaches.
Q1 & Q2 = flows on major and minor approaches.
S1 & S2 = 1600 vehicles/hour

ddelv = increased vehicular delay (sec per hour)
ddelp = reduction in pedestrian delay (sec per hour)
NET$ = Net value per hour,1993 dollars,time value=$10/hr

In most cases, pedestrian-actuated signals should not be installed on streets with the one-lane by one-lane configuration. In many other cases, pedestrian volume needs to be only at least 0.02 to 0.10 pedestrians per minute, or 1 to 6 pedestrians per hour. Pedestrian-actuated signals are beneficial at very low pedestrian volumes, but not at non-existent volumes.

The same type of analysis of net economic value can be performed for fixed pedestrian signals (no pedestrian activation) using time delays and savings for vehicles and pedestrians from Tables 5.5 and 5.7 (5.6 and 5.8). Although not presented in this section, this case is summarized in Chapter 8.

5.6 Analysis of Hourly Variation of Pedestrian and Vehicle Volumes

The net values of Tables 5.10 and 5.11 are presented as per hour numbers. These numbers appropriately describe cases for hourly vehicular and pedestrian volumes compared to those for optimized traffic signals without pedestrian indications. However, both vehicular and pedestrian volumes change within and among the hours of a typical 24-hour day.

Using the results obtained in Section 5.5, the net value or benefit/cost over a 24-hour period can be calculated if hourly information on pedestrian and vehicle volumes is available. In most instances, the average hourly vehicle volume counts will be available, but not the average hourly pedestrian volume counts. This section illustrates the extension of the previous approach to consider varying conditions over a 24-hour period. As noted in Figure 5.8, the 24-hour analysis is applicable only to actuated vehicle traffic controllers. Analysis of pre-timed vehicle control is limited to peak hours only, because the incremental delays are relative to optimized cycle lengths and because pre-timed controllers generally have only a single timing plan optimized for one design hour condition.

The numbers of lanes per approach, major and minor street volumes, saturation flow rate (or typical value), pedestrian volumes, and the information from the appropriate delay tables (see Figure 5.8) are needed to perform this analysis. This information is needed for each of the 24 hours for the intersection under consideration.

For this example, a typical major and minor street approach has two lanes, a saturation flow rate of 1,600 vehicles per hour, and a vehicle distribution represented by Table 5.12. Further, assume a 24-hour pedestrian arrival rate of 0.05 pedestrians per hour, except during the late-night/early-morning hours (for which it is 0 ped/hour). The 24-hour net value of pedestrian-actuated signals is calculated using Table 5.11. The results are shown, and the benefit/cost is summed over the 24-hour period. Since this total is negative, costs exceed benefits on a 24-hour basis.

The above methodology can be used when all 24 hours of pedestrian and vehicular volumes are available; however, this is usually not the case. To simplify the amount of pedestrian, as well as vehicular, information required, yet consider variation of traffic and pedestrian volume, a simplified approach is presented. This approach yields a weighted net value sum with the day divided into three parts based upon pedestrian arrival rates. These three parts include peak, non-peak, and zero, or near-zero, pedestrian arrivals.

TABLE 5.12 AN EXAMPLE OF 24-HOUR NET VALUE ESTIMATION

Time	Q1	Q2	Net Value	Time	Q1	Q2	Net Value
12 AM	250	100	-0.32	12 PM	900	500	-0.32
1 AM	150	100	-0.32	1 PM	650	400	-0.09
2 AM	100	50	-0.32	2 PM	550	350	-0.09
3 AM	100	50	-0.32	3 PM	500	350	-0.09
4 AM	50	25	-0.32	4 PM	1100	700	-0.32
5 AM	150	50	-0.32	5 PM	1300	700	-0.32
6 AM	400	200	-0.32	6 PM	750	600	-0.32
7 AM	1000	400	-0.32	7 PM	400	400	0.23
8 AM	1200	600	-0.32	8 PM	450	400	-0.09
9 AM	500	300	-0.13	9 PM	350	300	0.23
10 AM	400	250	-0.32	10 PM	400	250	-0.32
11 AM	750	350	0.04	11 PM	250	200	-0.32

Total Net Value = -5.11

Q1 & Q2 = Flows on Major and Minor Approach
Net Values from Table 5.5

Models which predict numbers of pedestrian arrivals from surrounding land uses are presented in Chapter 7. The land-use classification system can be implemented through a map and/or "windshield" site survey. The numbers (and times of day) of peak and non-peak pedestrian volume hours and arrival rates are presented in Table 7.6. The number of zero pedestrian hours is based on the concept that very few pedestrians appear at most intersections between 11 pm and 7 am; hence, H_0 is estimated as eight hours. At zero pedestrian volumes, the net/value is $-0.32 for each of the eight early-morning hours, for a daily net value $-2.56. Other net value numbers are derived from Table 5.11 using the median (not mean) vehicle of volume per hour during the peak or non-peak pedestrian time period.

$$\text{Net Value (24 hour)} = H_p \times (B_p) + H_{np} \times (B_{np}) + H_0 \times (B_0)$$

where

H_p number of hours of peak pedestrian volumes (from Table 7.6)

H_{np} number of hours of non-peak pedestrian volumes (from Table 7.6)

H_0 number of hours of zero pedestrian volumes (usually 8 hours)

B_p net value during the peak pedestrian hour (from Table 5.10 or 5.11, using pedestrian arrivals from Table 7.6)

B_{np} net value during the non-peak pedestrian volume hour (from Table 5.10 or 5.11, using pedestrian arrivals from Table 7.6)

B_0 net value during the zero pedestrian volume hour (usually $-0.32)

5.7 Summary

This chapter illustrated that with higher numbers of lanes, low vehicular flows, and large numbers of pedestrians, pedestrian-actuated signals exhibit potential for net economic savings. Delay analyses showed that streets with one lane in each direction do not require additional time for pedestrians; hence no pedestrian-actuated signals are needed. The benefit/cost analysis illustrated that pedestrian volume needs to be only 1 to 6 pedestrians per hour for pedestrian-actuated installation for most scenarios. By examining the 24-hour time period, this analysis takes into account vehicle and pedestrian volume fluctuations. A simplified 24-hour methodology using pedestrian peak, non-peak, and zero-volume time periods was presented. With this model, the inputs are vehicular volumes, numbers of approach lanes, and pedestrian arrival rates. The vehicular volumes and number of approach lanes are easily obtainable, while pedestrian volumes are not; therefore, pedestrian arrival rates are provided through Chapter 7 models and tabulations (Table 7.6).

CHAPTER 6. PEDESTRIAN BEHAVIOR ANALYSIS

6.1 Introduction

This chapter presents a summary of the analysis of pedestrian gap-acceptance behavior governing crossing at signalized intersections. The material summarized in this chapter is reported in detail in a companion report [Ref 50]. That report presents extensive mathematical model formulations and a detailed discussion of the estimation procedures and results. For the convenience of the reader, this chapter highlights the substantive results of the analysis, with limited reference to the advanced mathematical modeling procedures followed to derive them.

At signalized intersections, pedestrians arrive when the signal indication is "walk," flashing "don't walk," or steady "don't walk." Pedestrians arriving on "walk" have the right-of-way and usually cross immediately. Past experience suggests that pedestrians treat flashing "don't walk" as steady "walk" and usually cross immediately. Therefore, arrivals on this phase are treated no differently from those on "walk." However, those arriving on a steady "don't walk" can either (a) wait for "walk" or (b) cross when possible. If pedestrians choose the second option, they look for gaps in the traffic and, if an acceptable gap is found, they cross on "don't walk"; otherwise they wait to cross on "walk." A fraction of the pedestrians choosing option (b), those who cannot find an acceptable gap, cross on "walk." Even though these pedestrians ultimately cross on walk," their behavior is different from that of those initially choosing to wait for "walk," because they sought a gap but failed to find one.

Roadside observations can identify whether the pedestrian crossed on "walk" or "don't walk" and the corresponding gap sizes. However, pedestrians choosing to cross on "don't walk" who fail to find a gap cannot be identified. Therefore, the observed choice of pedestrians between "walk" and "don't walk" is not necessarily their preferred choice. Limiting the study to pedestrians crossing on "don't walk" alone would create a so-called endogeneity bias because some pedestrians may have crossed on "walk" because they could not find safe gaps. At low-volume intersections, almost all pedestrians cross when they see no vehicles on the street, even though the signal may be "don't walk." It is hence assumed that pedestrians prefer to cross whenever there is an opportunity, irrespective of the signal indication status. This assumption helps circumvent endogeneity, but is again not completely valid. Pedestrians who choose to wait for "walk" may reject many adequate gaps, and including these pedestrians would overestimate the critical gap. Figure 6.1 is a schematic representation of assumed crossing behavior.

The gap-acceptance theories are presented in the next section. Then, in Section 6.3, preliminary gap-acceptance parameter estimates are presented. Behavioral model calibration and specification using these gap-acceptance parameters are described in Sections 6.4 and 6.5. The summary is presented in Section 6.6.

6.2 Gap-Acceptance Theory

According to gap-acceptance theory, each pedestrian has a minimum acceptable critical gap. At the intersection, the pedestrian compares available gaps to the critical gap and decides either to accept the gap and cross or to reject the gap. If the gap is rejected, the next gap is considered. This sequential decision process ends when the pedestrian finds a gap to cross the entire approach or when the phase changes to provide the right-of-way to the pedestrian. The critical gap is an intrinsic quantity specific to the individual facing a particular gap situation. It is also a latent quantity that cannot be measured directly but must instead be inferred from the pedestrian's behavior. The critical gap is expected to decrease with waiting time because the longer the wait, the more likely it is that a pedestrian will accept smaller gaps. On the other hand, the critical gap is expected to increase as the remaining time for "walk" decreases. The critical gap is also a function of person-specific attributes such as age and gender, as well as other unobservable factors.

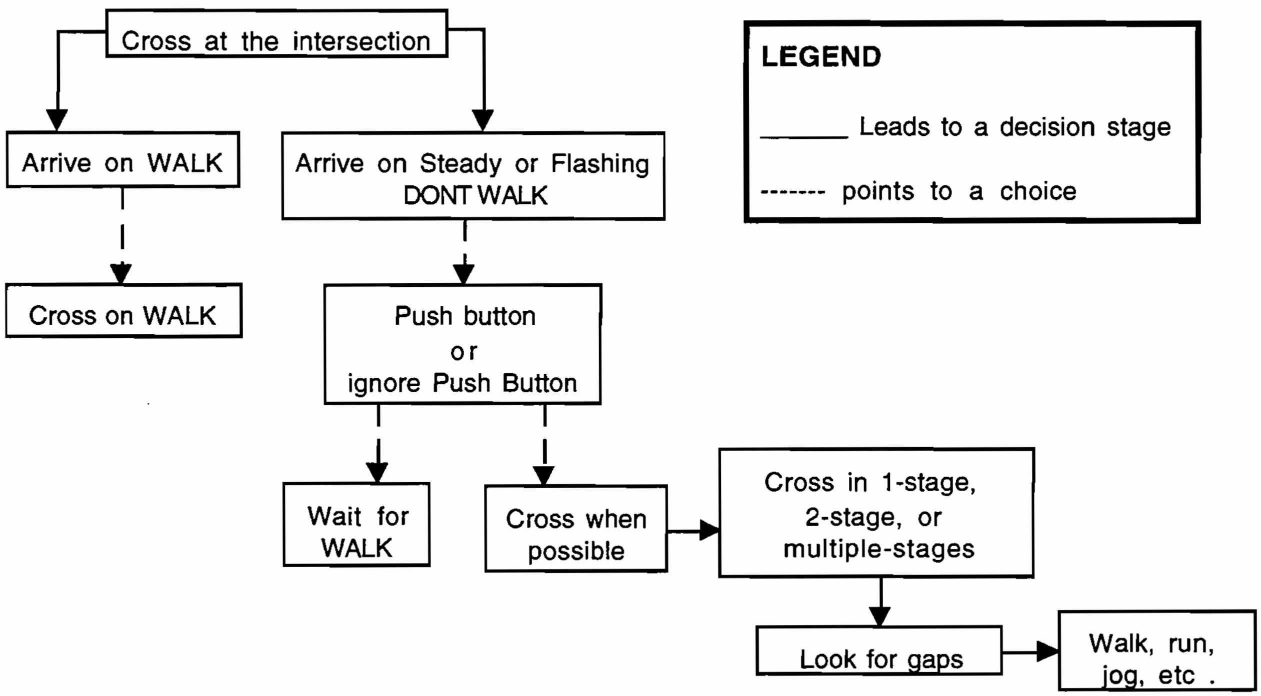


Figure 6.1 Pedestrian Crossing Behavior

In light of the above sources of variation, the critical gap is treated as a random variable, the mean and variance of which are estimated from the data, along with other parameters that capture its systematic dependence on observed attributes. In the above-mentioned companion report [Ref 50], Daganzo's formulation [Ref 34] for a single-lane approach forms the starting point for the gap-acceptance models. The formulation is then extended to a multi-lane approach and related. Throughout this analysis it is assumed that the decision to cross at the intersection versus mid-block is independent of the gap-acceptance behavior at the intersection.

There are two levels of gap-acceptance theories: single-lane crossing and multi-lane crossing. Single-lane crossings occur only at intersections with very wide medians. In the case of a multi-lane approach, four crossing modes are possible. The pedestrian may:

a) look for a combined gap in the entire approach and cross in a single stage;
b) look for gaps in the near and the far (opposite) stream, and cross in a single stage;
c) look for a gap in the near stream, cross, and then look for a gap in the far stream, i.e., a two-stage crossing; or
d) cross lane-by-lane.

The first three modes are most commonly observed at signalized intersections, while the last usually occurs mid-block. Mode (a) is typical on a one-way street, and mode (c) is observed predominantly in the presence of a median. While it would be desirable to model the pedestrian's choice of the particular crossing mode, the determinants of this process are not evident and could not be captured with the available data. Instead, a separate gap-acceptance behavior model is developed for each mode. The formulations developed in this research, summarized in the following sections, are conditioned on the mode selected.

Before proceeding with the presentation, the following definitions for lags and gaps are provided. First, an "epoch" is defined as the instant at which a vehicle clears the crosswalk. After the initial crossing decision made upon arrival at the intersection (to accept or reject the first lag, as defined below), the pedestrian makes a decision to wait or cross at the epoch. The terms "lag" and "gap," for each mode, are defined as follows:

For mode a:

Lag: Time interval between the pedestrian arrival and the first epoch.
Gap: Time between successive epochs, irrespective of the lane position of vehicle in the traffic stream.

For mode b:

Lag: There are two lags for this mode, near and far lags. The near (far) lag is the time interval between the pedestrian arrival instant and the first epoch in the near (far) stream.
Gap: Gaps are defined only after the first epoch (could be a near epoch, or a far epoch). A near (far) gap is defined as the time remaining for the next near (far) epoch. At every epoch, there are two gaps—a near gap and a far gap.

For modes c and d: The definitions for mode (a) are applied locally, at each crossing stage.

In the analysis, the instant of pedestrian "arrival" is defined as the time at which the pedestrian steps off the curb (for an immediate crossing), or slows at the corner (when the lag is rejected). The definitions are illustrated in Figure 6.2 for modes (a) and (b) only.

In single-stage crossing with combined gaps (mode a), the pedestrian looks for a gap in the entire approach. The model formulation is identical to that for a single-lane crossing. However, a gap in the farthest lane is perceived differently from a gap in the nearest lane.

In single-stage crossing with near and far stream gaps (mode b), the pedestrian is assumed to have two critical gaps, one for the near stream, and another for the far stream. A crossing is possible only when both gaps are acceptable.

In two-stage crossing (mode c), the pedestrian would first search for a gap in the near stream, cross, and then search for a gap in the far stream. The first-stage crossing is independent of the second-stage crossing. However, the crossing experience gained during the first stage would influence all gaps considered during the second stage.

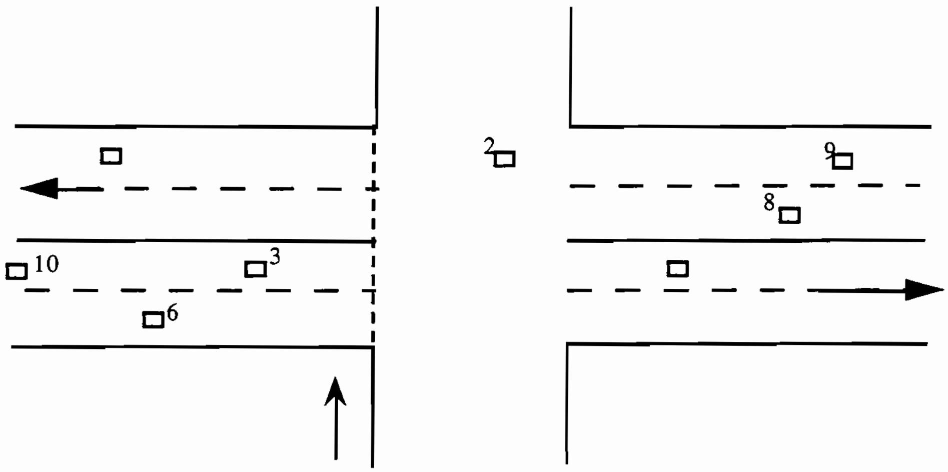
In multi-stage crossing (mode d), the pedestrian is assumed to cross lane-by-lane. This is an extension of the previous two-stage case to multiple stages. It is again assumed that a previous stage crossing would influence all the future stage crossings. However, shorter gaps in farther lanes might deter a pedestrian from crossing because of the high risk involved in waiting unprotected in the middle of the street. This mode is generally observed at low traffic volumes.

In addition to the situation when pedestrians arrive individually and cross independently, the models developed in this study address group crossings and push-button behavior. When pedestrians arrive in groups, the interactions taking place among the members of the group must be recognized in modeling individual behavior. However, the behavior across groups can still be assumed independent, because the group arrivals are independent. This assumption holds only when the group crosses as one entity. If a group splits, the lagging group is more likely to accept a smaller gap to reunite with the leading group.

If the crosswalk has a push-button, the pedestrian can either push the button or ignore it. Pedestrians using push-buttons tend to accept longer gaps because they are more likely to wait for the WALK indication. Therefore, the push-button choice behavior is not independent of gap-acceptance behavior. In the companion report [Ref 50], the choice to activate a push-button is explicitly analyzed and modeled, yielding useful insights into the determinants of this behavior.

6.3 Preliminary Data Analysis

The behavioral analysis is based on 17 sites out of the 20 intersections included in the survey. Most of the intersections had very low pedestrian arrival rates, with two of them having as few as five pedestrians during a five or six-hour survey period. Observations of pedestrian arrivals during the "walk" phase are excluded, as no gap-acceptance behavior is associated with them. Arrivals on the flashing "don't walk" are also excluded. This leads to an almost 50 percent reduction in the potential sample size. Mid-block crossings are not considered because they are outside the scope of the behavioral study. As models are conditioned on the mode selected, data are subdivided based on mode choice, i.e., one-stage, two-stage, and multiple-stage crossing. Because the data set is too small for modes (c) and (d), with fewer than 35 observations for each, the analysis is restricted to one-stage crossing which includes (a) and (b), for which 135 observations (pedestrian crossings) were available. In the final data set, very small gaps (below a minimum G_{min} = 2.25 sec), that tend to occur at heavy traffic intersections, are omitted because they contribute virtually no useful information yet significantly increase the computational requirements of the model calibration.



The number at the head of each vehicle denotes the time in which the vehicle clears the indicated crosswalk. Arrows indicate direction of movement.

No.	Time	Mode (a)	Mode (b) Near	Mode (b) Far
1)	0	2	3	2
2)	2	1	1	6
3)	3	3	3	5
4)	6	2	4	2
5)	8	1	2	1
6)	9	1	1	99
7)	10	99	99	99

Notes:
1) A lag occurs when the wait time = 0
2) An entry of 99 indicates a long gap, i.e., no vehicle in sight

Figure 6.2 Example Illustrating the Definitions of Lag and Gaps for Crossing Modes (a) and (b)

In order to identify the influential variables, an exploratory analysis is conducted to study the distribution of accepted and rejected gaps with respect to other gap characteristics, as well as intersection and pedestrian attributes. Prior to an examination of the actual data, Figure 6.3 shows a hypothetical situation where all pedestrians behave consistently and have the same critical gap (deterministic critical gap behavior). In this situation, if one plots the rejected gaps and the accepted gaps (in seconds) against the waiting time already incurred by the pedestrian, one would expect the decreasing trend shown in Figure 6.3. Under the deterministic critical gap idealization, all gaps above the curve are accepted, and those below are rejected.

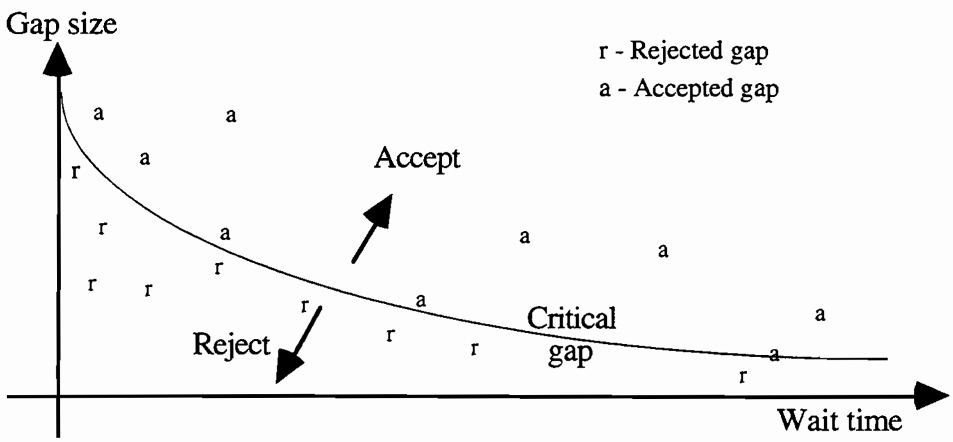


Figure 6.3 Distribution of Gap Size with Wait Time Under an Idealized Deterministic Scenario

In actual data, there will be rejected gaps above the mean critical gap curve and accepted gaps below it, which is why the critical gap is modeled as a random variable. Figure 6.4 depicts the actual rejected and accepted gaps (and lags) as a function of the wait time for those pedestrian crossing decision instances observed in the data set obtained in this study. While the demarcation between accepted and rejected gaps is no longer clear-cut (as expected), the general trend of decreasing mean with waiting time can still be observed. In this figure, the plotted gaps corresponding to a waiting time of zero are actually lags (by definition). The plot seems to suggest that the accepted lags tend to be smaller than the accepted gaps. This result is plausible in light of the respective definitions given earlier of lags versus gaps. A lag is measured from the instant at which the pedestrian steps off the curb (in case of an immediate crossing) or slows at the corner (in case of a rejected lag) to the instant at which the vehicle clears the crosswalk (epoch). Therefore, in this study, the critical lag is the time required to cross safely, whereas the critical gap includes the time to perceive a gap in addition to the time to cross safely.

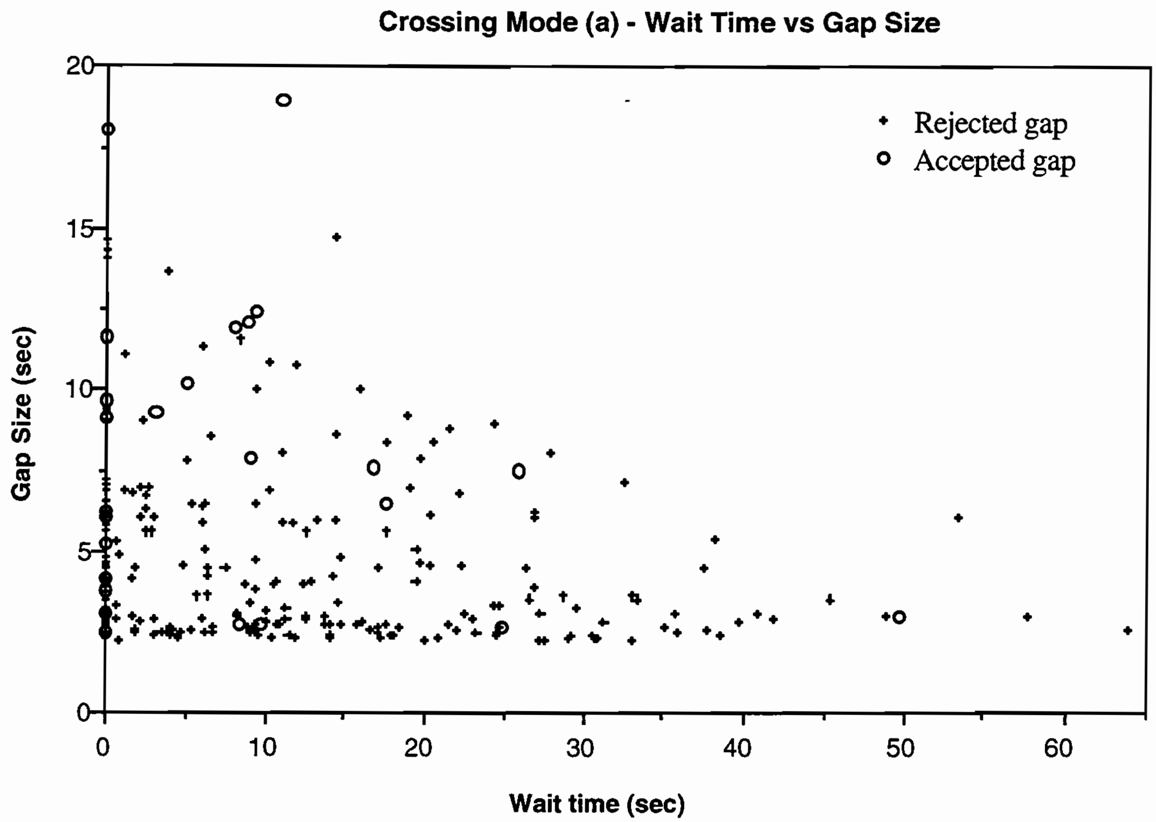


Figure 6.4 Distribution of Gap Size with Wait Time

Similar plots to Figure 6.4 are included in the companion report [Ref 50], with different variables along the abscissa (x-axis). In particular, the rejected and accepted gaps are plotted against various pertinent intersection attributes, individual pedestrian characteristics, and arrival group size, yielding insights into the systematic effect of these explanatory variables, taken separately, on the mean critical gap. The principal conclusions suggested from this exploration include the following:

a. The critical lag and gap values for the far stream seem to be smaller than those for the near stream, suggesting that pedestrians may be less vigilant in judging gaps in the far stream.

b. Wide intersections (greater than 5 lanes), or intersections with at least a commercial land use (IST = 1), tend to cause pedestrians to accept long gaps.

c. Working-age males (19 ≤ Age ≤ 55, and gender = male) are usually more aggressive and tend to accept shorter gaps. Few observations are available in the sample to capture the effect of group interactions, and, although results suggest no group correlation, they may not be conclusive.

6.4 Model Calibration

6.4.1 Estimation Procedure

As described previously, the critical gap is modeled as a random variable, distributed across pedestrians and gap crossing instances. The mean value of this critical gap for a given pedestrian crossing a particular gap can be related systematically to the characteristics of the pedestrian (e.g., age, gender) and those of the crossing situation (e.g., intersection attributes, waiting time until current gap). The actual value of the critical gap is then randomly distributed around this mean. This can be expressed as follows:

$$GC(i,n) = \overline{GC}(i,n) + e(i,n)$$

where $GC(i,n)$ is the critical gap for pedestrian n facing the i-th gap (in a given sequence of gaps);
$\overline{GC}(i,n)$ is the mean value of the critical gap; and
$e(i,n)$ is the random component of the critical gap.

One of the principal objectives of the model calibration process is to determine the factors or variables that influence the mean critical gap $\overline{GC}(i,n)$ and establish the functional relationship between $\overline{GC}(i,n)$ and the explanatory variables. To perform such calibration, it is necessary to specify the distributional properties of the random component $e(i,n)$. When this component is assumed to follow a normal (Gaussian) distribution, the gap-acceptance function (which gives the probability that a given pedestrian accepts a particular gap) is given by the so-called probit model, commonly used to model individual choice behavior among discrete alternatives. The normality assumption for the distribution of $e(i,n)$ is very plausible and consistent with existing knowledge in human factors and statistical theory. To calibrate the resulting probit choice model, observations of actual choices (crossing decisions) made by pedestrians are required, along with corresponding values of the explanatory variables. The calibration is performed using special-purpose software for maximum likelihood estimation of multinomial probit models. The mathematical details of the model formulation and estimation procedure are described in the companion report by Palamarthy et al [Ref 50].

As alluded to in a previous section, a major source of difficulty in the estimation process arises from the distribution properties of the random component $e(i,n)$. In particular, because of the presence of common factors for the same pedestrian considering a sequence of gaps, one expects $e(i,n)$ and $e(j,n)$, where $i \neq j$, to exhibit a certain degree of correlation. This leads to a model with serial correlation. Furthermore, if individuals n and m are traveling together as part of a group, their behavior is expected to exhibit some interaction, thereby leading to (contemporaneous) correlation between $e(i,n)$ and $e(i,m)$, $n \neq m$. These sources of correlation can be addressed in the framework of multinomial probit models, as discussed in the companion report [Ref 50]. However, estimation of such models is only now possible because of recent advances in estimation software at The University of Texas at Austin [Ref 51]. The present study represents a breakthrough in this regard, and it constitutes the first instance in which realistic gap-acceptance functions with general flexible specifications have been estimated using a multinomial probit discrete choice modeling framework.

Four different gap-acceptance models were developed:

Model I: applies to crossing mode (a), with push-button or no group interactions.
Model II: applies to crossing mode (a), with push-button but no group interactions.
Model III: applies to crossing mode (a), with push-button and with group interactions.
Model IV: applies to crossing mode (b), with no push-button or group interactions.

Comparison of the results of Model I to those of Model II allow testing the significance of push-button interactions or crossing behavior for mode (a). Model III is intended to access the significance of the effect of group interactions on crossing behavior for mode (a). In addition, a model of push-button choice behavior has also been developed and calibrated in conjunction with Model II..

The specifications of the functional relationship between the critical gap and the explanatory variables for the gap-acceptance functions, and of the push-button behavior model, are summarized next, along with the implied a priori hypotheses. This is followed by highlights of the estimation results. Complete details are provided in the companion report [Ref 50].

6.4.2 Model Specification and Hypotheses

The variation of the mean critical gap (and lag) can be systematically related to the following categories of explanatory variables:

a) Initial Critical Gap (or Lag)
b) Gap Characteristics
c) Intersection Characteristics
d) Pedestrian Characteristics

The variable definitions are listed in Appendix B. The hypotheses tested in this specification are:

(i) The initial mean critical lag is assumed to be different from the initial mean critical gap.
(ii) For a given gap size, a gap in the farthest lane is less preferred. A variable describing the lane position of the vehicles intended to capture the systematic variation of the critical gap across lanes.
(iii) Pedestrians are more likely to risk crossing a gap when the oncoming vehicle is a turning vehicle or a vehicle in the opposite far stream.
(iv) At busy intersections, pedestrians are less likely to cross during a "don't walk" indication.

The systematic specification of the push-button choice function is comprised of the following components:

a) Constant Term
b) Pedestrian Characteristics
c) Intersection Characteristics

The hypotheses to be tested in this specification are that:

(i) Pedestrians are reluctant to use the push button.
(ii) At busy traffic intersections and wide crosswalks, pedestrians are more likely to use the push-button.
(iii) If one member of the group pushes the button, other pedestrians may ignore it.

6.5 Highlights of Estimation Results

The behavioral implications of the model estimation results are highlighted in this section. Results are discussed for each of the four gap-acceptance models and for the push-button behavior model described in Section 6.4.1.

Model I: Crossing mode (a) with no push-button or group interactions

The analysis of the model results indicates that the initial mean critical lag is significantly different from (smaller than) the initial mean critical gap. The critical gaps and lags decrease with waiting time (confirming the existence of a pedestrian impatience factor). At busy intersections, these values are higher because the pedestrian must be more attentive in order to make a safe crossing maneuver. At wide intersections, the values increase again because of the higher risk associated with longer crossing time. As the coefficient of the left-turning vehicle indicator variable is negative, it appears that pedestrians may not always see turning vehicles, or they may be less alert during left-turn phases. The sign of the coefficient of a variable indicating the direction of traffic suggests that pedestrians are less vigilant in judging vehicle gaps in the far traffic stream. Medians apparently encourage lane-by-lane crossing effectiveness. Additional study may be necessary to determine the effectiveness of medians as a pedestrian control strategy. The "aggressive population" ($55 \geq$ age ≥ 19, and gender = male) have lower critical gap values. The estimation results also suggests that there is somewhat less variability of the critical gap "within" individuals (across gaps) than "across" individuals.

Model II: Crossing mode (a) with push-button but no group interactions

The signs of the estimated coefficients for the push-button function meet a priori expectations. Unfortunately, only 52 observations had the option of a push-button. The results establish that pedestrians, by nature, may be less inclined to use a push button. This behavior is more pronounced when the pedestrians' hands are engaged. The positive coefficients of the number of lanes variables and the intersection land-use indicator suggest that at wide or busy intersections, push-buttons seem to be of some assistance. Although the correlation between push-button behavior and gap-acceptance is statistically significant, its magnitude is very small, suggesting that the correlation between push-button behavior and gap-acceptance behavior may be ignored for the rest of the analysis.

Model III: Crossing mode (a), with no push-button but with group interactions

One of the main conclusions from this model is that group interactions are not negligible and cannot be ignored. While one might expect higher critical lag and critical gap values as compared to those of Model I, only the critical lag appears greater. The effect of the "aggressive population" indicator attribute (if $19 \leq$ age ≤ 55 and gender = MALE) is less pronounced here compared to Model I, apparently because of group interaction effects. Also, the "within" and "across" pedestrian variance components are smaller because some variation is now explained by the group interactions. As expected, this model provides a better fit to the data than Model I.

Model IV: Crossing mode (b), with no push-button or group interactions

The estimation results indicate that the mean critical gap for the near stream is statistically different from that for the far stream, as are the mean critical lags. The near stream values are, on average, higher than the far stream values, which is consistent with the estimation results from Model I. This result confirms the previous findings that pedestrians appear less concerned about gaps in the far stream. This premise is further substantiated by a (statistically significantly) higher negative coefficient of the elapsed waiting time variable for the far stream gaps compared to the near stream gaps. This result may have serious safety implications and warrants further investigation. The general conclusions for Model I hold for this case as well.

This model improves upon the results of Model II in a manner that parallels that of Model III relative to Model I. Fundamentally, the behavioral insights derived from Model II remain unchanged. This model allows for further establishment of the significance of group interaction effects.

6.6 Summary

In this chapter, models of gap-acceptance behavior under different scenarios, corresponding to one-stage crossing, are calibrated using a multinomial probit approach. Detailed model derivation and estimation results are documented in the companion report [Ref 50]. The following conclusions can be drawn from the analyses conducted in this chapter:

(a) On gap-acceptance behavior:

1) In general, the critical gap is different from the critical lag.
2) At busy or wide intersections, these gap and lag values are higher.
3) People are less cautious while crossing on turn phases.
4) The far stream vehicles seem to have less impact on gap-acceptance behavior than the near stream vehicles.
5) Group interactions are significant, and should not be ignored.

(b) On push-button behavior:

1) People may have an inherent tendency to avoid using push buttons.
2) At busy or wide intersections, push buttons might be of some assistance to the pedestrians. Greater push-button compliance could be achieved at wider intersections.
3) Pedestrians are likely to ignore the push buttons when their hands are not free.

CHAPTER 7. PEDESTRIAN ARRIVAL RATES

7.1 Introduction

The benefits of delay savings of pedestrian-actuated over fixed pedestrian signals are more apparent at low pedestrian flows. Hence the focus of this effort is to determine when and where intersections have low pedestrian arrival rates. Since most pedestrian arrival or generation rate studies have been conducted in downtown or other relatively high-density areas, those results are not readily applicable to this study. Hence, a model for pedestrian arrival rates is developed using land uses other than downtown areas.

With any predictor variables in the specification, some variability is expected to remain unexplained. After preliminary statistics on land use are described, the following sections examine how other variables that describe the intersection and its area influence pedestrian arrival rates.

7.2 Preliminary Statistics

As described in Chapter 4, the methodology for choosing sites included a two-tier classification. The dominant land use in the 1.609 km (1 mile) radius included residential, commercial, institutional, and recreational areas. The exclusive land use in the 0.402 km (0.25 mile) radius included residential, minor-retail, major-retail, institutional, and recreational areas.

The pedestrian arrival rate derived is not simply pedestrian volume over time. As explained in the behavioral analysis in Chapter 6, if arrivals are in groups, the behavior among individuals within a group is correlated because of interactions among them. However, the behavior across groups can still be assumed independent when the group arrivals are independent. Consequently, the pedestrian arrival rate is taken as the number of groups (including one-person groups) over time.

From the data collected, the average 15-minute pedestrian count for the 0.402 km (0.25 mile) land use is presented in Figure 7.1. As shown, the residential and minor-retail land uses generate similar levels of pedestrians, while major-retail and recreational land uses are similar. Institutional land use appears to generate more than twice as many pedestrians as another category.

The average 15-minute pedestrian count for the 1.609 km (1 mile) land use is presented in Figure 7.2. As shown, the residential land use appears to generate only a very small number of pedestrian trips. In contrast, the three other land uses generate three to four times as many.

Figure 7.3 shows the results of all land uses combined over the period during which the data were collected; the average 15-minute pedestrian volume shows considerable variation over the period of the day. In order to determine when peak and non-peak times occur, hourly volumes were calculated using these 15-minute counts at each 15-minute interval (Figure 7.4). It appears that there are three peak times starting: (1) shortly after 8 am, (2) at the end of the lunch hour - 1 pm, and (3) shortly before 4 pm. These patterns seem to replicate known travel activity as morning peak hour, lunch hour, and evening peak hour.

The hourly distribution (calculated similarly as in Figure 7.4) for each land use within a 0.402 km (0.25 mile) is shown in Figure 7.5. The most evident feature is the high volume of pedestrians generated from the institutional land use, which also shows a prominent lunch hour. Volume also appears to peak in the evening, but this peak is not as high as that in the morning hours. Although its morning peak hour appears visible, its peak is not much higher than the peaks for the other morning hour volumes. Perhaps more surprising is that the other land uses generate similar pedestrian volumes in the morning hours, but, in the afternoon, the major-retail and recreational land uses appear to increase substantially. The minor-retail land use is fairly constant during the day.

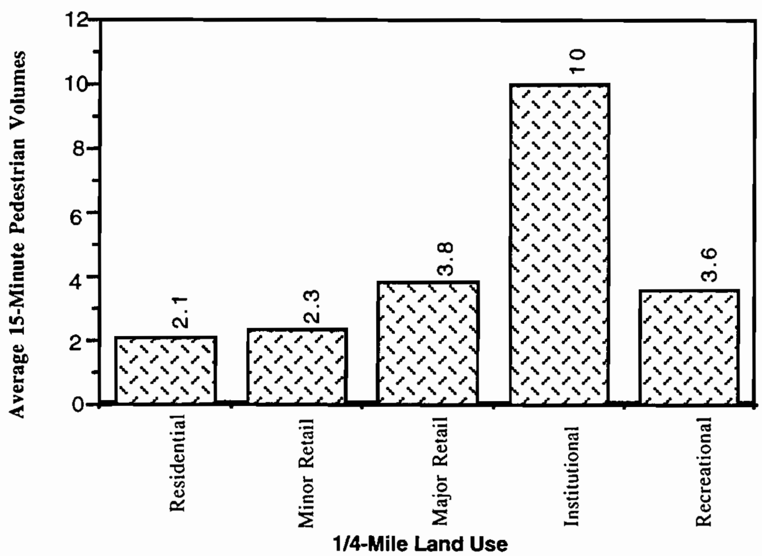


Figure 7.1: Average 15-Minute Pedestrian Volumes by Quarter-Mile Land Use

Note: 1 mile = 1.609 km; 1/4 mile = 0.402 km

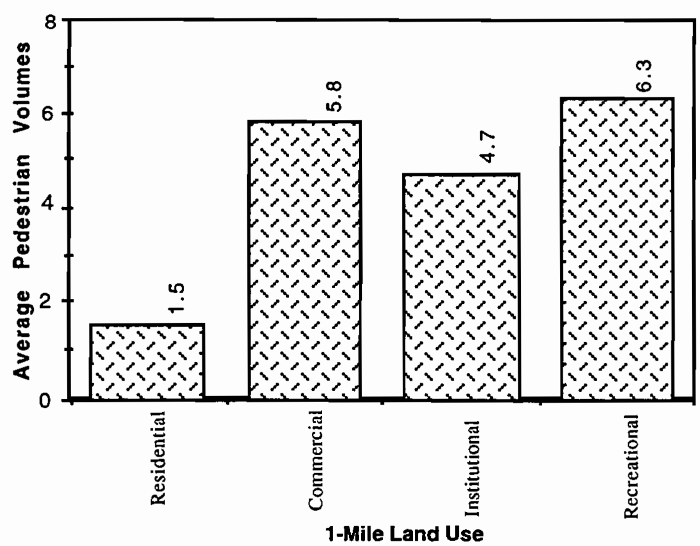


Figure 7.2: Average 15-Minute Pedestrian Volume by 1-Mile Land Use

Note: 1 mile = 1.609 km; 1/4 mile = 0.402 km

The hourly distribution for each land use (in a 1.609 km [1 mile] radius) over the time period for the 1.609 km (1 mile) land use is shown in Figure 7.6. In this case, the residential land use exhibits a consistently low pedestrian volume at all times. The recreational land use has a high pedestrian volume in the peak hour, including the highest morning peak hour. The commercial land use has the highest peak lunch hour, whereas the afternoon peak hour is divided between the commercial and the institutional land uses.

The results from the 0.402 km (0.25 mile) and 1.609 km (1 mile) land uses were heavily influenced by sites that have high pedestrian volumes. For instance, the site with the highest pedestrian generator in the 1.609 km (1 mile) recreational land use had an institutional land use in the 0.402 km (0.25 mile) radius; based on visual inspection at the site, it appears that this 0.402 km (0.25 mile) land use seemed to have more influence than its 1.609 km (1 mile) land use.

These results point out the need to re-examine land use as a predictor variable and explore other variables that will explain the variation within the categories of land use. In the next section, the data collection for this exploration is described.

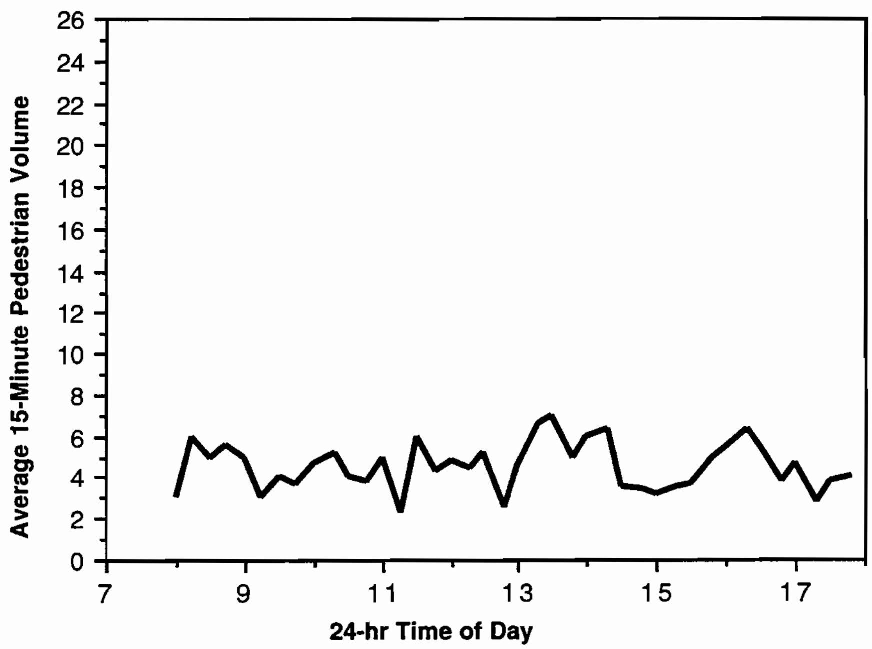


Figure 7.3: Average 15-Minute Pedestrian Volume over all Land Use

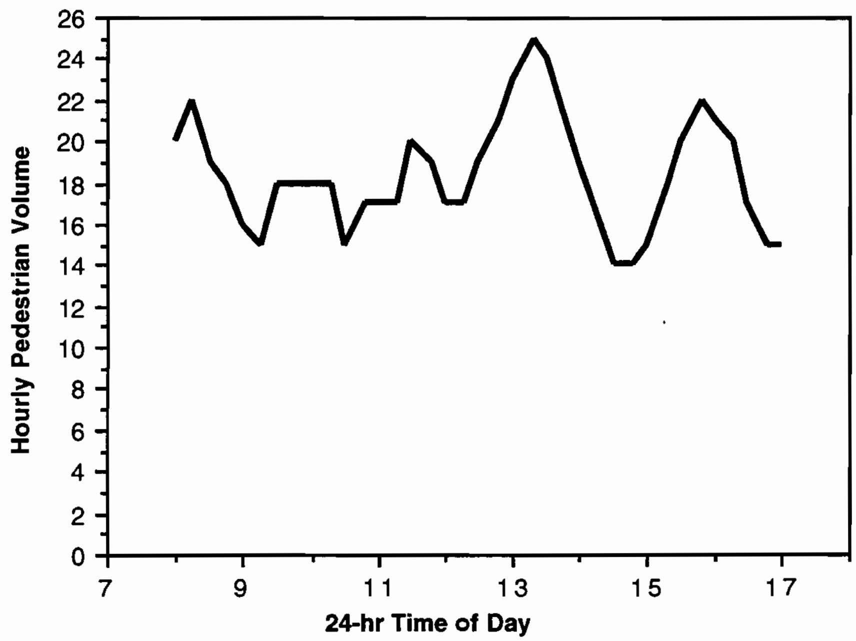


Figure 7.4: Average Hourly Pedestrian Volume over all Land Use

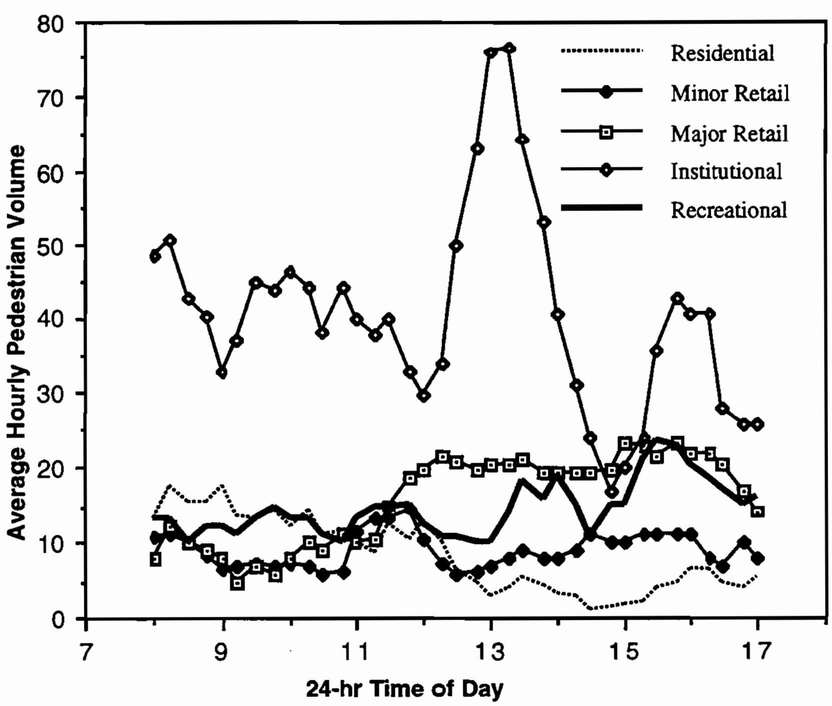


Figure 7.5: Average Hourly Pedestrian Volumes by Quarter-Mile Land Use

Note: 1 mile = 1.609 km; 1/4 mile = 0.402 km

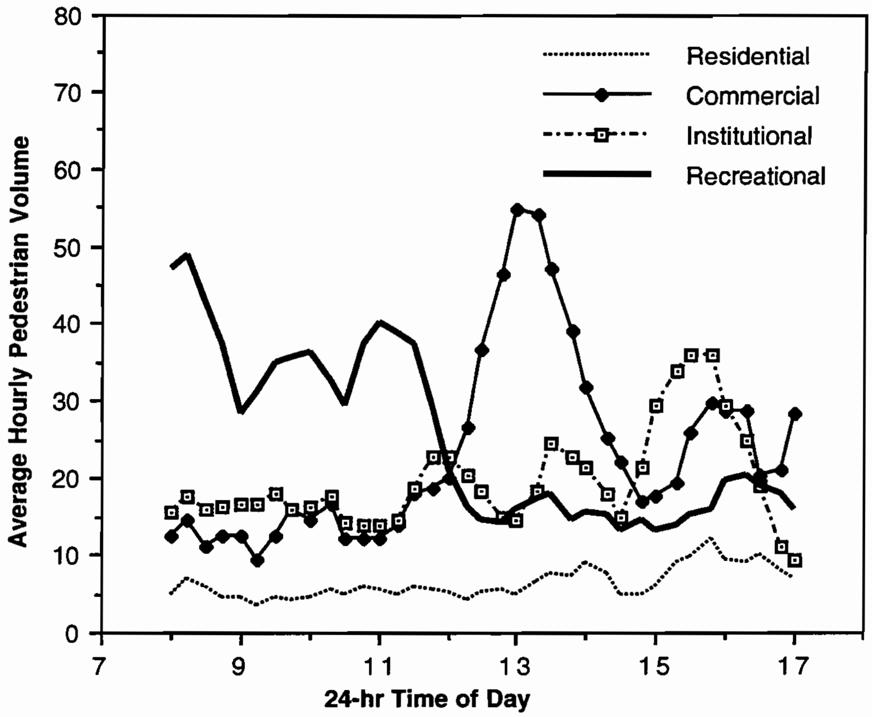


Figure 7.6: Average Hourly Pedestrian Volumes by One-Mile Land Use

Note: 1 mile = 1.609 km; 1/4 mile = 0.402 km

7.3 Data Collection

As shown in the previous section, there is considerable variability in the categorization of sites by land use. Within each land use, there are many factors which cause pedestrians to arrive at the intersection. These factors have been characterized as land use, transit activity, and socio-economic categories. The variables considered in each category have been selected so that data collection is kept at a minimum. A brief description of each category is given in this section, and the basic list of the explanatory variables is given in Appendix C.

From the previous section, the results from the preliminary land-use hypothesis suggest that a better classification should be tried; therefore, several land-use arrangements are tested. Based on field observation, it appears that the presence of major parking lots/garages located across a street from a major land-use generate many pedestrian crossings. Another measure of land-use intensity is the distance from the downtown area. For these variables, information is retrieved from the previous section and from descriptive road maps.

Transit activity brings pedestrian traffic to many areas of the city. Since the typical pedestrian walks as much as a 0.402 km (0.25 mile) to a station, transit activity is measured in the 0.402 km (0.25 mile) radius. Several types of variables analyzed are number of bus lines, bus frequency per hour, and number of passengers on each bus line. Transit activity information was obtained from Capital Metro schedule booklets and from Capital Metro (passenger volumes only).

The socio-economic characteristics of pedestrians can vary widely and can influence the amount of walking (or not walking). For instance, people in areas with lower incomes may be forced to walk to their destinations more often. Unfortunately, average income is not available; surrogates include median housing value, median rent level, and population density. Each of these variables was obtained from the 1990 Census Tract Data.

Although many of these variables are possibly good predictors of pedestrian arrival rates, they are expected to be correlated to one another. Hence, the next section presents results of examination regarding the predictive nature of these variables and presents a viable model for use.

7.4 Results

A preliminary correlation analysis was performed to determine which variables seem to vary with pedestrian arrivals. The results are given in Table 7.1.

TABLE 7.1 PRELIMINARY CORRELATION ANALYSIS

Significant at 95% level:	Presence of parking lot/garage, Number of bus passengers, Median age, Percentage of owner-occupied dwellings
Significant at 90% level:	Bus frequency per hour, Percentage of Hispanics
Significant at 80% level:	Approximate density, Percentage of individuals 18-24 years old, Number of bus lines, Median rent

A general correlation analysis examining the degree of any linear relationships among predictor variables yielded a number of patterns. Sites that have a major parking lot/garage across the street from a major land use have the highest correlation with pedestrian arrival rates. This variable was expected to have a very significant effect in the correlation analyses. Surprisingly, this variable is also correlated with the number of bus passengers. Since only one site has a major parking garage, another site with a major parking lot in Fort Worth was used to help verify its importance. The one mile (1.609 km) land use is positively correlated with density and number of bus lines and negatively correlated with percentage of owner-occupied dwellings. The quarter mile (0.402 km) land use is also positively correlated with density. The number of bus passengers was positively correlated with bus frequency per hour and with the number of bus lines in the area. Other variables that are correlated are approximate density, percentage of 18–24 year olds, and percentage of owner-occupied dwellings. In other words, college-aged students tend to live in apartments which are part of high-density areas and are not owner-occupied buildings. Median age and percentage of 18-24 year olds are positively correlated.

Various specifications and explanatory variables are examined next.

In attempting to order the 0.402 km (0.25 mile) land uses by increasing mean pedestrian generation rate, the following is obtained:

1 - Residential
2 - Minor-Retail
3 - Recreational
4 - Major-Retail
5 - Institutional

However, there is considerable variability that cannot be explained by the 0.402 km (0.25 mile) radius. Unexplained variability in arrival rate for the 0.402 km (0.25 mile) radius is a result of two factors. First, the presence of a major parking lot/garage across a street from a major land use (i.e., major retail, institutional) forces people to cross the street. This effect was observed at two sites: Riverside & Congress in Austin and SH10 near Bellaire in Fort Worth/Dallas area. The Austin site has a parking garage shared by a multi-story hotel and several businesses on that block, and, according to the hotel personnel, parking regulations are not enforced. Many people practically use it as a parking garage and cross Congress (and Riverside) to the Riverside Complex and other businesses. The FWD site has a parking lot across the street from a major business, Bell Helicopter Plant, which is used by its employees. Second, the presence of a retail establishment across a street from a land use with many people having little auto access, particularly high school students at lunch hour, causes many people to cross the street. This effect has been examined at only one site in this study: Cameron and St. John at Reagan High School. These two factors are similar to reasons for high pedestrian arrival rates in downtown areas.

Surrogate variables explaining these two factors are included into the models, along with the one mile (1.609 km) land use as the major predictor.

Based upon experience with variability in the 0.402 km (0.25 mile) land use, experimentation was performed on the 1.609 km (1 mile) land use deleting the sites with major parking and school-commercial activity interactions. Since these variables are significant, they tended to interact with the one mile (1.609 km) land use effect. Without these sites, the modified 1.609 km (1 mile) land use form is shown in Figure 7.7 on the following page in the following order of increasing mean generation rate:

1 - Residential
2 - Commercial (including recreational)
3 - Institutional

This approach allows the basic variability to be explained by the 1.609 km (1 mile) land use. Hence, the original data set was supplemented by two more (extra) sites, and by two more variables, namely Parking Lot/Garage Presence and School-Commercial Activity Presence (as in Table 7.2). This addition improved the ability of the model to explain the variability in the generation rate, though the very small number of these types of sites in our sample does not allow reliable coefficient estimation.

To explain the rest of the variability, other variables were added and examined, but, because of the high correlation between these variables and the modified 1.609 km (1 mile) land use variable, their effect was not statistically significant. The models in Table 7.2 are offered as preliminary specifications to explain pedestrian generation rates.

TABLE 7.2 MODELS FOR OVERALL GENERATION RATE

Variable Name	Model 1	Model 2
	coefficient (t-statistic)	coefficient (t-statistic)
Constant	0.251 (6.35)	0.171 (4.00)
One mile (1.609 km) Residential Land Use	-0.147 (-1.91)	
Modified One mile (1.609 km) Institutional Land Use	0.111 (1.62)	
Presence of Major Park Lot/Garage	1.129 (10.10)	1.15 (10.22)
Presence of School & Commerce	0.939 (6.14)	1.02 (6.48)
Number of Observations	22	22
Significance of F-statistic	0.000	0.000
Adjusted R-Squared	0.875	0.869

Model number one can be used at intersections classified as residential under the 1.609 km (1 mile) criterion, while model two is better applied when 1.609 km (1 mile) institutional land use is present.

To illustrate the practical use of these models, an example is shown. If an intersection has one mile (1.609 km) institutional land use with the presence of a major parking lot, then the predicted generation rate is 0.171 + 0.111 x 1 + 1.15 x 1 + 1.02 x 0 = 1.43 pedestrians per minute. Note that the predictor variables are simply binary choices, meaning the user inserts a "1" if the land use or activity is present or a zero otherwise.

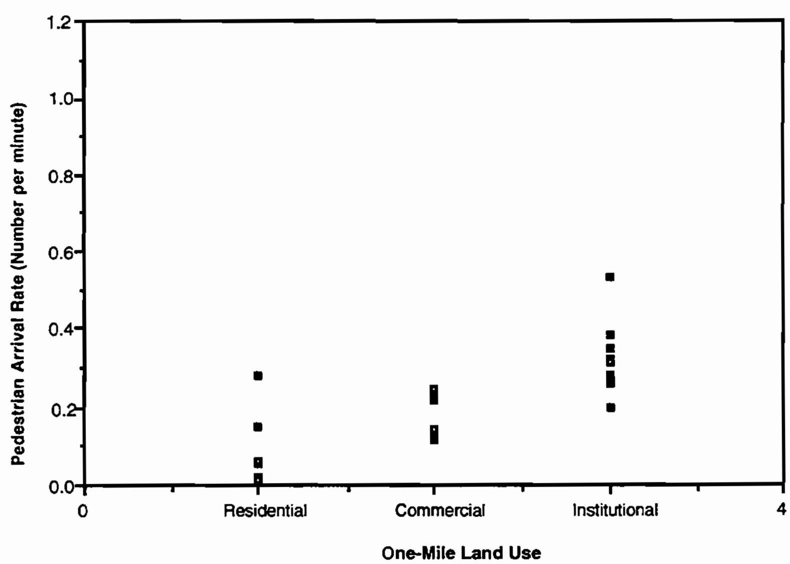


Figure 7.7 Pedestrian Arrival Rates by Modified 1.609 km (One mile) Land Use

Another method of determining the pedestrian arrival rates based on land use is the separation of peak hour(s) from the non-peak hours. Table 7.3 shows peak hour and non-peak arrival rates (on a per minute basis). Some cells of Table 7.3 have no entry, indicating these cases had no identifiable peak arrival rate. Table 7.4 shows two specifications for the prediction of peak hour volumes. The models differ in the use of the original and modified 1.609 km (1 mile) land use. Table 7.5 presents a specification for a model of pedestrian generation for non-peak hour volumes. The models in both tables apply to intersections without major parking and without the school/commercial interaction.

TABLE 7.3 PEAK HOUR VS NON-PEAK HOUR MEAN GENERATION RATE BY LAND USE (Pedestrians Per Minute)

LAND-USE		INTERSECTION	
1.609 km (1 mile) zone	0.402 km (1/4 mile) zone	Peak Hour (Peds Per Minute)	Non-peak Hour (Peds Per Minute)
Residential	Residential	-	0.01
	Minor retail	-	0.02
	Major retail	-	0.15
	Institutional	0.18	0.04
	Recreational	-	0.20
Commercial	Residential	0.33	0.22
	Minor retail	-	0.03
	Major retail	0.38	0.09
	Institutional	2.10	0.82
	Recreational	-	0.22
Institutional	Residential	0.43	0.22
	Minor retail	-	0.28
	Major retail	0.60	0.28
	Institutional	0.49	0.24
	Recreational	0.60	0.32
Recreational	Residential	0.20	0.08
	Minor retail	-	0.20
	Major retail	-	0.51
	Institutional	1.47	0.99
	Recreational	0.25	0.10

TABLE 7.4 MODELS FOR PEAK HOUR GENERATION RATE

Variable Name	Model 1	Model 2
	coefficient (t-statistic)	coefficient (t-statistic)
Constant	0.350 (8.79)	0.321 (7.45)
Quarter mile Residential & Minor Retail LU	-0.169 (-3.81)	-0.173 (-3.97)
One mile Residential Land Use	-0.170 (-3.19)	-0.140 (-2.53)
One mile Institutional Land Use	0.198 (3.71)	
Modified One mile Institutional Land Use	0.197 (3.87)	
Number of Observations	18	18
Significance of F-statistic	0.000	0.000
Adjusted R-Squared	0.750	0.760

Note: One mile = 1.609 km; Quarter mile =0.402 km

TABLE 7.5 MODEL FOR NON-PEAK HOUR GENERATION RATE

Variable Name	Model 1
	coefficient (t-statistic)
Constant	0.105* (3.89)
Modified One mile** Institutional Land Use	0.187 (4.31)
Number of Observations	18
Significance of F-statistic	0.001
Adjusted R-Squared	0.508

* Note: if the one mile land use is residential and the quarter mile land use is residential or minor retail, then the non-peak hour generation rate is 0.01.
** Note: One mile = 1.609 km; Quarter mile = 0.402 km

7.5 Implications

From the peak and non-peak hour generation rate regression models (Table 7.4 Model #2 and Table 7.5), the resulting 15-land-use combination is illustrated in Table 7.6:

Using the Benefit/Cost Tables, several conclusions about several land-use combinations can be reached. First, if the 1.609 km (1 mile) land use is residential and 0.402 km (quarter mile) land use is residential or minor retail, then the benefits of pedestrian-actuated signals are negative. Second, if the 1.609 km (1 mile) land use is institutional[1] and if the pedestrian green time requirements do exceed the vehicular green time requirements (Figure 5.4), then the benefits of pedestrian-actuated signals are positive. Third, if the 0.402 km (0.25 mile) land use includes a major parking lot/garages that are across a street from a major land use or retail establishment across a street from a land use with many people who have little auto access, (particularly high school students at lunch hour) and if the pedestrian green time requirements do exceed the vehicular green time requirements (Figure 5.4), then the benefits of pedestrian-actuated signals are positive.

TABLE 7.6 PEDESTRIAN GENERATION RATE FOR LAND-USE COMBINATIONS

One mile* Land Use	Quarter mile* Land Use	Peak u	Peak Hours	Non-Peak u	Non-Peak Hours
Residential	Residential	-	-	0.01 (0.60)	7am-11pm
Residential	Minor Retail	-	-	0.01 (0.60)	7am-11pm
Residential	Recreational	0.181 (10.86)	4pm-5pm	0.105 (6.30)	7am-4pm, 5pm-11pm
Residential	Major Retail	0.181 (10.86)	12pm-4pm	0.105 (6.30)	7am-12pm, 4pm-11pm
Residential	Institutional	0.181 (10.86)	4pm-5pm	0.105 (6.30)	7am-4pm, 5pm-11pm
Com/Rec	Residential	0.148 (8.88)	8am-12pm	0.105 (6.30)	7am-8am, 12pm-11pm
Com/Rec	Minor Retail	-	-	0.105 (6.30)	7am-11pm
Com/Rec	Recreational	0.321 (19.26)	4pm-5pm	0.105 (6.30)	7am-4pm, 5pm-11pm
Com/Rec	Major Retail	0.321 (19.26)	12pm-4pm	0.105 (6.30)	7am-12pm, 4pm-11pm
Com/Rec	Institutional	0.321 (19.26)	4pm-5pm	0.105 (6.30)	7am-4pm, 5pm-11pm
Institutional	Residential	0.345 (20.70)	8am-12pm	0.292 (17.52)	7am-8am, 12pm-11pm
Institutional	Minor Retail	-	-	0.292 (17.52)	7am-11pm
Institutional	Recreational	0.518 (31.08)	4pm-5pm	0.292 (17.52)	7am-4pm, 5pm-11pm
Institutional	Major Retail	0.518 (31.08)	12pm-4pm	0.292 (17.52)	7am-12pm, 4pm-11pm
Institutional	Institutional	0.518 (31.08)	4pm-5pm	0.292 (17.52)	7am-4pm, 5pm-11pm

Com/Rec = One mile Commercial or Recreation Land Use

u = pedestrian generation rate

*Note: One mile = 1.609 km; Quarter mile = 0.402 km

7.6 Summary

The analysis presented in this chapter has established that the land use variables are good indicators of pedestrian arrival rates. Several alternative models were proposed which can be used to obtain initial estimates of expected mean pedestrian generation of peak/non-peak hours at intersections in non-CBD areas. Using the benefit/cost information from Chapter 5 and the estimated regression estimates, the pedestrian generation rate analyses produced reasonable results. The use of these estimates in the overall procedure to determine the desirability of pedestrian signal actuation is described in the next chapter.

CHAPTER 8. SUMMARY

8.1 Introduction

The literature review in Chapter 2 presented conflicting evidence regarding the effectiveness of pedestrian signals in terms of pedestrian safety, behavior, and delay. The findings warned against indiscriminate pedestrian signal use. One study that heeded these warnings used simultaneous criteria [Ref 53] to justify fixed-time pedestrian signal installation.

Building upon the simultaneous criteria concept, Chapter 3 described many different considerations that could be used to develop pedestrian signal installation guidelines. Three primary criteria subareas were identified: pedestrian-induced vehicular delay, pedestrian behavior, and pedestrian arrival rates. For these subareas, nine factors were identified for the analyses: vehicle delay, volumes, and saturation flow rate; number of lanes; and pedestrian delay, volumes, walk speed, start-up time, and compliance.

Chapter 4 described the data collection scheme for pedestrian behavior and arrival rate analyses. Using a stratified random sampling approach based on land use, two zones were defined to classify intersections regarding pedestrian generation. The classification system includes, within 0.402 km (0.25 mile) of the intersection, predominant residential, minor retail, major retail, institutional, and recreational land uses. Within 1.609 km (1 mile) of the intersection, the system identifies predominantly residential, commercial, institutional, and recreational land uses. From preliminary data analyses, the mean pedestrian walk rate and start-up time were estimated as 1.71 m (5.6 feet) per second and 1.6 seconds, respectively. Examination of pedestrian crossing paths indicates a high crosswalk pavement marking compliance rate.

Chapter 5 illustrated, with a pedestrian-induced vehicular and pedestrian delay model, an economic approach to pedestrian signalization. The pedestrian/vehicular delay model requires vehicular volumes, saturation flow rates, numbers of approach lanes, and pedestrian volumes. The 15th percentile pedestrian walk rate, start-up time, and lane width (from Chapter 4) used in these analyses were 1.07 m (3.5 feet) per second, 5 seconds, and 3.66 m (12 feet), respectively. The net value per hour for each of these inputs, and a 24-hour net value methodology, was presented. A simplified method using only three daily analysis periods—peak, non-peak, and zero pedestrian hours—was presented.

In Chapter 6, models of gap acceptance behavior (to determine compliance rates) under different scenarios were calibrated using a multinomial probit approach. The following conclusions are drawn from these analyses: Pedestrians are less cautious while crossing on turn phases; within-pedestrian-group interactions are significant; and pedestrians may have an inherent tendency to avoid using push buttons, but wide intersections tend to encourage use. Detailed model derivation and estimation results are documented in a companion report [Ref 50].

Chapter 7 established that land-use variables are good indicators of pedestrian arrival rates. Several alternative models were proposed which can be used to obtain initial estimates of expected mean pedestrian generation at intersections in non-CBD areas. The models yield estimates of pedestrian arrival rates and times of applicability based upon land use established through map or "windshield" surveys. Pedestrian arrival rates at most surveyed intersections are quite low (0 to 30 pedestrians/hour) except for intersections with a major parking lot/garage and/or with school-commercial activities. Certain land uses, especially the 1.609 km (one mile) residential land use, exhibited no peak/non-peak pedestrian arrival distribution.

In the next section, a preliminary pedestrian-signalization threshold is given.

8.2 Preliminary Pedestrian-Signalization Threshold

If the number of daily pedestrian crossings of the street with the highest pedestrian volume on the average day is less than 30, there is 99 percent certainty that pedestrian signals are not needed. This number was developed using the Section 8.3 net value procedures. It can be interpreted as saying that there is only a 1 percent chance that a location having less than 30 daily pedestrian crossings of the highest-volume crosswalk would produce a positive net value. If the number for the intersection falls below this number, then pedestrian signals should not be installed, and further analyses is not needed. If the daily number of pedestrians exceeds 30, then the guidelines presented in the next section should be followed.

8.3 Pedestrian Signal Installation Guideline

The procedure for determining whether or not pedestrian signals are desirable is described in flow chart form as Figure 8.1 and in text form as Table 8.1. Units used for this guideline are identified below, and significantly all rates (vehicles and pedestrians) are on a "per-hour" basis:

Name of variable	Symbols used	Units
number of approach lanes	N1, N2	unitless
hourly traffic	Q1, Q2	vehicles per hour
saturation flow rates	S1, S2	vehicles per hour
pedestrian arrival rate		pedestrians per hour
pedestrian compliance[1]		"likelihood" of compliance

The guideline presented is a step-by-step procedure for determining whether pedestrian-actuated signals should be installed. If intersection conditions exist that automatically determine signal feasibility, then the process is stopped or shortened.

Many combinations of major/minor street vehicle volumes, street configurations, and pedestrian volumes are presented in Tables 8.3 through 8.6. For similar combinations of these inputs that are not presented, the nearest Q1/S1, Q2/S2, and pedestrian volumes should be used. If vehicular flows are heavy, $Q1/S1 + Q2/S2 \geqq 0.90$ (or $Q1 + Q2 \geqq 1{,}440$ when $S = 1{,}600$); pedestrian crossing times are less than vehicular greens and do not affect optimized vehicular intervals. Under these conditions, the only cost of pedestrian signals is the amortized cost of installation and operation, which is \$0.32 per hour.

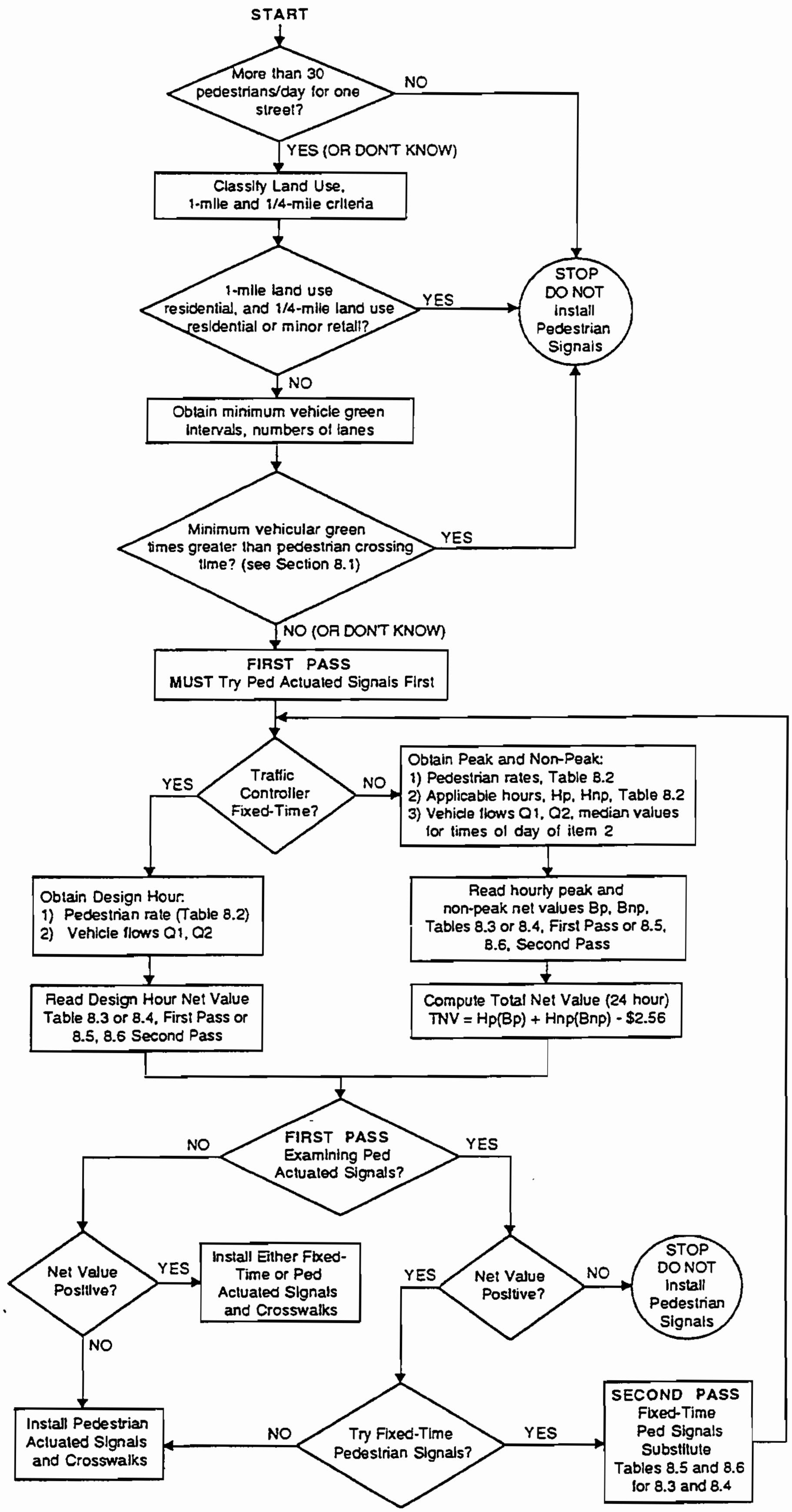


Figure 8.1 Pedestrian Signalization Guidelines Flow Sequence

TABLE 8.1 GUIDELINES TO ACTUATED PEDESTRIAN SIGNAL INSTALLATION

This procedure can be used to evaluate both pedestrian activated and fixed (no activation) pedestrian signals. Pedestrian actuated installation will always produce equal or less vehicular delay than fixed (no activation) signals with equivalent pedestrian delay savings and marginally increased initial installation and operating costs. Pedestrian activated signals are the "best case" economically. Therefore, the procedure should normally first check the viability of the pedestrian actuated case and, if the result is negative, the fixed time pedestrian signal case will only be more negative and installation is not justified. If pedestrian actuated produces a positive net value, a second pass through step 3 will determine the viability of a fixed time installation.

1. DETERMINE PEDESTRIAN GENERATION RATE

- **a.** Using the land use categories described in Chapter 7, classify the intersections according to the quarter mile and one mile criteria.

0.402 km (QUARTER MILE) ZONE	1.609 m (1 MILE) ZONE
Residential	Residential
Minor Retail	Commercial (& Recreational)
Recreational	Institutional
Major Retail	
Institutional	

- **b.** If the intersection's 1.609 km (1 mile) land use is residential <u>and</u> the 0.402 km (0.25 mile) land use is residential or minor retail, do not install pedestrian signals. STOP => Skip all other steps. Pedestrian generation rates are too small to justify installation.
- **c.** Otherwise, determine peak/non-peak pedestrian generation rates using Table 8.2.
- **d.** If there are no primary data describing pedestrian arrivals between 11 p.m. and 7 a.m., assume the "default" of essentially zero arrivals during this 8-hour period.

2. OBTAIN STREET AND VEHICULAR VOLUME DATA

- **a.** Obtain 24-hour vehicle volume counts for major and minor streets (Q1, Q2) (conventional road tube counts are excellent), saturation flow rates (S1, S2), and the number of approach lanes for each street (n1, n2).
- **b.** Check Figure 8.2 to determine whether or not **the shortest possible** vehicular green times exceed pedestrian green times. If so, do not install pedestrian signals. STOP => Skip all other steps. Adequate crossing times are provided by vehicular greens and pedestrian signals will have a negative economic value.
- **c.** Determine the median hourly vehicle volume for the major and minor streets in the peak and non-peak pedestrian periods. Times of day for peak and non-peak periods are given in Table 8.2. [**Note: Step 2.c and step 3 are applicable only to vehicular actuated signal controllers.** Net values of Tables 8.3 to 8.6 and incremental delays (vehicular and pedestrian) of Tables 5.3-5.8 assume the vehicle signal controller would provide approximately optimal cycle lengths without pedestrian signal intervention. Therefore, for pre-timed controllers, only design hours for which optimal timing can be provided should be analyzed. In the case of a simple single cycle pre-timed controller, this may be the design hour only.]

3. DETERMINE TOTAL NET VALUE

Net Value (24-hour) = H_p X (B_p) + H_{np} X (B_{np}) + H_0 X (B_0)
If the sum is greater than zero, install pedestrian-actuated signals
where

H_p	number of hours of peak pedestrian volumes (from Table 8.2)
H_{np}	number of hours of non-peak pedestrian volumes (from Table 8.2)
H_0	number of hours of zero pedestrian volumes (usually 8 hours)
B_p	net value during the peak pedestrian hour (from Tables 8.3-8.6, using pedestrian arrivals from Table 8.2)
B_{np}	net value during the non-peak pedestrian volume hour (from Table 8.3 or 8.6, using pedestrian arrivals from Table 8.2)
B_0	net value during the zero pedestrian volume hour (usually $-0.32)

- **a.** As noted in Step 1d, in the absence of night pedestrian counts, assume that net value between 11 pm and 7 am [H_0 X (B_0)] is $-2.56.
- **b.** For each peak and non-peak pedestrian period, use the median vehicle volume for both streets, pedestrian generation rate, and street configuration to determine from Tables 8.3-8.6 hourly net value estimates.

4. IF PEDESTRIAN SIGNALS ARE WARRANTED, ALSO INSTALL CROSSWALKS

Note: One mile = 1.609 km; quarter mile = 0.402 km

TABLE 8.2 PEAK/NON-PEAK HOUR PEDESTRIAN GENERATION RATES AND APPLICABILITY

LAND USE CATEGORY		PEAK PERIOD PEDESTRIAN GENERATION			NON-PEAK PERIOD PEDESTRIAN GENERATION		
One mile	Quarter-Mile	Ped/Min (Ped/Hr)	No. of Hours	Applicable Hours of Day	Ped/Min (Ped/Hr)	No. of Hours	Applicable Hours of Day
Residential	Residential	-	-	no peak hour	0.01 (0.60)	16	0700-2300
Residential	Minor Retail	-	-	no peak hour	0.01 (0.60)	16	0700-2300
Residential	Recreational	.181 (10.86)	1	1600-1700	.105 (6.30)	15	0700-1600, 1700-2300
Residential	Major Retail	.181 (10.86)	4	1200-1600	.105 (6.30)	12	0700-1200, 1600-2300
Residential	Institutional	.181 (10.86)	1	1600-1700	.105 (6.30)	15	0700-1600, 1700-2300
Com/Rec	Residential	.148 (8.88)	4	0800-1200	.105 (6.30)	12	0700-0800, 1200-2300
Com/Rec	Minor Retail	-	-	no peak hour	.105 (6.30)	16	0700-2300
Com/Rec	Recreational	.321 (19.26)	1	1600-1700	.105 (6.30)	15	0700-1600, 1700-2300
Com/Rec	Major Retail	.321 (19.26)	4	1200-1600	.105 (6.30)	12	0700-1200, 1600-2300
Com/Rec	Institutional	.321 (19.26)	1	1600-1700	.105 (6.30)	15	0700-1600, 1700-2300
Institutional	Residential	.345 (20.70)	4	0800-1200	.292 (17.52)	12	0700-0800, 1200-2300
Institutional	Minor Retail	-	-	no peak hour	.292 (17.52)	16	0700-2300
Institutional	Recreational	.518 (31.08)	1	1600-1700	.292 (17.52)	15	0700-1600, 1700-2300
Institutional	Major Retail	.518 (31.08)	4	1200-1600	.292 (17.52)	12	0700-1200, 1600-2300
Institutional	Institutional	.518 (31.08)	1	1600-1700	.292 (17.52)	15	0700-1600, 1700-2300

Com/Rec = One mile Commercial or Recreation Land Use

*Note: Install only if pedestrian green times exceed vehicular green times (See Figure 8.1).

Note: 1 mile = 1.609 km; 1/4 mile = 0.402 km

TABLE 8.3: PEDESTRIAN ACTUATED SIGNALS NET VALUE PER HOUR

Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.20	0.20	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.29	-0.22	-0.15	-0.04	0.03	0.10	0.20	0.37	0.55	0.72	0.90	1.08	1.43	2.32	3.21
2	2	-0.21	0.01	0.23	0.56	0.78	1.01	1.34	1.89	2.45	3.00	3.56	4.11	5.23	8.03	10.84
3	1	-0.29	-0.23	-0.18	-0.09	-0.03	0.02	0.11	0.26	0.41	0.56	0.71	0.86	1.16	1.95	2.75
3	2	-0.22	-0.02	0.18	0.48	0.68	0.88	1.18	1.69	2.20	2.71	3.22	3.73	4.76	7.35	9.97
3	3	-0.23	-0.06	0.12	0.38	0.56	0.74	1.00	1.45	1.89	2.34	2.80	3.25	4.16	6.47	8.80
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.35	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.27	-0.17	-0.08	0.07	0.17	0.27	0.41	0.66	0.90	1.15	1.39	1.64	2.13	3.35	4.58
2	1	-0.28	-0.20	-0.11	0.01	0.09	0.18	0.30	0.51	0.72	0.93	1.14	1.36	1.78	2.85	3.93
2	2	-0.28	-0.20	-0.13	-0.01	0.07	0.14	0.26	0.46	0.66	0.86	1.06	1.26	1.66	2.69	3.72
3	1	-0.29	-0.22	-0.14	-0.04	0.03	0.10	0.21	0.39	0.58	0.76	0.95	1.14	1.52	2.48	3.47
3	2	-0.29	-0.22	-0.15	-0.05	0.02	0.09	0.19	0.37	0.55	0.73	0.91	1.09	1.47	2.43	3.42
3	3	-0.20	0.03	0.27	0.62	0.86	1.10	1.46	2.06	2.66	3.27	3.88	4.49	5.72	8.82	11.95
0.35	0.25															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.27	-0.17	-0.07	0.08	0.18	0.28	0.43	0.68	0.93	1.17	1.42	1.67	2.17	3.42	4.67
2	2	-0.27	-0.18	-0.09	0.05	0.14	0.24	0.38	0.61	0.84	1.08	1.31	1.55	2.02	3.19	4.38
3	1	-0.28	-0.19	-0.10	0.03	0.11	0.20	0.33	0.55	0.77	0.99	1.21	1.43	1.88	3.01	4.15
3	2	-0.28	-0.20	-0.12	0.01	0.09	0.17	0.30	0.51	0.72	0.93	1.14	1.36	1.79	2.89	4.00
3	3	-0.18	0.10	0.38	0.80	1.09	1.37	1.79	2.50	3.21	3.92	4.64	5.35	6.79	10.39	14.02
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.50	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.26	-0.14	-0.03	0.15	0.27	0.39	0.57	0.86	1.16	1.46	1.76	2.06	2.65	4.16	5.66
2	2	-0.27	-0.16	-0.05	0.12	0.23	0.34	0.50	0.78	1.05	1.33	1.61	1.89	2.45	3.86	5.28
3	1	-0.27	-0.17	-0.06	0.09	0.19	0.30	0.45	0.72	0.98	1.24	1.51	1.78	2.32	3.69	5.07
3	2	-0.27	-0.18	-0.08	0.07	0.16	0.26	0.41	0.66	0.91	1.16	1.42	1.67	2.19	3.51	4.86
3	3	-0.27	-0.18	-0.09	0.05	0.15	0.25	0.39	0.63	0.88	1.13	1.38	1.64	2.15	3.47	4.81
0.50	0.25															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.25	-0.10	0.04	0.26	0.40	0.54	0.76	1.12	1.48	1.84	2.20	2.57	3.29	5.10	6.92
3	2	-0.25	-0.12	0.02	0.23	0.36	0.50	0.70	1.05	1.39	1.73	2.08	2.42	3.11	4.84	6.58
3	3	-0.25	-0.12	0.01	0.21	0.34	0.47	0.67	1.00	1.33	1.66	2.00	2.33	3.00	4.68	6.38
0.50	0.35															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	3	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.65	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.22	-0.01	0.20	0.52	0.73	0.94	1.25	1.77	2.30	2.82	3.35	3.87	4.92	7.54	10.16
2	2	-0.22	-0.03	0.17	0.46	0.65	0.85	1.14	1.63	2.11	2.60	3.09	3.58	4.55	6.99	9.43
3	1	-0.23	-0.04	0.15	0.43	0.62	0.81	1.09	1.56	2.04	2.52	2.99	3.47	4.43	6.83	9.25
3	2	-0.23	-0.06	0.12	0.39	0.56	0.74	1.01	1.46	1.90	2.35	2.81	3.26	4.17	6.46	8.76
3	3	-0.24	-0.07	0.10	0.35	0.52	0.69	0.95	1.38	1.81	2.24	2.68	3.12	3.99	6.20	8.43
0.70	0.15															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.19	0.06	0.32	0.70	0.96	1.22	1.60	2.24	2.88	3.53	4.17	4.82	6.10	9.33	12.56
3	2	-0.20	0.04	0.28	0.65	0.89	1.13	1.49	2.10	2.71	3.32	3.93	4.54	5.76	8.83	11.90
3	3	-0.20	0.03	0.26	0.60	0.84	1.07	1.42	2.00	2.58	3.17	3.75	4.34	5.51	8.46	11.42

N1 & N2 = Number of lanes on major and minor approaches.

Q1 & Q2 = flows on major and minor approaches.

S1 & S2 = saturation flow rates on major and minor approaches.

NET $ = Net Value, 1993 Dollars

TABLE 8.4: PEDESTRIAN ACTUATED SIGNALS NET VALUE PER HOUR
SATURATION FLOW 1600 VPH

Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
320	320	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.29	-0.22	-0.15	-0.04	0.03	0.10	0.20	0.37	0.55	0.72	0.90	1.08	1.43	2.32	3.21
2	2	-0.21	0.01	0.23	0.56	0.78	1.01	1.34	1.89	2.45	3.00	3.56	4.11	5.23	8.03	10.84
3	1	-0.29	-0.23	-0.18	-0.09	-0.03	0.02	0.11	0.26	0.41	0.56	0.71	0.86	1.16	1.95	2.75
3	2	-0.22	-0.02	0.18	0.48	0.68	0.88	1.18	1.69	2.20	2.71	3.22	3.73	4.76	7.35	9.97
3	3	-0.23	-0.06	0.12	0.38	0.56	0.74	1.00	1.45	1.89	2.34	2.80	3.25	4.16	6.47	8.80
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
560	240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.27	-0.17	-0.08	0.07	0.17	0.27	0.41	0.66	0.90	1.15	1.39	1.64	2.13	3.35	4.58
2	1	-0.28	-0.20	-0.11	0.01	0.09	0.18	0.30	0.51	0.72	0.93	1.14	1.36	1.78	2.85	3.93
2	2	-0.28	-0.20	-0.13	-0.01	0.07	0.14	0.26	0.46	0.66	0.86	1.06	1.26	1.66	2.69	3.72
3	1	-0.29	-0.22	-0.14	-0.04	0.03	0.10	0.21	0.39	0.58	0.76	0.95	1.14	1.52	2.48	3.47
3	2	-0.29	-0.22	-0.15	-0.05	0.02	0.09	0.19	0.37	0.55	0.73	0.91	1.09	1.47	2.43	3.42
3	3	-0.20	0.03	0.27	0.62	0.86	1.10	1.46	2.06	2.66	3.27	3.88	4.49	5.72	8.82	11.95
560	400															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.27	-0.17	-0.07	0.08	0.18	0.28	0.43	0.68	0.93	1.17	1.42	1.67	2.17	3.42	4.67
2	2	-0.27	-0.18	-0.09	0.05	0.14	0.24	0.38	0.61	0.84	1.08	1.31	1.55	2.02	3.19	4.38
3	1	-0.28	-0.19	-0.10	0.03	0.11	0.20	0.33	0.55	0.77	0.99	1.21	1.43	1.88	3.01	4.15
3	2	-0.28	-0.20	-0.12	0.01	0.09	0.17	0.30	0.51	0.72	0.93	1.14	1.36	1.79	2.89	4.00
3	3	-0.18	0.10	0.38	0.80	1.09	1.37	1.79	2.50	3.21	3.92	4.64	5.35	6.79	10.39	14.02
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
800	240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.26	-0.14	-0.03	0.15	0.27	0.39	0.57	0.86	1.16	1.46	1.76	2.06	2.65	4.16	5.66
2	2	-0.27	-0.16	-0.05	0.12	0.23	0.34	0.50	0.78	1.05	1.33	1.61	1.89	2.45	3.86	5.28
3	1	-0.27	-0.17	-0.06	0.09	0.19	0.30	0.45	0.72	0.98	1.24	1.51	1.78	2.32	3.69	5.07
3	2	-0.27	-0.18	-0.08	0.07	0.16	0.26	0.41	0.66	0.91	1.16	1.42	1.67	2.19	3.51	4.86
3	3	-0.27	-0.18	-0.09	0.05	0.15	0.25	0.39	0.63	0.88	1.13	1.38	1.64	2.15	3.47	4.81
800	400															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.25	-0.10	0.04	0.26	0.40	0.54	0.76	1.12	1.48	1.84	2.20	2.57	3.29	5.10	6.92
3	2	-0.25	-0.12	0.02	0.23	0.36	0.50	0.70	1.05	1.39	1.73	2.08	2.42	3.11	4.84	6.58
3	3	-0.25	-0.12	0.01	0.21	0.34	0.47	0.67	1.00	1.33	1.66	2.00	2.33	3.00	4.68	6.38
800	560															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	3	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
1040	240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.22	-0.01	0.20	0.52	0.73	0.94	1.25	1.77	2.30	2.82	3.35	3.87	4.92	7.54	10.16
2	2	-0.22	-0.03	0.17	0.46	0.65	0.85	1.14	1.63	2.11	2.60	3.09	3.58	4.55	6.99	9.43
3	1	-0.23	-0.04	0.15	0.43	0.62	0.81	1.09	1.56	2.04	2.52	2.99	3.47	4.43	6.83	9.25
3	2	-0.23	-0.06	0.12	0.39	0.56	0.74	1.01	1.46	1.90	2.35	2.81	3.26	4.17	6.46	8.76
3	3	-0.24	-0.07	0.10	0.35	0.52	0.69	0.95	1.38	1.81	2.24	2.68	3.12	3.99	6.20	8.43
1120	240															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.19	0.06	0.32	0.70	0.96	1.22	1.60	2.24	2.88	3.53	4.17	4.82	6.10	9.33	12.56
3	2	-0.20	0.04	0.28	0.65	0.89	1.13	1.49	2.10	2.71	3.32	3.93	4.54	5.76	8.83	11.90
3	3	-0.20	0.03	0.26	0.60	0.84	1.07	1.42	2.00	2.58	3.17	3.75	4.34	5.51	8.46	11.42

N1 & N2 = Number of lanes on major and minor approaches.

Q1 & Q2 = flows on major and minor approaches.

S1 & S2 = 1600 vehicle/hour

TABLE 8.5: PEDESTRIAN FIXED-TIME SIGNALS NET VALUE PER HOUR

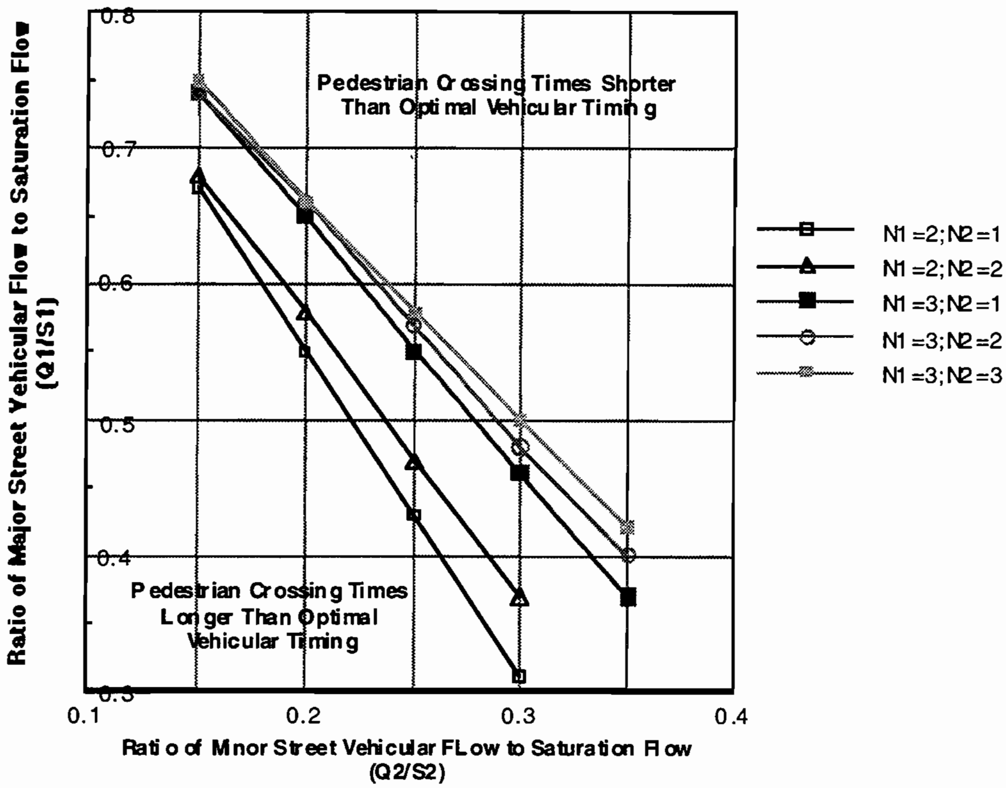
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.20	0.20	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.56	-0.49	-0.41	-0.30	-0.23	-0.15	-0.04	0.14	0.33	0.51	0.70	0.88	1.25	2.18	3.10
2	2	-0.65	-0.42	-0.19	0.15	0.38	0.61	0.95	1.52	2.09	2.67	3.24	3.81	4.95	7.80	10.66
3	1	-0.77	-0.71	-0.64	-0.54	-0.47	-0.40	-0.30	-0.13	0.04	0.21	0.38	0.55	0.90	1.75	2.60
3	2	-0.87	-0.65	-0.44	-0.11	0.10	0.32	0.64	1.18	1.71	2.25	2.79	3.32	4.40	7.09	9.77
3	3	-1.00	-0.80	-0.61	-0.32	-0.13	0.07	0.36	0.84	1.32	1.81	2.29	2.77	3.74	6.15	8.57
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.35	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.29	-0.19	-0.09	0.06	0.16	0.25	0.40	0.65	0.89	1.14	1.38	1.63	2.12	3.34	4.57
2	1	-0.52	-0.43	-0.34	-0.21	-0.12	-0.03	0.10	0.32	0.54	0.76	0.98	1.21	1.65	2.75	3.86
2	2	-0.68	-0.59	-0.51	-0.38	-0.29	-0.20	-0.07	0.14	0.36	0.58	0.79	1.01	1.44	2.52	3.61
3	1	-0.66	-0.58	-0.50	-0.37	-0.29	-0.21	-0.09	0.12	0.32	0.53	0.73	0.94	1.34	2.37	3.39
3	2	-0.81	-0.73	-0.64	-0.52	-0.44	-0.35	-0.23	-0.02	0.19	0.40	0.61	0.81	1.23	2.27	3.31
3	3	-0.85	-0.60	-0.34	0.04	0.30	0.56	0.94	1.58	2.22	2.86	3.50	4.14	5.42	8.62	11.82
0.35	0.25															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.33	-0.23	-0.13	0.03	0.13	0.23	0.38	0.63	0.88	1.13	1.38	1.64	2.14	3.40	4.65
2	2	-0.44	-0.34	-0.25	-0.10	-0.01	0.09	0.23	0.47	0.71	0.95	1.19	1.43	1.91	3.11	4.31
3	1	-0.56	-0.47	-0.38	-0.24	-0.14	-0.05	0.09	0.33	0.56	0.79	1.03	1.26	1.73	2.90	4.07
3	2	-0.71	-0.62	-0.53	-0.39	-0.29	-0.20	-0.06	0.17	0.40	0.63	0.87	1.10	1.56	2.72	3.88
3	3	-0.73	-0.44	-0.14	0.30	0.60	0.89	1.33	2.07	2.81	3.55	4.28	5.02	6.50	10.18	13.87
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.50	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.40	-0.28	-0.16	0.03	0.15	0.27	0.45	0.76	1.06	1.37	1.67	1.98	2.59	4.11	5.63
2	2	-0.51	-0.39	-0.28	-0.10	0.01	0.13	0.30	0.59	0.88	1.17	1.46	1.75	2.33	3.77	5.22
3	1	-0.56	-0.44	-0.33	-0.16	-0.05	0.06	0.23	0.51	0.80	1.08	1.36	1.64	2.20	3.61	5.02
3	2	-0.67	-0.56	-0.45	-0.28	-0.17	-0.06	0.10	0.38	0.65	0.93	1.21	1.48	2.03	3.41	4.79
3	3	-0.77	-0.66	-0.55	-0.38	-0.27	-0.16	0.01	0.28	0.56	0.84	1.12	1.40	1.95	3.34	4.73
0.50	0.25															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.31	-0.17	-0.02	0.20	0.34	0.49	0.71	1.07	1.44	1.80	2.17	2.53	3.26	5.08	6.90
3	2	-0.39	-0.25	-0.11	0.10	0.24	0.38	0.59	0.94	1.29	1.64	1.99	2.35	3.05	4.80	6.55
3	3	-0.46	-0.33	-0.19	0.02	0.15	0.29	0.50	0.84	1.18	1.53	1.87	2.21	2.90	4.61	6.33
0.50	0.35															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	3	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
Q1/S1	Q2/S2	Pedestrian Arrival Rate (Pedestrians/Hour)														
0.65	0.15	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.22	-0.01	0.20	0.51	0.72	0.93	1.24	1.77	2.29	2.82	3.34	3.87	4.91	7.54	10.16
2	2	-0.26	-0.06	0.13	0.43	0.62	0.82	1.11	1.60	2.09	2.58	3.07	3.56	4.54	6.98	9.43
3	1	-0.38	-0.19	0.01	0.30	0.49	0.68	0.98	1.46	1.95	2.43	2.92	3.40	4.38	6.80	9.23
3	2	-0.45	-0.26	-0.08	0.20	0.39	0.57	0.85	1.31	1.78	2.24	2.70	3.17	4.10	6.41	8.73
3	3	-0.51	-0.33	-0.15	0.12	0.30	0.48	0.75	1.20	1.65	2.10	2.55	3.00	3.90	6.15	8.40
0.70	0.15															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.26	0.00	0.26	0.64	0.90	1.16	1.55	2.20	2.85	3.49	4.14	4.79	6.08	9.32	12.56
3	2	-0.31	-0.06	0.18	0.55	0.80	1.05	1.42	2.03	2.65	3.26	3.88	4.50	5.73	8.81	11.89
3	3	-0.35	-0.11	0.12	0.48	0.72	0.95	1.31	1.90	2.50	3.09	3.69	4.28	5.47	8.44	11.41

N1 & N2 = Number of lanes on major and minor approaches.
Q1 & Q2 = flows on major and minor approaches.
S1 & S2 = saturation flow rates on major and minor approaches.
NET $ = Net Value, 1993 Dollars

TABLE 8.6: PEDESTRIAN FIXED-TIME SIGNALS NET VALUE PER HOUR,
SATURATION FLOW 1600 VPH

Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
320	320	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.56	-0.49	-0.41	-0.30	-0.23	-0.15	-0.04	0.14	0.33	0.51	0.70	0.88	1.25	2.18	3.10
2	2	-0.65	-0.42	-0.19	0.15	0.38	0.61	0.95	1.52	2.09	2.67	3.24	3.81	4.95	7.80	10.66
3	1	-0.77	-0.71	-0.64	-0.54	-0.47	-0.40	-0.30	-0.13	0.04	0.21	0.38	0.55	0.90	1.75	2.60
3	2	-0.87	-0.65	-0.44	-0.11	0.10	0.32	0.64	1.18	1.71	2.25	2.79	3.32	4.40	7.09	9.77
3	3	-1.00	-0.80	-0.61	-0.32	-0.13	0.07	0.36	0.84	1.32	1.81	2.29	2.77	3.74	6.15	8.57
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
560	240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.29	-0.19	-0.09	0.06	0.16	0.25	0.40	0.65	0.89	1.14	1.38	1.63	2.12	3.34	4.57
2	1	-0.52	-0.43	-0.34	-0.21	-0.12	-0.03	0.10	0.32	0.54	0.76	0.98	1.21	1.65	2.75	3.86
2	2	-0.68	-0.59	-0.51	-0.38	-0.29	-0.20	-0.07	0.14	0.36	0.58	0.79	1.01	1.44	2.52	3.61
3	1	-0.66	-0.58	-0.50	-0.37	-0.29	-0.21	-0.09	0.12	0.32	0.53	0.73	0.94	1.34	2.37	3.39
3	2	-0.81	-0.73	-0.64	-0.52	-0.44	-0.35	-0.23	-0.02	0.19	0.40	0.61	0.81	1.23	2.27	3.31
3	3	-0.85	-0.60	-0.34	0.04	0.30	0.56	0.94	1.58	2.22	2.86	3.50	4.14	5.42	8.62	11.82
560	400															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.33	-0.23	-0.13	0.03	0.13	0.23	0.38	0.63	0.88	1.13	1.38	1.64	2.14	3.40	4.65
2	2	-0.44	-0.34	-0.25	-0.10	-0.01	0.09	0.23	0.47	0.71	0.95	1.19	1.43	1.91	3.11	4.31
3	1	-0.56	-0.47	-0.38	-0.24	-0.14	-0.05	0.09	0.33	0.56	0.79	1.03	1.26	1.73	2.90	4.07
3	2	-0.71	-0.62	-0.53	-0.39	-0.29	-0.20	-0.06	0.17	0.40	0.63	0.87	1.10	1.56	2.72	3.88
3	3	-0.73	-0.44	-0.14	0.30	0.60	0.89	1.33	2.07	2.81	3.55	4.28	5.02	6.50	10.18	13.87
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
800	240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.40	-0.28	-0.16	0.03	0.15	0.27	0.45	0.76	1.06	1.37	1.67	1.98	2.59	4.11	5.63
2	2	-0.51	-0.39	-0.28	-0.10	0.01	0.13	0.30	0.59	0.88	1.17	1.46	1.75	2.33	3.77	5.22
3	1	-0.56	-0.44	-0.33	-0.16	-0.05	0.06	0.23	0.51	0.80	1.08	1.36	1.64	2.20	3.61	5.02
3	2	-0.67	-0.56	-0.45	-0.28	-0.17	-0.06	0.10	0.38	0.65	0.93	1.21	1.48	2.03	3.41	4.79
3	3	-0.77	-0.66	-0.55	-0.38	-0.27	-0.16	0.01	0.28	0.56	0.84	1.12	1.40	1.95	3.34	4.73
800	400															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.31	-0.17	-0.02	0.20	0.34	0.49	0.71	1.07	1.44	1.80	2.17	2.53	3.26	5.08	6.90
3	2	-0.39	-0.25	-0.11	0.10	0.24	0.38	0.59	0.94	1.29	1.64	1.99	2.35	3.05	4.80	6.55
3	3	-0.46	-0.33	-0.19	0.02	0.15	0.29	0.50	0.84	1.18	1.53	1.87	2.21	2.90	4.61	6.33
800	560															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	3	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
Q1	Q2	Pedestrian Arrival Rate (Pedestrians/Hour)														
1040	240	0.60	1.80	3.00	4.80	6.00	7.20	9.00	12.00	15.00	18.00	21.00	24.00	30.00	45.00	60.00
N1	N2	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $	NET $
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.22	-0.01	0.20	0.51	0.72	0.93	1.24	1.77	2.29	2.82	3.34	3.87	4.91	7.54	10.16
2	2	-0.26	-0.06	0.13	0.43	0.62	0.82	1.11	1.60	2.09	2.58	3.07	3.56	4.54	6.98	9.43
3	1	-0.38	-0.19	0.01	0.30	0.49	0.68	0.98	1.46	1.95	2.43	2.92	3.40	4.38	6.80	9.23
3	2	-0.45	-0.26	-0.08	0.20	0.39	0.57	0.85	1.31	1.78	2.24	2.70	3.17	4.10	6.41	8.73
3	3	-0.51	-0.33	-0.15	0.12	0.30	0.48	0.75	1.20	1.65	2.10	2.55	3.00	3.90	6.15	8.40
1120	240															
1	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	1	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
2	2	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32	-0.32
3	1	-0.26	0.00	0.26	0.64	0.90	1.16	1.55	2.20	2.85	3.49	4.14	4.79	6.08	9.32	12.56
3	2	-0.31	-0.06	0.18	0.55	0.80	1.05	1.42	2.03	2.65	3.26	3.88	4.50	5.73	8.81	11.89
3	3	-0.35	-0.11	0.12	0.48	0.72	0.95	1.31	1.90	2.50	3.09	3.69	4.28	5.47	8.44	11.41

N1 & N2 = Number of lanes on major and minor approaches.
Q1 & Q2 = flows on major and minor approaches.
S1 & S2 = 1600 vehicles/hour
NET $ = Net Value, 1993 Dollars



For S = 1600

Q/S	Q(vphpl)
0.20	320
0.35	560
0.45	720
0.55	880
0.65	1,040
0.70	1,120

N1 & N2 = Number of lanes on major and minor approaches.

Q1 & Q2 = flows on major and minor approaches.

S1 & S2 = saturation flow rates on major and minor approaches.

Usage Note: Locate vertical and horizontal lines representing the minor and major street ratios of flow to saturation flow (Q1/S1 and Q2/S2). If their lines intersect below the line representing numbers of traffic lanes on the two streets, then pedestrian minimum greens force longer than optimal vehicular traffic green intervals.

Figure 8.2 Minimum Vehicular Flows Over Which Pedestrian Green Times Do Not Govern

NOTES

Chapter 2

1 This crossing rate 6.7 sec divided by the number of pedestrians and by the widths of pedestrian groups.

Chapter 3

1 "Normal" is meant to imply every day traffic conditions without the concerns of accidents, special population groups, etc.

Chapter 5

1 This conversion factor also uses a discount rate of 8%. although current inflation and interest rates are below 8% at this time, they may increase substantially again in the future.

2 Since the pedestrian delay analysis and arrival rate study was done with "number of pedestrian group per minute" as the true measure, a factor of 1.25 was used to indicate the true number of pedestrians per minute.

Chapter 7

1 or if the one mile land use is commercial/recreational and the quarter mile land use is major retail.

Chapter 8

1 Since compliance is difficult to compare with the other variables directly, it is used to identify certain situations instead.

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APPENDIX A:

VARIABLES COLLECTED ON-SITE AND BY VIDEO

The data collection effort included two methods: on-site and video. The main purpose of the on-site data effort is to include every pedestrian crossing whereas for the video data effort, timing and viewing is repeated to ensure accuracy. The following is a list of variables that were used in the analyses.

I) Attributes of the Arrival Process

a) Arrival Time: The time that pedestrian arrives to cross street; i.e., when a pedestrian stops on sidewalk/street while waiting to cross or when a non-stopping pedestrian steps off curb (or starts walking from an "on-street" location).

b) Group Arrival size: It is the number of pedestrians arriving in the same group.

c) Platoon Departure size: It is the number of pedestrians crossing together as an entity. The arrivals within the platoon could be either independent or in groups.

II) Pedestrian Attributes

c) Gender of the pedestrian.

d) Age of the pedestrian estimated on-site.

e) Race of the pedestrian.

III) Signal Indications (of pedestrian's arrival & departure) and Push Buttons

f) Traffic signal indication noted as either green or red.

g) Pedestrian signal indication, if present, noted as WALK, flashing DON'T WALK or a steady DON'T WALK.

h) Push button usage, if present.

IV) Intersection Characteristics

i) Number of lanes in the crossing direction.

j) Median usage, if present.

V) Other Crossing Information

k) Total wait time until crossing. If the pedestrian crossed on DON'T WALK, it is defined as the time when the pedestrian comes to a momentary stop to the instant when the pedestrian steps off the curb and begins to cross. Otherwise, it is defined as the time when the pedestrian comes to a momentary stop to the instant when the signal changes from DON'T WALK to WALK. The remaining time is recorded as the reaction time to WALK.

l) Lane-by-lane gap information from the instant of arrival. A gap is defined as the time interval between successive vehicles. The first gap, i.e. a lag, however, is measured as the time between the pedestrian and the first vehicular arrival. Once, gaps for each individual lane are available, it is easy to manipulate and obtain gaps for the near and far streams separately, or for the approach as a whole.

m) The wait time at the beginning of each gap. It is obtained by adding all the previous gaps for that lane.

n) Start-up time: The elapsed time when the pedestrian reacts to the walk signal and then, enters the crosswalk is recorded as start-up time.

o) Mode of crossing, i.e. walk, run, skate, etc.

p) Method of crossing, i.e. one stage, two stage or lane-by-lane crossing.

q) Crossing time: The crossing time for the pedestrian to clear the crosswalk includes stoppages. The start of the crossing time begins when the pedestrian steps off the curb and ends when the pedestrian steps on the curb on the other side of the street. If the pedestrian waits on the street immediately before starting to walk, the first step that he/she takes is the beginning of the crossing time.

APPENDIX B:

DEFINITIONS OF VARIABLES IN THE UTILITY SPECIFICATION

For the behavioral analyses, additional variables were created from the data set.

IST Intersection Status, an indicator, intended to reflect the activity level at the intersection. Not applicable at odd hours when the traffic volume is low.

= 1, for intersections with at least a major retail land use

= 0, otherwise

AGSX Interaction term between Gender and Age

= 1, if $19 \leq$ age ≤ 55 and gender = MALE

= 0, otherwise

RACE

= 1, if non-white

= 0, otherwise

HDS Hands, an attribute of non-compliance behavior with push button

= 0, if the pedestrian is empty handed or carrying small items

= 1, otherwise

NOLNS Number of lanes in the cross-walk

= 1, if no. of lanes ≥ 5

= 0, otherwise

WAIT Elapsed time at the beginning of each gap
I Indicator variable to identify a lag

= 1, if wait time > 0

= 0, otherwise

GAP Gap size in sec

LNPST Lane position of the vehicle. Lanes are numbered moving away from the pedestrian. For mode (b), lanes are numbered separately for the near and far streams.

TURN Vehicle type

= 1, if it is a turning vehicle

= 0, otherwise

DIRXN Direction of traffic.

= 1, if vehicle is in the far stream.

= 0, if it is in the near stream

GPB Group's push button response

= 1, if the pedestrian ignores the button, but not the group

= 0, if the group ignores the push button, or if the pedestrian uses it

APPENDIX C:

VARIABLES USED IN PEDESTRIAN GENERATION RATE ANALYSIS

The land use, traffic, transit and socioeconomic variables for the pedestrian generation rate analysis are presented:

Land Use Variables from the On-Site Data:

1) Distance from Downtown - This measure (in miles) provides a level of population intensity
2) 0.402 km (1/4-Mile) Land-Use:
    1 - Residential
    2 - Minor Retail
    3 - Major Retail
    4 - Institutional
    5 - Recreational
3) 1.61 km (1-Mile) Land-Use:
    1 - Residential
    2 - Commercial
    3 - Institutional
    4 - Recreational
4) 0.805 km (1/2-Mile) Land-Use - Similar to the 1.61 km (1-Mile) Land-use purpose, this variable was created to compare with the 1-Mile Land-use.
5) Parking Lot Presence - When a major parking lot is directly across the street from the land-use for which it is suited for, then an abnormally high number of crossings/midblock crossings may occur.
6) Number of Legs present at Intersection

Transit Availability Variables from Capital Metro Data:

1) Presence of Bus Service - Bus is available when a site is within 1/4 mile to bus service
2) Number of Bus Stops
3) Total Bus Frequency / Hour
4) Number of Bus Passengers

Socioeconomic Variables from the 1990 Census Tract Data:

The census statistics were calculated using weights (such as population, area, # of specified housing units, etc.). Most intermediate steps are shown in this document:

1) Population Density - The total population divided by the total area
2) Median Age
3) Percent under 18
4) Percent over 65

5) Percent 18-24

6) Percent Group Quarters - The percentage of the population living in a closed housing unit.

7) Percent Black

8) Percent Asian

9) Percent Hispanic

10) Percent Owner Occupied

11) Median Housing Value

12) Median Rent Level