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16. Abstract

Previous pedestrian signalization research indicated that pedestrian signals provide limited benefits to either pedestrians or vehicles. Furthermore, most pedestrian research is concentrated on downtown or high density areas, thus neglecting suburban environments. Many of these studies have used a very focused approach limiting the scope to one criterion. Without considering the full range of implications of the complex pedestrianism phenomena around signalized intersections, it is difficult to examine the delay and safety differences between pedestrians and vehicles.

This research proposes an integrated model using a mathematical/statistical approach. Since delay, safety, and behavior concepts have different units, they cannot be directly compared; hence, they are assessed using a cost/benefit approach. Outputs from the models produced an overall answer on pedestrian signalization benefits. Inputs were based on non-complex, readily available, and useful variables such as traffic, geometric, and land use characteristics surrounding signalized intersections. From this formulation, the question of delay and safety differences and sensitivities is addressed.

This solution approach consists of four components. A delay procedure formulates fixed and actuated delay for pedestrian and vehicular traffic. A behavior procedure determines pedestrian compliance and other measures responsive to pedestrian and vehicular traffic and signals. A safety procedure assesses pedestrian interactions with vehicular traffic. A pedestrian generation rate procedure determines the number of pedestrians crossing at a signalized intersection based on land use categorizations. The solution is tested with sample suburban scenarios and with data generated from the traffic system in Austin, Texas.

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AN ANALYSIS OF PEDESTRIAN SIGNALIZATION IN SUBURBAN AREAS

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ABSTRACT

Previous pedestrian signalization research indicated that pedestrian signals provide limited benefits to either pedestrians or vehicles. Furthermore, most pedestrian research is concentrated on downtown or high density areas, thus neglecting suburban environments. Many of these studies have used a very focused approach limiting the scope to one criterion. Without considering the full range of implications of the complex pedestrianism phenomena around signalized intersections, it is difficult to examine the delay and safety differences between pedestrians and vehicles.

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EXECUTIVE SUMMARY

Previous pedestrian signalization research indicated that pedestrian signals provide limited benefits to either pedestrians or high-density areas, thus neglecting suburban environments. Many of these studies used a very focused approach limiting the scope to one criterion. Without considering the full range of implications of the complex pedestrianism phenomena around signalized intersections, it is difficult to examine the delay and safety differences between pedestrians and vehicles.

This research proposes an integrated model using a mathematical/statistical approach. Since delay, safety, and behavior concepts have different units, they cannot be directly compared; hence, they are assessed using a cost/benefit approach. Outputs from the models produced an overall answer on pedestrian signalization benefits. Inputs were based on non-complex, readily available, and useful variables such as traffic, geometric, and land use characteristics surrounding signalized intersections. From this formulation, the question of delay and safety differences and sensitivities is addressed.

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The integrated model's general results showed that vehicular delay predominated even when pedestrian safety & delay, and equipment costs were significant. This effect caused fixed timing schemes to be costly when pedestrian timing requirements were greater than optimal vehicular signal cycle timings. When vehicular delay was unaffected, pedestrian signalization showed some promise in increasing compliance on wider streets and with higher volumes on adjoining streets. Thus, outcomes showed that pedestrian signals are most likely to be beneficial when the peak and non-peak volume patterns are similar (e.g. pedestrian and vehicular peak hours occur simultaneously). By using the convenient method of land use categorization to predict pedestrian volume at signalized intersections, these patterns can be found and the benefits of pedestrian signalization can be realized.

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CHAPTER 1. INTRODUCTION

PROBLEM STATEMENT

Pedestrianism is becoming more popular due to growing concerns for energy efficient transportation, time-space mobility constraints and environmental pollution. In the past 50 years, cities have become more suburban, with sprawling land-use and the increasing need for automobiles. In addition, with increased vehicle-miles traveled per trip and congestion, drivers are more prone to stress on the roadway and are increasingly tending to behave irresponsibly and aggressively, otherwise known as "road rage." Combined with pedestrianism, the consequences can be fatal. This mixture is ever so more present at signalized intersections where pedestrians and vehicles often have conflicting movements and needs.

A traffic control strategy that deals with this problem is pedestrian signalization. However, most research in dealing with traffic control system design is based upon significant vehicular and pedestrian traffic as found in central business districts (CBD). Research of pedestrian signalization in suburban environments is essentially neglected.

Past studies noted that pedestrian signals have inherent problems as pedestrians do not completely comply with them. Even though demand-responsive systems such as push-buttons are provided, it appears they are not completely trusted. Zegeer et al. (1982) found that installation of pedestrian signals and crosswalk markings may create a false sense of safety. Most pedestrian studies have focused on CBD intersections, where compliance characteristics may differ from those in suburban environments.

Another concern is the question of the operation of pedestrian and vehicular signals which affect delays, safety factors and other costs between pedestrian and vehicular traffic. Currently, the operation of pedestrian signals, especially the timing issue, is governed primarily by vehicular traffic. Compliance with signals is, however, dependent on these factors, all of which affect pedestrian safety.

Although pedestrian accidents are a rare occurrence relative to vehicular accidents (IIHS, 1991), the severe loss inflicted by these accidents is the compelling reason to study the phenomena and develop solution techniques. Characterization and understanding of pedestrian safety with respect to behavior at intersections, signalized and unsignalized, can enable more effective signal operation and allow further development and evaluation of pedestrian and vehicular control strategies. Therefore, there is a need to improve the underlying characteristics of the interaction between pedestrian behavior and the traffic control system.

MOTIVATION

Traffic control systems provide a variety of capabilities for improving travel quality; however, only limited evaluations of tradeoffs among different transportation modes have been performed. One of the major reasons is that the variety of transportation modes prevent thorough tradeoff investigations.

Across the nation, researchers are developing new traffic control technologies for improving commuter travel quality. A primary concern is the minimization of unnecessary delay through information dispersion and other related techniques. At present, many researchers are studying the allocation of delay among vehicular traffic streams or paths. Researchers have recognized, however, that it is not "vehicular delay" that must be reduced, but rather, it is "person delay." In that sense, the process must include pedestrians.

A particular issue that has not been examined is delay, safety, and cost allocation between vehicle users and pedestrians. There are two questions that must be addressed: (1) What are the differences between these two user classes? and (2) What is the sensitivity of delay and safety to different traffic and geometric conditions? A framework which allows this examination must be developed. These issues are the primary motivation for this proposed research and understanding them will allow inclusion of pedestrian as well as vehicular delay in traffic control strategy design.

SCOPE AND OBJECTIVES OF THE STUDY

The goal of the proposed work is to develop an integrated model to assess delay, safety, and behavior (i.e. compliance) in a single framework for a suburban setting. Reaching this goal entails fulfilling the following objectives:

1) Develop a delay model for assessing pedestrian and vehicular delay to include compliance/safety information.
2) Characterize mathematical functions for pedestrian compliance/ safety based upon typical suburban traffic patterns.
3) Test different traffic control strategies using alternative scenarios.
4) Determine the impact suburban environment has on pedestrian/ vehicular system.

The integrated and combinatorial nature of the signalized intersection problem precludes solutions by exact optimization models. Newell (1989) developed a vehicular delay approach that included the following two features: 1) development of vehicular delay expressions, and 2) examination of these expressions under different vehicular traffic conditions. In addition, expressions developed by Webster offers practical equations for usage. These models are applicable to many different traffic control strategies.

In this study, the above heuristic approach is extended and further developed to include pedestrian delay and safety concepts oriented toward the kind of land use and traffic patterns found at traffic signalized intersections in most suburban U.S. cities. These concepts are tested under several different control strategies, namely fixed or actuated vehicular signals with no, fixed, or actuated pedestrian signals. With such an integrated framework, future pedestrian/vehicular traffic control concepts can be tested with minor computational changes and data requirements.

This framework differs from existing approaches in the following aspects:

1. Ability to assess differences between pedestrian and vehicular traffic incorporating pedestrian compliance, delay and safety and vehicular delay. This framework also identifies optimal control strategies for different traffic conditions.
2. Inclusion of a methodology for assessing pedestrian-induced vehicular delay for traffic signalization under different pedestrian signalization schemes.
3. Characterization of pedestrian safety/compliance functions which are integrated into the pedestrian and vehicular delay model and interpreted as functions of traffic conditions.
4. Development of a methodology for data collection enabling examination of both pedestrian generation rate of a suburban environment and compliance using video, on-site and geographic information.
5. Examination of pedestrian generation rates based upon suburban land use to provide an efficient way of determining pedestrian volume impact at suburban intersections. Also, these rates are analyzed for their time-dependent nature of

peak hour(s), non-peak hour(s), and no-volume hour(s) of pedestrian traffic.

In addition, the solution approach allows different weights to be assigned to pedestrian and vehicular streams for analyzing different scenarios.

STUDY OVERVIEW

This chapter described the significance of pedestrian signalization in the context of its general problem and defines research objectives and general approach.

Chapter 2 presents an in-depth literature review of various published pedestrian studies, namely safety, behavior, vehicular delay, and pedestrian generation rates.

Chapter 3 presents an overview of the analytical research framework. It basically describes framework elements for pedestrian /vehicular delay, pedestrian safety/compliance (and pedestrian volumes) for general modeling. Framework elements are described at an abstract level, including the objective function, its inputs and outputs.

Chapter 4 presents the theoretical development of the vehicular delay framework, pedestrian safety/compliance functions, and pedestrian generation rate analyses. The vehicular delay framework evaluates the trade-offs between the conflicting needs of pedestrian and vehicular traffic. The framework allows estimation of pedestrian-induced vehicular delay, and assessment of relative merits of different pedestrian accommodation strategies. In addition, costs behind the delays are presented.

The pedestrian safety/compliance functions in Chapter 4 are integrated into the delay framework. Two factors, compliance and potential accident rates, are developed for different traffic conditions, namely number of lanes, vehicle volume, and traffic control type.

The pedestrian generation rate theory development is presented in Chapter 4, containing two components: 1) the definition development of pedestrian generation rate, and 2) the determination of peak-hour and non-peak hour pedestrian generation rates. In addition, a dual land use methodology for the pedestrian generation rate analyses is described.

Chapter 5 presents results from application of the theories presented in Chapter 4, namely, the pedestrian generation rate analyses, the compliance rates and their resulting pedestrian safety functions, and finally, the aggregated results from all components integrated into benefit/cost answers. The pedestrian generation rate analyses are performed first by examining volume patterns over time and land use, and then by developing regression models to determine peak and non-peak hour rates. Results from the pedestrian compliance/safety section will state the implications of the answers obtained, especially with respect to the traffic conditions. Finally, the aggregated methodology will be tested for reasonableness through sensitivity analysis, and the delay differences will be examined through different traffic/geometric conditions and compliance rates.

Chapter 6 presents conclusions from the research results and discusses directions for future research.

CHAPTER 2. REVIEW OF PEDESTRIAN LITERATURE

INTRODUCTION

Researchers have taken different approaches analyzing 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 four headings:

i) Safety

ii) Behavior (i.e. compliance)

iii) Vehicular Delay

iv) Pedestrian Generation Rates

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

SAFETY

Characterization of pedestrian safety is an ongoing research opportunity for which parameter definitions, coding, practicality, accuracy, and effectiveness remain problematic. Different researchers have tried different methods with mixed results, and this section generally describes these efforts, starting with the number of accidents as a pedestrian safety indicator.

Accident frequency is a measure of safety problems, and 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 (1967). However, their limited sample size did not allow conclusive statistical analysis. Robertson and Carter

(1984b) 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 predominant. Also, they found that the young and the elderly are more accident susceptible. In addition, Robertson (1984a) found that left turns are almost three times more hazardous to pedestrians than through movements, and he quoted other studies that found after implementation of Right-Turn-on-Red, pedestrian accidents increased. Another study (Zegeer et al., 1982) provided evidence using accident data to show that pedestrian signalized intersections are no safer than unsignalized intersections. Witkowski (1988) studied the relationship between land-use type and accident rates. He concluded that intersection-related accidents more often occur in areas of commercial or financial land-use, and residential land-use is more frequently associated with mid-block accidents. Zaidel and Hocherman (1988) used accident rates to compare performance of pedestrian crossing arrangements. A general drawback of the accident analysis approach is that accidents are rare phenomena, and not all are reported. They occur under various circumstances making identification of generic causes difficult. Some researchers have felt that development of site-specific remedies is easier; hence, it is the usual practice.

Since accidents are rare and available databases are not extensive, researchers 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 (Cynecki, 1980; Davis et al., 1989). Conflicts can be obtained from road-side observations. Cynecki (1980) 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 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 (1982) also used this technique to relate conflict and accident data.

The conflict technique is more effective than the accident analysis approach at developing intersection-specific remedies. The disadvantage of this method is that site-specific deficiencies; therefore, identification of general causes may not be possible. In other words, this method may not allow safety (or lack of) to be related to geometric/traffic conditions. Pedestrian and/or driver movements, which is the primary precursor to an accident or a conflict, has not been directly addressed.

Another method for predicting accident rates is the use of exposure measures (indicators of pedestrian and vehicle volume). Knoblauch (1984) has shown that exposure measures yield high hazard scores for certain groups such as the young and elderly, 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 studies have shown mixed results (i.e. conflicting information) when tested against accident rates.

Within the conflicting results, there were a number of consistent findings, especially when geometric/traffic variables were used. However, this paradox indicates that a different approach is needed for characterizing and evaluating pedestrian safety at signalized intersections. The factors must be analyzed and a different safety concept should be introduced.

BEHAVIOR

Pedestrian crossing behavior is defined as the phenomena surrounding decisions/movements for crossing streets at signalized intersections. Of particular importance is the decision when to cross the intersection, or in other words, when they decide to comply or not comply with traffic/pedestrian signals. Compliance rates are affected by many factors for which a general overview is provided in this section.

Mortimer (1973) 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 proven effective. Zegeer et al. (1982) 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. Another reason could be that pedestrians signals do not change the cycle lengths; hence, pedestrians might feel that they are insufficiently served. One study (Bailey et al., 1991) on the elderly reports that sixty-four percent of the respondents lacked adequate signal phase understanding. Also, most avoided crossing during peak hours and at low visibility periods. Studies of young pedestrians show that they have 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 and to be convinced that they are valuable tools.

Signal timing also has an impact on compliance. A study by Robertson and Carter (1984b) reports that when too much green was given to the vehicular traffic relative to its volume, pedestrian violations increased. Also, they found that longer pedestrian clearance time increased the number of violations. Khasnabis et al. (1982), in their review of behavior studies, observed that (i) at low vehicle volumes, pedestrians are likely to ignore signal indications, (ii) compliance rate for steady "walk" is higher than flashing "walk", and (iii) pedestrian clearance intervals increase compliance rates.

Another result obtained from characterizing pedestrian crossings comes from gap acceptance theory. Palamarthy (1993) modeled pedestrians' gap acceptance behavior under different scenarios using a multinomial probit approach. Estimation results pointed to trends on gap acceptance and push-button behavior. On the gap acceptance behavior at busy or wide intersections, these gap acceptance values are higher, people are less cautious while crossing on turn phases, and group interactions are significant and should not be ignored. On the push-button behavior, people may have an inherent tendency to avoid using push buttons, but at busy or wide intersections, push buttons might be of some assistance to the pedestrians.

Although choice models are preferable to simple statistical correlation of compliance with geometric/traffic variables, using gap acceptance parameters as independent variables is difficult. Relating gap acceptance parameters to geometric/traffic parameters is difficult and mixing other parameter types and providing specific numerical results to crossing choice phenomena is highly problematic. In this sense, choice modeling using geometric/traffic parameters directly appears to be a preferable methodology.

VEHICULAR DELAY

For determining pedestrian impacts on vehicular traffic, most researchers have used statistics. Many have not mathematically modeled the crossing phenomenon, though some efforts have been assisted by simulation. In this section, these efforts are reviewed.

Although researchers have studied both vehicular and pedestrian delay, more emphasis has been given to vehicular delay. Robertson (1984b) studied pedestrian and vehicle delay at signalized intersections, which 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 (1977) used pedestrian delay as a principal traffic signal warrant criterion, 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 total delay allocation. His 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 even though he stated that pedestrians are less comfortable standing than drivers (and passengers) sitting inside vehicles.

A major study (Griffiths et al., 1984a, b, & c, 1985) 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 signal impact.

Abrams and Smith (1977a & b) 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. These alternatives determined when all or right-turning only vehicles are allowed to proceed. The early release alternative allowed pedestrians to cross before right-turning vehicles could proceed, and vice versa for the late release alternative. Scramble timing is also called "exclusive timing" because a phase for pedestrians only (for all crosswalks) is provided. These alternatives were evaluated in terms of pedestrian and vehicle delay and safety. The data collection included vehicle delay, pedestrian generation 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 (1989) examination of traffic signal timings 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. Moreover, Newell's approach to quantifying traffic signal expressions allows researchers to change parameters to incorporate new ideas, try different approaches, and to effectively analyze the outcome without resorting to overly extensive efforts. In this case, his approach should be used and extended to evaluate pedestrian-induced vehicular delay and examine trade-offs underlying signal operation strategies.

PEDESTRIAN GENERATION RATES

Pedestrian volumes have generally been the major variables for determining when pedestrian signals should be installed. Traditionally, the number of pedestrians has been obtained through field counting. In addition, methods for predicting pedestrian volumes using secondary data have been concentrated in CBD areas or other relatively high density areas. These studies are described in this section.

Expressions predicting pedestrian volume characteristics based only on short volume counts were developed (Seneviratne et al., 1990a & b, Hocherman et al., 1988). A similar study in Israel examined CBD and residential areas (Hocherman et al., 1988), but recommended the developed models only be used with similar sites, and additional counts would be needed to attain transferability. Sandrock (1988) suggested land use should be considered as a predictor variable.

Another CBD study attempted to explain pedestrian volumes using land-use types and quantities as predictor variables (Behnam, 1977); however, the results 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). One-third mile was the average walking distance, and half of all pedestrians walked less than 1,000 feet.

A study in Washington D.C. used land use as the principal site selection criterion (Davis et al., 1988). Mathematical models which use short volume counts as predictor variables were developed, and the authors claimed that the models worked well, although 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 Washington D.C. areas.

A promising variable is land use surrounding the site. However, since land use in relation to pedestrian traffic in suburban areas has not been studied extensively, an examination of land use impact on pedestrian traffic in suburban areas is needed.

SUMMARY

This chapter discussed and assessed the literature relevant to pedestrian safety and behavior, vehicular delay, and pedestrian generation rates. The findings reveal that research is needed in modeling pedestrian crossing phenomena. Results from other studies show promise in models using geometric/traffic variables.

In addition, these findings point out that very little effort has been concentrated on pedestrian behavior in suburban environments. Although many similarities to CBD areas are expected, certain characteristics, including pedestrian volumes and vehicular speeds are different and these are expected to affect pedestrian behavioral responses.

These findings provide a focus for the next chapter which discusses the general framework for the conceptual and methodological approach to address the concerns.

CHAPTER 3. MODELING FRAMEWORK

INTRODUCTION

This chapter presents an overview of the analytical research framework. It describes the previously identified components, namely pedestrian/vehicular delay, pedestrian safety/compliance (and pedestrian volumes) for the general modeling framework. Framework elements are described at an abstract level, including the objective function, inputs and outputs.

CONCEPTUAL MODEL DEVELOPMENT

Figure 3.1 illustrates the conceptual model development flow.

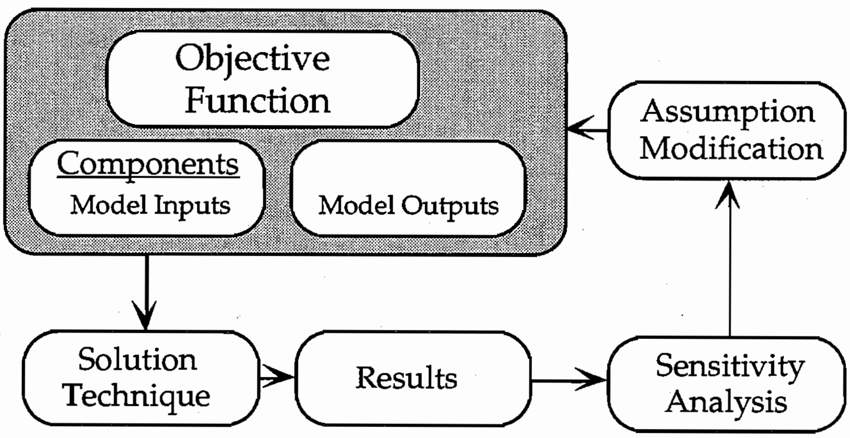


Figure 3.1 Conceptual Model Development

All elements in the shaded area except solution techniques are described briefly in this chapter. The objective function is stated, and a discussion of the units is described. The range of possible modeling inputs are briefly described; then, preselected primary inputs are identified. The complexity of the output units that affects the objective function is described, and a unit-output solution is presented. In addition, a brief discussion on intermediate model outputs is described; the purpose of these output types is to examine statistical trends behind pedestrian crossings.

The solution technique is described in Chapter 4 theoretical modeling efforts. The results, sensitivity analysis, and assumption modifications are presented in Chapter 5. The major results use the objective function presented in the next section.

OBJECTIVE FUNCTION OVERVIEW

Traffic control strategies are usually implemented expecting several benefits. One major potential benefit is accident reduction and the other is user delay minimization. At traffic-signalized intersections, the decision to implement pedestrian control devices depends upon these pedestrian delay and safety benefits, and vehicular delay and hardware costs for the given traffic/geometric scenario. Ideally, all direct costs should be minimized and all direct benefits maximized. Such an objective function would be very difficult to solve, if not impossible. For this research, all units were converted to costs which were transformed to monetary benefits, and thus, all benefits, direct and indirect (e.g. proxy variables), are maximized.

Monetary benefits of pedestrian signalization are expected to vary over time, especially as pedestrian/vehicle volumes change. Many cost/benefit studies compute annual costs because the information needed is available. However, because of lack of information regarding many pedestrian traffic characteristics, particularly pedestrian volumes, this research focuses on costs/benefits on a typical day.

Since intersections under study already have basic vehicular signal equipment, it is necessary only to determine the increase/decrease in overall daily benefits due to installing pedestrian signals. Therefore, the basic objective of this research is Eq 3.1:

$$\text{Maximize } D_P + HI + D_V + C_E \qquad \text{Eq 3.1}$$

where each of these components is the added daily cost/benefit due to the implementation of traffic control strategy (i.e. increase relative to previous solution):

D_P = Difference in Pedestrian Delay Benefit
HI = Difference in Pedestrian Hazard Index Benefit
D_V = Difference in Vehicular Delay Benefit
C_E = Difference in Traffic Control Equipment Benefit

These benefits are not subject to the non-negativity constraints; hence, when the benefit is negative, it becomes a cost. For instance, when pedestrian signalization is implemented, vehicular delay usually increases; hence, it is a negative benefit, or a "cost".

Some component units need transformation in order to be assessed in monetary terms. However, it is recognized that the assignment of monetary units is a continuing debate; this issue is not within the scope of this research. Therefore, simple assumptions are made for the basis of this research, and complex issues can be addressed later. Nevertheless, the equipment component needs no transformation since it is already stated in monetary units. However, both the pedestrian and vehicular delay components must be transformed into delay costs. Most researchers use a "transportation" cost that is equivalent to average hourly wages to transform these components into monetary units. In addition, the pedestrian hazard index is probably the most difficult and controversial component when assigning monetary units. However, an attempt is made to use a somewhat established "cost of life/injuries" index. All these benefits except pedestrian hazard index are explained in detail in Section 4.1.4; the pedestrian hazard index is explained in Section 4.2.

POTENTIAL MODEL INPUTS OVERVIEW

A comprehensive modeling approach to predicting pedestrian signalization benefits might include all factors affecting benefits. However, benefits vary due to many factors including, geometrics, control type, human behavior, traffic conditions, and environmental elements. In addition to research studies from the previous section indicating the complexity of pedestrian signal phenomena, Robertson et al. (1984b) lists many factors that control pedestrian signal benefits. A main portion of this section describes some of these factors indicating the complexity of deciding which factors to include in analyses.

Geometric factors include median islands, lighting, parking, street width, and sight distance. Median islands vary in width from three to more than twenty feet and may encourage noncompliance. 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, is 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 of vehicle movements. 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 many different compliance 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 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. Crosswalks have also been used for pedestrians albeit with questionable concerns.

Human factors include age, gender, physical disability, walking speed, compliance, risk-taking, gap acceptance, group behavior, erratic behavior, comprehension, 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 may 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, deaf, or mobility-impaired. Audible signals are under intense debate among the visually-impaired community, 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 vary usually with vehicle volumes and other site characteristics; if pedestrians do not comply with the signal indications, then its benefits are questionable. Risk-taking and erratic behavior usually are 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 by 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 crossings, and gap distribution. Higher vehicle and pedestrian volumes, and vehicle speed and mix usually increase accident probabilities. Vehicle directional split may confuse pedestrians. Pedestrian delay increases reduce signal compliance rates. Vehicle arrival patterns may influence pedestrian signal phasing and pedestrian crossing patterns could dictate the type of pedestrian signal. If there are large but few pedestrian 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. Night-time conditions may be more difficult for vehicle drivers to detect pedestrians. Also, those with vision problems may find nighttime more difficult.

A framework which considers all factors would be nearly incomprehensible. Therefore, only those factors that have general importance and/or can be controlled are considered. As concluded from the literature review chapter, a primary focus in this research should be on geometric/traffic factors. Since many factors interrelate to many others on many different levels (e.g. vehicular signal timings are influenced by vehicle volumes, saturation flow rates, and other variables), the primary inputs to these models are listed here. In later chapters, the interrelations are described more fully. From this standpoint, the primary input variables are vehicle volumes, speed, saturation flow rates and number of lanes. In addition, to account for individual pedestrian characteristics, pedestrian volumes, walk speed, start-up time, and compliance are included. A total of eight input factors have been preselected. These factors along with several other input factors are tested and assessed in Chapter 5. Major and intermediate outputs from this model using these inputs are described next.

MODEL OUTPUT OVERVIEW

Model output is a recommendation on whether or not to install pedestrian signals. Units used for the outcome are in dollars per hour. However, as stated before, there is considerable variation of pedestrian/vehicular traffic characteristics in a 24-hour period.

Since every traffic demand case is based upon optimized cycle lengths, one could use 24 different hourly demand conditions of a typical day and determine 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). Analysis of pre-timed vehicle signals is limited to peak hours only, because incremental delays are relative to optimized cycle lengths and simple pre-timed controllers are generally optimized for one design-hour condition.

Using hourly benefits 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, average hourly vehicle volume counts will be available, but not average hourly pedestrian volume counts.

The above methodology could 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 traffic and pedestrian volume variation, a simplified approach is presented. This approach yields a weighted net value sum with the day divided into three parts based upon pedestrian generation rates. These three parts include peak, non peak, and zero (or near zero) pedestrian crossings. 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.

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

where

H_p	number of hours of peak pedestrian volumes
H_{np}	number of hours of non-peak pedestrian volumes
H_0	number of hours of zero pedestrian volumes (usually 8 hours)
B_p	net value during the peak pedestrian hour
B_{np}	net value during the non-peak pedestrian volume hour
B_0	net value during the zero pedestrian volume hour

Pedestrian volumes of all hours between 7 am and 11 pm are determined using numbers from the pedestrian generation analyses presented in Section 5.1. The theoretical framework behind pedestrian generation rates is presented in Section 4.3.

Before the ultimate output is obtained, other types of outputs are examined not just for reasonableness, but also to gain insight on the pedestrian crossing phenomenon. More detail will be given in Chapter 4; however a brief overview is given here.

Vehicular delay can be affected by pedestrian crossings. That is, given certain traffic/geometric intersection characteristics, pedestrian signalization may require greater green phase durations than provided by vehicular indications. Preliminary outputs from Section 4.1 on vehicular delay analyses indicate how likely this scenario is.

Concurrently, vehicular delay can be affected by pedestrian compliance especially under pedestrian actuation. However, pedestrian non-compliance can affect pedestrian safety; since non-compliance is heavily influenced by traffic and geometric characteristics, compliance variability is examined. The theory from Section 4.2 explains how compliance and safety are interrelated.

How compliance affects vehicular delay is also determined by the number and manner of pedestrian crossings. Section 4.3 describes the cause/effect of pedestrian crossing volume on the vehicular traffic stream.

Ultimately, results from Chapter 5 provide insight derived from analyzing pedestrian impacts on vehicular traffic in the modeling and statistical analyses. Through sensitivity analysis, combinatorial effects of these changes are tracked.

SUMMARY

Figure 3.2 describes Figure 3.1 when the information from Sections 3.2 through 3.4 are added. The delay model is developed along with the pedestrian generation rates, pedestrian safety/compliance functions. The outcome is subjected to sensitivity analysis and analysis of delay differences, and the assumptions are modified when necessary.

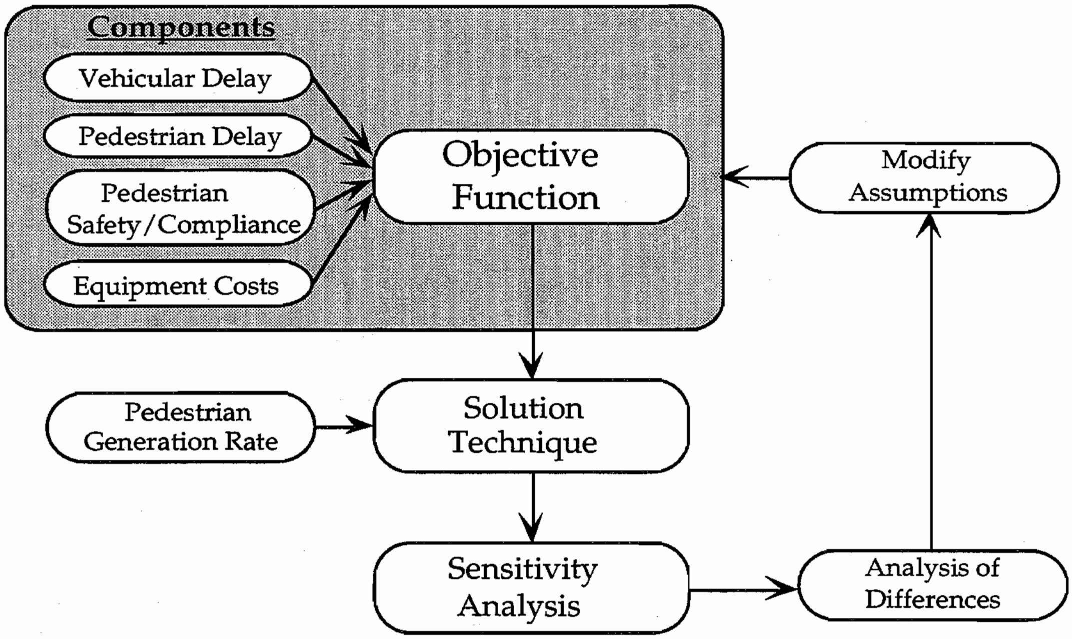


Figure 3.2 Modified Conceptual Model Development

Basic input units in this model are the eight variables: vehicle volumes, speed, saturation flow rates and number of lanes; and pedestrian volumes, walk speed, start-up time, and compliance. The model outcome unit is in dollars per day, and the major decision is whether or not to implement pedestrian signals.

The detail behind each step is explained in subsequent chapters; a brief description is given here. The pedestrian-induced vehicular delay model is developed in Section 4.1, and it considers the impact of pedestrian and vehicle volumes, and the number of lanes on vehicle delay for both fixed pedestrian and pedestrian-actuated signals. In addition, the delay cost for the benefit/cost analysis using different scenarios is derived. For these scenarios, vehicle volumes and numbers of lanes are relatively easy to obtain. Since pedestrian volume data is not readily available; they must be obtained through on-site counting (which is expensive) or through predictive modeling which is presented in Sections 4.3 and 5.1. The safety and compliance of pedestrians is modeled and analyzed in Sections 4.2 and 5.2.

The source of information for the predictive pedestrian generation rate model, compliance and safety analyses is gathered through on-site observation and video recording. The site selection criteria and data collection efforts are described primarily in Sections 4.3 and 5.1.

CHAPTER 4. MODELING THEORY

INTRODUCTION

The theoretical framework for assessing relative delay and safety benefits is explained, and some effects of its implications are illustrated in this chapter. In addition, modeling for determining intersection pedestrian volume levels is shown.

PEDESTRIAN-INDUCED VEHICULAR DELAY

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-signal activation is one strategy for avoiding wasted vehicular green and delay to vehicles. A framework is developed in this section to evaluate the trade-offs between the conflicting needs of pedestrians and vehicular traffic. The framework allows the estimation of pedestrian-induced vehicular delay and assessment of the relative merits of different pedestrian accommodation strategies.

Delay times for vehicles for the three possible pedestrian signalization conditions are examined. 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 Webster's equations and Newell's (1989) "Theory of Highway Traffic Signals." Fixed-time signal timings follow Webster's equations. Since suburban intersections frequently have low vehicle volumes, short cycles could result from Webster's equations; hence, cycle failure analysis was performed to determine minimum cycle lengths for all situations. This cycle failure discussion follows the Section on Newell's theory on vehicular-induced vehicular delay. Newell's theory is then adapted to include 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, cost estimates of delay for the 24-hour vehicle volume variation are presented.

Vehicular Delay Model

Signal operation at an isolated intersection involves conflicting objectives. The desired outcome is the 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 explicitly considered 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 would have shorter red-time waiting periods. Minimization of the number of vehicular stops favors longer cycles because fewer vehicles would have to stop due to 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.

This section focuses on Newell's development because of its explanatory nature, but also describes Webster's equation used for fixed-time signals. The analysis begins with a description of the processing of vehicles through the intersection. In Figure 4.1.1, 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.)

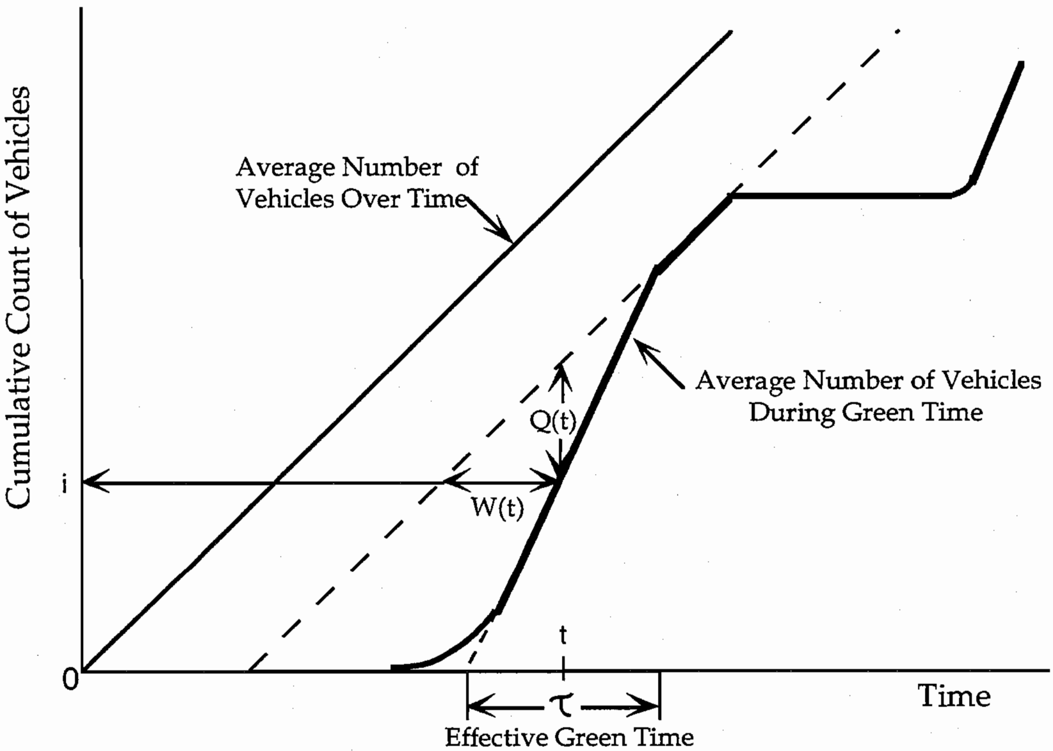


Figure 4.1.1 (Newell, 1989): Graphical Interpretation of Queue Length Q(t) and Delay W(t).

From this simple deterministic analysis, the fraction of vehicles that are delayed is calculated as Eq. 4.1.1.

$$f = \frac{(C - G + \tau)}{C} \qquad \text{Eq. 4.1.1}$$

where
f = fraction of vehicles that are delayed
C = cycle length in seconds
G = green phase length in seconds
τ = effective green time in seconds

Since the effective green time, $\tau = q(C-G)/(sat-q)$, depends on several variables, including vehicular and satuation flow, this equation can be converted to exclude τ (Eq. 4.1.2).

$$f = \frac{(1-G/C)}{(1-q/sat)} \qquad \text{Eq. 4.1.2}$$

where
q = vehicular flow in vehicles per hour[1]
sat = saturation flow rate in vehicles per hour

The average delay per vehicle that "experiences" delay is taken to be half the red time, (C-G)/2 . Thus, the total average delay (Eq 4.1.3) for all vehicles is the fraction of those delayed multiplied by the average delay per vehicle.

$$\bar{w} = \frac{1}{2}\left(1-\frac{G}{C}\right)^2 \frac{C}{(1-q/sat)} \qquad \text{Eq. 4.1.3}$$

where
$\bar{w}$ = average delay (in seconds) 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 is added to take into account variability in the arrival and departure procedure. This delay term is used to

[1]"q" is used instead of "v" just for this section to follow Newell's notation

incorporate variability into the signal timings can be used to account for the hourly differences in timing plans. Newell gives an extensive discussion on the formulation of this stochastic term, Q; the form given in Eq. 4.1.4 divided by the vehicular flow and added to the above deterministic form presented in Eq. 4.1.3. Its main component, I, is a stochastic term used for taking into account the variance of the number of arrivals per cycle versus the mean number of arrivals per cycle.

$$Q = \frac{I}{2\left(1 - \frac{C\,(q/sat)}{G}\right)} \qquad \text{Eq. 4.1.4}$$

where
Q = the stochastic term for the average queue at start of red
I = the main stochastic term
C = cycle length in seconds
G = green phase length in seconds
q = vehicular flow in vehicles per hour
sat = saturation flow rate in vehicles per hour

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 (Eq. 4.1.5). Therefore, since all of Newell's calculations are based on optimized signals, they could be either actuated or pre-timed.

$$C = \frac{L}{(1 - q_1/sat_1 - q_2/sat_2)}\left(1 + \sqrt{\frac{I_1 sat_2}{Lq_2(sat_1+sat_2)}} + \sqrt{\frac{I_2 sat_1}{Lq_1(sat_1+sat_2)}}\right)$$

Eq. 4.1.5

where
L = total lost time before and after signal changes phasing in seconds
Subscripts "1" and "2" refer to major and minor street, respectively

Webster's equation (Eq. 4.1.6) shows frequently used fixed-timed signal cycle. Its critical lane flows are based on the heaviest vehicle volumes for each signal indication by multiplying a weight to each turning movement.

$$C = \frac{1.5L+5}{1-\sum b_i} \qquad \text{Eq. 4.1.6}$$

where
L = total lost time before and after signal changes phasing in seconds
b_i = critical lane flow divided by saturation rate

The free time remaining after the green phase has been used to serve q/s for both streets is split (Eq. 4.1.7) using not the q/s split as in Webster's studies, but as the square root of "Iq/sat".

$$K = \sqrt{\frac{I_1(q_1/sat_1)}{I_2(q_2/sat_2)}} \qquad \text{Eq. 4.1.7}$$

where
K = cycle split ratio used for distributing the "free time"

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 fixed-time controllers. Minimum cycle length causes cycle failure i.e. vehicles not processed efficiently because the green phase is too short; this phenomena is discussed next.

Cycle Failure

Since suburban vehicular volumes are low during most hours of an average day, an analysis of the cycle lengths using Webster's equation for fixed cycles was performed. The reason for these analyses is that low vehicular volumes generally cause cycle lengths to be small, especially 2-phase cycles, causing some cycles to be as short as 20 seconds under Webster's equation. For actuated cycles, small cycle lengths are generally not a problem since the signal is more responsive to vehicular volume changes.

However, for fixed cycles, if the cycle length is very short, then cycle failures are likely. Cycle failure occurs when any green phase duration of any cycle is insufficient to clear the waiting vehicle queue. For example, if a green phase is 10 seconds, and there are 5 vehicles queued at the beginning of the green phase which happen to require 15 seconds to move through the intersection, then possibly 2 vehicles have to wait until the next cycle. Although cycle failures may not be avoidable during rush hours, they are highly undesirable during low vehicular volume periods because they cause unnecessary congestion. In addition, cycle failures, if at all possible should be avoided so that vehicle driver frustration does not lead to over-aggressive behavior.

Cycle failure performance analysis was created using simulation of vehicles arriving at the intersection in a random process and moving through the approach taking into account lost time and saturation flow. Vehicles that arrived during the red phase, but could not get through the intersection in the following green phase were considered to be cycle failure victims. If the vehicles arrived during the green phase after the waiting queue has cleared, then they are not considered to be cycle failure victims. Hence, cycle failure occured only when all available green phase time was spent processing the waiting queue, but the initial waiting queue could not be completely served.

Since vehicular volumes of 100 to 400 vph have been noted during non-peak hours in suburban areas, this analysis was performed using lost times, L, (clearance intervals) between three and six seconds and cycle lengths of 20, 30, 35, 40 and 45 seconds (with green phase exactly half of cycle lengths). Cycle lengths of 20 seconds were generally the outcome from Webster's cycle equation, but cycle failure experimentation included 30, 35, 40 and 45 seconds to determine a reasonable minimum cycle length.

From Figures 4.1.2 (400 VPH) and 4.1.3 (200 VPH), the cycle failure percentage (over all cycles in one hour) increased dramatically for 20-second cycle lengths compared to longer cycle lengths. The increase from 30-seconds to 35-seconds or longer is much less significant. For vehicular volumes of 100 or less, the results were less dramatic.

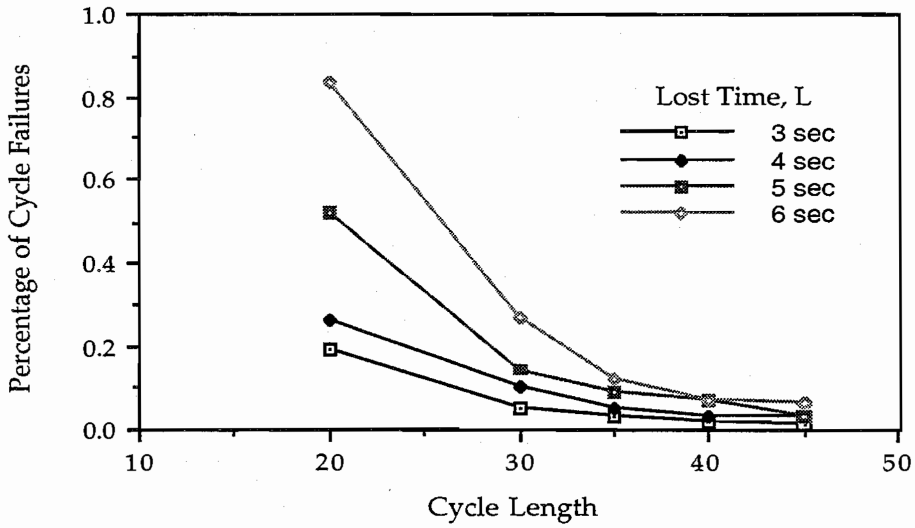


Figure 4.1.2 Cycle Failure Analysis for 400 vph

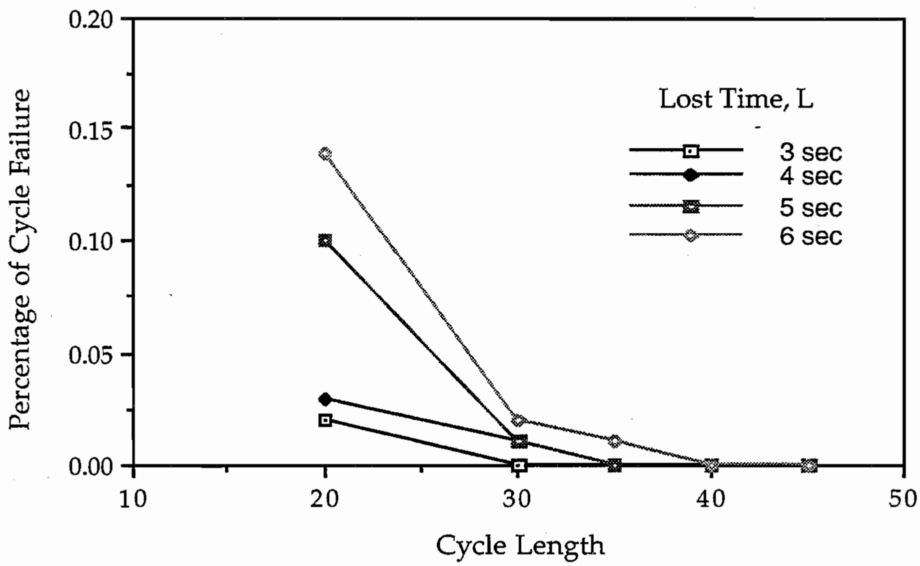


Figure 4.1.3 Cycle Failure Analysis for 200 vph

This cycle failure analysis shows that for a few cycle lengths, the percentage of cycle failures can be too high even for just 2-phase cycles. Considering that most suburban signal cycles have more than 2 phases and additional phases add lost time, the number of cycle failures will increase with increased lost time. Generalizing the results from this analysis, it is recommended that the minimum length of green cycle lengths be 30 seconds. If analyses from Webster's equation gives answers above 30 seconds, then that cycle length can be used; otherwise, a minimum of 30 seconds should be used. These short cycles are affected most by pedestrian signals which as presented next.

Pedestrian Signalization Effect

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

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. 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 children. The time to cross the street depends on the street width and the walk rate (for which a typical accepted value of 3.5 feet per second is used for this section's illustration purposes).

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 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 4.1.4 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 Fig. 4.1.4 ensures that the new G_1 also

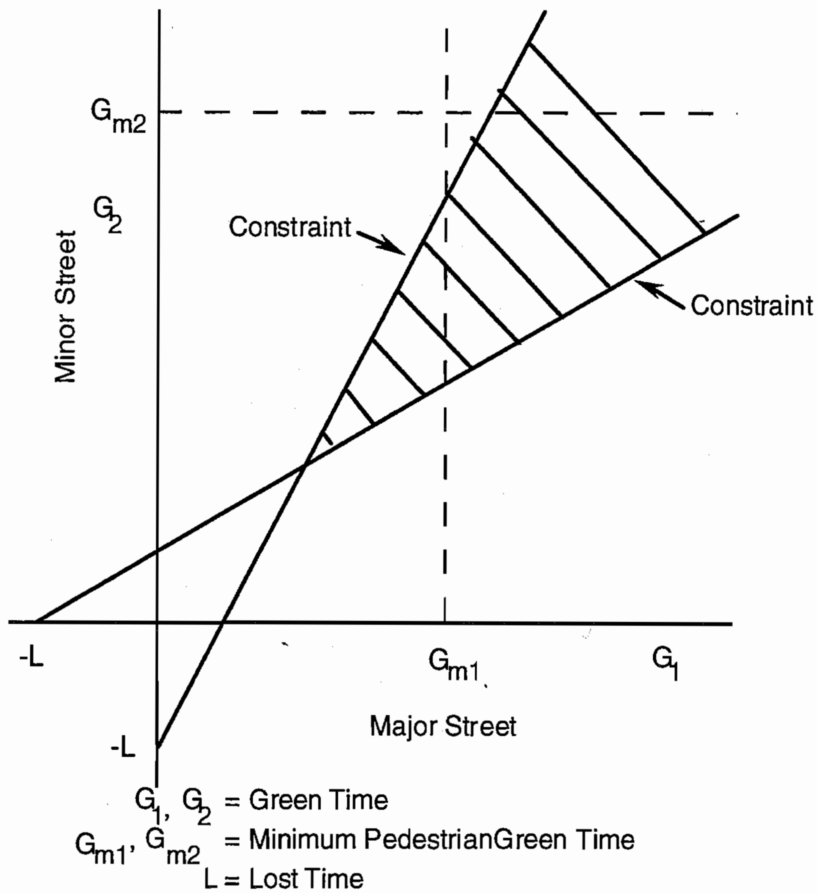


Figure 4.1.4 Admissible Ranges of Green Intervals

satisfies the pedestrian minimum G_{m1}. The delay from pedestrian constrained operations is calculated using the same equations discussed earlier.

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 4.1.5.

The following assumptions are made in this comparison for this section. First, on a street with no obstacles other than traffic signals, ideal saturation flow rate was frequently assumed as 1800 vehicles per hour. However, there are usually several factors which limit this saturation rate (buses, trucks, grades, etc.); hence, a practical value of 1600 vehicles per hour was assumed. Street widths were calculated on the basis of 12 feet 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.

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 are shown in Figure 4.1.6.

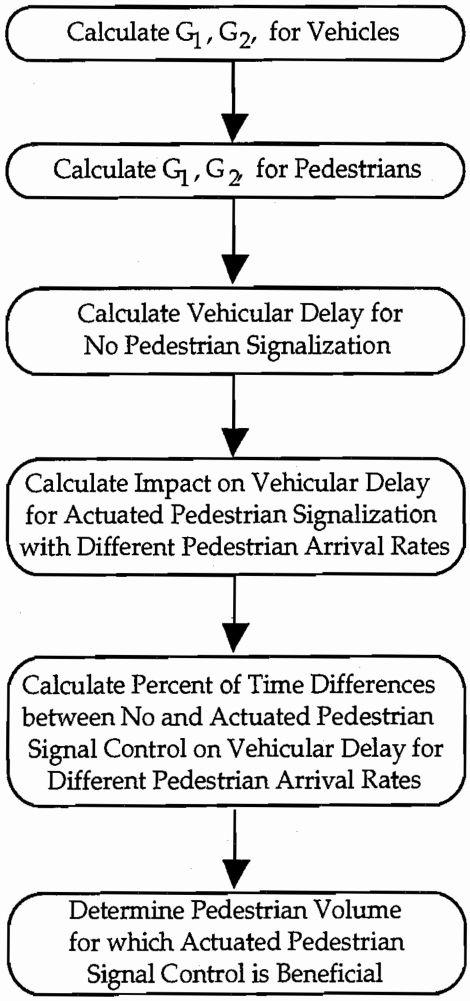
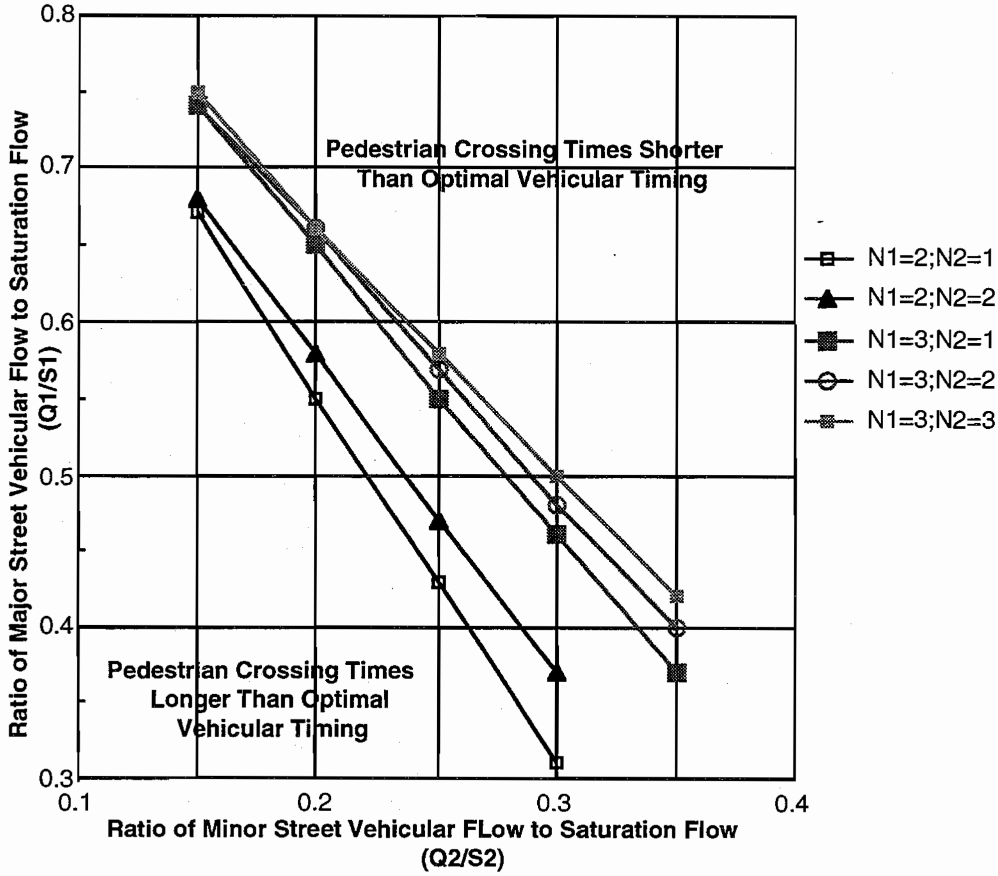


Figure 4.1.5 Overview of Pedestrian-Induced Vehicular Delay Model



For S = 1600

Q/S	Q(vphpl)
0.20	320
0.35	560
0.45	720
0.55	880
0.65	1040
0.70	1120

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 4.1.6 Minimum Vehicular Flows over which Pedestrian Green Times do not Govern

Figure 4.1.7 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).

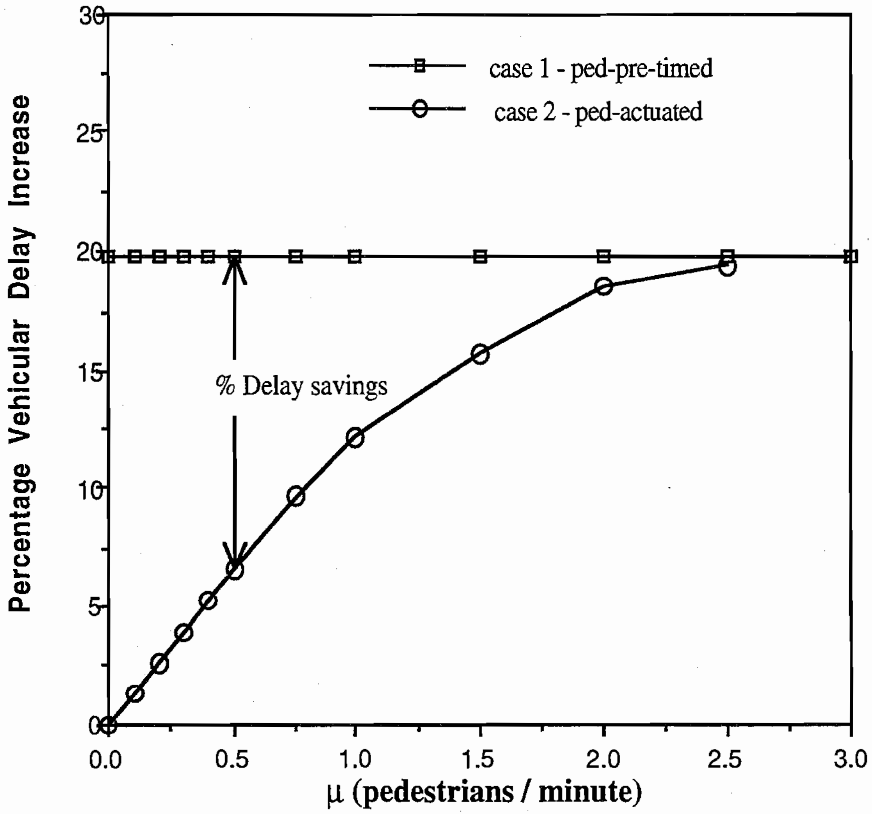


Figure 4.1.7 Percentage Delay Savings of Pedestrian Actuated Compared to Pretimed Pedestrian Signals for a 2 x 2 Intersection with: Q1/S1=0.35 Q2/S2=0.15

Figure 4.1.8 illustrates the variation of percentage delay increase caused by pre-timed pedestrian phases compared to vehicular traffic optimized phases with the number of lanes. The wider the street, particularly the major street, the higher the potential is for delay savings with pedestrian-actuated signals.

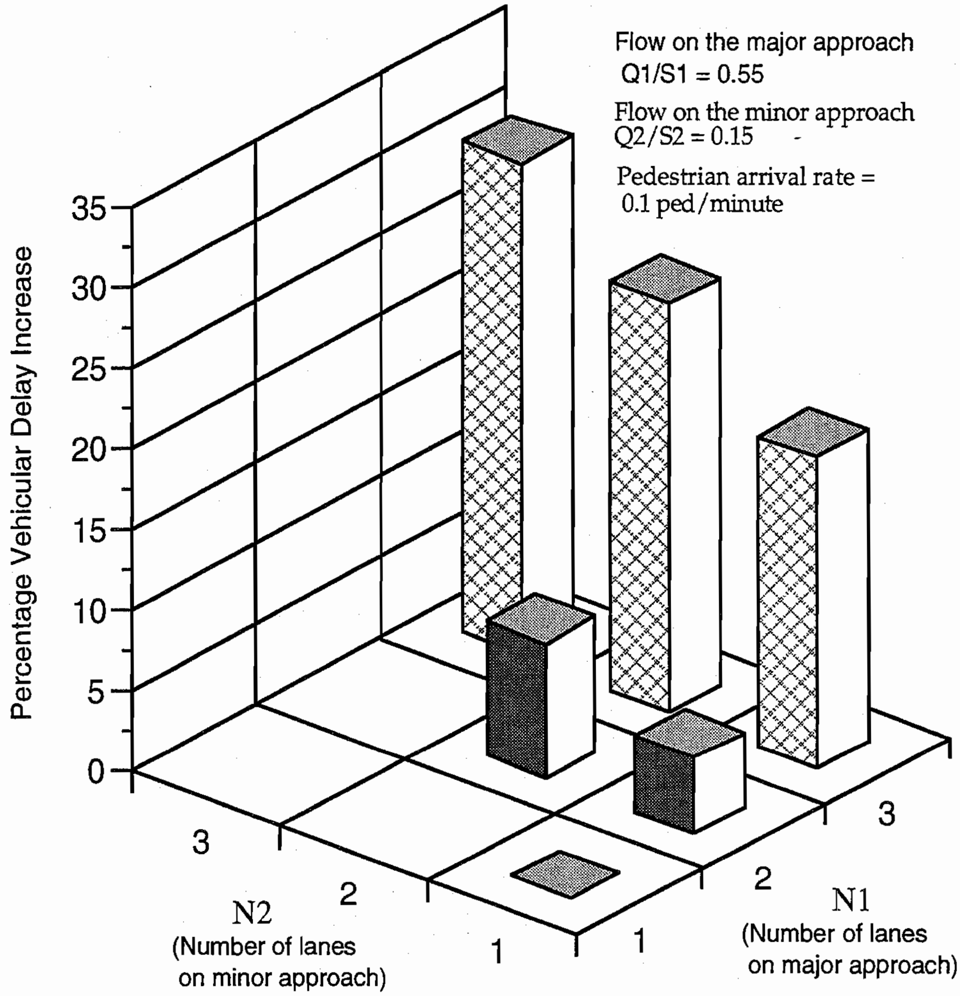


Figure 4.1.8 Variation of Percentage Vehicular Delay Increase with N1 and N2

Figure 4.1.9 shows vehicular delay increase with the volume over capacity ratios of both streets. As the major and minor street flows decrease, the savings with pedestrian-actuated signals increase.

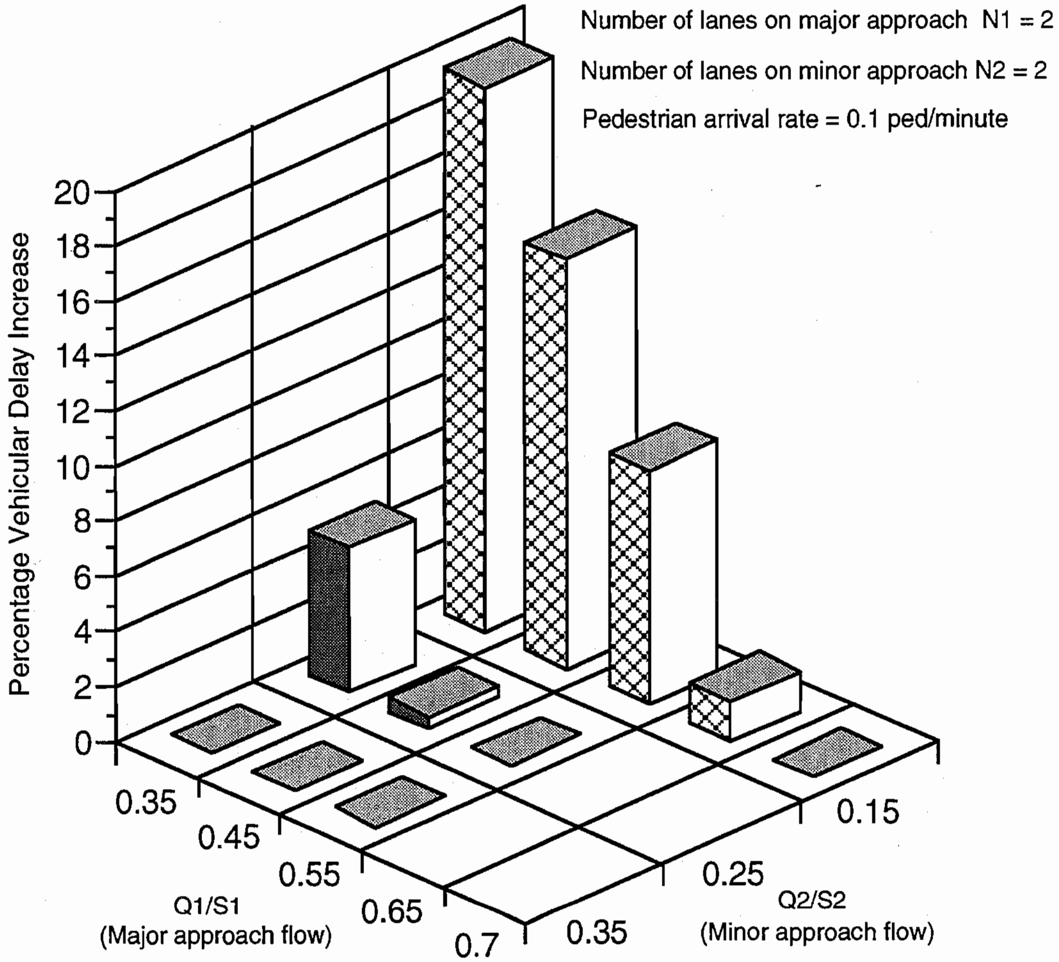


Figure 4.1.9 Variation of Percentage Vehicular Delay Increase with Q1/S1 and Q2/S2

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.

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.

Cost Estimates of Delays and Traffic Control Equipment

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 (Schlesinger Jr, 1993). For 1993, the rate is adjusted to $19,323. As stated in Section 3.2, assumptions are simplified for cost analysis since cost assignment is not within this research scope. Pedestrian and drivers' values of time are assumed equal. Since there are approximately fifty 40-working-hour-weeks per year, the cost per hour is set at $10.

Table 4.1.1 displays the estimated cost of actuated pedestrian signals, which is the sum of the fixed pedestrian signal costs from Robertson's study (1984) 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) is assumed to be negligible. Since costs are quoted in 1981 dollars, an inflation factor of 2.52 was used to convert to 1993 dollars[2]. 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 with eight pedestrian signals per intersection, the total cost is $2800. This cost becomes $0.32 per hour when divided by 8760 hours per year.

[2] This conversion factor also uses a discount rate of 8%. Although current inflation and interest rates are below 8% at this time, it may increase substantially again in the future.

Table 4.1.1 Summary of Annualized Cost of Pedestrian Actuated Indications (Incandescent-Fiberoptics) [Robertson, 1984]

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[1] 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[1] (see footnote)
NOTE: All costs have been converted to 1981 dollars

The total cost, or net value, of actuated pedestrian signals includes 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.

Many different combinations of major/minor street vehicle volumes, street configurations and pedestrian volumes are used. However, many more cases are not considered for analyses 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 $Q1/S1 + Q2/S2 \geqq$

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[1] Robertson has both $0.05, and $0.06 per KWH in his document.

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 late-night or early-morning hours. If these conditions appear, then the net value number is $-0.32 per hour.

These net values appropriately describe cases for hourly vehicular and pedestrian volumes compared to optimized traffic signals without pedestrian indications. However, both vehicular and pedestrian volumes change among the hours of a typical 24-hour day.

Summary

This section illustrated that with higher numbers of lanes, low vehicular flows, and large numbers of pedestrians, pedestrian-actuated signals exhibit potential for net economic savings. By examining the 24-hour time period, this analysis takes into account vehicle and pedestrian volume fluctuations. With this model, the inputs are vehicular volumes, numbers of approach lanes, and pedestrian generation rates. The vehicular volumes and number of approach lanes are easily obtainable while pedestrian volumes are not; therefore, pedestrian generation rates are provided in Section 4.3. Next, the implications of pedestrian safety in this framework are presented for which pedestrian delay is then derived from.

PEDESTRIAN SAFETY AND BEHAVIOR ANALYSES

Introduction

The effectiveness of pedestrian signals in maximizing safety (i.e. minimizing accident rates) depends on two factors: compliance and potential accident rates. These two factors depend on several factors, namely number of lanes, presence of median, vehicle volume, vehicular speed, pedestrian volume, and traffic control type. The potential accident rate is a measure of intersection safety and the compliance rate is a measure of pedestrian behavior. This section first presents an overview of the potential accident theory and then, explains how compliance is embedded in it.

Overview of Potential Accident Rate Theory

As shown in the literature review, accident rates are difficult to analyze using observational data; hence, the concept of "potential accidents" is developed. A modified form of the traditional conflict theory is used.

The traditional conflict concept enumerates the number /severity of potential vehicle and pedestrian "contacts." It is measured by counting the number of types of close encounters between vehicles and pedestrians. For example, a conflict occurs when a pedestrian runs to avoid being hit. Researchers have developed models correlating accident and conflict rates. There are four drawbacks to this traditional concept. First, statistical relationships between conflict rates and accident rates have not always been significant and consistent. Second, a large conflict database is required; which means, at low pedestrian volumes, an enormous amount of time spent acquiring data is required to obtain reasonable statistical models. Third, even if statistically significant results were obtainable, significant field data quantities would be required in order to apply the model(s). Finally, it is difficult to apply the traditional conflict theory in a theoretical framework because it is difficult to determine how conflict rate increases are due to different geometric/traffic conditions. For instance, given the earlier conflict example of a pedestrian running to avoid being hit, it is nearly impossible to determine what this event's likelihood is due to changes in vehicular volume, or this event's likelihood differences between four- and six-lane approach streets.

A concept that overcomes these problems is the time-space potential accident rate concept (or "PAR" for simplicity) illustrated in Figures 4.2.1a and 4.2.1b. The boxes aligned along the crosswalk path indicate when pedestrians are, or are not, free from potential vehicle conflicts with respect to the traffic signal timing. The three boxes in each lane of the two-lane road represent the three available vehicular movements: left, through, and right. The four-lane road has two boxes in each lane since left turns are not permissible from right lanes and right turns are not permissible from left lanes. The marked boxes indicate potential vehicle-pedestrian accidents whereas the unmarked boxes signify absence. For instance, in Figure 4.2.1a, the major street has the green light; therefore, the minor street's crosswalk has more PAR-free zones. In Figure 4.2.1b, the situation is reversed; the minor street has the green.

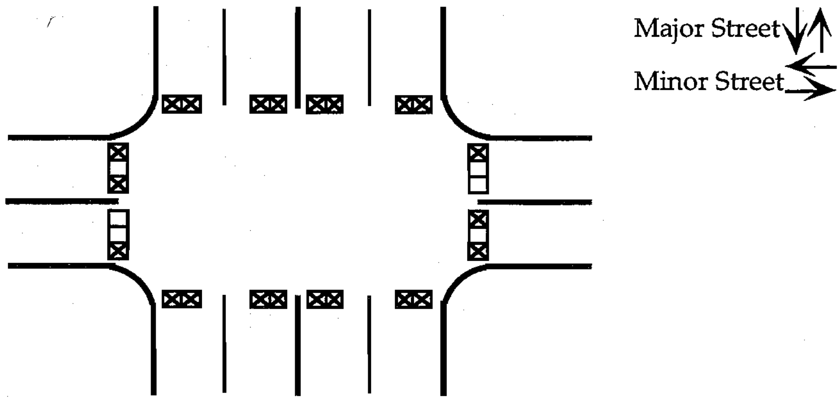


Figure 4.2.1a Time-Space Concept of Potential Accident Rate Theory Signal with Green Light on Major Street

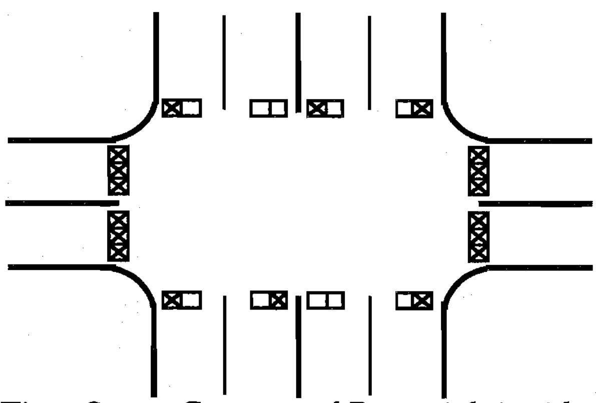


Figure 4.2.1b Time-Space Concept of Potential Accident Rate Theory Signal with Green Light on Minor Street

The theory behind using different PAR zones for different vehicular movements is that certain vehicular movements are more hazardous to pedestrians, usually because of lack of visibility or noncompliance. Although literature sources have indicated mixed results regarding left/right turn movements, most have indicated that turning movements are more hazardous than straight movements.

Figures 4.2.1a & b present scenarios with permitted left turns and right-turns-on-red (RTOR). If RTOR and/or left turns were prohibited when pedestrian movements occurred, then the number of PAR-free pedestrian zones increases.

In addition, walking out of crosswalks presents conflicts to pedestrians in every signalization strategy since pedestrians are not protected in these areas. The PAR zones can be seen in Figure 4.2.2.

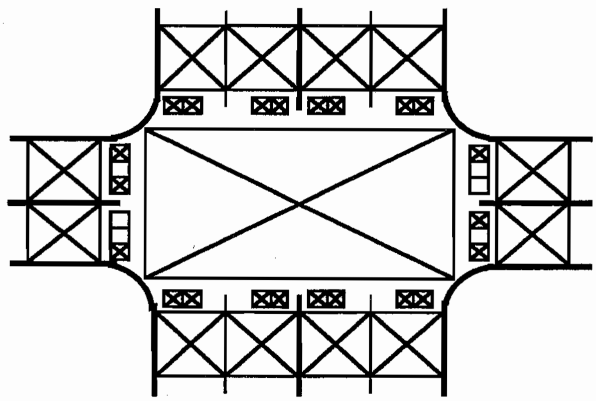
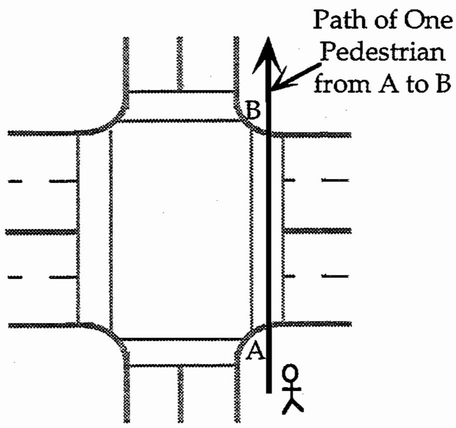


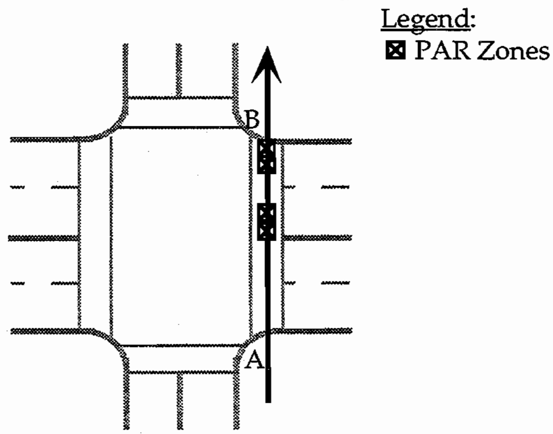
Figure 4.2.2 Time-Space Concept of Conflict Theory
Signal with Green Light on Major Street
and Conflict Zones Outside of Crosswalk

The differences between intersections with or without pedestrian signals and/or crosswalks in terms of PAR-free zones can be insignificant. However, if the cost of having certain types of potential conflicts is great, then small differences in traffic control strategies can produce desired results. Since PARs are direct indicators of accidents, the costs are likely to be very high.

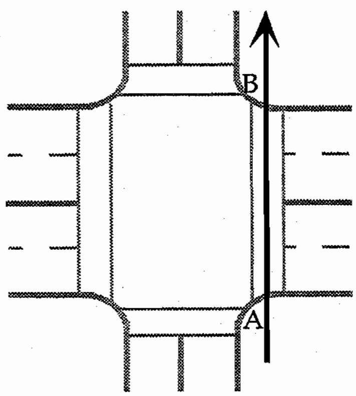
Individual crossing cases as shown in Figure 4.2.3 shows example PAR zone combinations for a compliant or non-compliant pedestrian crossing under different green time lengths. The first illustration shows a path (from A to B) of a hypothetical pedestrian.



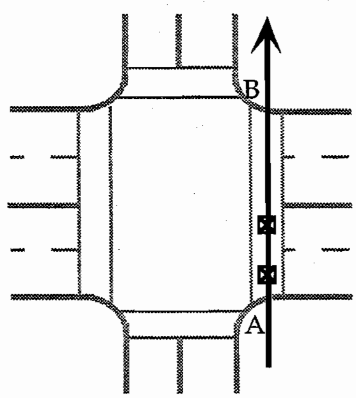
Direction of Pedestrian Path



Case 1: Compliant Pedestrian Crossing in Insufficient Green Time



Case 2: Compliant Pedestrian Crossing in Sufficient Green Time



Case 3: Non-Compliant Pedestrian Crossing (for which signal turns green when pedestrian reaches center of roadway)

Figure 4.2.3 Example Scenarios of Pedestrian Crossings of 2-Phase Cycle

For purposes of simplicity, the PARs from the minor street are omitted and no right-turn-on-reds are permitted in these illustrations to demonstrate how different green times and compliance characteristics affect potential accidents. Case #1 shows a compliant pedestrian provided with insufficient green time; the pedestrian will face potential conflicts at the end of the crossing. Case #2 also shows a compliant pedestrian, but provided with sufficient green time; no potential accidents will occur[2]. Case #3 shows a non-compliant pedestrian; the potential accidents could occur in the beginning of the crossing because, in this example, the signal turns green when the pedestrian reaches the roadway center.

From the single pedestrian case, the multiple pedestrian case is examined next. In Figure 4.2.4, examples of compliant and non-compliant pedestrians crossing against the red are shown. In each of the individual crossing examples, a pedestrian is either crossing with the green (0%) or crossing against the red (100%). The results are dichotomized according to what the signal indication is (i.e. red or green) when a pedestrian is in the middle of each lane. As illustrated, it is expected that compliant pedestrians, if faced with a red signal, will most likely have PAR zones toward the end of the crosswalk if their walking time exceeds available signal time. However, the opposite is true for non-compliant pedestrians; they are expected to face the red light in the beginning of the crosswalk because they usually wait until a platoon of vehicles passes before starting to cross and thus, the green light appears before crossing is completed. In these examples, to simplify the presentation, only crossings from sidewalk A to sidewalk B are shown; in reality, both directions are computed simultaneously.

In order to obtain an overall percentage of pedestrians crossing against the red, several procedures are carried out: 1) calculation of the percentage of pedestrian crossings expected for each possible case, 2) aggregation over all compliant and all non-compliant pedestrians, and 3) calculation of overall percentage by dividing for each case, the total

[2] except for right-turn-on-green movements from the south leg

number of pedestrian crossings. For the examples presented in Figure 4.2.4, the overall percentage is divided by the four possible cases.

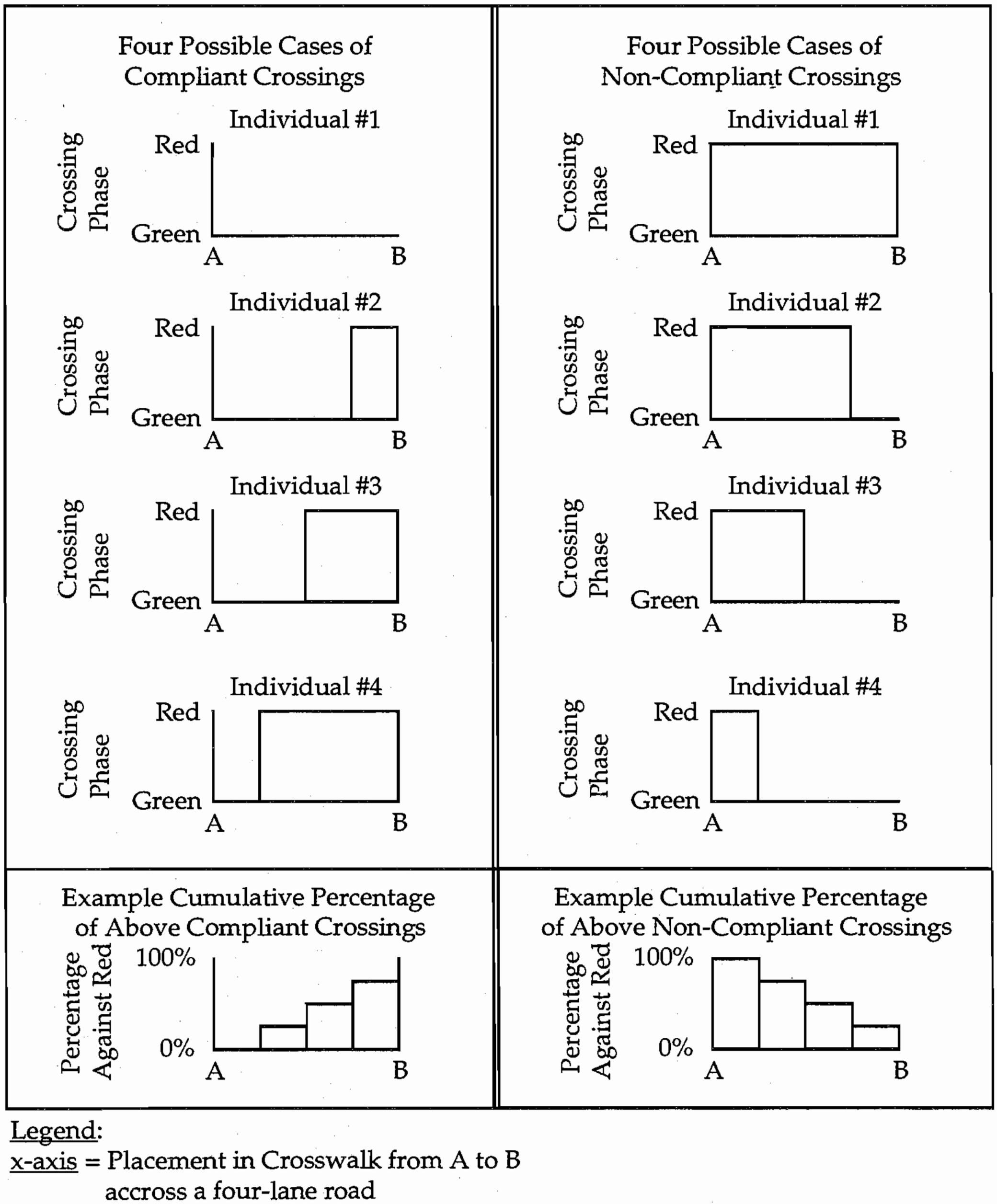
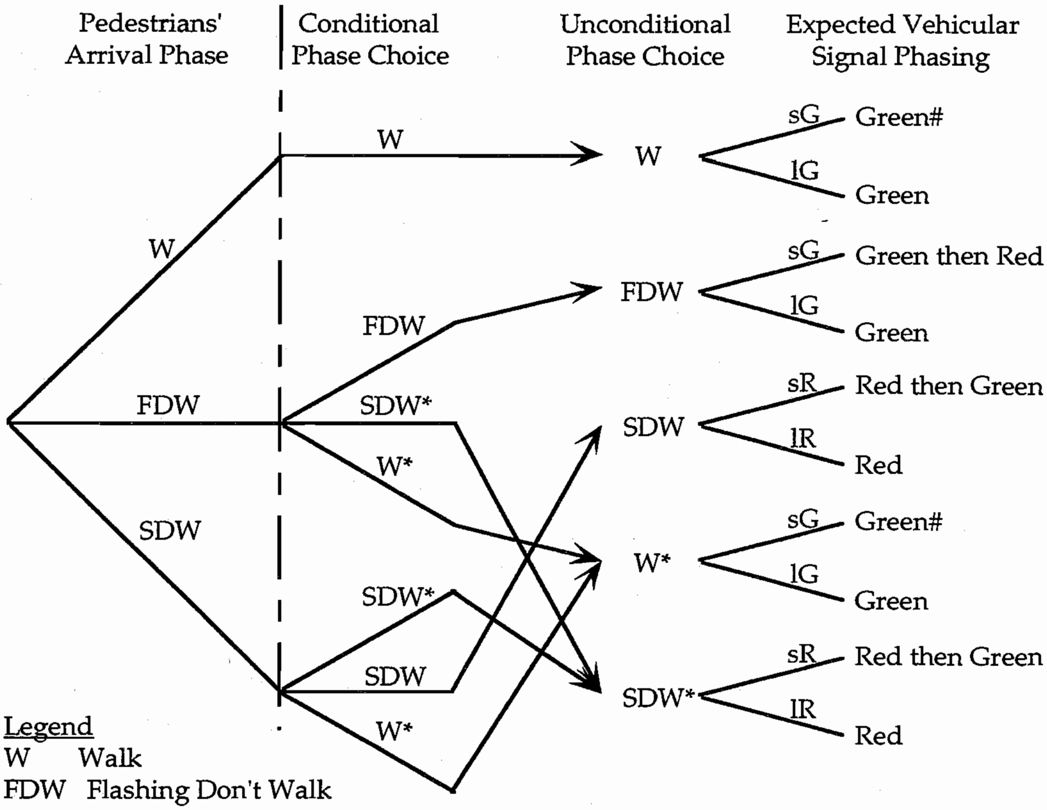


Figure 4.2.4 Four Possible Cases of Compliant and Non-Compliant Pedestrians Crossing Against the Red

The calculation of the percentage of pedestrian crossings expected for each signal indication is modeled using multinomial logit for the choice to cross using the logic illustrated in the case for which the pedestrian signal is present as in Figure 4.2.5a and in the case for which only the vehicular traffic signal is present as in Figure 4.2.5b. In Figure 4.2.5a, pedestrians arrive during the Walk, Flashing Don't Walk, or Steady Don't Walk phase. They can either cross immediately or wait until the desired moment, whether that is when the queue is dissipated or when the desired pedestrian signal phase begins. The logic behind pedestrian crossing choice for vehicular traffic signals without pedestrian signals is similar, but simpler as shown in Figure 4.2.5b because of fewer choices available. Since pedestrian hazards depend on when they cross regardless of when they arrived, an "Unconditional Phase Choice" is calculated by aggregating similar conditional movements as shown in both figures. Finally, the expected amount of hazard for each lane during these unconditional phase choices depends on the length of the vehicular signal phase. For illustration purposes only, the simplified short/long green/red phase designation in both figures shows what signal phasing a pedestrian may face when crossing.

Using a hypothetical percentage of pedestrians expected for each possible case, the aggregation over all compliant and over all non-compliant pedestrians for one direction for a cumulative percentage of pedestrians crossing against the red is shown in Figure 4.2.4. In addition to pedestrians crossing from A to B, pedestrians also cross from B to A, and it is expected that the patterns obtained for the B-to-A direction will be mirror images of patterns obtained for the A-to-B direction. It is also expected that patterns obtained for both compliant and non-compliant pedestrians will be similar, but that non-compliant cases will have flatter but higher cumulative distributions.

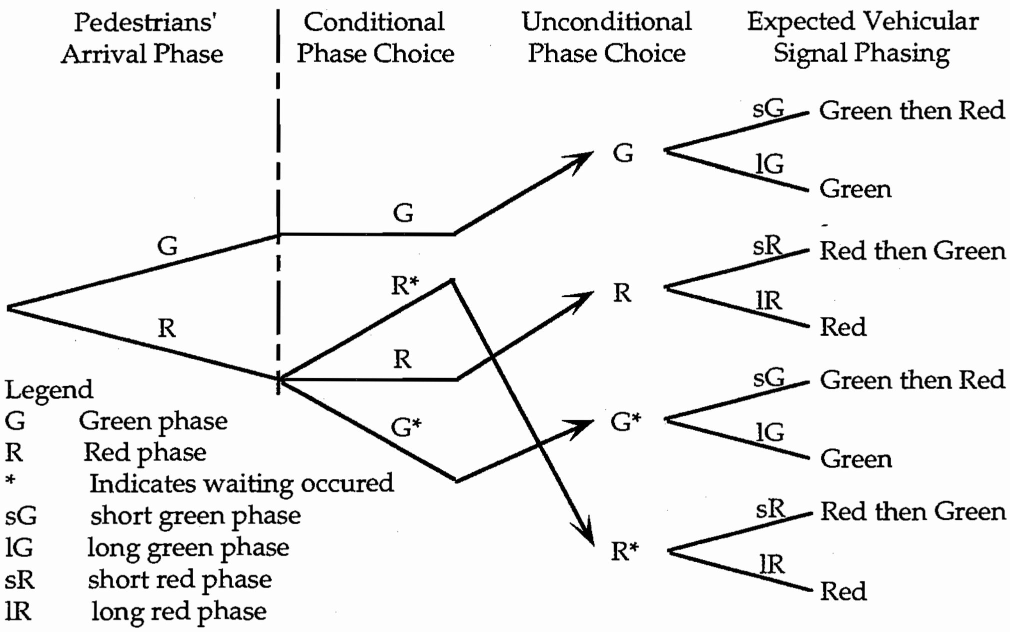


Legend

W	Walk
FDW	Flashing Don't Walk
SDW	Steady Don't Walk
*	Indicates waiting occured (see explanation in text)
sG	short green phase
lG	long green phase
sR	short red phase
lR	long red phase
#	Provided that green phase is sufficent

Note:
"Expected Vehicular Signal Phasing" signifies expected phase or proportion of phase is certain to appear while pedestrian is crossing (and asterisk indicates requirement).

Figure 4.2.5a Pedestrian Signal Model of General Pedestrian Crossing Choice Behavior Conditioned and Unconditioned on Phase of Arrival with General Expected Vehicular Signal Phasing



Note:
"Expected Vehicular Signal Phasing" signifies expected phase or proportion of phase is certain to appear while pedestrian is crossing (and asterisk indicates requirement).

Figure 4.2.5b Vehicular Signal Model of General Pedestrian Crossing Choice Behavior Conditioned and Unconditioned on Phase of Arrival with General Expected Vehicular Signal Phasing

Each PAR zone will be assessed in terms of hazard indexes and accident costs. For each intersection, all PAR zones (combined with hazard indexes, accident costs and compliance rates) will be combined for an overall net safety cost.

If there are more compliant pedestrians when pedestrian signals and/or crosswalks are present, then the safety differences between different traffic control devices can be quite significant. Next, the mathematical development of the different types of PAR is presented, starting with the pedestrian aspect.

Potential Accident Rate Model - Pedestrian Aspect

The potential accident rates are defined as the possibility that a vehicle and pedestrian meet in an intersection. To simplify the concept, PARs are spatially broken down to two levels: 1) the intersection crosswalks, and 2) its lanes. In addition, the PAR is temporally split into the intersection's signal phases. The pedestrian aspect of the PAR is composed of its crossing characteristics which is its crossing rate and arrival rate.

The pedestrian lane crossing time is the width of the lane divided by walk rate. Since pedestrian walk rates are stochastic, they will have a statistical distribution which is identified and tested in Chapter 5. Equation 4.2.1 is presented as an example distribution generator which would create an approximately normal distribution of walk rates.

$$WR = \bar{x}_{wr} + s_{wr} \times (RV) \qquad \text{Eq. 4.2.1}$$

where
WR = walk rate generated from distribution in feet per second
$\bar{x}_{wr}$ = average walk rate in feet per second
s_{wr} = standard deviation of walk rate in feet per second
RV = the random variable (from -3.0 to 3.0)

The probability that a pedestrian will have a walk rate and associated crossing time[3], t_i, which is equal to w/WR (where w is lane width) is $P(t_i)$. It is assumed that pedestrian walk rates (i.e. inverse crossing times) are independent of signal indications[4] (i.e. $P(t_{is}) = P(t_i)$). Using a theorem (Meyer, 1970) for transforming continuous random variables, the distribution for crossing times (assuming that walk rates follow a

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[3] "i" is used to discretize t because the assumed distribution is not integrable
[4] "s" is signal indication

normal distribution) is calculated using the average area under the function's curve as in Equation 4.2.2.

$$f(t) = \left[\left(\frac{w}{t_i^2 \sigma \sqrt{2\pi}}\right) e^{-\left(\frac{w/t_i - \mu}{\sigma}\right)^2/2} + \left(\frac{w}{t_{i-1}^2 \sigma \sqrt{2\pi}}\right) e^{-\left(\frac{w/t_{i-1} - \mu}{\sigma}\right)^2/2} \right] (t_i - t_{i-1})/2 \quad \text{Eq. 4.2.2}$$

where
$f(t)$ = probability that pedestrian has walk time, $(t_i + t_{i-1})/2$
w = lane width in feet
t = average crossing time in seconds in $(t_i - t_{i-1})$ increments
where i is increment number of t distribution
μ = mean walk rate in feet per second
σ = standard deviation of walk rate in feet per second

The pedestrian arrival time is expected to be independent of the intersection geometric and traffic characteristics. A representative statistical distribution for this arrival process is poisson. However, the probability that the pedestrian will cross immediately upon arriving at the intersection is a different problem, dependent on the pedestrian's crossing behavior as well vehicular characteristics (covered in next section).

Vehicular Component of PAR Zones

The other conflict component is vehicle presence. Without this component, PARs between vehicles and pedestrians cannot occur. The vehicle component is affected by six factors: vehicular arrival rate distribution, hourly vehicle volume (for different vehicle movements), green time for vehicles (and queue dissipation time), lane widths, stochastic pedestrian walk rates, and number of lanes.

Theoretically, to obtain the vehicular component of PARs, the expected number of vehicles should be derived from the vehicular arrival distribution. However, a PAR occurs only when at most one vehicle hits a pedestrian. Therefore, instead of using the expected number of vehicles arriving, the number of vehicles is derived from the probability that at least one vehicle arrives (multiplied by one). Thus the number of vehicles for each potential pedestrian is a fraction between zero and one.

This vehicular arrival rate distribution can be any one of many possible statistical distributions. The poisson distribution, as shown in Equation 4.2.3, may be appropriate for suburban intersections because they are commonly isolated, and during many hours have low to moderate traffic volumes. The probability of one or more vehicles arriving in a lane during time t_i is calculated as one minus the probability of zero arrivals. The number of vehicles present is this probability multiplied by one.

$$P(x_{is} \geq 1) = 1 - P(x_{is} = 0) = 1 - e^{-(v_s t_i)/3600} \qquad \text{Eq. 4.2.3}$$

where
$P(x_{is} \geq 1)$ = probability that one or more vehicles arriving in lane
x_{is} = number of vehicles in lane that appears during time t_i
t_i = time in seconds that pedestrian occupies lane
v_s = hourly vehicle volume in lane during signal indication
((vehicle volume per hour) x (cycle duration/phase duration))
"3600" = number of seconds per hour

The presence of one or more vehicles depends on the length of time t_i that a pedestrian occupies the lane under consideration. The fraction of the hour for which the PAR time occurs is largely dependent on the signal phase timing, but can also be dependent on green time remaining after vehicular queue dissipation. Pedestrians typically wait for vehicle queues to dissipate before considering crossing. (In addition, in multiple lane cases, pedestrians usually wait until all lanes have completely dissipated queues; this factor is a function of intersection congestion.) Calculation of time remaining for pedestrians to cross the street is directly dependent on the number of vehicles queued during the red phase, hence, dependent on the hourly vehicle volume, signal phasing, and saturation rate as in Equation 4.2.4 (May, 1988).

$$T_{non\text{-}q} = C - T_q = \frac{((C\text{-}G)/sat)}{1/sat\text{-}V} \qquad \text{Eq. 4.2.4}$$

where
$T_{non\text{-}q}$ = available time for pedestrians to cross (ie. PAR time) in seconds
T_q = red time plus queue time for vehicles in seconds
C = cycle length in seconds
G = green time in seconds
V = hourly vehicle volume converted into vehicle/second
sat = saturation flow rate in vehicles per hour

Combined with the pedestrian component from Section 4.2.2, the expected number of PARs for a particular crossing time per signal indication per lane in a crosswalk is shown in Equation 4.2.5

$$E(PAR/t_i.s.l.c) = [P(x_{is} \geq 1)][1][P(t_i)][N_{sc}] \qquad \text{Eq. 4.2.5}$$

where
$E(PAR/t_i.s.l.c)$ = expected number of PAR for a particular crossing time per signal indication per crosswalk lane
$P(x_{is} \geq 1)$ = probability that one or more vehicles arrive in lane
1 = total number of vehicle arriving (multiplied with $P(x_{is} \geq 1)$ to obtain expected number of vehicles
$P(t_i)$ = the probability that pedestrian will cross lane in t_i seconds
N_{SC} = the total number of pedestrians[5] crossing in the crosswalk for the signal phase

Aggregating over all crossing times for all pedestrians, the probability of a potential accident for a crosswalk lane is shown in Equation 4.2.6.

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[5] Number of pedestrians is influenced by pedestrian group size which is explained in Chapter 5.

$$E(PAR/s.l.c) = \sum_{i=1}^{n} [E(PAR/t_{is}.s.l.c)]\ N_i = \sum_{i=1}^{n} [P(x_{is} \geq 1)][1][P(t_i)][N_{sc}] \qquad \text{Eq. 4.2.6}$$

where
$E(PAR/.s.l.c)$ = expected number of PAR per signal indication per crosswalk lane
N_i = total number of pedestrians crossing during signal indication per crosswalk lane
n = number of t_{is} slots to be summed

The number of pedestrians crossing a crosswalk during signal indication, N_{sc} is calculated through multinomial logit analyses which is presented in the next section. Then, PARs for each lane of each crosswalk of each signal phase must be calculated before being multiplied by the representative hazard cost which is described in the following two sections.

Pedestrian Volume During Signal Phase

The number of pedestrians crossing a crosswalk during a signal indication, N_{sc} is dependent on the phase and cycle durations, probabilities of choosing phases, number of lanes and walk rate distributions.

The calculation begins with the probability of pedestrians arriving during a signal phase which is dependent on the proportion of pedestrians arriving in that phase (Eq. 4.2.7).

$$P[\phi_a] = f_s = (l_\phi)/c \qquad \text{Eq. 4.2.7}$$

where
$P[\phi_a]$ = probability that pedestrian arrives during phase
f_s = the proportion of pedestrians arriving in phase
l_ϕ = phase length
c = cycle length

Since the hazard of crossing depends on the actual pedestrian crossing phase, not the pedestrian arrival phase, the probability of pedestrians crossing during a particular phase (Eq. 4.2.8) is the summation of all conditional probabilities as illustrated through Figure 4.2.5.

$$P[\phi_c] = \sum_{a=1}^{A} P[\phi_c \cap a] = \sum_{a=1}^{A} P[\phi_{c/a}]\, P[\phi_a] \qquad \text{Eq. 4.2.8}$$

where
$P[\phi_c]$ = probability that pedestrian crosses during phase
$P[\phi_c \cap a]$ = joint probability that pedestrian is in certain crossing and arrival phases
$P[\phi_{c/a}]$ = conditional probability that pedestrian crosses during phase given certain arrival phase
a = arrival phases up to A arrival phases

Logit analysis is used to calculate $P[\phi_{c/a}]$ through segmenting data into separate analyses based on pedestrian arrival phase as explained in Section 5.2.

Since the hazard of movement is dependent on whether the movement occurs during the green or red phase, the probability of pedestrians crossing for each lane during the signal indication must be calculated as in Eq. 4.2.9.

$$P[G_l \cap \phi_v] = \sum_{c=1}^{c \in V} P[\phi_{G_l} \cap \phi_c] = \sum_{c=1}^{c \in V} P[\phi_{G_l}/\phi_c]\, P[\phi_c] \qquad \text{Eq. 4.2.9}$$

where
$P[G_l \cap \phi_v]$ = probability that pedestrian crosses lane facing green vehicular signal during particular vehicular signal
$P[\phi_{G_l} \cap \phi_c]$ = joint probability that pedestrian crosses is in certain green signal duration and crossing phase
$P[\phi_{G_l}/\phi_c]$ = conditional probability that pedestrian faces green signal indication during given certain crossing phase
c = crossing phase up to C crossing phases in vehicular signal

Complex processes are used to calculate $P[\phi_{Gl}/\phi_c]$ which depends on number of lanes, pedestrian arrival times, crossing time distributions, lane positions, pedestrian and vehicular signal indications, queue lengths, and start up time. A discretized approach assuming that the pedestrian arrival rate is evenly distributed in the arrival phase is currently used in calculating this probability. Results from this approach are shown in Section 5.2.

Lastly, the number of pedestrians in a crosswalk lane during a vehicular signal indication is shown in Eq. 4.2.10.

$$N_{SC} = P[G_l \cap \phi_V]\, N/4 \qquad \text{Eq. 4.2.10}$$

where
N_{SC} = number of pedestrians in crosswalk for signal indication
N = total number of pedestrians at intersection
"4" is number of crosswalks in intersection

With this number plugged back into Eq. 4.2.6, the number potential accidents can be calculated. The hazard associated with this potential accident is broken down into turning movements, which is explained in the next section.

Hazard Associated with Turning Movements

The cost for pedestrians associated with the lane is calculated as a combination of costs associated with the proportion of left, right, and through vehicular movement encounters as shown in Equation 4.2.11.

$$C_{ls} = \sum_{m=1}^{M} f_{mslc} * \omega_m * w_{lc} * C_B \qquad \text{Eq. 4.2.11}$$

where
M is number of movements
f_{mslc} is the fraction of turning vehicles per signal indication in lane of crosswalk
ω_m is the weight assigned to a vehicular turning movement
w_{lc} is lane width in crosswalk
C_B is the general accident cost per foot of crosswalk per pedestrian (will be discussed in Section 4.2.4)

Since other research studies have indicated that left and right turns are more hazardous than through movements, each lane's hazard index is a combination of the hazard (i.e. weights, ω_m) associated with each movement present in the lane for each approach.

The cost associated with each movement is calculated from hazard indexes and other accident information presented from three research studies. First, Knoblauch et al. (1984) characterized pedestrian hazards based on the exposure measures of 612,395 vehicles and 60,906 pedestrians and associated pedestrian accident data. They calculated hazard scores by computing ratios of the percentage of pedestrian accidents to the percentage of vehicle and/or pedestrian population or vice versa. In keeping the interval scale, they divided the larger percentage by the smaller percentage. Thus, the hazard scores that are greater than 1.0 indicate that pedestrians were exposed to more hazards than normally expected; otherwise these scores are less than -1.0 as shown in Table 4.2.1.

The signs of the hazard indexes in Table 4.2.1 appear reasonable except for the diagonal crossing pattern (although little accident data is known for this maneuver, hence should not be taken for granted). In addition, the hazard indexes show that the turning maneuvers, except right-turn-on-red, are not hazardous.

Table 4.2.1 Hazard Indexes from Knoblauch et al (1984)

Characteristic	Percentage Accidents	Percentage Observed	Hazard Index
Pedestrian Signal Response:		Pedestrians	
With Signal: Green	51.3	90.4	-1.8
Against Signal: Red	46.7	9.6	5.1
Vehicle Action:		Vehicles	
Going Straight	90.0	84.6	1.1
Turning Right	3.8	7.7	-2.0
Turning Left	4.6	7.2	-1.6
Right Turn on Red	1.6	0.5	3.2
Pedestrian Crossing Location:		Pedestrians	
Crosswalk	24.0	54.3	-2.3
Within 50' of Intersection	24.1	9.4	2.6
Diagonally Across Inter'n	0.9	1.7	-1.9
Midblock	51.0	34.6	1.5
		PV Exposure*	
Crosswalks:			
Not Marked	61.2	24.8	2.5
Marked	38.8	75.2	-5.5

Thus, right-turn-on-green maneuvers are relatively safe. However, it is unclear what the circumstances are for the left turns (i.e. whether or not pedestrian movements are allowed during left turn maneuvers). Hence, another study (Zaidel and Hocherman, 1988) found that most studies indicate that turning maneuvers are more hazardous. More specifically, they cited that left turns were noted as three to four times more hazardous than through movements. The exception to this trend was their study in Israel which indicated that left turning maneuvers were safer than through movements only because pedestrians were not allowed when left turns occurred. Using the data presented by Zegeer et al. (1982), the turning maneuvers were recalculated using 15% and 20%[6] of movements as left and right turns, respectively. With this modification, the following hazard indexes were obtained as shown in Table 4.2.2.

Table 4.2.2 Modified Hazard Indexes

Characteristic	Percentage Accidents	Percentage Observed	Hazard Index
Vehicle Action:		Vehicles	
Going Straight	61.4	65.0	-1.1
Turning Right	14.8	19.5	-1.3
Turning Left w/ Peds	22.5	15.0	1.5
Right Turn on Red	1.6	0.5	3.2

For this research, these hazard indexes must be further modified to allow direct comparisons between different vehicular streams. Meaning that, all hazard index ratios are created by dividing the percentage of the accident population by the exposure population. Thus, all hazard indexes are positive, and some may be less than 1.0 as shown in Table 4.2.3.

Hence, the hazard indexes for the turning movements from Tables 4.2.3 are reflective of the expected turning movement hazard. Similar modifications to the other hazard indexes in Table 4.2.1 were made.

Table 4.2.3 Modified Hazard Indexes to be used in Models

Characteristic	Percentage Accidents	Percentage Observed	Hazard Index
Vehicle Action:		Vehicles	
Going Straight	61.4	65.0	0.9
Turning Right	14.8	19.5	0.8
Turning Left w/ Peds	22.5	15.0	1.5
Right Turn on Red	1.6	0.5	3.2

[6] Zaidel mentioned that turning movements represent 15-25% of all movements.

Cost Estimates for Conflicts

To obtain the cost of each pedestrian movement, a general accident cost, C_B, per foot of crosswalk is calculated. Three different sources of information were used for a rough estimate of pedestrian accident costs as shown in Table 4.2.4. Since all cost estimates are not current, two inflation factors were applied, one is to reflect the typical engineering inflation factor - 8%, and the other resembles the medical costs' inflation factor more accurately - 12%.

Table 4.2.4 General Pedestrian Accident Costs (in Thousands)

		Inflation Rates	
Source of Information	Year	12%	8%
NHTSA (Biotech)	1971	$366	$153
AASHTO (R & C)	1981	$112	$ 67
NSC (Zegeer & Deen)	1974	$ 87	$ 40

Based on pedestrian accident fatality rates of 6.6% in 1971 (Biotechnology, 1973) and 5.9% in 1992 (1992 Traffic Safety Statistics Report), these estimates were obtained by using a 6% fatality rate. The National Highway Traffic Safety Administration's estimate was based on motor vehicle costs, and it appears to be too high. The other sources of information are more similar and appear to be closer to what is expected.

The number of accidents expected for a signalized intersection with less than 1200 pedestrians per day is 0.12 pedestrian accidents per year (Zegeer, 1982). If we assume that a typical suburban intersection has two approach lanes in each direction (i.e. four 12-foot lanes plus two extra feet), the total crosswalk length for a typical intersection is 200 feet (i.e. the sum of all four crosswalks). Using The City of Austin's pedestrian volume base as typical for a suburban-like environment, the average daily pedestrian volume (conservative estimate) at a typical intersection is 150. If we use AASHTO's pedestrian accident cost estimate at a medical inflation rate of 12%, then with all of these factors multiplied, the cost of an accident per person per foot in crosswalk at an intersection is (\$112,000/acc't/year)* (0.12acc't/yr/int) / (150ped/day/int * 200ft/int * 365days/yr) = \$0.0012 per pedestrian crossing per foot of crosswalk. However, not all pedestrians cross at times that are hazardous; in fact, nearly 70% of pedestrians cross when the light is green. Therefore, the cost of a PAR is 1/(1 - 0.70)(\$0.0012) = \$0.004 per potential pedestrian accident per foot of crosswalk. For example, a PAR for one pedestrian for a typical intersection approach (i.e. 50 feet wide) costs 20¢ .

$$E(\text{hazard}) = [E(PAR)][C_{ls}] = \sum_{c=1}^{C}\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{i=1}^{n}\sum_{m=1}^{M}[P(x_{is} \geq 1)][1][P(t_i)][N][(f_{mslc})(\omega_m)(w_{lc})(C_B)]$$

Eq. 4.2.12

where
L is the total number of lanes
C is the total number of crosswalks
S is the total number of signal indications

Combining Equation 4.2.10 with Equation 4.2.11, the total hazard cost for the intersection is obtained in Equation 4.2.12.

Summary

With this hazard cost, the delay and equipment cost is integrated to determine when pedestrian signals are not beneficial. The results of the testing and integration as well as preliminary examination of the fundamental questions underlying pedestrian signalization are addressed in Section 5.4. Next, the model for determining pedestrian volume input is described.

PEDESTRIAN DELAY

Introduction

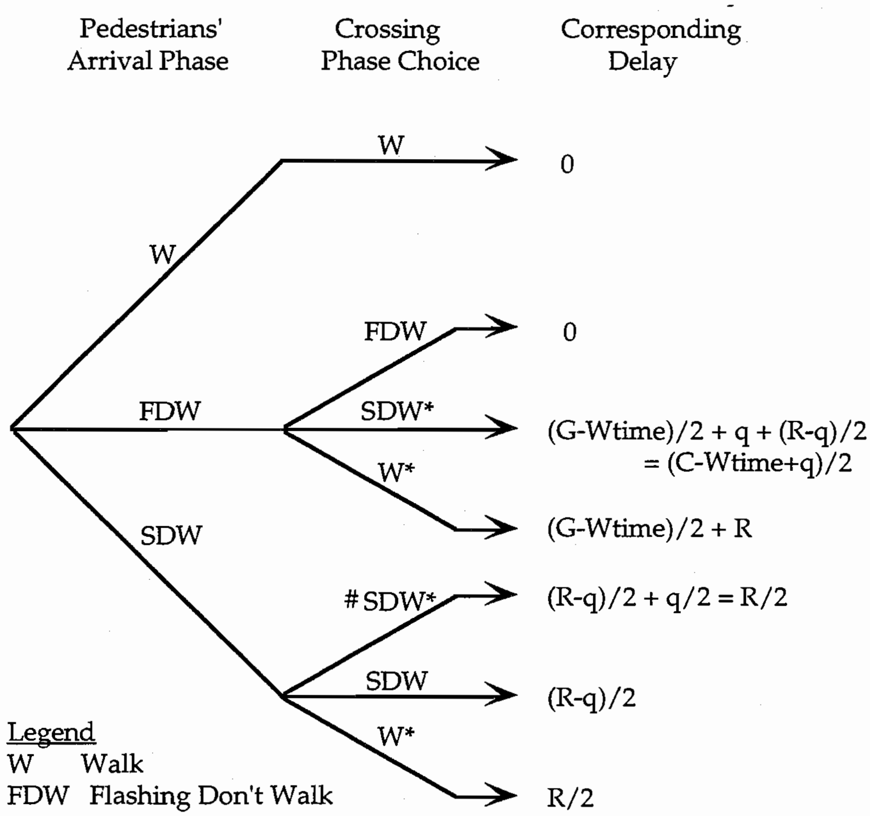
Like vehicles, pedestrians incur delay at intersections. However, the delay is not solely caused by signalization only. If all pedestrians did comply with signalization, then formulating delay would be nearly straightforward because signalization would be dictated mostly by vehicular traffic and pedestrian crossing time requirements. In actuality, some pedestrians comply with signals while other cross whenever an available gap exists. The framework allows the estimation of pedestrian delay and assessment of the relative merits of different pedestrian accommodation strategies.

This framework is developed on the basis of signalization sceme developed in Section 4.1 and compliance theory developed in Section 4.2.1's Potential Accident Rate Theory. It is adapted here to illustrate the effects of compliance and signalization.

Pedestrian Delay

Pedestrian delay times for the three possible pedestrian signalization conditions are examined. Fixed-time pedestrian signals may force longer cycle lengths to allow pedestrians to cross in compliance with signals and allow pedestrians experience less delay. Pedestrian-actuated pedestrian signals may also force longer cycle lengths when a pedestrian phase is called, but also allow pedestrians to cross with the green phase. Intersections without pedestrian signals do not consider pedestrian requirements, and pedestrians may experience delays and increased non-compliance.

Figure 4.3.1a illustrates pedestrian delay when confronted with either fixed-time or actuated pedestrian signalization. As no pedestrians need to wait when facing the steady WALK indication, there is no delay. Pedestrians arriving during the flashing WALK indication, have to make choice to whether to wait or cross immediately and some may choose to comply, further increasing their delay. Pedestrians arriving during the DONT WALK indication usually have delay especially during the queue dissipation period.



Legend
W Walk
FDW Flashing Don't Walk
SDW Steady Don't Walk
* Indicates required waiting
# Arrival during queue dissipation period
G Green phase length
R Red phase length
C Cycle length
Wtime "Walk" time
q queue dissipation time

Figure 4.3.1a Pedestrian Delay Expectation Model due to Vehicular and Pedestrian Signals

Figure 4.3.1b illustrates pedestrian delay when confronted with no pedestrian signalization. As with WALK indication, usually no pedestrians facing the green need to wait. Pedestrians arriving during the red phase have to make similar choice decisions as pedestrians arriving during DONT WALK; they usually have delay especially during the queue dissipation period.

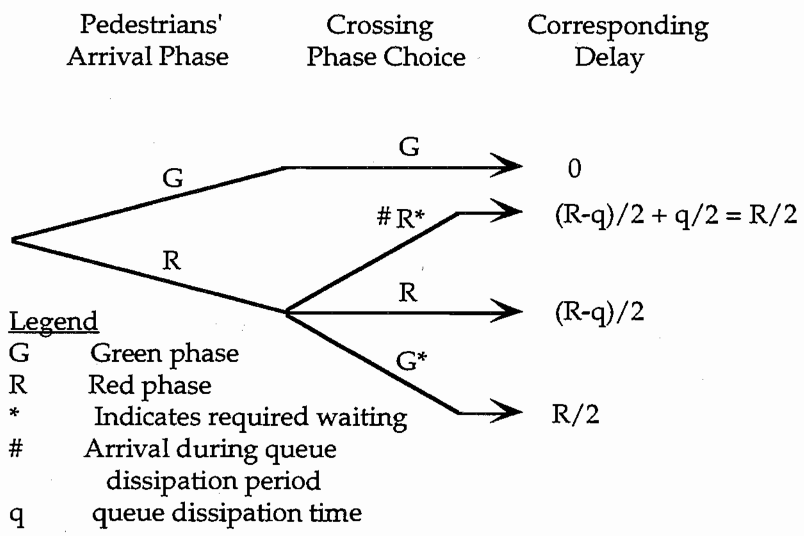


Figure 4.3.1b Pedestrian Delay Expectation Model due to Vehicular Signals Only

The information for the probabilility that pedestrians will comply or not comply is the same probabilities described in Section 4.2.1. In addition, the probability of arrival is similarly characterized.

Summary

Pedestrian delay formulation is essentially a composite of vehicular and pedestrian signalization and pedestrian compliance characteristics. Section 5.2 describes the outcome of the logit probabilites describing pedestrian compliance, and Section 5.3 describes the outcome of the pedestrian delay models along the vehicular delay results.

PEDESTRIAN GENERATION RATES

Introduction

With low pedestrian flows, the delay savings benefits of pedestrian-actuated over fixed-time pedestrian signals are more apparent. Hence the focus of this effort is to determine when and where intersections have these relatively low pedestrian generation rates. Since most pedestrian generation rate studies have been conducted in downtown or relatively high density areas, those results are not readily applicable to this study. Hence, the purpose of this section is to identify mathematical relationships between pedestrian generation rates and predictor rates for pedestrian signalization purposes.

This section starts off with theory behind pedestrian generation rate development. From this, a classification scheme for determining pedestrian volume is described and illustrated. Finally, a summary is given in the last section.

Pedestrian Generation Rate Theory

This section presents the theory behind pedestrian generation rates which has two components: 1) the definition development of pedestrian generation rate, and 2) the determination of peak-hour and non-peak hour pedestrian generation rate.

Definition Development of "Pedestrian Generation Rate"

Figure 4.4.1 illustrates the overview of the definition-development of "pedestrian generation rate." The term, pedestrian generation rate, is not used similarly as in vehicle generation rate studies where the demand for parking spaces generally depends on the size of the building (e.g. square area, number of chairs). The demand for the "WALK" indication of pedestrian signals does not depend on the size of the building as much as it depends on the "mix" and

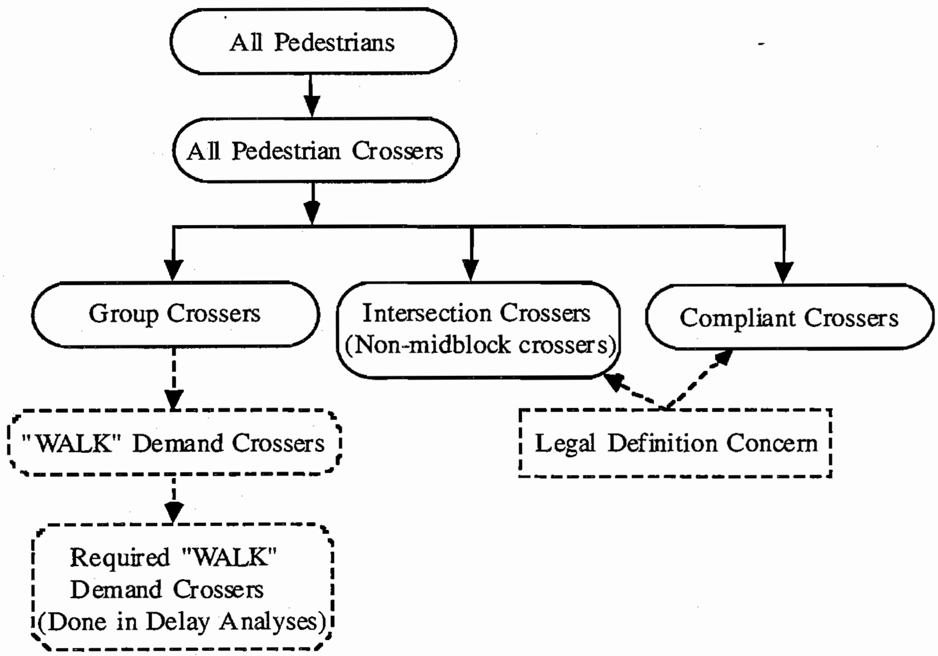


Figure 4.4.1 Definition Development of Pedestrian Generation Rate

"distribution" of buildings on opposite sides of streets. At a basic level, pedestrians who need pedestrian signals are those who cross streets. This demand is due to the need to get from one site to another site which are separated by street(s). A more appropriate name would be "pedestrian crossing rate."

It appears that those who need pedestrian signals are those who cross at the intersection, not those who cross at midblock. It is arguable to state that those who cross at midblock should not be included in the pedestrian generation rate. However, pedestrians are obliged to cross at intersections. Also, many pedestrians who arrive at the intersection cross at their convenience (by disobeying signals) whenever they can shorten their walking time. Again, one might argue that these pedestrians do not need pedestrian signals and should not be included in the pedestrian generation rate. In both types of non-compliance, it is difficult to prove that all non-compliant pedestrians do not need pedestrian signals; hence, at this point, all crossers are included in the pedestrian generation rate.

Furthermore, if a group of pedestrians arrive and cross at the intersection together, their crossing time should be no different than a single pedestrian's crossing time. For example, for a group of three pedestrians arriving and crossing together, three different crossing times will not be required, just one. In fact, Palamarthy's behavior analysis (1993) found that if pedestrian arrivals are in groups, the behavior among individuals within a group is correlated because of interactions among them. Hence, each group can be treated similarly as a single demand unit; however, "pedestrian group crossing rate" is more useful for actuated signal analysis rather than for crossing analysis.

If pedestrians cross on opposite sides of the road at nearly the same time, they may also demand the same pedestrian WALK indication. For example, if a pedestrian chooses path "14" and another chooses "23" at the same time (see Figure 4.4.2), both demands can be handled in one pedestrian WALK indication. In this respect, "pedestrian group crossing rate" is more accurately named as "pedestrian WALK[7] demand rate."

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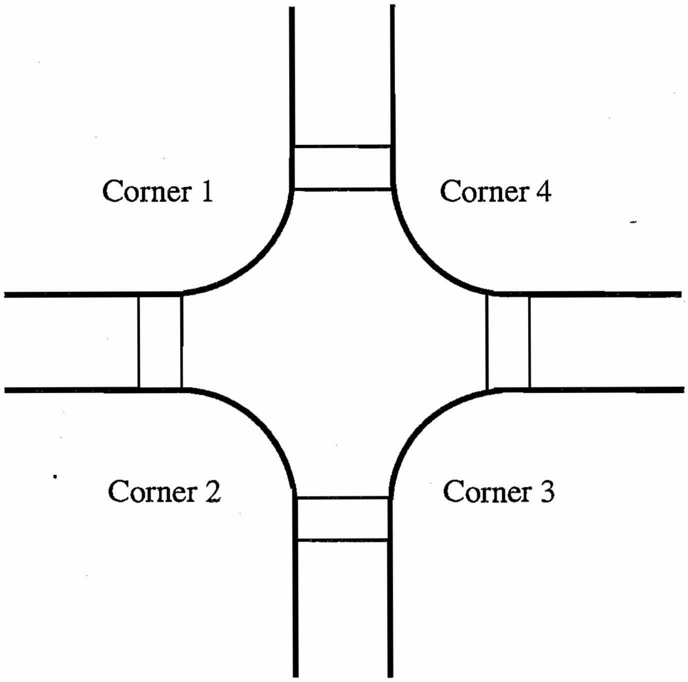
[7]WALK and WALK-indication have the same meaning.



Note: For this typical intersection, a pedestrian who arrives to corner two and crosses to corner three, his path is labeled as "23."

Figure 4.4.2 Typical Intersection Layout with Labeled Corners

In a more complex scenario, one street may have sufficient green time, but the other street does not. The "pedestrian WALK demand rate" then becomes the "required pedestrian WALK demand rate." Both "pedestrian WALK demand rate" and "required pedestrian WALK demand rate" require the knowledge of cycle length and pedestrian crossing time to determine when the WALK indication is needed. However, this approach requires knowing the exact arrival rates of pedestrians with respect to the variation of signal timing plans. Instead, the demand for WALK indications is modeled into the delay framework presented in Section 4.1; hence, the focus is on "pedestrian crossing rate."[8]

Pedestrian Generation Rate Analysis: Peak-hour vs. Non-Peak Hour

With the definition of pedestrian generation rates, the next step is the examination of crossing patterns over time, particularly with respect to peak hours. At the simplest level, pedestrian volume peak-hour can be defined similarly as vehicular peak-hour. However, this approach can lead to inaccurate peak-hour description(s) of pedestrian volume. While street network performance is dependent on vehicle volumes, they are relatively unaffected by pedestrian volumes. Vehicular traffic is confined to streets because of vehicular dynamics, and street networks are often operated near capacity during peak-hour. Pedestrian traffic, on the other hand, have more degrees of freedom in movement, occupy less space in street networks, and have unlimited capacity (unless perhaps in downtown areas). Also, vehicle drivers are affected by latent demand (i.e. the spreading of the peak-hour of vehicular traffic), but pedestrians are not necessarily affected (unless they are also vehicle drivers in the same trip). Because of these differences in vehicular and pedestrian traffic, peak pedestrian volumes do not need to be defined similarly as the vehicular traffic's peak hour.

In addition, the time-frame for which peak pedestrian volume occurs does not need to be restricted to a one-hour period. Peak volume of pedestrians may occur during a few minutes or several hours. However, with few sites for peak-period measurements, the peak-period should not be less than one hour for two reasons: (1) statistical significance is problematic for short peak periods, and (2) the other non-peak period(s) of the day would outweigh short peak

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[8]For the rest of the section, the term "pedestrian generation rate" will be used for simplicity.

period(s) in cost/benefit analyses. The time length of each peak period is determined through regression analyses based on land use and other factors described in the next section.

When a potential peak-period is detected, its significance must be proven in two tests: (1) the peak-period must have a rate equal to or higher than a pre-specified reasonable number of pedestrians per hour, and (2) it must be significantly different from the non-peak pedestrian period(s). A minimum pre-specified number of pedestrians is necessary to prevent low peak-period volumes from occurring and it is determined by examining actual pedestrian volumes presented in the next chapter.

If a site does not have a peak period, the average rate (over the data collection time) is used instead. Two regression analyses are performed using peak and non-peak rates. Where there is no peak or non-peak rates, average rates were used.

Hence, in this section, the pedestrian generation rate has been defined as "pedestrian group crossing rate." In addition, peak-hour, non-peak hour, and average pedestrian generation rates were defined. The independent variable for classifying signalized intersections is presented and illustrated.

Classification Scheme

Previous pedestrian volume studies have used different predictor variables for which those using land use showed the most promise. In practice, generation rates based on land use are commonly used for vehicular trips as in the ITE trip generation rate manual (ITE, 1983). However, very few studies have examined pedestrian generation rates, especially based on land use in suburban areas.

Hence, many different land use variables were examined to determine how pedestrian generation rate predictor relationships could be developed. Based on these previous studies, a concern for developing pedestrian generation rates based on land use is transferability. In addition, a larger concern is the methodology development that would be understandable, quantifiable, and applicable.

Although the pedestrian generation rate depends on the mix and distribution of buildings on opposite sides of streets, having an intensive classification scheme of variables reflecting this distribution would be far beyond usefulness. In that sense, using land use surrounding the intersection is perhaps the easiest classification scheme that is most understandable, quantifiable, and useful.

Therefore, a data collection methodology was designed using a stratified random sampling technique based on land-use. This approach serves a dual purpose for the following reason. One objective of the data collection was to obtain pedestrian generation rate information, and land-use is a strong explanatory variable. Also, land-use is an exogenous factor to behavior, and it thus would allow unbiased estimation of safety parameters for Section 5.2. The sampling strategy also allows for a comparison study by not precluding intersections from any specific category.

Land-use surrounding a candidate intersection was divided into two concentric zones as shown in Figure 4.4.3. The first zone is defined by a circle of quarter-mile radius which is the typical pedestrian walking distance. The second zone is a circle of one-mile radius, not including the first zone. It is used to account for inter-zonal trip activity levels.

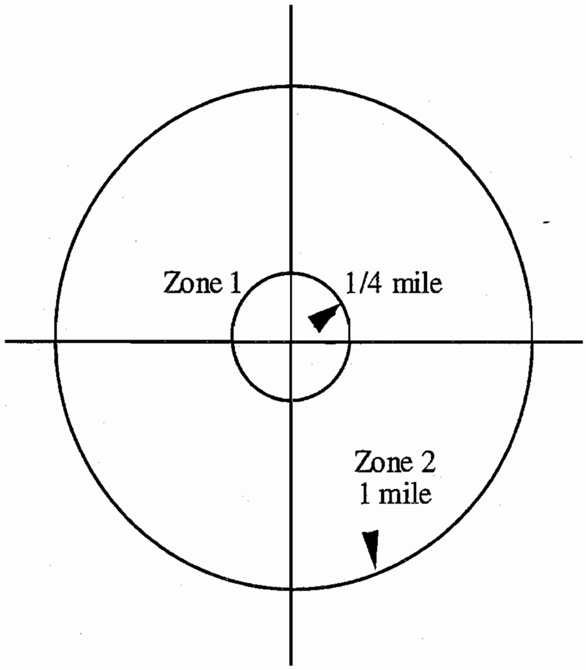

Figure 4.4.3 Zonal Demarcation of Land Use at the Intersection

As most sites have a mixture of land-use, the dominant pedestrian generating land-use type was used to classify the intersection. Different categories were assigned on the basis of quarter- and one- mile characteristics. Five land-use types for the quarter-mile zone and four for the one-mile zone are identified as shown in Table 4.4.1. Though the mixture of land use is important, due to combinatorial effects, a hierarchical system is used to simplify classification. They are listed in ascending order of dominance.

Table 4.4.1 Land Use Type for Zones 1 and 2

Quarter-Mile Zone	One-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 quarter-mile zone, buildings for residential and other living purposes, and vacant land is 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 with large numbers of people accessing them by foot.

For the one-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 the quarter mile zone.

As an example application of the classification design, Figure 4.4.4 illustrates a case for which there is minor retail in the quarter-mile zone and commercial land use in the one-mile zone. As shown, there are other land uses in the zones, but the dominating land use is the principle criterion for classifying the intersection's land use variables.

If the intersection under study is in a sparsely populated area, as in rural areas, the one-mile land-use zone will most likely fall into the residential land-use category.

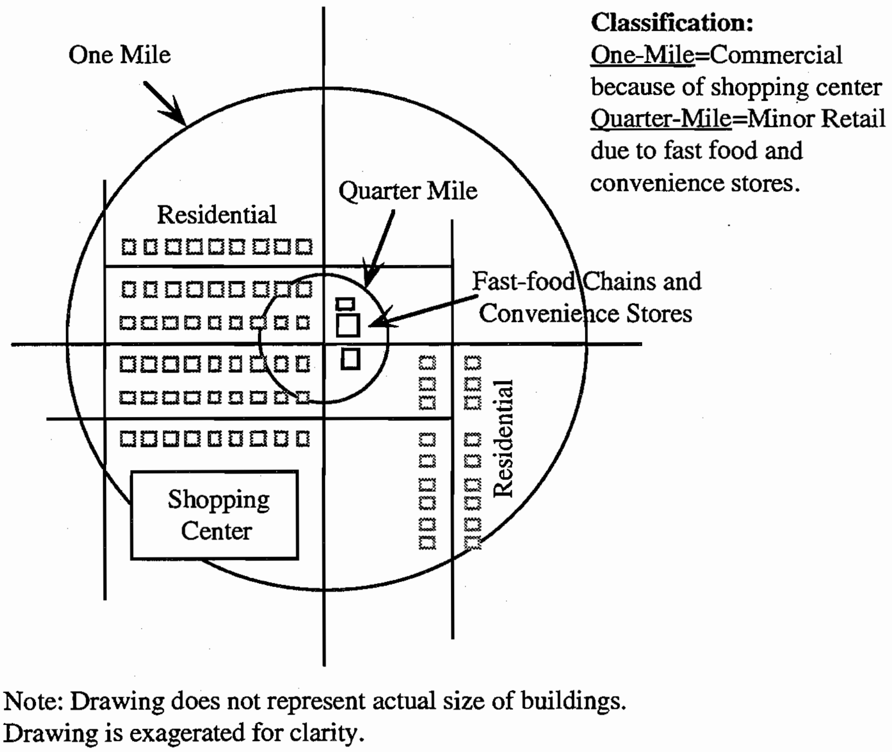

Figure 4.4.4 A Case Study: Minor Retail in the Quarter-Mile Zone and Commercial Land Use in the One-Mile Zone

Summary

Expected pedestrian volume patterns at signalized intersections was described for both peak and non-peak periods. In addition, useful predictor variables based on land use was briefly described and illustrated.

SUMMARY

From this theoretical framework, the pedestrian generation rate, pedestrian delay and safety and vehicular delay concepts were presented. The results and implications from the data collection and further analyses are presented in the next chapter.

CHAPTER 5. MODELING RESULTS

INTRODUCTION

Using the models developed in Chapter 4, data were obtained to determine the results of the pedestrian generation rate and compliance characteristics as well as the overall results of pedestrian signalization.

PEDESTRIAN GENERATION RATE

Introduction

The 20 land-use combination methodology presented in Section 4.3 to the City of Austin was applied to initially test the procedure's robustness as well as the city's land use proportion. After the data was collected, statistically analyses were conducted to determine the final robustness of the procedure for which minor adjustment were made and regression analyses were done.

Application of Data Collection Methodology

In order to test the robustness of the procedure, the methodology was applied to intersections in the City of Austin, Texas. The city has approximately 500 traffic-signalized intersections, of which about 200 were selected from all geographical regions (e.g. northwest Austin). They were classified based on a priori knowledge, with the aid of a map, and in some cases, a visit to the intersection. On a map of Austin, most of the major commercial centers, institutions, and recreational facilities are clearly marked and could be identified with ease. The distribution of the intersections from this design procedure is shown in Table 5.1.1. For purposes of the survey, a site from each subset was randomly selected. Since the object of this data collection was also to obtain information on the distribution of pedestrian crossings over time, each site was surveyed for a duration of five to six hours.

Table 5.1.1 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)

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 higher data credibility. The video with time recorder was setup at one intersection corner and was operated only when a pedestrian was crossing.

Pedestrian events (e.g. walking times) were measured using a continuous time-event recorder. With this instrument, time intervals between events could be measured to an accuracy of 0.1 second. The time intervals are recorded similarly in the manner that stopwatches record events except that it stores up to 30 time intervals.

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 5.1.1 illustrates the procedure.

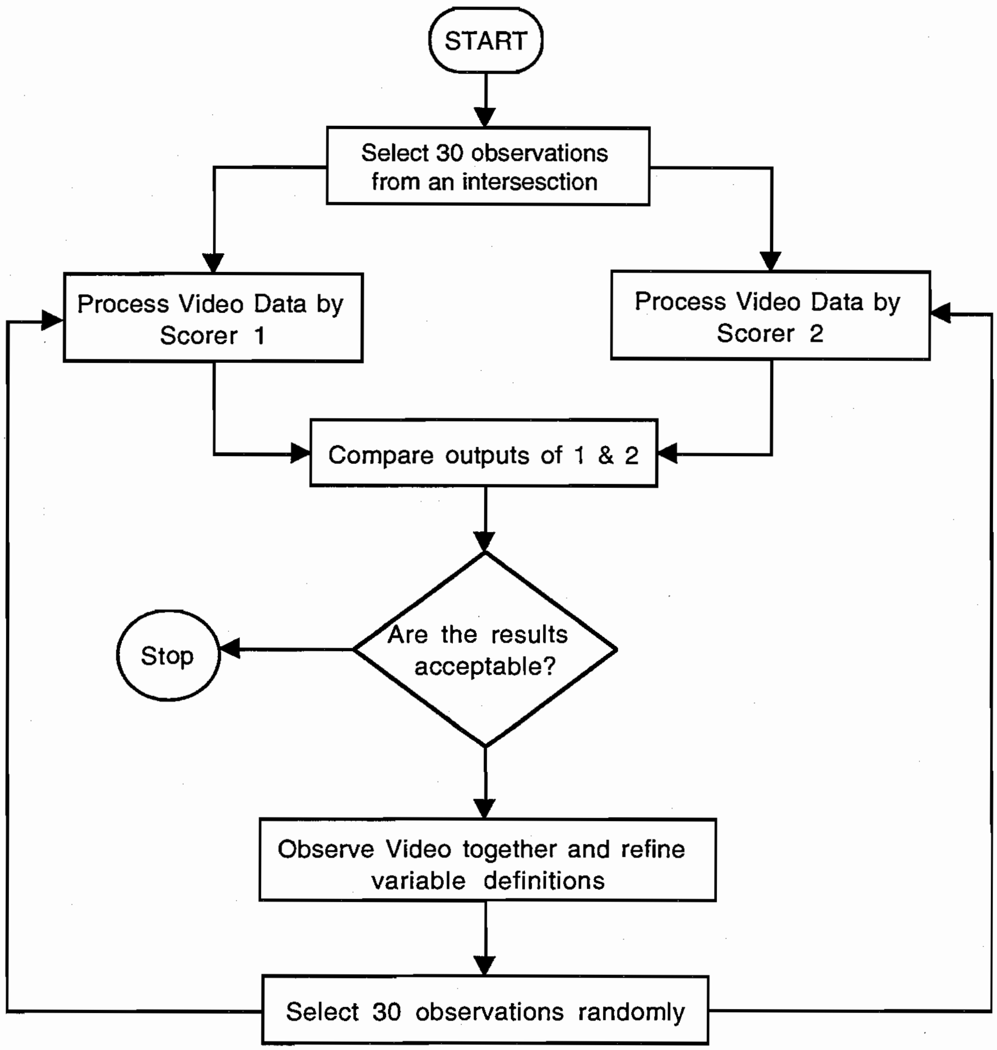

Figure 5.1.1 Inter-Scorer Data Reliability Procedure

Preliminary Statistics

As described in Section 4.3.2, the methodology for choosing sites included a two-tier classification. The dominant land use in the 1-mile radius included residential, commercial, institutional, and recreational areas. The dominant land use in the quarter-mile radius included residential, minor-retail, major-retail, institutional, and recreational areas.

The pedestrian generation rate derived is not simply pedestrian volume over time. As explained in the last section, 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 generation 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 quarter-mile land use is presented in Figure 5.1.2. 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 any other category.

The average 15-minute pedestrian count for the 1-mile land use is presented in Figure 5.1.3. As shown, the residential land use appears to generate a very small number of pedestrian trips. In contrast, the three other land uses generate three to four times more.

Figure 5.1.4 shows the results of all land uses combined over the period during which the data was 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 5.1.5). 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 5.1.5) for each land use (within the quarter-mile) period is shown in Figure 5.1.6. The most evident feature is the high volume of pedestrians generated from the institutional land use, which also shows a prominent lunch hour. It also appears to peak in the evening, but this peak is not as high as the morning. Although its morning peak hour appears visible, its peak is not much higher than 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 rather constant during the day.

The hourly distribution for each land use (in a one-mile radius) over the time period for the one-mile land use is shown in Figure 5.1.7. 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 mixed between the commercial and institutional land use.

The results from the quarter and one-mile land uses were heavily influenced by sites that have high pedestrian volumes. For instance, the site with the highest pedestrian generator in the one-mile recreational land use had an institutional land use in the quarter-mile radius; based on visual inspection at the site, it appears that this quarter-mile land use appeared to have more influence than its one-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 land use categories. In the next section, data collection for this exploration is described.

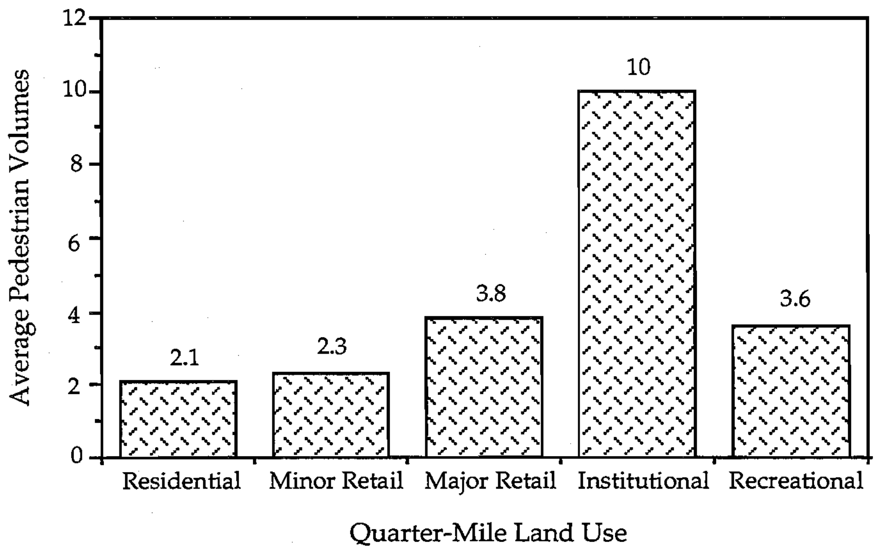

Figure 5.1.2 Average 15-Minute Pedestrian Volumes by Quarter-Mile Land Use

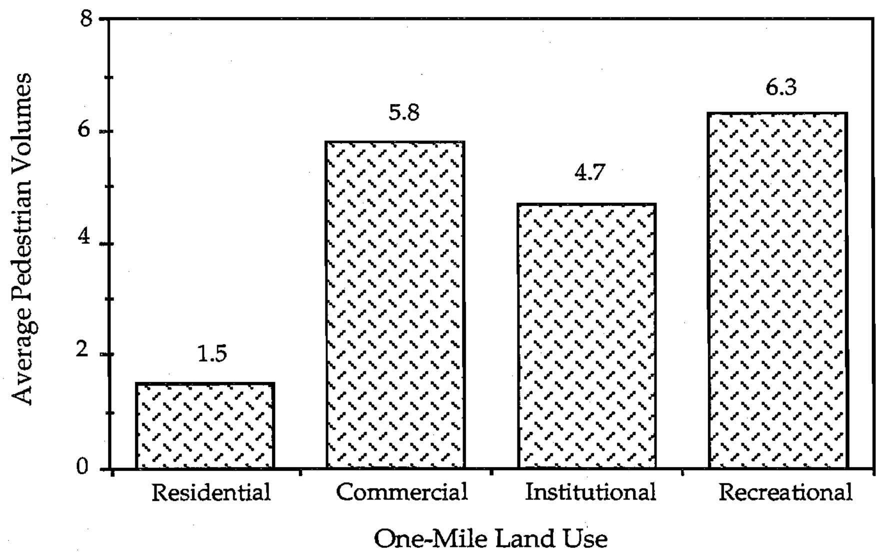

Figure 5.1.3 Average 15-Minute Pedestrian Volume by One-Mile Land Use

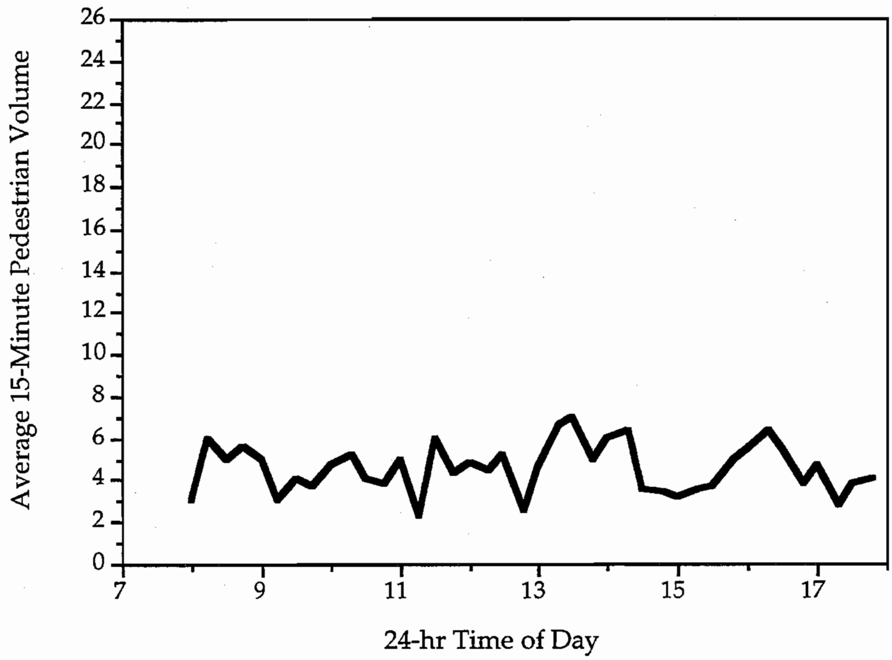

Figure 5.1.4 Average 15-Minute Pedestrian Volume over all Land Use

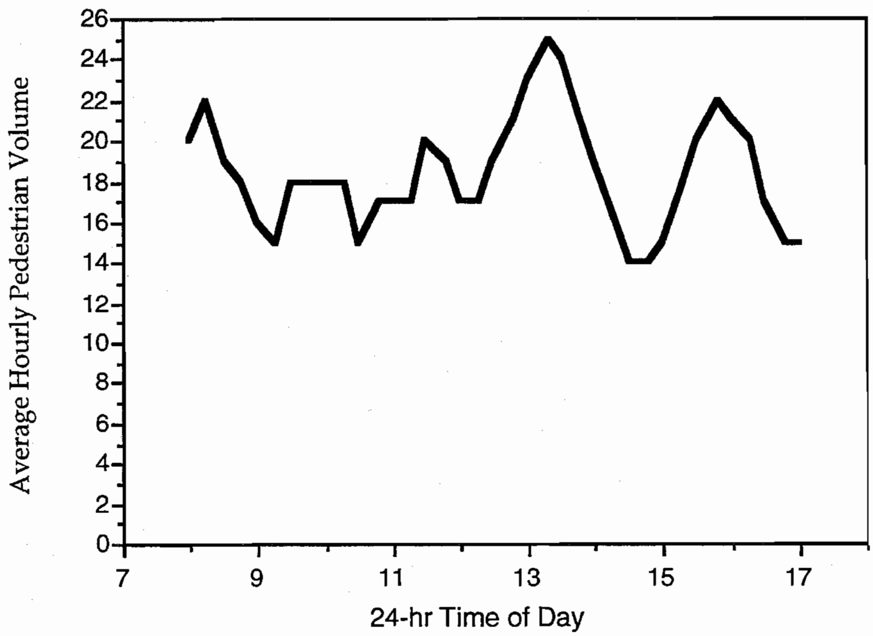

Figure 5.1.5 Average Hourly Pedestrian Volume over all Land Use

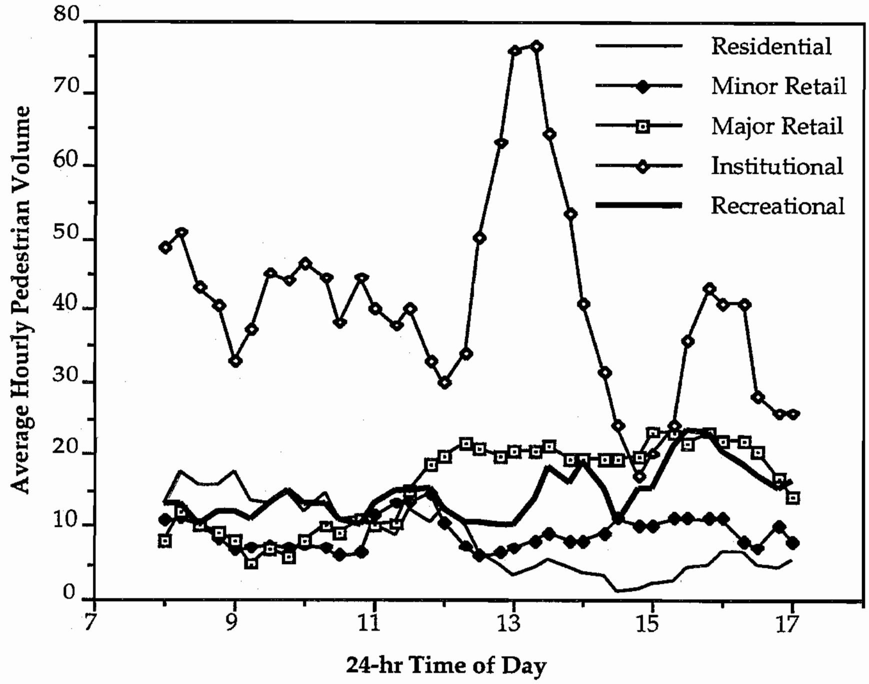

Figure 5.1.6 Average Hourly Pedestrian Volumes by Quarter-Mile Land Use

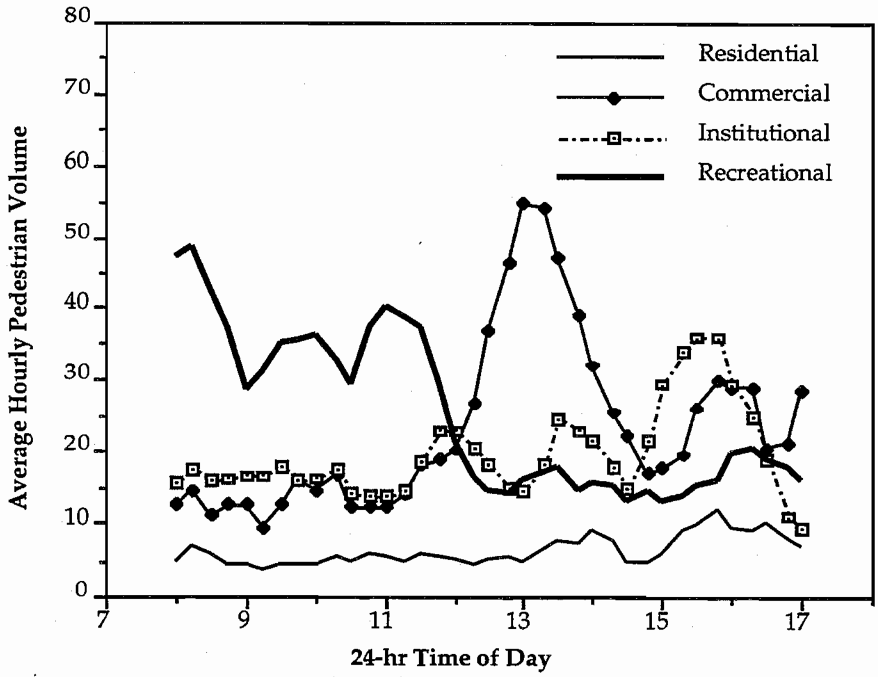

Figure 5.1.7 Average Hourly Pedestrian Volumes by One-Mile Land Use

Results of Pedestrian Generation Rate Regression Analyses

Thus through numerous regression analyses, it was found that land use is the strongest indicator of pedestrian volumes. Hence, the analysis on pedestrian volume predictor variables is focused on the quarter-mile and one-mile land use variables.

The order of the quarter-mile land uses by increasing mean pedestrian generation rate is listed as the following:

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

However, there is considerable variability that cannot be explained by one dominant quarter-mile land-use characteristics. Unexplained variability in the pedestrian generation rate for the quarter-mile radius is due to 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. Second, the presence of a retail establishment across a street from a land use with many people that have little auto access, particularly high school students at lunch hour, causes many people to cross the street. These two factors are similar to reasons of high pedestrian generation rates in downtown areas; therefore, these two sites were excluded from further analyses to prevent their influence from distorting regression analyses on low pedestrian volumes.

Based upon experience with variability in the quarter-mile land use, experimentation was performed on the one-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 land use effect. Without these sites, the modified one-mile land use form is in the following order of increasing mean generation rate:

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

This approach allowed the basic variability to be explained more accurately by the one-mile land use which 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 high R-squares.

The method of determining the pedestrian generation rates based on land use is the separation of peak hour(s) from the non-peak hours. Table 5.1.2 shows specifications for the prediction of peak hour and non-peak hour volumes. The models apply to intersections without major parking and without school/commercial interaction; hence, low pedestrian volumes can be predicted with these models.

Table 5.1.2: Models For Pedestrian Generation Rates

Variable Name	Peak Model (ped/hour) coefficient (t-stat)	Non-Peak Model (ped/hour) coefficient (t-stat)
Constant	19.26 (7.45)	6.30* (3.89)
1/4-Mile Res.& Minor Retail LU	-10.38 (-3.97)	
One-Mile Res. Land Use	- 8.40 (-2.53)	
One-Mile Institutional Land Us	11.82 (3.87)	11.22 (4.31)
Number of Observations	18	18
Significance of F-statistic	.000	.001
Adjusted R-Squared	.760	.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 0.6.

From the peak and non-peak hour generation rate regression models, the reuslting 15 land-use combination is illustrated in Table 5.1.3. These rates and times are used in the analyses in Section 5.3.

Table 5.1.3 Pedestrian Generation Rate for Land Use Combinations

One Mile Land Use	Quarter-Mile Land Use	Peak PGR	Peak Hours	Non-Peak PGR	Non-Peak Hours
Residential	Residential	-	-	0.60	7am-11pm
Residential	Minor Retail	-	-	0.60	7am-11pm
Residential	Recreational	10.86	4pm-5pm	6.30	7am-4pm, 5pm-11pm
Residential	Major Retail	10.86	12pm-4pm	6.30	7am-12pm, 4pm-11pm
Residential	Institutional	10.86	4pm-5pm	6.30	7am-4pm, 5pm-11pm
Commercial/ Recreational	Residential	8.88	8am-12pm	6.30	7am-8am, 12pm-11pm
Commercial/ Recreational	Minor Retail	-	-	6.30	7am-11pm
Commercial/ Recreational	Recreational	19.26	4pm-5pm	6.30	7am-4pm, 5pm-11pm
Commercial/ Recreational	Major Retail	19.26	12pm-4pm	6.30	7am-12pm, 4pm-11pm
Commercial/ Recreational	Institutional	19.26	4pm-5pm	6.30	7am-4pm, 5pm-11pm
Institutional	Residential	20.70	8am-12pm	17.52	7am-8am, 12pm-11pm
Institutional	Minor Retail	-	-	17.52	7am-11pm
Institutional	Recreational	31.08	4pm-5pm	17.52	7am-4pm, 5pm-11pm
Institutional	Major Retail	31.08	12pm-4pm	17.52	7am-12pm, 4pm-11pm
Institutional	Institutional	31.08	4pm-5pm	17.52	7am-4pm, 5pm-11pm

SAFETY AND BEHAVIOR ANALYSES

Behavior Analysis

A descriptive analysis was conducted to study the basic compliance characteristics of pedestrians for intersections with and without pedestrian signals. This approach illustrates when signalization benefits occur.

Data from different intersections are pooled depending on the presence or absence of a pedestrian signal as well as which phase pedestrians arrived on as explained in Section 4.2.2. A total of 712 and 231 intersection crossings were observed at signalized and unsignalized intersections, respectively. The number of arrivals and crossings on each signal indication are reported in Table 5.2.1. 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 (FDW) cross immediately, and only a small fraction wait for WALK indication.

Table 5.2.1 Arrivals And Crossings At Signalized And Unsignalized Intersections

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

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

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

Results of Logit Modeling of Compliance Rates

The understanding of pedestrian compliance as outlined in Chapter 4 begins with multinomial logit analyses of pedestrian response to signalization. As explained, pedestrian compliance is dependent on when pedestrians arrive at the signalized intersection. Thus, the data is segmented into five sets for which three are analyzed for compliance characteristics: pedestrians arriving on Steady Don't Walk (SDW), on Flashing Don't Walk (FDW) and on Red where no pedestrian signal exists. The two data sets for which pedestrians arrive on WALK or on Green where no pedestrian signal exists do not need to be analyzed since virtually all those pedestrians cross during that phase.

Based on the numbers of available data points, results for pedestrians arriving on steady don't walk or during the red phase when there is no pedestrian signal, was expected to be promising. However, because of insufficient data points, results for pedestrians arriving on flashing don't walk are less promising, but still worth examining.

The type of variables used in the logit modeling analyses are associated with intersection characteristics: total number of lanes and crossing width, number of approach lanes and its crossing width, speed, type of median, and vehicular volumes. In addition, many dummy variables, composite variables and different levels of details were analyzed, representing over 200 different variations examined. Logit analysis was performed for each of the three different scenarios: Pedestrians arriving on "Steady Don't Walk," "Flashing Don't Walk" and on "Red Phase" (i.e. no pedestrian signal). Some information presented in the section on Pedestrians Arriving on Steady Don't Walk is the same as for the other sections (e.g. correlation analyses).

Pedestrians Arriving on Steady Don't Walk

The data set for pedestrians arriving on Steady Don't Walk (SDW) indicates two pedestrian crossing choices: SDW and WALK. Although Flashing Don't Walk (FDW) is present, no pedestrians were observed choosing to cross on FDW.

Based on preliminary correlation analysis, many different variables were highly correlated with one another. Considering the similarities between many variables, this was not surprising. For instance, it was expected that "total number of lanes" and "total crossing width" would be correlated since they both signify essentially the same roadway dimension. In addition, since many variables were composite variables, there should be high correlation levels. Also, because of the large number of possible variables, several variables of each category were analyzed individually to determine their "stand alone" effect on pedestrian crossing behavior. Before giving the final model, several remarks on individual variable effects (i.e. behavioral implications) are given. The following variables are described in this analysis: posted street speed, number of approach/street lanes, approach/street width, type of median, and approach/street vehicular volumes (including left and right turn indicators). After individual effects are examined, the effects resulting from using composite variables and/or using several variables together in logit modeling are described.

The analysis on posted street speed showed surprising results. It was expected that pedestrians would use the WALK indication more often if the speed was high, but the opposite appeared to happen. A possible explanation for this surprising discovery is that posted speeds are correlated with vehicular volumes and street widths which masked the real effect speed has on pedestrian behavior. The only possible independent variable that appeared to show the expected results (i.e. higher compliance at higher speeds) was the separation of the speeds into 30 and 35+ mph categories; however, this method just hides the contradictory effect. In other words, using this variable type hid the non-linear effect of speed on pedestrian compliance. Separating the other variables' effects on speed is needed, but not likely to be possible because real world conditions do not allow all combinations of speed and vehicular volume / street width to occur. For example, many residential streets are two-lane roads with low volumes and speed limits; very few would have high speeds nor high volumes.

The analysis on the number of approach lanes appeared to follow expectations. Though there were some discrepancies, it was found that the higher the number of lanes the more likely pedestrians would be using the WALK indication. Using a dummy variable separating the number of approach lanes from 1-3 lanes from 4+ lanes appeared promising. Using the total number of lanes produced similar results, perhaps even more promising. Separating the total number of lanes into 2-4, 5-6, and 7+ lanes also appeared promising.

The analysis on the approach width also produced consistent results. If a dummy variable separating total width into <40 feet and 40+ feet was used, the results are the same as the dummy variable for the number of approach lanes because of the 100% correlation between the two variables or otherwise said, all streets with 4+ lanes have a width of 40+ feet. Using a dummy variable separating the total width into 0-40, 40-100, and 100+ feet appeared promising.

Also initially promising are two types of median. First, raised concrete medians that are most typically typecast as medians was almost significant, and it appeared that pedestrians were more likely NOT to cross during the WALK signal because of it. Second, two-way left turn lanes (TWLTL) produced the opposite effect. Perhaps, pedestrians felt they could not predict when vehicles would turn into these dual usage lanes; hence, they were less apt to cross than when these TWLTL are absent.

Finally, the analysis on vehicular volumes (divided by street width or number of lanes) produced the most surprising results. It was initially predicted that pedestrians would use the information about the approach street's volume over other vehicular volumes (i.e. opposite approach and adjoining streets). Interestingly, the approach street vehicular volume has little bearing on the pedestrian's decision to cross. Instead, the vehicular volumes of the opposite approach in addition to the adjoining street's two directions proved to be more significant in pedestrians' crossing choice. Perhaps, pedestrians cannot judge when distant vehicles will cross their crosswalk whereas they know that the approach street vehicles will cross their crosswalk. In this sense, results appear to support a theory that pedestrians may have only a limited capacity of assessing danger that is far away from them. Another reason could be that pedestrians can only judge potential conflict one street at a time; this theory suggests that pedestrians have limited judgment capabilities which are compromised by more complex traffic operations. In other words, without the assistance of pedestrian signals, pedestrians might feel crossing at mid-block locations would be much easier than crossing at intersections with complicated geometrics and changing traffic signal timing/phasing.

After analyzing the results of single variable effects on crossing choice, it was found that the analysis using composite variables proved to be less promising. In general, composite variables were less statistically significant than the variables alone. Experimentation with combinations of vehicular speed and other similar variables showed that results were overshadowed by other variables (e.g. roadway width). In that sense, vehicular speed was dropped from further consideration.

Logit modeling with multiple variables yielded consistent results yet several variables' significance ceased. For instance, when the two types of previously significant medians were used, both variables' became insignificant. Also, when several vehicular volume variables were used together, the approach street volume still remained insignificant.

More importantly, when the different vehicular volume rate variables were used together, very different coefficient estimates and insignificances occurred. For instance, when the side street volume variables were used together, the variable for the side street representing left turning vehicles ceased to be significant, and both variables had diminished coefficient values. The most likely reason for this is that vehicular volume rates for both adjoining street approaches are correlated; hence, a volume rate variable representing both adjoining street volumes at once proved to be more reliable. However, using the opposite street volume with the adjoining approach street volume caused the opposite street volume to be insignificant.

When determining which model would become final, all previous significance issues were taken into consideration. Also, the fact that several variables were highly correlated to one another limited the scope of possible models. A few models came up with all variables being correct, consistent, and significant; out of these, one was chosen based on its applicability to the desired modeling efforts. Table 5.2.2 shows the model for pedestrians arriving on Steady Don't Walk and choosing to wait for WALK:

Table 5.2.2 Logit Model for Pedestrians Arriving on Steady Don't Walk and Choosing Walk over Steady Don't Walk

Variable	Value	t-stat.
Constant	-1.74	-3.62
Alane	0.289	3.19
Svolan	0.00368	3.70

Note:
Alane = Number of Approach Lanes
Svolan = Side Street Vehicle Volume per Lane

Pedestrians Arriving on Flashing Don't Walk

Unlike the data set for pedestrians arriving on Steady Don't Walk (SDW), the data set for pedestrians arriving on Flashing Don't Walk (FDW) did not have the benefit of substantial data size with significant information for each phase choice. In addition, the FDW data set has three different choices: pedestrians choosing to cross on existing FDW, waiting and then crossing on SDW, or choosing to wait for crossing on WALK. This extra choice requires that the FDW data set be larger than the SDW data set.

Even with these disadvantages, the FDW data set was analyzed for any possible pedestrian compliance characterization. As expected, the results from the multinomial logit analysis did prove to be very limited and contradictory. Significant and possibly significant cases are reported.

With respect to adjoining street vehicular volume rate variables, pedestrians were more likely to cross on FDW (and to lesser degree on WALK) as volumes increased. This was probably the most consistently expected result because increased hazard usually prompts compliance.

Pedestrians were also more likely to cross during FDW when a grass median was present. In other words, when given a wide rather natural median, pedestrians were more likely to attempt crossing because of the safety net of having a median to buffer them against possible phase changes.

Pedestrians were less likely to cross during the FDW when speed is higher. A possible explanation for this is that pedestrians, not knowing when the signal would change, opted to wait, even at the chance of crossing against the signal (during SDW).

Perhaps the most surprising result was that when there was 5+ lanes (or greater width), pedestrians were less likely to cross during the

WALK or FDW phase. This effect is probably the result of some other underlying unexplained effect due to lack of sufficient data size.

The overall characteristic from this FDW analysis that seems to appear is that the FDW phase seems to encourage non-comformant behavior. Because of the compliance characterizations problems, the market share was used as the FDW model because of the lack of data set size which could mislead research results.

<u>Pedestrians Arriving on Red Phase</u> (no pedestrian signal present)

As explained before, the data set for pedestrians arriving on the red phase is sufficient in size and phase proportion. Like the data set for pedestrians arriving on Steady Don't Walk, this data set has only two choices, but only because just two choices are available: crossing on Red or Green.

However, the multinomial logit analysis showed very little predictive results. This output probably signifies that pedestrians do not depend on traffic and geometric conditions to determine in the absense of pedestrian signals whether or not to comply with vehicular signals. None-the-less, significant and possibly significant cases are reported.

Pedestrians appeared to be more likely to choose the green phase when the vehicular volume rate is higher. Though this trend is similar as in the other data sets, the significance is much less prominent.

Pedestrians also appeared to cross during the green phase when speed was 35+ mph. However, when examining speed on a full scale, this dummy variable masked the contradictory effect as explained in the section on pedestrians arriving on SDW.

One surprising result is that in the absence of pedestrian signals, pedestrians were more likely to cross during the green phase when crosswalks were provided. However, when testing this effect for when pedestrian signals were provided, there was no significance.

As with the FDW data set, the market share was used to represent the results from this data set.

Modeling Inputs

Values used for the variable inputs for the developed integrated model need to mirror realistic suburban environments. Using the twenty intersections from Section 5.1, information was obtained from the City of Austin regarding vehicular volumes. Typical suburban vehicular volumes range from 100 to 400 vehicles per lane per hour.

Results from this vehicular volume level indicate that for fixed-timed vehicular signals without pedestrian signalization, the cycle lengths tended to be less than 30 seconds with exception of intersections with 400 vehicles per lane per hour for both major and minor streets. Since municipalities generally do not allow cycle lengths to be less than 30 seconds, the minimum cycle lengths were set to 30 seconds and the green light split to critical flows.

For fixed-timed vehicular signals with pedestrian signals, cycle lengths tended to be 30 seconds or greater, up to 135 seconds. When the critical volume for both streets were equal, cycle lengths were identical regardless of vehicle volume level. Likewise, when similar splits in green phases were used, cycle lengths were similar regardless of vehicle volume levels.

Using typical suburban values as vehicular volumes between 100 to 400 vehicles per lane and one to three lanes per approach, logit results differed significantly as shown in Table 5.2.3. As expected, as the number of vehicles on the side street increased and/or as the number of approach lanes on the crossing street increased, pedestrians generally tended to comply with pedestrian signals.

Table 5.2.3 Example Logit Model Results for Pedestrians Arriving on Steady Don't Walk and Choosing Walk over Steady Don't Walk

		Number of Approach Lanes	
		1	3
Side Street Vehicle Volume per Lane	100	0.25	0.38
	200	0.33	0.47
	400	0.51	0.65

Next, results from the safety model using these compliance rate are illustrated.

Potential Accident Rate (PAR) Trends

Pedestrian crossing safety was mathematically modeled using the Potential Accident Rate (PAR) methodology as described in Section 4.2. The components include the hazard rates and accident costs as well as the walk rate, number of lanes, compliance rates, vehicular and pedestrian volumes, signal timings, and other variables. The complexity of this method is briefly shown in the appendix as a sample outcome of one scenario (i.e. base case). Many other steps which were described in Section 4.2 are not shown, but none-the-less important. The safety model outcomes are described in terms of costs for easier understanding of results and implications. The safety cost is described through different geometric and traffic conditions: pedestrian volume, vehicular volume, number of lanes, and signal type. In addition, specifications for the inputs following typical suburban characteristics are described above.

The base case as shown in the appendix consists of the following characteristics in Table 5.2.4. It is the basic two-phase fixed-time signal with pedestrian signals for which each street has 4 lanes (i.e. 2 approach lanes) and 200 vehicles per lane. In addition, its 19.26 pedestrians per hour represent the pedestrian peak hour for several land use combinations (as shown in Table 5.1.3).

Table 5.2.4: Base Case Specifications

Component	Specification
number of phases	2
pedestrian volume	19.26
pedestrian signal?	yes
fixed/actuated timing?	fixed
major street:	
number of lanes	4
vehicular vol/lane	200
minor street:	
number of lanes	4
vehicular vol/lane	200

This base case output shows a hazard cost of $0.57. In other words, for the entire intersection with the specifications just described, the expected hazard cost amounts to a rather small amount.

This hazard cost varied linearly with pedestrian volume by design. In other words, through randomization and walking rate variation, the mathematical process behind hazard cost was found not to be influenced by pedestrian volume. Thus obtaining the hazard cost only required the rate to be directly multiplied by pedestrian volume. This effect is possible only if two conditions hold: crossing group size typically consists of one pedestrian and pedestrian volume is low (i.e. likelihood of more than one pedestrian in signal cycle is small). Since suburban pedestrian volumes and group sizes are very low, these assumptions are possible. None-the-less, the range of hazard costs for suburban areas range from the nearly non-existent $0.02 (for 0.6 pedestrians per hour) to some level more significant $0.92 per hour (for 31.1 pedestrians per hour).

The hazard cost increases non-linearly when vehicular volume increases. At very low volumes (i.e. less than 200 vehicles per lane per hour), the relationship is primarily linear because higher probability of vehicles not platooning. However, at higher volumes, the hazard rate starts to level off because once vehicular platoons become a regular feature of congested roadways, the chances of pedestrians interacting with each vehicle is much smaller. The expected hazard costs due to 50 to 400 vehicles per lane per hour ranges from $0.16 to $0.96 per hour.

The hazard cost also increased at a decreasing rate when the number of lanes increased. Though it might be expected that changes in the number of lanes would produce greater changes in hazard cost than vehicular volume changes, lane functions also depend on vehicular patterns. The changes ranged from $0.30 to $0.78 for configurations ranging from 2X2 to 6X6 lanes for each street.

All in all, hazard cost is small. Comparing different signal types showed the smallest change. Many times signalization benefits do not exceed $0.10. The reason behind this very small change is that the hazard cost method dimishes the role compliance plays in pedestrian safety. Though compliance differences could be significantly different, not all compliant scenarios are safe for some types of movements. As mentioned in Section 5.2.1, many pedestrians arriving on Flashing Don't Walk, cross immediately whether or not the green phase is ending and face an impending red light. Without pedestrian signals, there is also the danger of facing the red when crossing near the end of the green phase.

In the next section, the safety cost is compared to other model components, and the role of suburban land use in pedestrian signalization is explained.

SCENARIO ANALYSIS FOR SUBURBAN AREAS

The approach taken to study the combinatorial effect of all four factors, namely pedestrian and vehicular delay, safety, and equipment costs, was the base case scenario re-examination. Next, an analysis with respect to pedestrian/vehicular volume patterns (i.e. peak/non-peak hours from Section 5.1.3) and fixed/actuated signals is given.

The base case scenario produced the following costs as in Table 5.3.1. The most noticeable effect is that vehicular delay is approximately 100 times larger than the hazard cost. The magnitude of pedestrian delay is also small and as mentioned in Section 4.1.2, pedestrian delay changes are small. Upon pedestrian signal installation, pedestrian delay increases because compliance increases and in some cases, signal timing increases. The equipment cost is a constant in all pedestrian signal installation cases.

Table 5.3.1: Base Case Costs

Component	Cost
Hazard (PAR)	0.57
Pedestrian Delay	1.05
Vehicular Delay	65.33
Equipment*	0.32

*Note: Additional cost due to pedestrian signalization installation

The trends of pedestrian signalization benefits associated with these four factors are discussed with respect to fixed and actuated signalization types.

<u>Fixed Pedestrian/Vehicular Cycle Times</u>

The benefit outcome regarding fixed pedestrian cycles compared to fixed vehicular cycles is categorized by whether or not the pedestrian cycle is longer than the vehicular cycle.

If the vehicular cycle is shorter than the pedestrian cycle, then with the pedestrian traffic requirement causing higher vehicular delays, fixed pedestrian cycles are costly. This scenario is likely to occur during non-peak times when optimal vehicular cycles are shorter than pedestrian cycles.

If the vehicular cycle is longer than the pedestrian cycle, then pedestrian signalization does not impact vehicular delay. The comparison is then between pedestrian delay, hazard and equipment cost. However, the differences of pedestrian delay and equipment costs can offset the gain by pedestrian hazard costs. This scenario is likely to occur during peak times when high vehicle volumes cause longer cycle lengths.

However, daily traffic demands have peak and non-peak hours. With the fixed pedestrian/vehicular signal scenario, non-peak hour costs dominate the possible benefit fixed pedestrian signals may have during peak hour times.

These results seem contradictory to the idea of installing pedestrian signals in the first place. In theory, pedestrian signals' primary function is to increase pedestrian phases where needed when vehicular traffic signals do not meet crossing time needs. However, as explained, suburban fixed pedestrian signals point to large vehicular delay costs. Hence, potential benefit with fixed pedestrian cycles can only be realized when pedestrian signal timing does not require longer than optimal vehicular signal timing.

Actuated Pedestrian/Vehicular Cycle Times

As with fixed pedestrian timing, actuated pedestrian timing is discussed with respect to cycle timing.

If the vehicular cycle is shorter than the pedestrian cycle, then pedestrian requirements cause vehicular delay which is proportional to the number of cycles used by pedestrians. As explained in Section 4.1.2, this relationship is not linear with the number of pedestrians; in other words, once all cycles are occupied by pedestrians, then it doesn't matter how many more pedestrians arrive to cross. Hence, in this case, the smaller the number of pedestrians at an intersection, the less vehicular delay is experienced. Also, additional pedestrian delay is much smaller when pedestrian volumes are low because it is more likely that compliant pedestrians will arrive during the shorter vehicular cycle time. Hence, the costs and benefits come down to equipment costs and hazard savings; the lowest pedestrian volumes do not offset equipment costs. Optimal benefits occur when pedestrian volumes are low, but not at their lowest.

If the vehicular cycle is longer than the pedestrian cycle, then the net result is similar to fixed cycles. In this case, though vehicular delays caused by pedestrian signals are nonexistent, pedestrian delay differences dominate.

For daily variation, the optimal design pedestrian volume will be when non-peak pedestrian volumes occur during non-peak vehicular volumes. Some land use combinations produced peak-hour pedestrian volumes during non-peak vehicular hours which offsets any possible benefits. Hence, the most promising land uses that meet this criteria are presented in Table 5.3.2:

Table 5.3.2: Desirable Land Use Combinations for Actuated Signals

Combination #	Quarter-Mile Land Use	One-Mile Land Use
1	Recreational	Residential
2	Instituational	Residential
3	Minor Retail	Commercial
4	Recreational	Commercial
5	Institutional	Commercial

SUMMARY

In summary, land use proved to be a good indicator of pedestrian volumes at signalized intersections. Through modification, this hierarchical classification generates 0.6 to 31.1 pedestrians per hour.

The compliance analyses, though limited, seemed to illustrate that simpler pedestrian crossing scenarios lead to perhaps a safer environment. The two major supporters of this theory are that compliance rates increase when the number of lanes increase and/or side street volume increases. Also, pedestrians will cross when given the opportunity especially when medians are provided.

The safety analyses, PAR rates, on the other hand show very little benefit associated with compliance. In all, pedestrian hazard costs is relatively small compared to vehicular delay costs. This effect heavily affected the possible pedestrian signalization outcomes especially with fixed pedestrian signalization.

For different land uses, the effect of pedestrian signalization over time varies significantly since vehicular/pedestrian peak/non-peak hours may not coincide. Possible land use patterns for warranting actuated pedestrian signals were suggested.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The objective of this study has been to develop an integrated approach to assess delay, safety, and behavior (i.e. compliance) in a single framework for a suburban signalized intersection. In order to accomplish this objective, the study was divided into four objectives. First, delay models were developed to incorporate pedestrian behavior to determine pedestrian impact on vehicle and pedestrian signals. Second, mathematical functions for pedestrian compliance and behavior were developed to evaluate pedestrian safety. Third, land use patterns were studied to determine impact on suburban pedestrian volume patterns. Fourth, different traffic control strategies were tested to determine suburban environment impact on vehicle and pedestrian signalization. The findings of these four objectives are summarized as the following conclusions and recommendations:

(1) The delay model allowed practical examination of vehicular and pedestrian delay. Extending Webster and Newells' equations for fixed and actuated timing, respectively, is very useful for determining pedestrian impact. Incorporation of pedestrian behavior allowed reduction of expected pedestrian delay and actual pedestrian signal response timing.

(2) Pedestrian behavior was mathematically modeled as a balance between the two extreme pedestrian safety indicators: conflict (underestimate) and exposure (overestimate). This method, the potential accident rate (PAR), allows the safety indicator to be scientifically based rather than a statistical estimate which could change over time. PAR is an estimation based on physical proximity, phasing, and volume levels rather which is significantly less than the multiplication of sheer pedestrian and vehicle volumes as in the exposure measure. On the other hand, PAR is a method that allows

every close encounter between pedestrian and vehicular to be characterized as an encounter whereas the traditional conflict method requires that an observer determine whether or not pedestrians and/or vehicles reacted toward one another in the roadway.

(3) Pedestrian compliance, using multinomial logit, in a suburban setting was found to have several unique characteristics. The foremost findings are that pedestrians are more compliant on wider streets and higher volumes on adjoining streets. Medians seem to encourage non-compliant behavior (except for the two way left turn lanes). Compliance with respect to speed had very mixed results. The overall evidence shows that pedestrian signals show some promise in increasing pedestrian compliance given certain traffic/geometric situations.

(4) General results from the integrated model showed that vehicular delay would dominate the outcomes. Though safety benefits occurred with different signalization strategies, the amount was small as with pedestrian delay and equipment costs. This effect caused fixed timing schemes to be costly when pedestrian timing requirements were greater than optimal vehicular signal cycle timings.

(5) Land use variables appear to be useful in characterizing pedestrian generation (i.e. crossing) rates. The useful quarter-mile categories are residential, minor and major retail, recreational and institutional land uses. The useful one-mile categories are residential, commercial, and institutional land uses. The overall pedestrian generation rates ranged from a low of 0.6 to a high of 31.1 pedestrians per hour which is significantly lower than the range of suburban vehicular volume rates. These categories also have distinct peak/non-peak volume patterns.

(6) The peak/non-peak hour volume patterns affected the outcomes of the integrated model. During low vehicular volume periods (i.e. vehicular non-peak periods), low pedestrian volumes

should predominate. During peak vehicular periods, high pedestrian volumes should predominate. Thus, pedestrian peak and non-peak periods should coincide with vehicular volume patterns as well. Examining these characteristics, promising land uses following this pattern include those with quarter-mile zones of recreational and institutional land uses for all one-mile land uses, particularly residential and commercial land uses.

Recommendations

The following recommendations are based upon the modeling efforts, analysis, and conclusions. They are intended to point out needed future research as well as point out other types of closely related research ideas.

(1) The transferability of the behavioral and generation rate results to other suburban areas should be studied to determine regional differences. Since Austin, Texas has year-round warm weather, a primary concern is the effect of cold weather upon pedestrian traffic characteristics. In addition, a useful and insightful approach to understanding the pedestrian phenomena is to study the effect of different cultures by comparing pedestrianism between different countries.

(2) An interesting issue is the effect transit systems have on pedestrian volume patterns. First, the Austin transit system currently consists of buses, and like most U.S. suburbs, relies heavily on automobiles for typical passenger travel. Cities with more extensively developed transit systems may have significantly different pedestrian travel patterns. Second, the Austin school students are usually transported by bus; hence, the effect of students on the traffic system is smaller. Other cities not having a school bus system will likely experience different pedestrian volumes. Third, the Austin transit

system has a policy of providing bus stops at relatively fixed distances apart whether or not they are needed; this phenomena made the possible independent variables relating to transit difficult to use. In the absence of this policy, it would be interesting to determine the true effect transit has on pedestrian volume patterns.

(3) Though these models were used for the pedestrian crossing phenomena, further studies could be performed to determine effectiveness for other engineering applications. For instance, pedestrian generation rates might be studied for sidewalk volumes.

These analyses, results and conclusions should encourage other researchers to study suburban environments separately as a unique entity not only for the pedestrian phenomena, but also for other transportation systems.

APPENDIX

Base Case

											N				C	Cb		
											19.26				40	0.004		
					Total					Total								
Leg	Xwalk	Phase	Lane	lane	Veh		Vehicle Volume			Lane	Comp			Ped	Green	Basic	PAR	Hazard
				width	Vol	Right	Thru	Left	Total	weight	Ped			Face	Time	Cost	per ped	Cost
	C	S	L	w	V	Vr	Vt	Vl	V	ω	N	Pgl	Nscl		G	Cls	PAR/N	H
	#	#	#	feet	vph	vph	vph	vph	vph		pph		pph		second	$ph	#	$ph
North	1	1	1	12	400	40	0	0	40	3.20	4.82	0.65	3.13	W/F	20	0.1536	0.054	0.0083
		1	2	12		0	0	0	0	0.00	4.82	0.65	3.15	W/F	20	0	0	0
		1	3	12		0	0	50	50	1.50	4.82	0.65	3.15	W/F	20	0.072	0.067	0.0152
		1	4	12		40	0	0	40	0.80	4.82	0.65	3.13	W/F	20	0.0384	0.054	0.0065
		2	1	12		40	135	0	175	0.88	4.82	0.35	1.68	SDW	20	0.0421	0.214	0.0151
		2	2	12		0	135	50	185	1.06	4.82	0.35	1.67	SDW	20	0.051	0.225	0.0191
		2	3	12		0	135	0	135	0.90	4.82	0.35	1.67	SDW	20	0.0432	0.17	0.0122
		2	4	12		40	135	0	175	1.43	4.82	0.35	1.68	SDW	20	0.0684	0.214	0.0246
East	2	1	1	12	400	40	135	0	175	0.88	4.82	0.35	1.68	SDW	20	0.0421	0.214	0.0151
		1	2	12		0	135	50	185	1.06	4.82	0.35	1.67	SDW	20	0.051	0.225	0.0191
		1	3	12		0	135	0	135	0.90	4.82	0.35	1.67	SDW	20	0.0432	0.17	0.0122
		1	4	12		40	135	0	175	1.43	4.82	0.35	1.68	SDW	20	0.0684	0.214	0.0246
		2	1	12		40	0	0	40	3.20	4.82	0.65	3.13	W/F	20	0.1536	0.054	0.026
		2	2	12		0	0	0	0	0.00	4.82	0.65	3.15	W/F	20	0	0	0
		2	3	12		0	0	50	50	1.50	4.82	0.65	3.15	W/F	20	0.072	0.067	0.0152
		2	4	12		40	0	0	40	0.80	4.82	0.65	3.13	W/F	20	0.0384	0.054	0.0065
South	3	1	1	12	400	40	0	0	40	3.20	4.82	0.65	3.13	W/F	20	0.1536	0.054	0.026
		1	2	12		0	0	0	0	0.00	4.82	0.65	3.15	W/F	20	0	0	0
		1	3	12		0	0	50	50	1.50	4.82	0.65	3.15	W/F	20	0.072	0.067	0.0152
		1	4	12		40	0	0	40	0.80	4.82	0.65	3.13	W/F	20	0.0384	0.054	0.0065
		2	1	12		40	135	0	175	0.88	4.82	0.35	1.68	SDW	20	0.0421	0.214	0.0151
		2	2	12		0	135	50	185	1.06	4.82	0.35	1.67	SDW	20	0.051	0.225	0.0191
		2	3	12		0	135	0	135	0.90	4.82	0.35	1.67	SDW	20	0.0432	0.17	0.0122
		2	4	12		40	135	0	175	1.43	4.82	0.35	1.68	SDW	20	0.0684	0.214	0.0246
West	4	1	1	12	400	40	135	0	175	0.88	4.82	0.35	1.68	SDW	20	0.0421	0.214	0.0151
		1	2	12		0	135	50	185	1.06	4.82	0.35	1.67	SDW	20	0.051	0.225	0.0191
		1	3	12		0	135	0	135	0.90	4.82	0.35	1.67	SDW	20	0.0432	0.17	0.0122
		1	4	12		40	135	0	175	1.43	4.82	0.35	1.68	SDW	20	0.0684	0.214	0.0246
		2	1	12		40	0	0	40	3.20	4.82	0.65	3.13	W/F	20	0.1536	0.054	0.026
		2	2	12		0	0	0	0	0.00	4.82	0.65	3.15	W/F	20	0	0	0
		2	3	12		0	0	50	50	1.50	4.82	0.65	3.15	W/F	20	0.072	0.067	0.0152
		2	4	12		40	0	0	40	0.80	4.82	0.65	3.13	W/F	20	0.0384	0.054	0.0065
					1600				3200									$0.57

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