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16. Abstract

The traditional approach to reduce accidents at intersections has been to install traffic control devices. However, it has not been established that installation of such devices as signals, signs, or pavement markings, substantially improves pedestrian safety. On the contrary, empirical investigations have indicated that these devices tend to create a false sense of security. The major criteria used in installing these devices are vehicular volumes, pedestrian volumes, and engineering judgment. The compliance with these devices is, however, dependent on the pedestrian behavior. It is therefore necessary to study the crossing behavior, not only to realize the full benefits of signalization, but also to develop and evaluate new strategies to deal with the pedestrians.

This report focuses on the crossing behavior of pedestrians at traffic signalized intersections. Since a non-compliant pedestrian attempting to cross on a "don't walk" phase looks for gaps in the traffic stream, the gap-acceptance theory is used to model the crossing maneuver. An inconsistent behavior model is assumed wherein the critical gap is treated as a random quantity varying both within and across individuals.

Four possible crossing modes are identified, but only two could be studied because of sample size restrictions. Group interactions are incorporated in the models, as the behavior of individual pedestrians within the group may not be independent. Also, the pedestrians within the group may not be independent. Moreover, the pedestrian push-button choice behavior is integrated with the gap-acceptance models, as these two behaviors are correlated. Models are developed in the framework of random utility maximization theory using a multinomial probit approach.

A data collection methodology was developed using a stratified sampling approach, with land use as the exogenous variable. The procedure was applied to selected intersections from the city of Austin, Texas. On-site surveys were conducted to obtain information on the behavior using a video recording technique.

The calibration package used applies the Monte Carlo simulation technique to compute the choice probabilities, and obtains maximum likelihood estimates for the model parameters.

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by

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Pedestrian Signals: Warrants and Effectiveness

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in cooperation with the

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IMPLEMENTATION STATEMENT

The findings of this study can be used by traffic engineers in the Texas Department of Transportation and cities in Texas. The final report from this project, 1296-2F, contains more specific implementation guidelines based on this study.

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

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

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SUMMARY

The main objective of this work is to study the gap-acceptance behavior of pedestrians crossing at signalized intersections. The gap-acceptance theory has been extensively used to model drivers waiting to cross the major street, or involved in merging or passing maneuvers. Daganzo (1982) has formulated the driver gap-acceptance problem in a multinomial probit framework for a single-lane crossing. This work applies his methodology to study the pedestrian gap-acceptance behavior and further extends it from single-lane crossing to a crossing on multi-lane approaches. A pedestrian can follow one of four possible types of crossings as follows. He/she may cross in one stage by seeking either a gap in the entire traffic stream, or a separate gap each in the near stream and in the far stream. Another option is to cross in two stages by considering the near stream first and then the far stream. This is a strong possibility at intersections with medians. The last possibility is a multi-stage crossing where the pedestrian crosses the street lane by lane. This work presents a formulation for each of these modes using a multinomial probit approach. Individual gap-acceptance behavior is influenced when pedestrians arrive and cross as a group. Also, the presence of a push-button is likely to affect gap-acceptance behavior. The modeling framework is extended to incorporate these interactions.

A data collection methodology was designed using a stratified random sampling approach. A stratification based on land use was adopted because one of the main objectives of the survey was to obtain information on pedestrian arrival rates. Five land uses in the quarter-mile (402-meter) zone and four land uses in the one-mile (1,609-meter) zone were identified. Intersections were classified using this nomenclature. If either of the zones has more than one land-use type, the dominant pedestrian-generating land use was used. A total of twenty intersections, one for each land-use combination, were selected for a survey from the city of Austin, Texas. Data was obtained through on-site observation and video recording techniques. Lane-by-lane gap information was obtained from the video using a continuous event-time recorder. A program was written to extract gaps for each of the crossing modes discussed earlier. The analysis was restricted to first two modes because of insufficient data for the other two modes.

The estimation was conducted using a program based on Monte Carlo simulation developed earlier on the Cray Y-MP environment at The University of Texas at Austin. It

was assumed in the analysis that all pedestrians look for gaps when they arrive at the intersection. The following cases were estimated:

- a) One-stage crossing, pedestrian looks for an overall gap in the traffic, i.e., mode (a)
  - i) no push-button or group interactions
  - ii) push-button but no group interactions
  - iii) group interactions but no push-button interactions
- b) One-stage crossing, but the pedestrian looks for a gap in the near and far streams, i.e., mode (b)
  - i) no push-button or group interactions

From a preliminary analysis, it was found that the sample does not have a sizable representation of groups in it, and, also, only a small fraction of these groups had a push-button option. So, a model with both push-button and group interactions was not estimated. From mode (a) estimation results, it was found that these interactions were very small. The model specification to the estimation program is more complicated for mode (b), and, since these interactions are not significant, they were not considered for this case.

The estimation results generally confirmed a priori expectations. The initial mean critical gap was greater than the initial mean critical lag because the lags could not be measured with the perception component. These critical values decreased as the waiting time increased. At busy or wide intersections, the critical values were found to be higher, implying that pedestrians are more cautious at these intersections. Also, on turn phases, the pedestrians were found to accept smaller gaps or lags than at through phases. Regarding push-buttons, it was found that pedestrians have an inherent tendency to avoid using these devices. However, push-buttons were likely to be used at busy or wide intersections. The results indicate that group interactions and push-buttons do not affect the gap-acceptance behavior significantly. It may not be conclusive, as the sample has no sufficient representation of these interactions in it. Comparing across modes, it was found that pedestrians are more likely to look for an overall gap (i.e., mode (a)) rather than two gaps (i.e., mode (b)).

CHAPTER 1: INTRODUCTION

1.1 Motivation

With renewed interest in physical fitness, and a growing concern for environmental pollution, walking is becoming an increasingly popular mode of transportation. As the control system design is governed more by vehicular traffic, this transition is causing an increased level of pedestrian-vehicle conflicts (Braun et al., 1978; Smith et al., 1987). Part of the safety problem can be attributed to pedestrian indifference towards the control system. At intersections with no pedestrian signals, the absence of a clear assignment of right-of-way requires pedestrians to look for gaps in the traffic, and, in some cases, to cross prematurely. At intersections with pedestrian signals, the pedestrian's unwillingness to wait for the "walk" phase, or the occurrence of a perceived safe gap, may result in a crossing on the "don't walk" phase. Even though demand-responsive systems such as push-buttons are provided, personal experience suggests that they are rarely trusted and are used only by a small pedestrian population segment. One study (Zegeer et al., 1982) has found that installation of pedestrian signals and crosswalk markings have, in a few cases, created a false sense of safety. Currently the major criteria for installing pedestrian signals are based on vehicle volumes, pedestrian volumes, and engineering judgment (MUTCD 1978). As the question of an equitable distribution of delay between pedestrian and vehicular traffic remains unresolved, the operation of pedestrian signals, especially the timing issue, is governed primarily by the vehicular traffic. Compliance with these signals is, however, dependent on pedestrian behavior.

Pedestrian accidents are a rare occurrence. However, the severity of these accidents is a compelling reason to conduct an engineering study on their cause and to develop solutions to reduce them in future. Also, the characterization and understanding of pedestrian behavior at intersections, signalized and unsignalized, can result in more effective signal operation, and can further allow development and evaluation of strategies to deal effectively with pedestrians. There is therefore a need for proper understanding of pedestrian behavior in context of its interaction with the control system.

1.2 Scope and Objectives of the Study

Pedestrian crossing at an intersection can be viewed as a sequence of decisions, each affecting subsequent decisions. At the onset, a decision is made whether to cross at the intersection, or to cross mid-block, also referred to as a jaywalk. If the pedestrian decides to cross at the intersection, and arrives on a "don't walk" phase, he/she can either opt to wait for a "walk" phase or cross when possible. The latter behavior requires that the pedestrian look for gaps in the traffic. The pedestrian may cross in one stage, in two stages (i.e., cross near stream and then the far stream), or in multiple stages (i.e., cross lane-by-lane). The flow chart in Figure 1.1 illustrates the behavior described above.

This study is concerned with pedestrian gap-acceptance behavior at intersections. Only the first two types of crossing will be considered. The multiple-stage crossing is associated with a high degree of risk and should be discouraged by all means.

The objectives of this study are:

i) To obtain the critical gap parameters in the gap-acceptance function.

ii) To examine differences in gap-acceptance behavior between pedestrian signalized and unsignalized intersections.

iii) To examine the effect of groups on crossing behavior.

These objectives are part of the overall study aim of providing a general characterization of pedestrian crossing behavior at signalized intersections based on field observations.

1.3 Study Approach and Overview

In this study, gap-acceptance theory is used to model pedestrian crossing behavior. An "inconsistent behavior" model is assumed wherein the pedestrian may reject a longer gap before accepting a short one. The critical gap is treated as a random variable at the individual and at the population level. Each gap has a probability of acceptance given by the gap-acceptance function. The gap-acceptance function is assumed to have a multivariate normal distribution, and the parameters are estimated using the maximum-likelihood method.

A review of the literature is presented in the following chapter. The main focus is on gap-acceptance theory. Gap-acceptance theory is not limited to pedestrian behavior, and has been used to study the merging and passing maneuvers and to represent the behavior of drivers on the side street waiting to cross the main street traffic. Statistical analysis can be performed at an aggregate or a disaggregate level. The current approach can be classified as a disaggregate approach. In the past, researchers have used accident analysis and conflict

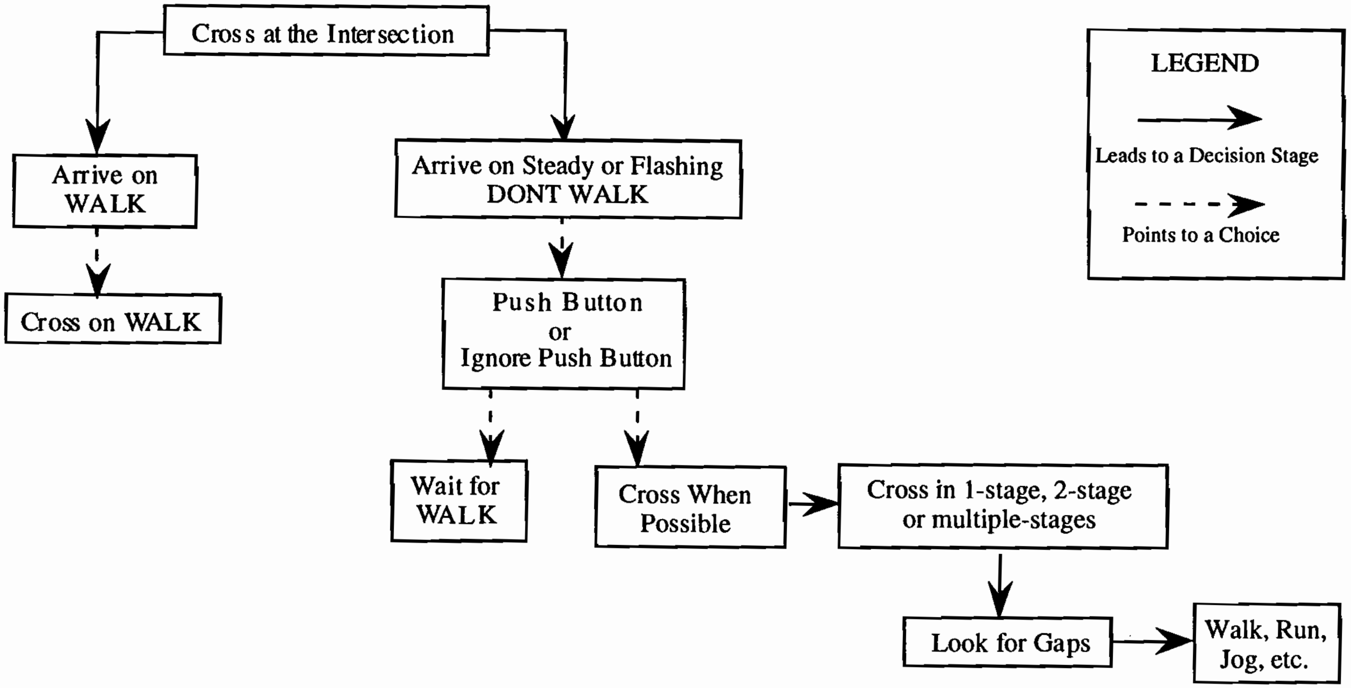


Figure 1.1
Pedestrian Crossing Behavior

analysis to evaluate safety. These are aggregate approaches, and, though easier to use, have limited power in capturing the actual process. A short review is presented on these topics as well.

In Chapter 3, the gap-acceptance models are presented in the framework of random utility maximization theory using a multinomial probit approach. A single-lane crossing is considered. Initially, it is also assumed that the pedestrian behavior is independent even when the arrivals are in groups. The formulation is extended to a multi-lane crossing where three modes of crossing, identified earlier, are possible. If a group arrives at the intersection, the behavior of pedestrians within the group is correlated, and the independence assumption breaks down. This case is considered next. Finally, push-button choice behavior, which is again correlated with the gap-acceptance behavior, is integrated with the model.

Chapter 4 focuses on the data collection aspects. As no prior data was available for the model calibration, on-site surveys are conducted using the video recording technique. A survey methodology is developed using a stratified random sampling approach with land use as the exogenous variable. The procedure is applied to selected intersections, primarily in the city of Austin. The videotapes are viewed to obtain information on a number of variables. An inter-scorer reliability check is also performed to ensure high credibility of the data. An analysis of the basic behavioral and compliance characteristics is also presented.

The model specifications and estimation results are the main focus of Chapter 5. Once the data has been obtained, the next step involves calibration of the models. Initially, a preliminary data analysis is conducted to study the gap size distribution with other gap characteristics, and with intersection and person-specific attributes. It is followed by a discussion on the specification and the structure of variance-covariance matrices estimated. The multinomial probit models are calibrated using a program developed on the Cray Y-MP supercomputer at The University of Texas at Austin. This program computes the probabilities using the Monte Carlo simulation technique, and parameter estimates using the maximum-likelihood method. The chapter concludes with an interpretation of the results.

Finally, in the last chapter, a brief summary is presented with a few suggestions for further research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Researchers have taken different approaches to address safety issues associated with pedestrian movement. They have devised various means of measuring safety based either on accident rates, on conflict analysis, or on a critical gap study. The literature reviewed can be grouped under three major headings:

i) Accident analysis
ii) Conflict analysis
iii) Gap-acceptance studies

Each of these is elaborated below. The effectiveness of safety measures depends to a large extent on the behavior of pedestrians and their compliance with the traffic devices. A review of the findings on these aspects is reported in section 2.5.

2.2 Accident Analysis

Accident frequency is a measure of safety, and can be used to identify accident causation factors. One of the often-quoted studies for using pedestrian accident data to study safety impacts of pedestrian signals was made by Fleig and Duffy [1967]. However, its limited sample size did not allow conclusive statistical analysis. Robertson and Carter [1984] used existing data bases from different states for their study. They found that approximately one out of every five vehicles involved in an accident was a turning vehicle, with left-turning vehicles being more predominant. Also, they found that the young and the elderly are more susceptible to accidents. Another study (Zegeer et al. [1982]) provided evidence from 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 that residential land use is associated more with mid-block accidents. Zaidel and Hocherman [1988] used accident rates to compare the performance of different pedestrian crossing arrangements.

A general drawback of accident analysis is that accidents are rare phenomena, and not all of them are reported. Also, they occur under various circumstances. It is therefore difficult to identify generic causation factors. Accident analysis is more suitable to develop site-specific remedies, and to prioritize unsafe intersections, when necessary.

2.3 Conflict Analysis

In the light of the above limitations of accident data, researchers have attempted to use conflict data instead. A conflict occurs when a driver takes an evasive action to avoid an accident. This type of data can be obtained from roadside observations. Cynecki [1980] identified thirteen different types of conflicts, and defined a conflict severity index to reflect the degree of hazard at a given intersection. The index allows comparison of different sites and identification of risky intersections. This approach requires the observers to undergo rigorous training so that an acceptable degree of uniformity can be obtained in correctly classifying a conflict and its severity index. Garder [1989] has also used this technique to relate conflict data with the accident data.

Conflict analysis is more effective than accident analysis when developing intersection-specific remedies. A possible disadvantage of this method is that the influence of site-specific deficiencies, such as sight distance, may interfere with the ability to identify general causation factors. Pedestrian or driver behavior, which is the primary cause of an accident or a conflict, is not directly addressed.

2.4 Gap-Acceptance Studies

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

i) Constant critical gap model: In this model, it is assumed that the critical gap is a constant, and is the same for the entire population. When the available gap is greater than the critical gap, it is always accepted. Otherwise it is rejected. This concept was first introduced by Adams [1936]. Tanner [1951] also made this assumption in deriving the mean delay, and other queue statistics, for the pedestrian waiting to cross a road. However, this model is not realistic because there are both systematic and random variations in behavior within and across subjects.

ii) Consistent behavior model: This model differs from the first by assuming that the critical gap is constant for an individual but distributed over the population. For a given individual, the gap-acceptance function is still a step function. The across-subject variation may be attributed to the existence of both cautious and aggressive people in the population. Miller [1972] has reviewed nine different methods of estimating the mean critical gap, under the above behavioral assumption. Maze [1981] calibrated a logit model of gap acceptance. Radwan and Sinha [1982] estimated empirical models for five different merging maneuvers on a divided highway (right-turn, through crossing maneuver one-stage and two-stage, left-turn maneuver one-stage and two-stage). However, their estimates for the through and left-turn models may be biased because the sample subset for each crossing mode appears to be a choice-based sample, and no explicit corrections for this bias are reported.

iii) Inconsistent behavior model: Many authors have shown the presence of within-subject variance in gap-acceptance behavior using test-track and actual field data. In this case, the critical gap for an individual is no longer treated as a constant, but as a random variable, which need not be identically distributed across the population. The within-subject variability may be attributed to varying degrees of concentration displayed by the subjects during their crossing maneuver. Each gap has a probability of acceptance associated with it. Herman and Weiss [1961] assumed a displaced exponential distribution for the probability of acceptance. Others have used normal (Miller [1972]), log-normal (Cohen et al. [1955]), and gamma distributions (Blunden et al. [1962]). The within-subject variability was captured in the systematic component by Mahmassani and Sheffi [1981]. Daganzo [1981] tried to estimate the within-subject and across-subject variance components simultaneously in a multinomial probit framework. It should be noted that "inconsistent behavior" may not be an appropriate term for this model. Variation in individual behavior may well be due to differences in crossing situation rather than inherent randomness in behavior.

Different approaches have been designed to estimate the critical gap from empirical data. Only a few of them consider all the presented gaps. Miller [1972] compared nine different methods using simulated data and concluded that the maximum likelihood method is most reliable. Maximum likelihood method has the flexibility to incorporate factors other than gap size, such as waiting time, number of rejected gaps, and socio-economic variables in the estimation process. This estimation procedure has been implemented by Miller [1972], Mahmassani and Sheffi [1981], and Daganzo [1981].

2.5 Compliance and Behavior Studies

Pedestrian signals are installed to increase safety. Mortimer [1973] compared compliance rates at intersections with and without pedestrian signals, and concluded that signalized intersections have higher compliance. However, the installation of these signals has not always been proved effective. Zegeer et al. [1982] found no difference in accident frequency between pre-timed intersections with and without pedestrian signals. Lack of understanding and of uniformity of these signals could be one reason for their ineffectiveness. One study (Bailey et al. [1991]) on the elderly reports that 64 percent of the respondents lacked proper understanding of the signal phases. Also, most avoided crossing during peak hours and at low visibility periods. Signal timing also has an impact on compliance. A study by Robertson and Carter [1984] reports that when too much green was given to the vehicular traffic relative to its volume, pedestrian violations increased. Also, they found that increased pedestrian clearance time increased the number of violations. Rouphail [1984] conducted a user preference survey to document the behavior of pedestrians at mid-block crosswalks with and without signals. He found that pedestrians and motorists preferred unsignalized mid-block crosswalks. Khasnabis et al. [1982], in their review of behavior, observed that (i) at low volumes, pedestrians are likely to ignore the signal indications; (ii) the compliance rate for steady "walk" is higher than that for flashing "walk"; and (iii) clearance interval increases compliance rates. Hill [1984] studied the behavior of school children regarding route choice, walking speeds, trip lengths, and route complexity. He found their group walking speeds to be much higher than that of adult groups, (5.5 ft/s *vs* 4.7 ft/s){1.68 meters/s vs 1.43 meters/s}. Most children were found to run rather than walk. They took the shortest path, but, where more than one option existed, they were found to take a route with more turns. These conclusions were based on a small sample (about fifty students), and therefore may not be definitive.

From the above findings, it can be noted that conflicting evidence exists about the effectiveness of signals. The findings warn against indiscriminate use of pedestrian signals. To achieve greater respect for these devices, efforts should be directed at identifying scenarios where these are most appropriate. Also, special groups, such as the elderly, deserve careful attention.

2.6 Summary

In this chapter, the literature relevant to pedestrian safety is presented, including signal compliance and behavior. Three types of gap-acceptance models proposed in the context of either driver or pedestrian behavior are discussed. Of those, the "inconsistent" behavior model is more realistic and general, and is adopted for this study. For estimation, the maximum likelihood procedure has been shown to give unbiased estimates, and will be used. The next chapter focuses on the model development for different cases. The estimation results are presented in Chapter 5.

CHAPTER 3: MODEL DEVELOPMENT

3.1 Introduction

At signalized intersections, pedestrians arrive when the signal indication is "walk," flashing "don't walk," or a steady "don't walk." Pedestrians arriving on "walk" have the right-of-way and cross immediately. There is no crossing behavior of interest in this case. Personal experience suggests that pedestrians treat flashing "don't walk" as a steady "walk," and cross immediately. Therefore, arrivals on this phase are treated no differently from those on "walk." Further, pedestrians crossing on a flashing "don't walk" face no impending danger as they are accorded the right-of-way for entering the intersection legally. However, those arriving on a steady "don't walk" can either (a) wait for a "walk" or (b) cross when possible (refer to Figure 1.1). Only pedestrians who choose the second option look for gaps in the traffic. If an acceptable gap is found, they would cross on "don't walk," otherwise they would wait to cross on "walk." Therefore, all pedestrians with option (a) cross on "walk," but only a fraction of the pedestrians with option (b), those who cannot find an acceptable gap, cross on "walk." Even though these pedestrians cross on "walk," their behavior is still different from that of the former group because they look for gaps in the traffic, i.e., Pr (pedestrians reject all gaps on "don't walk" | they select (a)) is equal to 1 but, Pr (pedestrians reject all gaps on "don't walk" | they select (b)) is not always equal to 1.

From roadside observations, it is possible to determine whether the pedestrian crossed on "walk" or "don't walk" and the corresponding gaps in the traffic. However, it is not known whether the pedestrian followed (a) or (b), unless sufficient repeat observations are available. The observed choice of "walk" or "don't walk" is not necessarily a pedestrian's preferred choice. Limiting the study to pedestrians crossing on "don't walk" alone might result in endogeneity bias in the estimation of model parameters. Some pedestrians may have crossed on "walk" because they could not find safe gaps. At low-volume intersections, virtually all pedestrians cross when they see no vehicles on the street, even when the signal indicates "don't walk." It will hence be assumed that pedestrians prefer to cross whenever there is an opportunity, irrespective of the signal indication. This assumption helps circumvent endogeneity, but may not be valid, as illustrated in Figures 3.1 and 3.2, which show the scatter plot of gap size with wait time for pedestrians crossing

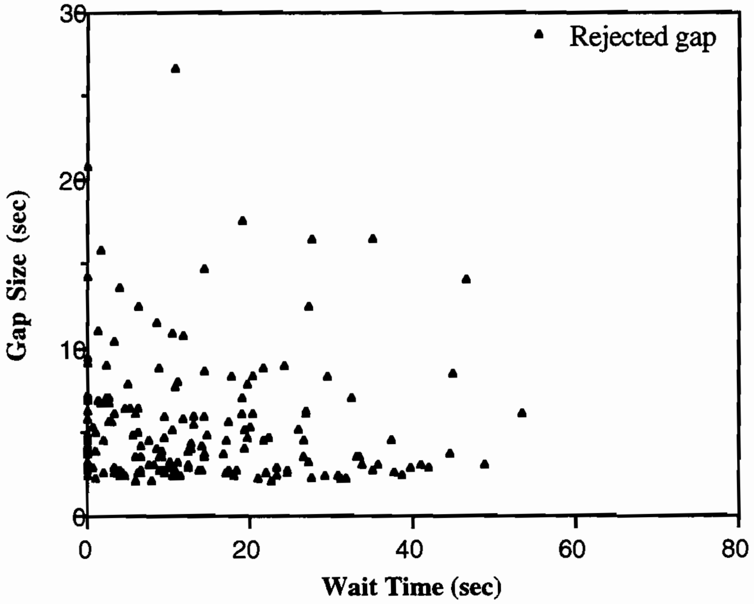


Figure 3.1
Scatter Plot of Gap Size Against Wait Time for Pedestrians Crossing on WALK

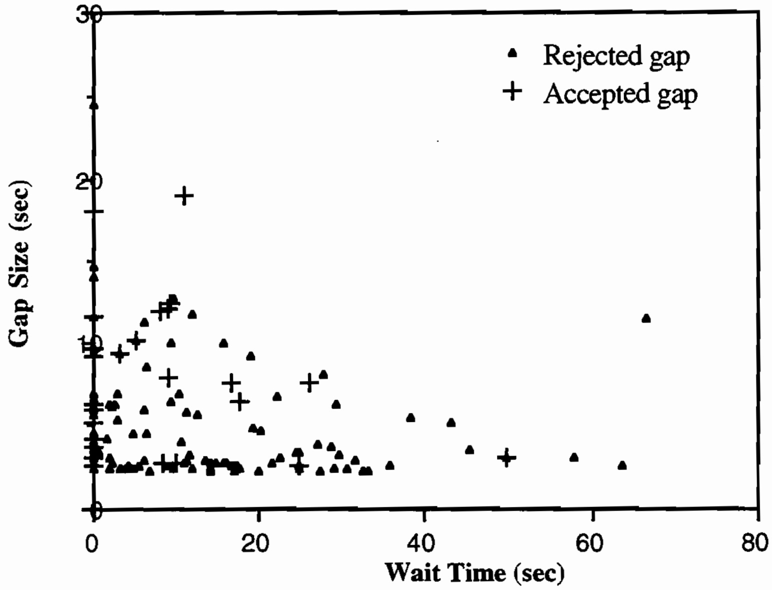


Figure 3.2
Scatter Plot of Gap Size Against Wait Time for Pedestrians Crossing on DON'T WALK

on "walk" and "don't walk," respectively. There are more rejected gaps of size 10 sec or greater in Figure 3.1 than in Figure 3.2, suggesting that those pedestrians may have no intent of crossing on "don't walk." Including them would overestimate the critical gap, and build a safety factor in the results. This behavior is mathematically formulated using the gap-acceptance theory.

According to the gap-acceptance theory, each pedestrian has a critical gap, defined as a minimum gap, below which a pedestrian will reject the gap. On arriving at the intersection, the pedestrian would check whether the available gap is greater than the critical gap and decide to either accept or reject the gap. If the gap is rejected, the next gap is considered. This sequential decision process ends when the pedestrian finds a gap to cross the entire approach or when the phase changes to provide the right-of-way to the pedestrian. The critical gap is an intrinsic quantity specific to the individual. It is expected to decrease with waiting time because the longer the wait, the more likely is the pedestrian to accept smaller gaps. On the other hand, the critical gap is expected to increase as the remaining time for "walk" decreases. The critical gap is also a function of person-specific attributes such as age and gender, and other unobservable factors.

The critical gap is therefore treated as a random variable, the mean and variance of which are estimated from the data, along with other parameters that govern its systematic variation. Initially, Daganzo's formulation [1981] for a single-lane approach is considered. The formulation is then extended to a multi-lane approach. Some special cases are also considered. Throughout this chapter, it is assumed that the choice behavior related to a crossing decision at the intersection versus mid-block, is independent of gap-acceptance behavior at the intersection. Biased estimates would be obtained if this assumption is not valid. When the behaviors are correlated, the unobservables which influence the pedestrian to cross at the intersection rather than jaywalk (e.g., being over-cautious) also influence the pedestrian to accept only long gaps, causing self-selectivity bias.

3.2 Single-Lane Crossing

Let t_{jn} be the mean critical gap for an individual n at the occurrence of the j^{th} gap g_{jn}. Define Y_{jn} as

$$Y_{jn} = t_{jn} - g_{jn} + \Omega_{jn} \qquad (3.1a)$$

where Ω_{jn} accounts for the unobservable factors which influence the decision of the individual n. If $Y_{jn} < 0$, the gap is accepted; otherwise it is rejected. If t_{jp} is the mean critical gap of the population at the occurrence of this jth gap, then (3.1a) can be rewritten as

$$Y_{jn} = t_{jp} - g_{jn} + (t_{jn} - t_{jp}) + \Omega_{jn} \qquad (3.1b)$$

Both t_{jn} and t_{jp} are unobservable quantities (latent variables). Therefore $(t_{jn} - t_{jp})$ is also an unknown quantity which reflects the critical gap variation across the population. Let $(t_{jn} - t_{jp})$, for all n, be identically and independently normally distributed with $E[(t_{jn} - t_{jp})] = 0$, and $Var[(t_{jn} - t_{jp})] = \sigma_T^2$. If all pedestrians behaved exactly in the same manner, then $\sigma_T^2 = 0$ and $t_{jn} = t_{jp}$. From (3.1b), it is clear that Ω_{jn} accounts for the "within" variation of the critical gap at the jth event for an individual n. If $\varepsilon_{jn} = (t_{jn} - t_{jp}) + \Omega_{jn}$, then

$$\begin{aligned} Y_{jn} &= t_{jp} - g_{jn} + \varepsilon_{jn} \qquad (3.1c) \\ &= [T_p + \beta_1 W_{jn} + \beta_2 X_n + \varepsilon_{jn}] - g_{jn} \end{aligned}$$

where

T_p = initial mean critical gap for the population, to be estimated from the sample;
W_{jn} = elapsed time from the arrival instant to the beginning of the jth gap;
X_n = person-specific attributes;
β_1 and β_2 = parameters to be estimated; and
ε_{jn} = total error term in the critical gap for individual n, facing jth gap.

It is assumed that Ω_{jn}, for all n, is identically and independently normally distributed with mean, $E[\Omega_{jn}] = 0$, and $Var[\Omega_{jn}] = \sigma_\varepsilon^2$. Also, it is assumed that $Cov[\Omega_{jn}, (t_n - t_p)] = 0$; i.e., the within-individual random variation is independent of the across-individual random variation. Hence, ε_{jn} follows a normal distribution with mean, $E[\varepsilon_{jn}] = 0$, $Var[\varepsilon_{jn}] = (\sigma_T^2 + \sigma_\varepsilon^2)$. Assuming that pedestrian arrivals and crossings are independent, the relationship between error terms can be shown to be

$$\begin{aligned} E[\varepsilon_{jn}\, \varepsilon_{km}] &= (\sigma_T^2 + \sigma_\varepsilon^2) && \text{if } j = k \text{ and } n = m, \\ &= \sigma_T^2 \text{ if } j \neq k \text{ and } n = m, && \text{because } (t_n - t_p) \text{ is common across gaps, and} \\ &= 0 \quad \text{if } n \neq m, && \text{because arrivals and crossings are assumed independent.} \end{aligned}$$

The covariance matrix Σ_{Y_n} for individual n would then be

$$\Sigma_{Y_n} = \begin{bmatrix} \sigma_T^2 + \sigma_\varepsilon^2 & & & & & \\ \sigma_T^2 & \sigma_T^2 + \sigma_\varepsilon^2 & & & & \\ \sigma_T^2 & \sigma_T^2 & \sigma_T^2 + \sigma_\varepsilon^2 & & & \\ \sigma_T^2 & \sigma_T^2 & \sigma_T^2 & \cdot & & \\ \cdot & \cdot & \cdot & \cdot & & \\ \cdot & \cdot & \cdot & & \cdot & \\ \sigma_T^2 & \sigma_T^2 & \sigma_T^2 & & & \sigma_T^2 + \sigma_\varepsilon^2 \end{bmatrix} \qquad (3.2)$$

with the number of rows (and columns) equal to the number of gaps presented to individual n.

Define $a^j_n = 1$, if gap j is accepted by individual n;

$= -1$, if it is rejected.

The probability that the pedestrian crossed on gap J

$$= \Pr(Y^1_n > 0,\ Y^2_n > 0,\ Y^3_n > 0,\ \ldots\ldots, Y^{J-1}_n > 0, Y^J_n < 0); \qquad (3.3)$$

$$= \Pr(a^j_n\ Y^j_n < 0,\ \ j = 1,\ldots, J).$$

Using the auxiliary alternative approach proposed by Daganzo and Sheffi [1982], the probability of this decision sequence is equivalent to the probability of selecting the auxiliary alternative, U_o (= 0), i.e.,

$$\Pr(a^j_n\ Y^j_n < 0,\ \ j = 1,\ldots, J) = \Pr(a^j_n\ Y^j_n < U_o,\ \ j = 1,\ldots, J), \qquad (3.4)$$

which is the probability of selecting U_o from a set of (J+1) alternatives where

$$\begin{aligned} U^j_n &= a^j_n\ Y^j_n & j &= 1,\ldots, J \\ &= 0 & j &= 0 \end{aligned} \qquad (3.5)$$

In matrix notation, it can be written as

$$U = A^T\, Y$$

where (subscript 'n' is dropped from the matrix)

$$A^T = \begin{bmatrix} 0 & 0 & 0 & 0 & . & . & 0 \\ 0 & a^1 & 0 & 0 & . & . & 0 \\ 0 & 0 & a^2 & 0 & . & . & 0 \\ 0 & 0 & 0 & a^3 & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ 0 & 0 & 0 & 0 & . & . & a^J \end{bmatrix} \quad \text{and} \quad Y = \begin{bmatrix} 0 \\ Y^1 \\ Y^2 \\ Y^3 \\ . \\ . \\ Y^J \end{bmatrix} \qquad (3.6)$$

Therefore,

$$\Sigma_U = A^T \Sigma_Y A = \begin{bmatrix} \sigma_T^2 + \sigma_\varepsilon^2 & & & & & \\ a^1a^2\sigma_T^2 & \sigma_T^2 + \sigma_\varepsilon^2 & & & & \\ a^1a^3\sigma_T^2 & a^2a^3\sigma_T^2 & \sigma_T^2 + \sigma_\varepsilon^2 & & & \\ \cdot & \cdot & \cdot & \cdot & & \\ \cdot & \cdot & \cdot & & \cdot & \\ \cdot & \cdot & \cdot & & & \cdot \\ a^1a^J\sigma_T^2 & a^2a^J\sigma_T^2 & a^3a^J\sigma_T^2 & & & \sigma_T^2 + \sigma_\varepsilon^2 \end{bmatrix}$$

In the above matrix, the $(a_j)2(\sigma_T2 + \sigma_\varepsilon2)$ term for the diagonal elements has been entered as $(\sigma_T2 + \sigma_\varepsilon2)$ for convenience. Its dimension is equal to $(J + 1)$. If the pedestrian crosses on "don't walk," gap J is accepted and the elements in the last row (and the last column by symmetry) of Σ_U except for the diagonal element are negative. All other elements have a positive sign. Therefore, if the pedestrian crosses on "walk" by rejecting all gaps on "don't walk," the matrix would have all positive elements.

3.3 Multi-Lane Crossing

In case of a multi-lane approach, four modes of crossing are possible. The pedestrian may:

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

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

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

For mode (a):

Lag: Time interval between the pedestrian arrival and the first epoch.

Gap: Time between successive epochs, irrespective of the lane position of vehicle in the traffic stream.

For mode (b):

Lag: There are two lags for this mode, near and far lags. The near (far) lag is the time interval between the pedestrian arrival instant and the first epoch in the near (far) stream.

Gap: Gaps are defined only after the first epoch (could be a near epoch or a far epoch). A near (far) gap is defined as the time remaining for the next near (far) epoch. At every epoch, there are two gaps, a near gap and a far gap.

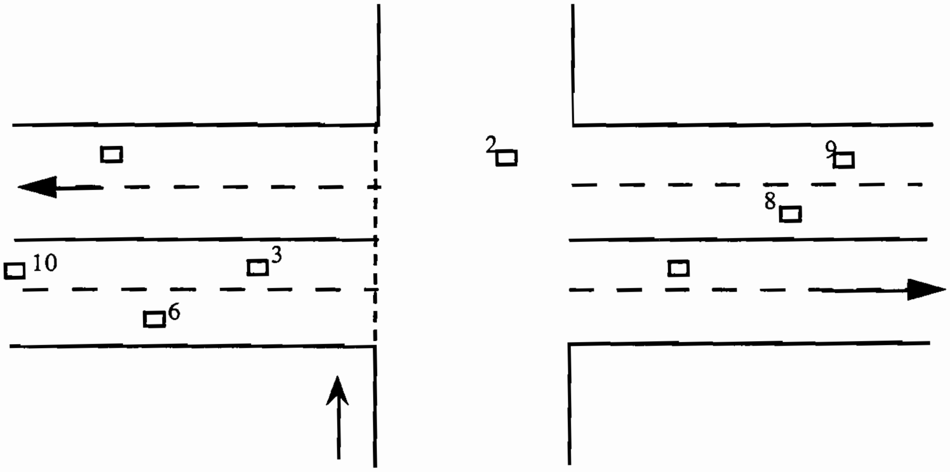
For mode (c) and (d):

The definitions for mode (a) are applied locally, at each crossing stage.

In the analysis, the instant of pedestrian "arrival" is defined as the time at which the pedestrian steps off the curb (for an immediate crossing), or slows at the corner (when the lag is rejected). The above definitions are illustrated in Figure 3.3 for modes (a) and (b) only.

3.3.1 One-Stage Crossing

i) Crossing by mode (a): In this mode, the pedestrian looks for a gap in the entire approach. The model formulation is identical to a single-lane crossing. The var-cov matrix is same as in equation set (3.6). The systematic specification would be different, however. A gap in the farthest lane is perceived differently from a gap in the nearest lane. This differential perception across lanes can be captured in the systematic specification.



The number at the head of each vehicle denotes the time a vehicle takes to clear the indicated crosswalk. Arrows indicate direction of movement.

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

Figure 3.3
Example Illustrating the Definitions of Lag and Gaps for Modes (a) and (b)

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

The data from intersections with a different number of approach lanes could be pooled to calibrate the model.

ii) Crossing by mode (b): In this mode, the pedestrian is assumed to have two critical gaps, one for the near stream and another for the far stream. At the decision instant, the pedestrian would have to decide on a gap g^j_{near} in the near stream and g^j_{far} in the far stream. The subscript 'n' for an individual is dropped for convenience. The subscript 'p' for the population is still retained. Define

$$Y^j_{near} = t^j_{near,p} - g^j_{near} + \varepsilon^j_{near} \qquad (3.6)$$
$$Y^j_{far} = t^j_{far,p} - g^j_{far} + \varepsilon^j_{far}$$

A crossing is possible only when both gaps are acceptable, i.e., when $Y^j_{near} < 0$ and $Y^j_{far} < 0$ simultaneously, for a one-stage crossing. The assumptions on the error terms in the previous section are made here also. However, the error terms of the near and far gap-acceptance functions are not independent because the unobservable factors that influence the pedestrian's decision to reject a near gap also influence the decision to reject a far gap and vice versa. Therefore

$$E[\varepsilon^j_{near}\, \varepsilon^k_{near}] = (\sigma_{Tn}^2 + \sigma_{\varepsilon n}^2), \text{ if } j = k, \text{ and for the same individual;} \qquad (3.7)$$
$$= \sigma_{Tn}^2, \text{ if } j \neq k, \text{ and for the same individual;}$$
$$= 0, \text{ otherwise.}$$

Similarly, for ε^j_{far}, the above quantities can be obtained by replacing subscripts Tnear and εnear with Tfar and εfar.

Let $$Cov[\varepsilon^j_{near}\, \varepsilon^k_{far}] = \sigma_{nf}^2, \text{ if } j = k, \text{ and for the same individual;} \qquad (3.8)$$
$$= 0, \text{ otherwise.}$$

Define the indicator variables μ^j_{near} and μ^j_{far} to be equal to 0, if the pedestrian has crossed, and = 1, otherwise. Note that if $\mu^j_{near} = 0$, then $\mu^{j+1}_{near} = \mu^{j+2}_{near} = \ldots = 0$.
Then the probability that the pedestrian accepts or rejects a given pair of near and far gaps at the decision instant is:

$$\Pr(\, \mu^j_{near}\, aj\, Y^j_{near} < 0 \text{ and } \mu^j_{far}\, aj\, Y^j_{far} < 0 \mid \text{all previous gaps were rejected}). \qquad (3.9)$$

The joint probability for the sequence of decisions can be written as

$$\Pr(\mu j_{near}\ aj\ Yj_{near} < 0,\ \mu j_{far}\ aj\ Yj_{far} < 0,\ j = 1,\ldots, J). \qquad (3.10)$$

Using the auxiliary approach, the above expression can be written in matrix notation as

$$U = A^T Y$$

where

$$A^T = \left[\begin{array}{c|cc:c:cc}
0 & & & & & \\ \hline
0 & a^1\mu^1_{near} & & & & \\
\cdot & & a^1\mu^1_{far} & & & \\ \hdashline
\cdot & & & & & \\
0 & & & & & \\
\cdot & & 0 & & & \\ \hdashline
\cdot & & & & a^J\mu^J_{near} & \\
0 & & & & & a^J\mu^J_{far}
\end{array}\right] \quad \text{and} \quad Y = \left[\begin{array}{c}
0 \\ \hline
Y^1_{near} \\
Y^1_{far} \\ \hdashline
\\
\\ \hdashline
Y^J_{near} \\
Y^J_{far}
\end{array}\right] \qquad (3.11)$$

The covariance matrix is shown in Figure 3.4. Its dimension is equal to (2J + 1). Even if $tj_{near} = tj_{far}$, the model would still be different from the earlier model because of the difference in specification of the covariance matrix. The decision to cross or wait is a consequence of two simultaneous decisions, as mentioned earlier. The earlier model makes no distinction between gaps in the near and far streams.

If $\mu j_{near} = 0$, then $\mu j_{far} = 0$, and vice versa. In preparing the data set, aj could be set to zero for the case where $\mu j_{near} = 0$. This notation is used to be consistent with variable definitions in the following sections.

3.3.2 Two-Stage Crossing

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

$$\Sigma_U = \left[\begin{array}{c|cc|c|cc}
0 & & & & & \\
\hline
 & (\mu^1_{near})^2(\sigma^2_{Tn} + \sigma^2_{\varepsilon n}) & & & & \\
 & \mu^1_{near}\mu^1_{far}\ \sigma^2_{nf} & (\mu^1_{far})^2(\sigma^2_{Tf} + \sigma^2_{\varepsilon f}) & & & \\
\hline
 & & & & & \\
\hline
 & a^1 a^2 \mu^1_{near}\mu^J_{near}\sigma^2_{Tn} & 0 & & (\mu^J_{near})^2(\sigma^2_{Tn} + \sigma^2_{\varepsilon n}) & \\
0 & 0 & a^1 a^2 \mu^1_{far}\mu^J_{far}\sigma^2_{Tf} & & \mu^J_{near}\mu^J_{far}\ \sigma^2_{nf} & (\mu^J_{far})^2(\sigma^2_{Tf} + \sigma^2_{\varepsilon f})
\end{array}\right]$$

Figure 3.4

Covariance Matrix for Mode (b)

during the second stage. The covariance matrix Σ_Y should reflect this interaction in the "forward" direction. Assuming crossing behavior is independent across individuals,

$$E[\varepsilon^j_{I}\,\varepsilon^k_{II}] = \mu^1_{near}\,\sigma_2^2 \tag{3.12}$$

where μ^1_{near} is same as defined earlier. The subscripts I and II refer to the first- and second-stage crossings, respectively. The assumptions made in section 3.3.1 are used for the corresponding error terms here. The covariance matrix Σ_Y for an individual n would then be

$$\Sigma_Y = \left[\begin{array}{ccc:ccc}
\sigma^2_{T,I}+\sigma^2_{\varepsilon,I} & & & & & \\
\sigma^2_{T,I} & \cdot & & & & \\
\sigma^2_{T,I} & \sigma^2_{T,I} & \sigma^2_{T,I}+\sigma^2_{\varepsilon,I} & & & \\
\hdashline
\mu^1_{near}\sigma^2_2 & \mu^1_{near}\sigma^2_2 & \mu^1_{near}\sigma^2_2 & \sigma^2_{T,II}+\sigma^2_{\varepsilon,II} & & \\
\mu^1_{near}\sigma^2_2 & \mu^1_{near}\sigma^2_2 & \mu^1_{near}\sigma^2_2 & \sigma^2_{T,II} & \cdot & \\
\mu^1_{near}\sigma^2_2 & \mu^1_{near}\sigma^2_2 & \mu^1_{near}\sigma^2_2 & \sigma^2_{T,II} & \sigma^2_{T,II} & \sigma^2_{T,II}+\sigma^2_{\varepsilon,II}
\end{array}\right] \tag{3.13}$$

where the first block diagonal elements refer to the first-stage crossing, the second block diagonal elements refer to the second-stage crossing, and the cross diagonal block elements refer to the influence of the first-stage crossing on the second-stage. Its dimension is equal to (J_{near} + J_{far}), where J_{near} and J_{far} refer to the number of gaps faced by individual n in near and far streams, respectively. The probability of crossing in two stages is equal to

$$\begin{aligned} &\Pr(\, \mu^j_{near}\, a^j_{near}\, Y^j_{near} < 0,\ j = 1,\ldots, J_{near} \\ &\quad \text{and } \mu^j_{far}\, a^j_{far}\, Y^j_{far} < 0,\ j = 1,\ldots, J_{far}\,). \end{aligned} \tag{3.14}$$

The auxiliary alternative approach can be used to obtain the joint probability of the decision process as before.

3.3.3 Multi-Stage Crossing

In the multi-stage crossing (mode d), the pedestrian is assumed to cross lane-by-lane. This is an extension of the previous two-stage case to multiple stages. The joint probability of crossing the entire approach is given by

$$\Pr(\mu_{jlane}\, a_{jlane}\, Y_{jlane} < 0,\ j = 1,\ldots, J_{lane} \text{ and } lane = 1,\ldots, NL) \qquad (3.15)$$

where NL is the total number of lanes to be crossed, and J_{lane} is the number of gaps considered on that lane. The final covariance matrix Σ_U can be derived following the steps used earlier. It is again assumed that a previous stage would influence all future stage crossings, i.e., interaction of the errors in the "forward" direction only. However, shorter gaps in farther lanes might deter a pedestrian from crossing because of the high risk of waiting unprotected in the middle of the street. This causes interaction in the "backward" direction too. This mode is generally observed at low traffic volumes.

3.4 Special Cases

3.4.1 Group Crossings

So far, pedestrian arrivals have been assumed independent. In this case, the log-likelihood of the sample, when the probabilities are computed using the auxiliary approach, can be written as

$$L = \Sigma_{i=1,N} \log \Pr_i (U_o).$$

$$\text{Also, } N = \Sigma_G\, (G\, N_G) \qquad (3.16)$$

where N is the total number of arrivals, U_o is the auxiliary alternative, and N_G is the number of arrivals of group size G. If the arrivals are in groups, the behavior of individuals within a group is correlated because of interactions among group members. However, the behavior across groups can still be assumed independent because the group arrivals are independent. The log-likelihood of the sample with group arrivals can be written as

$$L = \Sigma_{i=1,N1} \log \Pr_i (U_o) + \Sigma_{i=1,N2} \log \Pr_i (U_o, U_o)$$
$$+ \quad \Sigma_{i=1,N3} \log \Pr_i (U_o, U_o, U_o) + \ldots \qquad (3.17)$$

The intra-group interaction adds another dimension to the covariance matrix. The joint probability of group's decision can be estimated as follows (assuming group size = 2; pedestrians i, j) :

$$U = \begin{bmatrix} A_i^T & 0 \\ 0 & A_j^T \end{bmatrix} \begin{bmatrix} Y_i \\ Y_j \end{bmatrix} \tag{3.18a}$$

where Y_i and A_i^T are as defined in equation set (3.11). The covariance matrix for this group is

$$\Sigma_{U_2} = \begin{bmatrix} \Sigma_{U_i} & \\ Cov(i,j) & \Sigma_{U_j} \end{bmatrix} \tag{3.18b}$$

The diagonal block element Σ_{U_i} and Σ_{U_j} are covariance matrices derived earlier in equation set (3.11). Cov(i,j) $\neq 0$ because there is interaction among the group members. If the error terms are assumed to be identically distributed across members within a group, then cov(i,j) is also equal to Σ_U. This assumption holds only when the group crosses as a single entity. If a group splits, the lagging group is more likely to accept a smaller gap to reunite with the leading group. The covariance term for the non-shared gaps would therefore be different from the shared gaps. In a general case, cov(i,j) = Σ_U for all shared gaps, and assumed equal to another parameter $[\sigma_{32}]$ for all non-shared gaps; σ_{32} can be estimated along with Σ_U from the sample.

3.4.2 Intersections with Push-Buttons

If the crosswalk has a push-button, the pedestrian can either push the button or ignore it. Let ΔU_{PB} denote the difference in utilities for pushing and not pushing the button. Then

$$\Delta U_{PB} = \beta_{pb} X_{pb} + \varepsilon_{pb}\text{ , and } \varepsilon_{pb} \sim \text{iid } N(0, \sigma_{pb}2). \tag{3.19}$$

Pedestrians using the push-button tend to accept longer gaps because they are more likely to wait for the WALK indication. Therefore, the push-button choice behavior is not independent of gap-acceptance behavior, i.e., $E[\ \varepsilon_{pb}\ \varepsilon_{jn}\ ] \neq 0$. A joint estimation is appropriate. Let $E[\ \varepsilon_{pb}\ \varepsilon_{jn}\ ] = \pi_1$. If $\Delta U_{PB} > 0$, the pedestrian pushes the button. Define λ = -1 if a push-button is used, λ = 1 if the push-button is ignored, and = 0 if there is no push-button. Then $\lambda \Delta U_{PB} \leq 0$. The gap-acceptance behavior and the push-button choice behavior can be jointly estimated as follows:

$$A^T_{PB} = \begin{bmatrix} A^T & 0 \\ 0 & \lambda \end{bmatrix} \quad \text{and} \quad Y_{PB} = \begin{bmatrix} Y \\ \Delta U_{PB} \end{bmatrix} \tag{3.20a}$$

where A^T and Y are the matrices derived earlier. The covariance matrix ΔU_{PB} can be derived as

$$\Sigma_{U_{PB}} = \left[\begin{array}{ccccc:c} & & & & & 0 \\ & & & & & \lambda a^1 \pi_1 \\ & & & & & \cdot \\ & & \Sigma_U & & & \cdot \\ & & & & & \cdot \\ & & & & & \lambda a^J \pi_1 \\ \hdashline 0 & \lambda a^1 \pi_1 & \cdot & \cdot & \cdot \; \lambda a^J \pi_1 & \lambda^2 \sigma^2_{pb} \end{array} \right] \tag{3.20b}$$

Its dimension is mode-specific (equal to (J+2) for the first mode, and to (2J+2) for the second mode); π_1 would be equal to zero if push-button behavior is independent of gap-acceptance behavior.

3.5 Summary

In this chapter, the gap-acceptance theory is extended from a single-lane crossing to a multi-lane crossing. The implicit behavioral assumption is that pedestrians look for gaps when they arrive at the intersection. Four modes of crossing are identified. Gap-acceptance behavior is formulated for each mode in a multinomial probit framework. The framework is modified to accommodate group crossings and intersections with push-buttons. The model calibration and data issues are discussed in the following chapters.

CHAPTER 4: DATA COLLECTION METHODOLOGY

4.1 Introduction

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

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

a) Intersections with no pedestrian signals,

b) Intersections with pre-timed signals,

c) Intersections with pedestrian-actuated signals.

Each signal type is associated with specific characteristics producing both systematic and random behavior variation. The above sampling strategy does not preclude intersections from any of the above three signal categories. The next two sections discuss the development and application of the sampling methodology, followed by an analysis of the basic behavior and compliance characteristics revealed in the data.

4.2 Procedure

The land use surrounding the intersection was divided into two concentric zones as shown in Figure 4.1. The first zone is defined by a circle of quarter-mile radius [402 meters], which is the typical pedestrian walking distance. The second zone is a circle of one-mile radius [1,609 meters], not including the first zone. It is defined to account for inter-zonal trips generating a crossing at the intersection. As most sites have a mixture of land uses, the dominant pedestrian generating land-use type was used to classify intersections. Five land-use types for the quarter-mile [402-meter] zone and four for the one-mile [1,609-meter] zone are identified in Table 4.1, listed in ascending order of dominance.

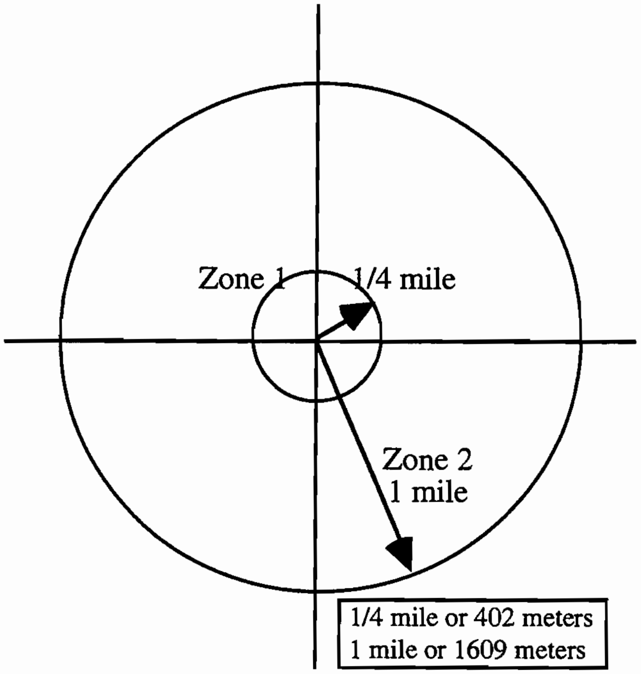


Figure 4.1
Zonal Demarcation of Land Use at the Intersection

Quarter-mile [402-meter] zone	One-mile [1,609-meter] zone
Residential	Residential
Minor-Retail	Commercial
Major-Retail	Institutional
Institutional	Recreational
Recreational	

Table 4.1
Land-Use Type for Zones 1 and 2

The above classification gives rise to twenty combinations. The land uses are defined as follows. Within the quarter-mile [402-meter] zone, buildings for residential and other living purposes, as well as vacant land, are identified under residential land use. A minor-retail land use is a combination of residential land use with small commercial centers such as convenience stores and fast-food centers. Major-retail land use is identified with shopping malls and major grocery stores. Institutional land use is comprised of hospitals, schools, universities, and major multi-story office buildings where large number of pedestrians are generated. Recreational land use includes major parks and recreational centers.

For the one-mile [1,609-meter] 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. The remaining two land uses have the same definitions as those for the quarter-mile [402-meter] zone.

4.3 Application

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

A video recording technique was used to obtain information on pedestrian behavior. The advantage of using video is the ability to review the information repeatedly, and at comfort, and thus to improve the reliability of the data collected. A Sony camcorder, CCD 410 FX model, was used. It has an built-in timer accurate to a second. The video was set up at one corner of the intersection, and operated only when a pedestrian was crossing. The tapes were replayed to obtain information on a large set of variables, and those relevant to this study are stated in Tables 4.2 and 4.3.

I) Arrival Process Attributes
   a) Group arrival size: number of pedestrians arriving in the same group.
   b) Platoon departure size: number of pedestrians crossing together as an entity; arrivals within the platoon could be either independent or in groups.

LAND USE 1-mile zone [1,609 meters]	 1/4-mile zone [402 meters]	INTERSECTIONS #	 (%)
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)

Table 4.2
Distribution of Intersections by Land Use

LAND USE 1-mile zone [1,609 meters]	 1/4-mile zone [402 meters]	INTERSECTION
Residential	Residential	Bull Creek & 45th
	Minor retail	W. Cannon & Brush County
	Major retail	W. Cannon & W. Gate
	Institutional	W. Cannon & Brodie
	Recreational	Oak Springs & Springdale
Commercial	Residential	Airport & 12th
	Minor retail	Lamar & Justin
	Major retail	Anderson & Shoal Creek
	Institutional	St. John's & Cameron
	Recreational	51st & Guadalupe
Institutional	Residential	Duval & 38th
	Minor retail	Lamar & 34th
	Major retail	Ben White & 1st
	Institutional	Main & Magnalion*
	Recreational	Guadalupe & 45th
Recreational	Residential	I-35 & Riverside
	Minor retail	Lamar & Treadwell
	Major retail	Lamar & Barton Springs
	Institutional	Riverside & Congress
	Recreational	Barton Springs & R.E. Lee

* Fort Worth location

Table 4.3
Intersections by Land Use Selected for the Study

II) Pedestrian-Specific Attributes

- a) Gender of pedestrian.
- b) Age of the pedestrian, estimated on-site.
- c) Ethnicity of the pedestrian, based on appearance.

III) Signal Indications and Push-Buttons

- a) Traffic signal indication, noted as either green or red.
- b) Pedestrian signal indication, if present, noted as WALK, flashing DON'T WALK, or steady DON'T WALK.
- c) Push button usage, if applicable.

IV) Intersection Characteristics

- a) Number of lanes in the crossing direction.
- b) Median usage, if present.

V) Gap-Acceptance and Behavior Information

- a) Total wait time until crossing. If the pedestrian crossed on DON'T WALK, this variable is defined as the time between the instant at which the pedestrian comes to a momentary stop and that at which he/she steps off the curb and begins to cross. Otherwise, it is defined as the time between the instant when he/she comes to a momentary stop and the instant at which the signal changes from DON'T WALK to WALK; the remaining time is recorded as the reaction time to the display of the WALK indication.
- b) Lane-by-lane gap information from the instant of arrival. A gap is defined as the time interval between successive vehicles. However, the first gap, i.e., a lag, is measured as the time between the pedestrian arrival and the first vehicular arrival. Using gaps from individual lanes, one could obtain gaps for the near and far streams separately, or for the approach as a whole, as described in the previous chapter.
- c) The wait time at the beginning of each gap, obtained by adding all the previous gaps for that lane.
- d) Mode of crossing, i.e., one-stage, two-stage, or lane-by-lane crossing.
- e) Crosswalk compliance, i.e., adherence to crosswalk markings during the crossing maneuver.

f) Crossing time, between the instant at which the person steps off the curb and that at which he/she then steps on the curb at the other end.

g) Start-up time, measured from the instant of steady WALK to the instant a pedestrian steps off the curb. It is measured for pedestrians who wait and cross on a steady/flashing WALK.

Inter-vehicular gaps were measured to an accuracy of 0.01 seconds using a continuous time-event recorder. When the pedestrian arrives at the intersection, or when a vehicle passes the crosswalk, a button is pushed to mark the event. The instrument automatically records the time between events. It can store up to thirty gaps. Waiting time was also similarly recorded. The task of decoding information from the videotapes was shared by two persons. In order to ensure consistent interpretation of variable definitions, a stringent inter-scorer reliability check was conducted according to the procedure shown in Figure 4.2. The data accuracy improved from 91 percent to 98 percent after going through the consistency check.

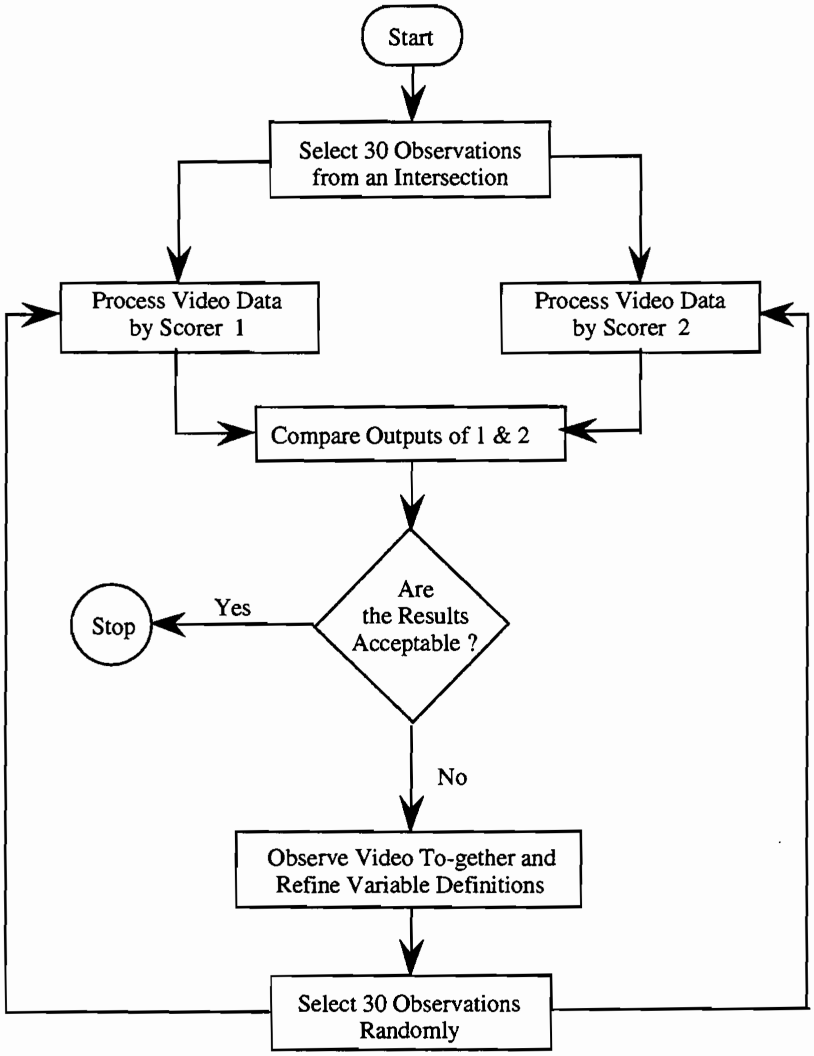
4.4 Behavior and Compliance Characteristics

A descriptive analysis was conducted to study the behavior and compliance characteristics of the pedestrians. A comparison is made between intersections with and without pedestrian signals. This approach is likely to provide some evidence on the benefits of signalization. Since behavior is person-specific, the behavior and compliance characteristics are studied with respect to individual attributes, namely gender, age, and race. The pedestrian population is segmented into five groups based on age and four groups based on race as follows:

Age $= 0$, if age < 9
$= 1$, if $9 \leq$ age ≤ 18
$= 2$, if $18 <$ age ≤ 39
$= 3$, if $39 <$ age ≤ 59
$= 4$, if age > 59

Ethnicity $= 1$, if White
$= 2$, if Black
$= 3$, if Hispanic
$= 4$, others

The following characteristics are considered in the analysis: signal compliance, push-button compliance, crosswalk compliance, walk rate, start-up time, and crossing manner (walk, run, etc.). Henceforth, a signalized intersection refers to an intersection with



<u>**Inter-Scorer Data Reliability Procedure**</u>
Figure 4.2

Figure 4.2
Inter-Scorer Data Reliability Procedure

pedestrian signal, and an unsignalized intersection is one with no pedestrian signal. All intersections considered in the study have a traffic signal.

Data from different intersections is pooled depending on the presence or absence of a pedestrian signal. A total of 712 and 235 intersection crossings were observed at signalized and unsignalized intersections respectively. The numbers of arrivals and crossings on each signal indication are shown in Table 4.4. The percentage of pedestrians making an illegal crossing, i.e., crossing on steady "don't walk" (SDW) or RED, is lower at signalized than at unsignalized intersections. Also, most of the pedestrians arriving on a flashing "don't walk" cross immediately, and only a small fraction wait for the next "walk" indication.

4.4.1 Pedestrian Signal Compliance

The first aspect considered is signal compliance. Table 4.5 compares signal compliance at signalized and unsignalized intersections, i.e., for arrivals on SDW/RED respectively. The signalized intersections have higher compliance (the percentage crossing on SDW is less than the percentage crossing on RED). At signalized intersections, there is no significant difference in compliance between male and female pedestrians. However, at unsignalized intersections, male compliance is lower by 13 percent. Very young pedestrians (age ≤ 8) are likely to be accompanied by adults, and their behavior is closer to that of their attendants. There is no significant difference between age groups 2 and 3 at signalized intersections. Due to insufficient data, no definite statements can be made about behavioral variation with age. Comparing across race, it appears that the second group pays less regard to the signal indications, especially at unsignalized intersections. Overall, it can be seen that signals produce better compliance.

4.4.2 Push-Button Compliance

The second aspect is push-button compliance. Two issues to be considered are: the fraction of pedestrians (with a push-button option) using the push-button, and, of those who use, the fraction waiting for a "walk" indication (i.e., those who cross on "walk" or flashing "don't walk"). The compliance percentages are shown in Table 4.6, again tabulated by gender, age, and ethnicity. The push-button compliance at signalized intersections is at most 50 percent. At unsignalized intersections, the sample size is too small to draw any definite conclusions. However, the percentage of pedestrians who push the button and wait for "walk" is quite satisfactory (over 70 percent). Even after pushing the button, the appearance of a safe gap is likely to encourage pedestrians to cross on "don't walk."

4.4.3 Crosswalk Compliance

The next aspect is crosswalk compliance. It should first be noted that jaywalkers are not part of the analysis. Throughout the crossing maneuver, a pedestrian may be entirely within the crosswalk, totally outside the crosswalk, or partially inside and partially outside the crosswalk. If compliance with crosswalk markings is poor, then these markings represent a futile investment of time and money. The compliance percentages by gender, age, and race are shown in Table 4.7. They are quite high, especially the sum of those inside or partially inside the crosswalk, even at unsignalized intersections. At signalized intersections, pedestrians are more likely to cross within the crosswalk. The current sample does not have sufficient representation of crossings at intersections without crosswalk markings.

4.4.4 Walk Rates and Start-Up Times

Information on pedestrian walk rate and start-up time is critical in evaluating the duration of the flashing "don't walk" phase. Shorter durations are likely to cause problems analogous to the dilemma zone problem when vehicles are faced with a yellow light, and may result in an uncomfortable crossing (running instead of walking). The average walk rates obtained for the population are shown in Table 4.8, again by gender, age, and ethnicity. Only crossings at signalized intersections are considered. Also, only those walking are considered. Males have a higher walk rate compared to females, but the values are not significantly different at the 5 percent level. The older population has the lowest walk rate compared to the rest. A mean value for the population is obtained as 5.57 ft/sec (1.70 m/sec) with a standard deviation of 1.25 ft/sec (0.38 m/sec). The mean start-up time for the population is 1.55 sec with a standard deviation of 2.97 sec. Comparing the start-up times across gender, males have a higher value, but the standard deviation is also high. Younger pedestrians appear to react more quickly than other age groups.

Signalized Intersections

Arrival / Crossing	W	FDW	SDW	Total
W	88(96)	7(9)	327(61)	422
FDW	3(3)	59(74)	23(4)	85
SDW	1(1)	14(18)	190(35)	205
Total	92	80	540	712

Unsignalized Intersections

Arrival / Crossing	GREEN	RED	Total
GREEN	78(96)	77(51)	155
RED	3(4)	73(49)	76
Total	81	150	231

Numbers in parentheses denote percentages.

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

Table 4.4

Arrivals and Crossings at Signalized and Unsignalized Intersections

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

*: % based on less than 30 observations

† Age = 0 (< 9 years); = 1 ($9 \leq$ age ≤ 18); 2 = ($18 <$ age ≤ 39); = 3 ($39 <$ age ≤ 59); = 4 (age > 59)

†† Ethnicity: 1 if white, 2 if Black, 3 if Hispanic, 4 if Other

Table 4.5

Percentage Signal Compliance at Signalized and Unsignalized Intersections

Push-Button		Signalized Intersection		Unsignalized Intersection	
Attributes		% YES †††	% NO	% YES	% NO
Gender	M	46 (80)	54	29*	71*
	F	44 (74)	56	22*	78*
† Age	0	0* (0)	100*	0*	0*
	1	36* (100)	64*	0*	100*
	2	50 (78)	50	57*	43*
	3	37 (72)	63	0*	100*
	4	0* (0)	100*	0*	100*
†† Ethnicity	1	50 (84)	50	25*	75*
	2	33* (88)	67*	0*	0*
	3	38 (60)	62	0*	0*
	4	0* (0)	0*	0*	0*
Total		45 (78)	56	25*	75*

*: % based on less than 30 observations

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

† Age = 0 (< 9 years); = 1 (9 ≤ age ≤ 18); = 2 (18 < age ≤ 39); = 3 (39 < age ≤ 59); = 4 (age > 59)

†† Ethnicity: 1 if white, 2 if Black, 3 if Hispanic, 4 if Other

††† The YES column gives the percentage of arriving pedestrians who pushed the pedestrian signal actuation button; No refers to those who did not.

Table 4.6

Push-Button Compliance at Signalized and Unsignalized Intersections

Crosswalk		Signalized Intersection			Unsignalized Intersection		
Attributes		1	2	3	1	2	3
Gender	M	72	25	3	70	25	5
	F	81	17	2	52	41	7
† Age	0	62*	38*	0*	71	25	4
	1	90*	10*	0*	67*	33*	0*
	2	77	20	3	54	37	8
	3	69	30	12	73	24	3
	4	82*	9*	9*	33*	67*	0*
†† Ethnicity	1	75	22	3	69	24	7
	2	80	19	1	52	41	7
	3	72	26	2	65	33	2
	4	67*	33*	0*	60*	40*	0*
Total		76	21	3	61	33	6

*: % based on less than 30 observations

_: 1 - Within Crosswalk; 2 - Partially Inside; 3 - Totally Outside

† Age = 0 (< 9 years); = 1 (9 ≤ age ≤ 18); = 2 (18 < age ≤ 39); = 3 (39 < age ≤ 59); = 4 (age> 59)

†† Ethnicity: 1 if white, 2 if Black, 3 if Hispanic, 4 if Other

Table 4.7

Crosswalk Compliance at Signalized and Unsignalized Intersections

Signalized Intersection		Walk Rate (ft/sec)	Start-Up Time (sec)
Gender	M	5.705 (1.253)	1.60 (3.41)
	F	5.317 (1.203)	1.43 (1.67)
Age	0	5.471 (1.502)*	3.74 (3.52)*
	1	5.367 (1.126)*	2.46 (3.01)*
	2	5.684 (1.263)	1.09 (1.48)
	3	5.301 (1.150)	2.67 (5.38)
	4	4.768 (1.304)*	2.38 (1.82)*
Ethnicity	1	5.618 (1.289)	1.58 (3.30)
	2	5.662 (1.182)	0.92 (2.01)*
	3	5.237 (1.090)	1.91 (2.14)
	4	6.018 (1.070)*	1.300 (0.700)*

*: % based on less than 30 observations

Values in parentheses are standard deviations (1 ft/sec = 30 cm/sec)

Table 4.8

Walk Rates and Start-Up Times at Signalized Intersections

4.5 Summary

Data collection is an integral part of any behavioral modeling study. A stratified random sampling approach based on land use was developed. Two zones were defined to classify intersections. Using this approach, intersections were selected from the city of Austin. Data was obtained through on-site observations and video recording techniques. A descriptive analysis of the data was conducted to characterize aggregate behavior and compliance characteristics. This information forms the observational basis for calibrating the gap-acceptance models developed in the previous chapter. The results of the estimation and their implications are discussed in the next chapter.

CHAPTER 5: MODEL ESTIMATION

5.1 Introduction

With the model framework and the data collection methodology described in the previous two chapters, this chapter focuses on model estimation. In section 5.2, the sample size is briefly described. The gap size distribution is examined with respect to gap, intersection, and individual characteristics in section 5.3. Section 5.4 discusses the estimation methodology and the model specifications. The results are reported in section 5.5, followed by a summary in section 5.6.

The following terminology is used in this chapter. Two modes of one-stage crossing were identified in Chapter 3. In mode (a), the pedestrian is assumed to look for a gap in the entire traffic. In mode (b), the pedestrian looks for a near gap and a far gap. Four different gap acceptance models are developed in this chapter:

Model 1: mode (a), with no push-button or group interactions.
Model 2: mode (a), with push-button but no group interactions.
Model 3: mode (a), with group but no push-button interactions.
Model 4: mode (b), with no push-button or group interactions.

5.2 The Data

The model estimation is based on observations taken at seventeen intersections. Most intersections had very low arrivals (about 70), with two sites having as low as five pedestrians during a survey period that lasted five to six hours per site. Observations of pedestrian arrivals on the "walk" phase are excluded, as no gap acceptance behavior is associated with them. For the reason mentioned in section 3.1, arrivals on flashing "don't walk" are not included. Mid-block crossings are not considered, as they fall outside the study scope. As models developed in Chapter 3 are conditioned on the crossing mode selected, separate data sets were created for each chosen mode. A total of 135 observations were obtained for the one-stage crossing analysis. However, because fewer than 35 observations were available for each of the last two modes, the analysis is restricted to one-stage crossing, i.e., modes (a) and (b) only. Further, at heavy traffic intersections, most of the gaps are rather small. Their inclusion would unnecessarily increase the size of the variance-covariance matrix without contributing any valuable information. The size of the gap needs to be restricted to omit the smaller gaps. The minimum gap size (G_{min}) was selected based on two criteria. First, the minimum accepted gap should be greater than G_{min}. The second criterion is the size of the variance-covariance matrix. The computation time is highly dependent on the size of the variance-covariance matrix, which is a function of the number of gaps included for each observation. This constraint is addressed in section 5.4. A pre-processor was developed on a PC to obtain the gap data for modes (a) and (b) based on the above two constraints. The program is provided in Appendix B.

5.3 Preliminary Analysis

In order to identify the influential variables, the distribution of accepted and rejected gaps is examined with respect to other gap characteristics, as well as intersection and pedestrian attributes. First, the gap distribution is considered with respect to the waiting time. Figure 5.1 illustrates a hypothetical deterministic case, where all pedestrians behave consistently and have the same critical gap, represented by the solid curve in the graph. The critical gap is expected to decrease with waiting time. Each point (labeled 'a' for accepted and 'r' for rejected) on the graph represents a gap or a lag. Under the deterministic critical gap idealization, all gaps above the curve are accepted, and those below are rejected. In actual data, there will be rejected gaps above the mean critical gap curve and accepted gaps below it, which is why the critical gap is modeled as a random variable. Figure 5.2 depicts the actual rejected and accepted gaps (and lags) as a function of the wait time for the pedestrian crossing instances observed in the data set obtained for this study. While the demarcation between accepted and rejected gaps is no longer clear-cut (as expected), the general trend of decreasing mean with waiting time can still be observed. In this figure, the plotted gaps corresponding to a waiting time of zero are actually lags (by definition). The plot seems to suggest that the accepted lags tend to be smaller than the accepted gaps. A lag is measured from the instant at which the pedestrian steps off the curb (in the case of an immediate crossing), or slows at the corner (in the case of a rejected lag) to the instant at which the vehicle clears the crosswalk. Therefore, in this study, the critical lag is the time required to cross safely, whereas the critical gap includes the time to perceive a gap in addition to the time to cross safely.

Figures 5.3 and 5.4 show the gap distributions plotted against the waiting time for the near and the far stream, respectively. The critical lag and gap values for the far stream seem to be smaller than the corresponding near stream values, suggesting that the pedestrians may be less vigilant with respect to gaps in the far stream.

Figures 5.5 and 5.6 show the distribution of the gap size plotted against two intersection attributes, land use and crosswalk width, respectively. It can be seen that at wider intersections (≥ 5), or intersections with at least a commercial land use (IST = 1), pedestrians are more likely to accept long gaps.

Figure 5.7 shows the gap size distribution against a "young male" indicator variable (defined as =1, if $19 \leq \text{Age} \leq 55$, and gender = male, and as = 0, otherwise). These pedestrians are usually more aggressive and tend to accept short gaps. Note that the data was obtained on weekdays during normal work hours, and these conclusions may not be applicable at other times.

Figure 5.8 shows the distribution of gap size with the arrival group size. Only a few observations are available in the sample to capture the effect of group interactions, so results may not be conclusive.

Again, not many observations are available to capture the correlation between gap acceptance behavior and push-button behavior (Figure 5.9).

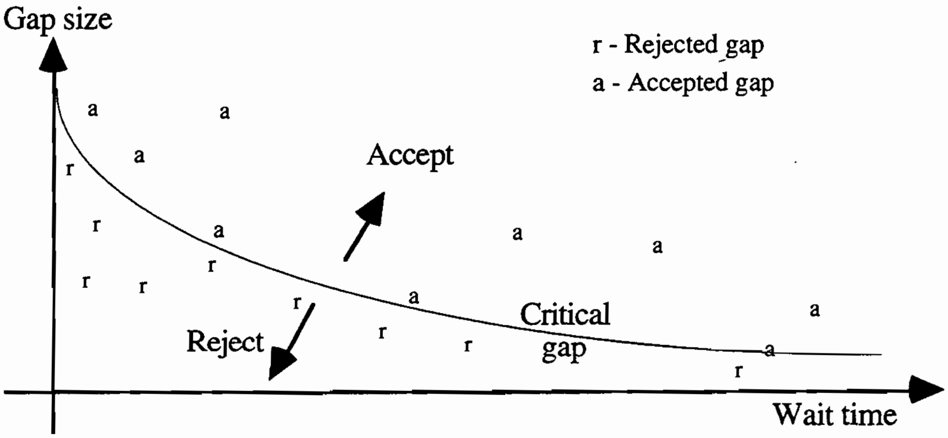


Figure 5.1

Hypothetical Distribution of Gap Size with Wait Time for a Deterministic Critical Gap

IST	Intersection Status, an indicator, intended to reflect the activity level at the intersection. Not applicable at odd hours when the traffic volume is low. = 1, for intersections with at least a major retail land use = 0, otherwise
AGSX	Interaction term between Gender and Age = 1, if $19 \leq \text{age} \leq 55$ and gender = MALE = 0, otherwise
RACE	= 1, if non-white = 0, otherwise
HANDS	Hands, an attribute of non-compliance behavior with push-button = 0, if the pedestrian is empty-handed or carrying small items = 1, otherwise
NOLNS	No. of lanes in the cross-walk = 1, if number of lanes ≥ 5 = 0, otherwise
WAIT	Elapsed time (in seconds) at the beginning of each gap
λ	Indicator variable to identify a lag = 1, if wait time > 0 = 0, otherwise
GAP	Gap size in seconds
LNPST	Lane position of the vehicle. Lanes are numbered moving away from the pedestrian. For mode (b), lanes are numbered separately for the near and far streams.
TURN	Vehicle type = 1, if it is a turning vehicle = 0, otherwise
DIRXN	Direction of traffic. = 1, if vehicle is in the far stream. = 0, if it is in the near stream
GPB	Group's push-button response = 1, if the pedestrian ignores the button, but not the group = 0, if the group ignores the button, or if the pedestrian uses it

Table 5.1

Definitions of Variables in the Utility Specification

(a) Gap-Acceptance Function

Parameter	Estimate	t-statistic
Initial Mean Critical Lag	8.95	8.18
Initial Mean Critical Gap	10.3	7.37
WAIT	-0.132	-2.18
IST	4.93	2.73
LNPST	1.49	0.56
TURN	-3.26	-2.75
DIRXN	-3.14	-0.63
AGSX	-2.17	-1.76
σ^2	19.37	14.60

Number of Observations	133
Initial Log Likelihood L (0)	-255.08
Log Likelihood at Convergence L (β)	-105.17
Adjusted Goodness of Fit (ρ^2)	0.55

(b) Push-Button Choice Function

Parameter	Estimate	t-statistic
Constant	0.637	-0.94
RACE	-1.10	-2.29
HANDS	-0.41	-0.90
NOLNS	1.28	1.59
IST	0.209	0.43
GPB	-4.56	-0.38

Number of Observations	52
Initial Log Likelihood L(0)	-36.04
Log Likelihood at Convergence L(β)	-22.61
Adjusted Goodness of fit (ρ^2)	0.21

Figure 5.2

Scatter Plot of Gap Size Against Wait Time for Mode (a)

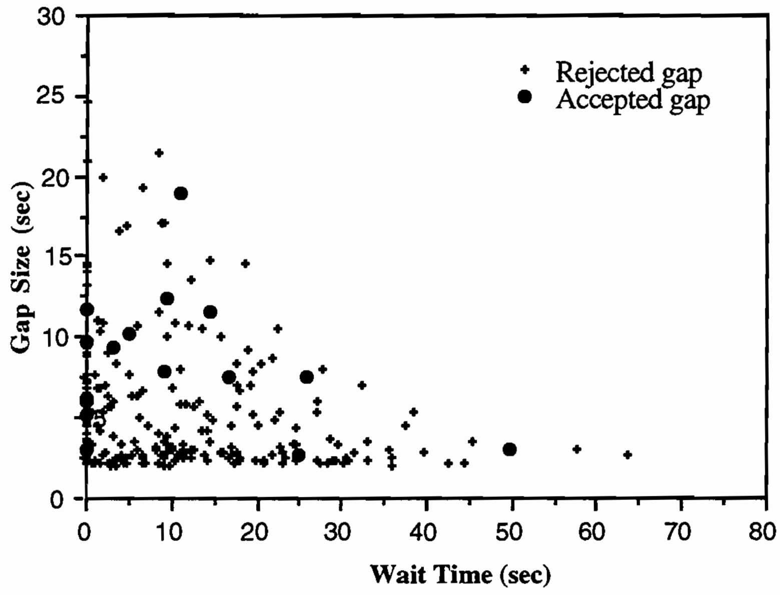


Figure 5.3
Scatter Plot of Gap Size Against Wait Time for Mode (b): Near Side

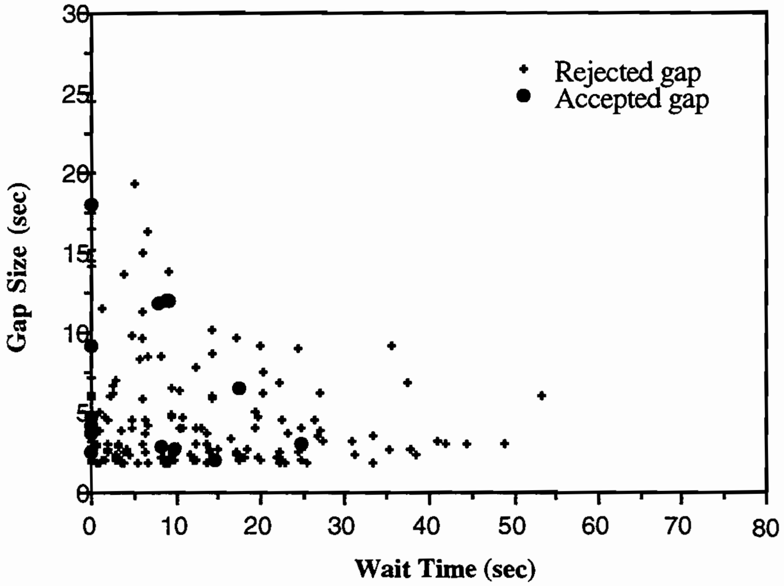
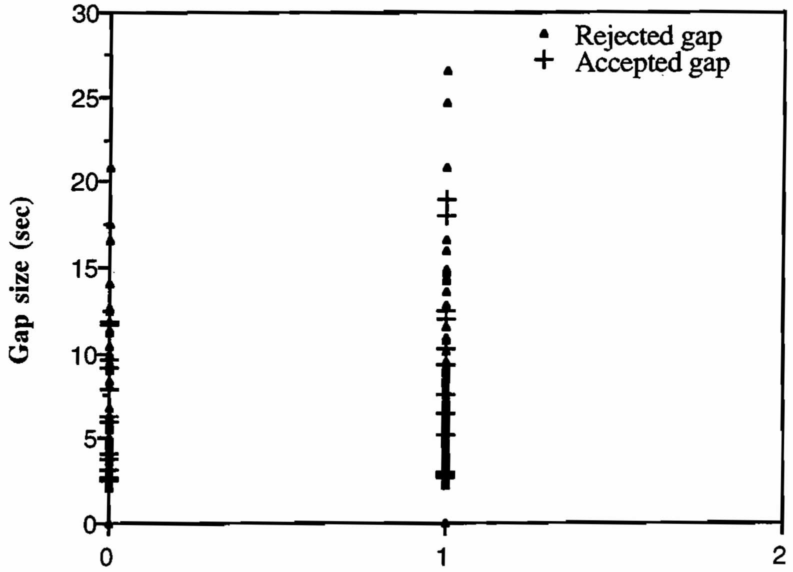


Figure 5.4
Scatter Plot of Gap Size Against Wait Time for Mode (b): Far Side

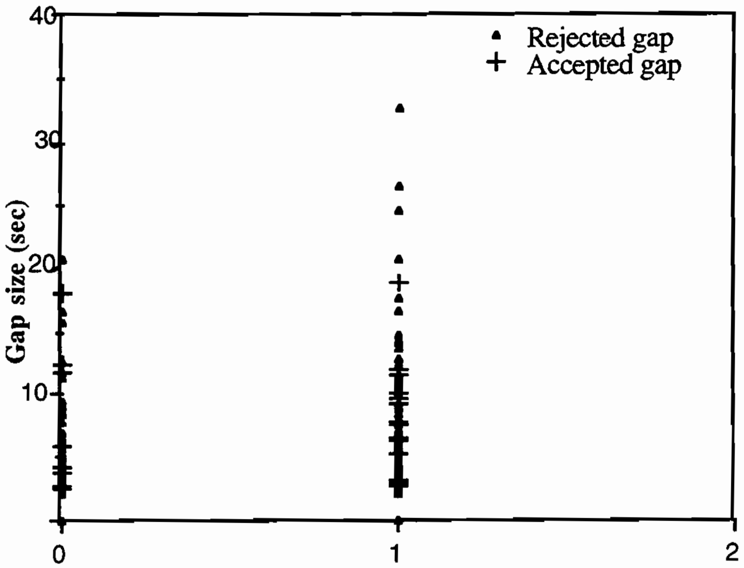


Variable: IST

(IST = 0, land use < major retail; =1, otherwise)

Figure 5.5

Scatter Plot of Gap Size Against Intersection Attribute: Land Use



Variable: NOLNS

(=1, if number of lanes ≥ 5; =0, otherwise)

Figure 5.6

Scatter Plot of Gap Size Against Intersection Attribute: Crosswalk Width

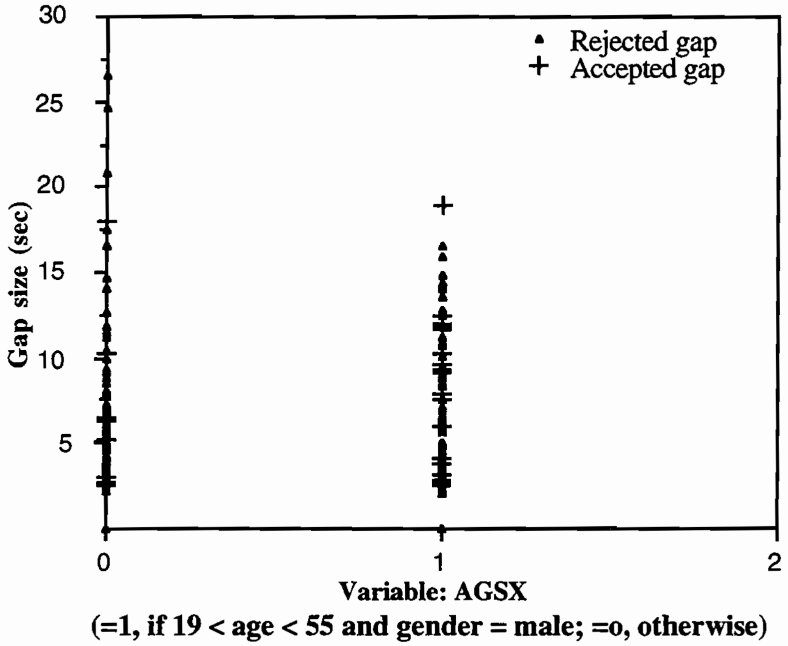


Figure 5.7
Scatter Plot of Gap Size Against Person-Specific Attribute

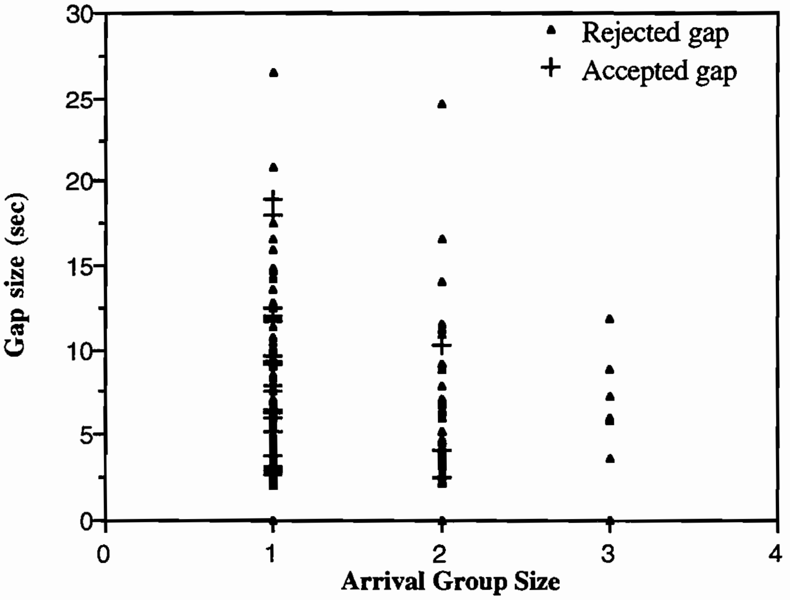


Figure 5.8
Scatter Plot of Gap Size Against Arrival Group Size

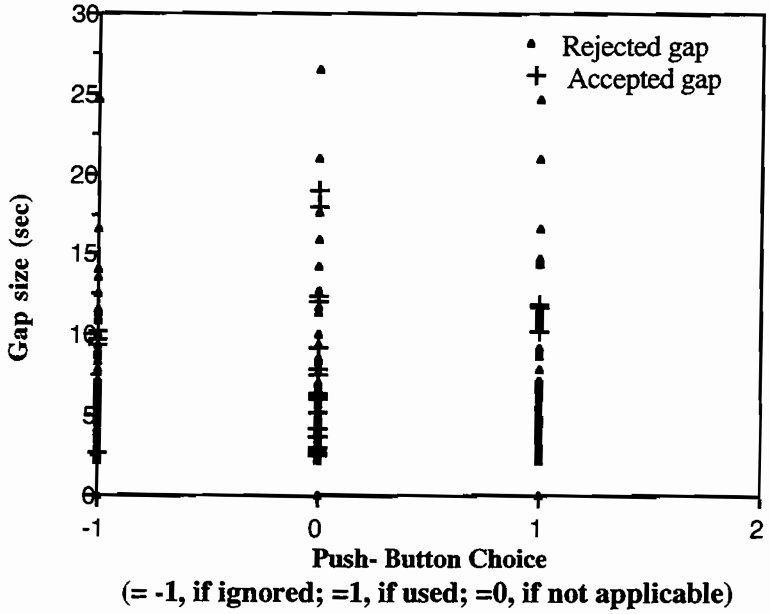


Figure 5.9
Scatter Plot of Gap Size Against Push-Button Choice

5.4 Model Calibration

5.4.1 Estimation Procedure

In Chapter 3 (sections 3.2 and 3.3), the models were developed in the random utility maximization framework using a multinomial probit (MNP) form. The main drawback of MNP is that the estimability condition, i.e., the strict concavity of the log-likelihood function, cannot be verified. There are no efficient algorithms that can guarantee a global optimum for the likelihood maximization problem. In order to obtain satisfactory estimates, the model estimation proceeded in three stages. First, a critical gap model is estimated with an assumption of independent errors across gaps and individuals (Mahmassani and Sheffi [1982]), so that

$$\text{Pr(accept or reject gap i | all attributes)} = \Phi\left(\frac{\delta(T_p + \beta X - g_i)}{\sigma}\right) \qquad (5.1)$$

where, $\Phi(.)$ denotes the standard normal distribution; T_p is the initial mean critical gap, g_i is the gap considered at i^{th} instant, and vectors X and β are the other attributes and corresponding coefficients in the critical gap specification. $\delta = -1$, if the gap is rejected, and $= 1$, if the gap is accepted. Using the above specification, an estimator for σ is obtained as the inverse of the estimator for $(1/\sigma)$, which is the coefficient of g_i in the model. This estimate of σ is used along with the initial values of the mean critical lag and gap to calibrate model 1 under the independence assumption both "within" and "across" individuals. This can be achieved by constraining the off-diagonal terms to zero in the variance-covariance matrix. Next, these estimates are used to calibrate model 1. Initial estimates of parameters in the push-button utility function are obtained from a binary probit analysis. These values along with the estimates of model 1 are used to calibrate model 2. The estimates from model 1 are used as starting values for the remaining models as well.

Since no closed form expressions are available to evaluate the multi-dimensional integral of a MNP model when the number of alternatives is greater than three, a program based on Monte Carlo simulation is used to compute the choice probabilities (Lam [1991]). This program obtains the maximum likelihood estimates of the parameters, and was developed on the Cray -YMP super computer at The University of Texas at Austin.

The computational time is a function of the size of the variance-covariance matrix. For model 1, the dimension of the matrix is equal to [maximum number of gaps for an observation in the sample + 1]. The auxiliary alternative increases the dimension by one unit. Incorporating the push-button behavior with the gap-acceptance behavior (i.e., model 2) adds another row (and a column, by symmetry) to the variance-covariance matrix. The maximum group size in this study is three. Therefore, the dimension for model 3 would be [3 (maximum number of gaps) + 1]. In model 4, the pedestrian has to consider a near stream gap and a far stream gap simultaneously, before crossing. So its dimension would be [2 (maximum number of gaps) + 1], again with the one coming from the auxiliary alternative.

Only gaps over 2.25 sec were included in the sample. It is to be noted that the number of gaps for a pedestrian in mode (a) need not be same as the number of gap pairs for the same pedestrian in mode (b). The maximum number of gaps was 11 for mode (a) and 12 for mode (b), resulting in the following dimensions for the models.

Model #	Dimension of the Var-Cov Matrix
1	12
2	13
3	34
4	25

Model 3 is considered mainly to assess the significance of group interactions and not so much to obtain precise estimates of gap-acceptance parameters. The maximum dimension of the matrix was limited to 25 for computational considerations. For model 3, the minimum gap considered was changed from 2.25 sec to 3 sec. This resulted in omission of few non-group (i.e., individual) arrivals. In order to test the consequence of discarding these records (and also, gaps between 2.25 and 3 seconds for some records), model 3 was re-estimated by constraining the terms capturing group correlation in the variance-covariance matrix to zero, and then comparing with model 1. This is possible because model 1 is a special case of model 3 when group correlations are constrained to zero. In the estimation, a high negative value is associated with all non-existent gaps. The results are discussed in section 5.5.

5.4.2 Model Specification

The critical gap varies across gaps and across individuals. Since data from different intersections is grouped in the analysis, part of the variation could also be explained using intersection-specific attributes. The systematic specification of the gap-acceptance function is comprised of the following components:

a)	Initial Mean Critical Gap	$T_{lag}(1 - \lambda) + T_{gap}\lambda$
b)	Gap Characteristics	$(-\text{GAP}) + \beta_3\,\text{WAIT} + \beta_4\,\text{LNPST}$ $+ \beta_5\,\text{TURN} + \beta_6\,\text{DIRXN}$
c)	Intersection Characteristics	$\beta_7\,\text{IST}$
d)	Pedestrian Characteristics	$\beta_8\,\text{AGSX}$

This specification is applicable to mode (a), i.e., models 1, 2, and 3. The variable definitions are listed in Table 5.1. β_i's are the parameters to be estimated along with other parameters in the variance-covariance matrix. The assumptions embedded in this specification are:

(i) The initial mean critical lag is assumed different from the initial mean critical gap.

(ii) The lane position of the vehicle captures the variation in gap-acceptance behavior across lanes.

(iii) Pedestrians are more likely to risk crossing a gap when the oncoming vehicle is a turning vehicle or if it is in the far stream.

(iv) At busy intersections, pedestrians are more cautious.

For mode (b) crossing, the same specification is used for the near stream and the far stream with some modifications. The stream-specific variable (DIRXN) is no longer considered, as it is redundant. Also, in mode (b), a gap pair may be rejected because the near stream gap is small, or the far stream gap is small, or both are too small to accept. An additional term is therefore introduced to account for the size of the other stream gap as follows: (c_1 β_9 GAP_{far} + $[1-c_1]$ β_{10}) for the near stream function, and (c_2 β_{11} GAP_{near} + $[1-c_2]$ β_{12}) for the far stream function. If GAP_{near} is greater than 15 sec, $c_1 = 0$, and = 1, otherwise; i.e., if the far stream is "too long," its size is inconsequential. Similarly, c_2 is defined with respect to GAP_{far}.

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

a) Constant Term	a_1
b) Pedestrian Characteristics	a_2 RACE + a_3 HANDS
c) Intersection Characteristics	a_4 NOLNS + a_5 IST + a_6 GPB

a_i's are the parameters to be estimated. The assumptions embedded in this specification are:

(i) Pedestrians are reluctant to use the push-button.

(ii) At busy traffic intersections and/or wide crosswalks, pedestrians are more likely to use the push-button.

(iii) If a member in a group uses the push-button, other pedestrians may ignore it.

5.5 Estimation Results and Discussion

Following the procedure discussed in section 5.4.1, the initial mean critical lag and the initial mean critical gap estimates were obtained as 8.95 sec and 10.3 sec, respectively, after the second stage. These estimates will be used as starting values for model 1. The remaining parameters of the gap-acceptance function and parameters of the push-button choice function are presented in Table 5.2. The signs of the parameters are as expected in both the functions. After satisfactory starting values are obtained, the MNP models estimated are discussed in the following sections.

5.5.1 Model 1: Mode (a) with No Push-Button or Group Interactions

In model 1, pedestrians look for a gap in the entire approach [mode (a)]. Behavior is assumed independent across individuals. Push-button interactions are ignored. The variance-covariance specification is

(a) Gap-Acceptance Function

Parameter	Estimate	t - statistic
Initial Mean Critical Lag	8.95	8.18
Initial Mean Critical Gap	10.3	7.37
WAIT	-0.132	-2.18
IST	4.93	2.73
LNPST	1.49	0.56
TURN	-3.26	-2.75
DIRXN	-3.14	-0.63
AGSX	-2.17	-1.76
$\sigma 2$	19.37	14.60

Number of observations	133
Initial Log likelihood L(0)	-255.08
Log likelihood at convergence L(ß)	-105.17
Adjusted Goodness of fit ($\rho 2$)	0.55

(b) Push-Button Choice Function

Parameter	Estimate	t - statistic
Constant	-0.637	-0.94
RACE	-1.10	-2.29
HANDS	-0.41	-0.90
NOLNS	1.28	1.59
IST	0.209	0.43
GPB	-4.56	-0.38

Number of observations	52
Initial Log likelihood L(0)	-36.04
Log likelihood at convergence L(ß)	-22.61
Adjusted Goodness of fit ($\rho 2$)	0.21

Table 5.2
Preliminary Estimates of Model Parameters

$$\Sigma_U = \left[\begin{array}{c|ccccc}
0 & 0 & & \cdot & \cdot\ \cdot & 0 \\
\hline
0 & a_1^2\sigma_1^2 & & & & \\
\cdot & & a_2^2\sigma_1^2 & & & \\
\cdot & & & \cdot & & \\
\cdot & & (a_j a_k \sigma_2^2) & & \cdot & \\
0 & & & & & a_J^2\sigma_1^2
\end{array}\right]$$

The estimates are listed in Table 5.3. The initial mean critical lag is significantly different from the initial mean critical gap at the 0.05 level. The mean critical gap (or lag) is the initial mean critical gap (or lag) plus adjustments from individual and intersection-specific attributes, and waiting time. It decreases as the waiting time increases. At busy intersections, it is larger because pedestrians have to be more attentive while crossing. At wide intersections, it is larger because of the higher risk associated with longer crossing time. The negative coefficient of TURN suggests that pedestrians are less observant of turning vehicles and less alert on turn phases. Accident studies (Robertson et al. [1984]) have reported that most accidents involve left turners. It is therefore important to educate pedestrians about the impending danger while crossing on turn phases. The coefficient of the stream-dependent variable, DIRXN, is also negative, suggesting that pedestrians are more willing to incur risk when vehicles are in the far stream. It may be necessary to provide a median to break the crossing into two stages. The "aggressive population" ($19 \leq$ age ≤ 55, and gender = male) has a lower mean value. Since these pedestrians are not overly represented in accident studies, it should not be a serious concern. The "within" component of the variance (10.5 sec^2) is less than the "across" component variance (12.33 sec^2). This result is inconsistent with the findings of Bottom and Ashworth [1978] and of Daganzo [1982]. However, the relative magnitudes depend to a large extent on the systematic specification of these components in the gap-acceptance function.

Parameter	Estimate	t - statistic
Initial Mean Critical Lag	9.85	4.24
Initial Mean Critical Gap	12.18	4.67
WAIT	-0.074	-2.71
IST	6.42	8.17
LNPST	1.20	2.59
TURN	-2.08	-3.66
DIRXN	-2.15	-4.69
AGSX	-2.89	-8.24
$\sigma_1^2 (= [\sigma_T^2 + \sigma_\varepsilon^2])$	22.83	15.96
$\sigma_2^2 (= \sigma_T^2)$	10.5	8.43

Number of observations	133
Initial Log likelihood L(0)	-255.08
Log likelihood at convergence L(ß)	-101.69
Adjusted Goodness of fit ($\rho 2$)	0.562

Table 5.3
Estimation Results for Model 1: Mode (a) with No Interactions

5.5.2 Model 2: Mode (a) with Push-Button but No Group Interactions

In model 2, pedestrians follow mode (a). Behavior is still assumed independent across individuals. However, push-button interactions are not ignored. The variance-covariance specification is

$$\Sigma_U = \left[\begin{array}{c|ccccc|c} 0 & & & & & & 0 \\ \hline & a_1^2\sigma_1^2 & & & & & \\ & & \cdot & & & & \\ & & & \cdot & & & \\ & & (a_j a_k \sigma_2^2) & & \cdot & & \\ & & & & & \cdot & \\ & & & & & a_J^2\sigma_1^2 & \\ \hline 0 & p a_1 \sigma_4^2 & \cdot & \cdot\ \cdot\ \cdot & & p a_J \sigma_4^2 & p^2\sigma_3^2 \end{array}\right]$$

The estimates are listed in Table 5.4. Again, the initial mean critical lag is not significantly different from the initial mean critical gap. All the parameters in the gap-acceptance function have the expected signs. In the push-button choice function, the signs of the estimated coefficients also meet a priori expectations. Some of the parameters are insignificant but are still retained, as the number of observations having the option of a push-button is rather small for the current sample (52 observations). The results suggest that pedestrians inherently may be less inclined to use a push-button (intercept is negative). This behavior is more pronounced when the pedestrians are carrying hand baggage. The positive coefficients for wide intersections (NOLNS) and busy intersections (IST) suggest that at these intersections, a push-button is likely to be of some assistance. When the push-button behavior is assumed independent of the gap-acceptance behavior, the ethnicity variable, RACE, was significant. However, when correlation is assumed, its coefficient is not significant even at the 0.10 level. It can be seen that the covariance between gap-acceptance and push-button behavior (σ_{42}) is significant, but its magnitude is small compared to that of other variance or covariance terms in the model. Since correlation between these two behaviors is very small, they will be assumed independent for the rest of the analysis.

5.5.3 Model 3: Mode (a) with No Push-Button but Group Interactions

In this model, pedestrians follow mode (a). However, behavior is assumed independent across groups. The push-button interactions are ignored following the results from the previous model. Assuming the group is of size two, the variance-covariance specification is

$$
\Sigma_{U_g} = \left[\begin{array}{c|c:c}
0 & & \\
\hline
 & \Sigma_{U_1} & \\
\hdashline
 & \begin{array}{cccc} a_{1_1}a_{1_2}\sigma_g^2 & 0 & 0 & 0 \\ 0 & . & 0 & 0 \\ 0 & 0 & a_{J_1}a_{J_2}\sigma_g^2 & 0 \\ 0 & 0 & 0 & 0 \end{array} & \Sigma_{U_2}
\end{array} \right]
$$

Parameter	Estimate	t - statistic
<u>Gap-Acceptance Function</u>		
Initial Mean Critical Lag	9.06	9.10
Initial Mean Critical Gap	11.21	9.83
WAIT	-0.19	-1.52
IST	6.03	3.59
LNPST	1.08	1.50
TURN	-2.53	-3.64
DIRXN	-2.64	-2.34
AGSX	-2.50	-4.53
$\sigma_1^2 (= [\sigma_T^2 + \sigma_\varepsilon^2])$	19.73	14.36
$\sigma_2^2 (= \sigma_T^2)$	9.13	9.12
<u>Push-Button Utility Function</u>		
Constant	-0.99	-0.47
HANDS	-2.28	-6.01
RACE	-2.98	-0.95
NOLNS	5.03	5.17
IST	0.18	0.29
GPB	-16.16	-15.35
σ_3^2	4.72	2.72
σ_4^2	0.62	4.42

Number of observations	133
Initial Log likelihood L(0)	-291.18
Log likelihood at convergence L(ß)	-130.84
Adjusted Goodness of fit (ρ^2)	0.488

Table 5.4
Estimation Results for Model 2: Mode (a) with Push-Button Interactions

Σ_{U_i} is a covariance matrix for the ith individual of a group. Its specification is same as in model 1. The subscript of a_j denotes the pedestrian, and j the gap. If $\sigma^2_g = 0$, then the effect of group interactions on the behavior is negligible. The actual group size in the sample is three. The results of the estimation are presented in Table 5.5. The parameter of most interest in this case is σ_g^2. It is statistically significant at the 5 percent significance level. This confirms the hypothesis that group interactions are not negligible. One would expect higher initial mean critical lag and gap values as compared to model 1 because groups have more inertia than individual pedestrians. However, only the initial mean critical lag is greater. The effect of person-specific attribute, AGSX, is less pronounced here than in model 1, which is expected in the presence of group interactions. Also, the "within" and "across" variance components are smaller because some variation is now explained by the group interactions.

Parameter	Estimate	t - statistic
Initial Mean Critical Lag	10.06	4.22
Initial Mean Critical Gap	11.56	6.26
WAIT	-0.075	-3.64
IST	5.06	8.19
LNPST	1.27	13.51
TURN	-3.32	-3.14
DIRXN	-1.23	-1.56
AGSX	-1.89	-5.54
$\sigma_1 2$	20.10	16.86
$\sigma_2 2$	8.62	9.00
$\sigma_g 2$	5.56	3.73

Number of observations	118
Initial Log likelihood L(0)	-191.30
Log likelihood at convergence L(ß)	-81.12
Adjusted Goodness of fit ($\rho 2$)	0.571

Table 5.5
Estimation Results for Model 3: Mode (a) with Group Interactions

In order to limit the size of the variance-covariance matrix for model 3 to about 25, the minimum gap size considered in the sample was raised to 3 sec, which led to deletion of smaller gaps and, also, few records. Model 3 is re-estimated by constraining $\sigma^2{}_g = 0$, and compared with model 1 to evaluate the consequences. The results of the estimation are presented in Table 5.6. Since the sample size here is different from that in model 1, standard tests of comparison are not applicable. However, by comparing the adjusted goodness of fit measures (0.533 vs 0.562), it is concluded that discarding small gaps has no serious consequences.

Parameter	Estimate	t - statistic
Initial Mean Critical Lag	12.06	13.36
Initial Mean Critical Gap	12.56	14.68
WAIT	-0.12	-9.69
IST	2.52	4.35
LNPST	1.59	8.42
TURN	-1.55	-3.06
DIRXN	-4.54	-11.14
AGSX	-1.37	-8.62
σ_1^2	22.36	18.86
σ_2^2	9.76	9.55
Number of observations		118
Initial Log likelihood L(0)		-191.30
Log likelihood at convergence L(ß)		-79.23
Adjusted Goodness of fit (ρ2)		0.534

Table 5.6
Estimation Results for Model 3: Mode (a) Ignoring Group Interactions

5.5.4 Model 4: Mode (b) with No Push-Button or Group Interactions

In this model, pedestrians look for a gap in the near stream and in the far stream [mode(b)]. Behavior is assumed independent across individuals, and push-button interactions are also ignored. The variance-covariance matrix is specified as

$$\Sigma_U = \left[\begin{array}{c|cc|ccc|cc}
0 & & & & & & & \\
\hline
\cdot & a_1^2\sigma_{1n}^2 & & & & & & \\
\cdot & a_1^2\sigma_3^2 & a_1^2\sigma_{1f}^2 & & & & & \\
\hline
\cdot & \cdot & \cdot & \cdot & & & & \\
\cdot & \cdot & \cdot & & \cdot & & & \\
\cdot & \cdot & \cdot & & & \cdot & & \\
\hline
\cdot & a_1 a_J\sigma_{2n}^2 & 0 & & & & a_J^2\sigma_{1n}^2 & \\
0 & 0 & a_1 a_J\sigma_{2f}^2 & \cdot & \cdot & \cdot & a_J^2\sigma_3^2 & a_J^2\sigma_{1f}^2
\end{array}\right]$$

Subscripts 'n' and 'f' denote the near stream and the far stream, respectively. The results of the estimation are presented in Table 5.7. The initial mean critical gap for the near stream is statistically different from that of the far stream at the 0.05 level. The initial mean critical lags are different at the 0.10 level. Also, the near stream values are higher than the corresponding far stream values. This is expected following the result in models 1 to 3, where the coefficient of stream-dependent variable for vehicles in far stream, DIRXN, was negative. It implies that people are more willing to incur risk on gaps in the far stream. Further evidence is provided by a higher negative coefficient for waiting time in the far stream function compared to the near stream function. The two coefficients are significantly different at the 0.05 level. Contrary to expectations, the coefficient of near gap in the far stream function is positive. The remaining coefficients have expected signs. The general conclusions drawn from earlier models hold for this case as well. The "within" and "across" components for the near stream are less than those for the far stream. However, the relative magnitudes of these components depends on the systematic specifications as well.

Despite acceptable results, the adjusted goodness of fit is surprisingly low. No formal comparison tests could be performed to compare mode (a) and mode (b). However, by comparing with ρ^2 of model 1, mode (a) seems to provide better fit to the data.

5.6 Summary

In this chapter, different models of gap-acceptance behavior, based on a one-stage crossing, are calibrated using a multinomial probit approach presented in a random utility framework. The following conclusions can be drawn from the analyses conducted:

(a) With regard to gap-acceptance behavior:
   1) In general, the initial mean critical gap is different from the initial mean critical lag.
   2) At busy or wide intersections, the critical values are higher.
   3) People are less cautious while crossing on turn phases.
   4) The far stream vehicles seem to have less impact on the gap-acceptance behavior than the near stream vehicles. This was conclusive from all the models. In models 1 to 3, the stream-specific parameter is negative. In model 4, not only are the mean critical values less for the far stream, but also the coefficient of waiting time in the far stream function is higher than the coefficient in the near stream utility.
   5) Group interactions are significant, and cannot be ignored.

(b) With regard to push-button behavior:

1) Pedestrians appear to have an inherent tendency to avoid using push-buttons.
2) At busy or wide intersections, push-buttons might be of some assistance to the pedestrians. The coefficient of NOLNS is much greater than that of IST, implying that at wider intersections, one could expect greater push-button compliance.
3) Pedestrians are likely to ignore the push-buttons when their hands are not free.

Parameter	Estimate	t - statistic
Initial Mean Critical Lag (Near)	10.02	3.69
Initial Mean Critical Gap (Near)	16.4	2.65
Initial Mean Critical Lag (Far)	6.89	4.65
Initial Mean Critical Gap (Far)	8.88	4.75
β_{10}	-6.07	-4.11
Far Gap Effect on Near Stream	-0.227	-2.46
β_{12}	-7.38	-3.34
Near Gap Effect on Far Stream	1.05	14.76
WAIT (Near)	-0.34	-10.94
WAIT (Far)	-0.76	-8.27
IST	3.11	5.35
LNPST	3.19	2.26
TURN	-1.29	-2.76
AGSX	-2.68	-3.63
σ_{1n}^2	20.8	3.02
σ_{2n}^2	7.52	4.31
σ_{1f}^2	25.1	3.39
σ_{2f}^2	9.6	5.54
σ_3^2	9.98	2.04

Number of observations	135
Initial Log likelihood L(0)	-1335.58
Log likelihood at convergence L(ß)	-1150.58
Adjusted Goodness of fit ($\rho 2$)	0.13

Table 5.7
Estimation Results for Model 4: Mode (b) Ignoring All Interactions

CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 Summary

The main objective of this work is to study the gap-acceptance behavior of pedestrians crossing at signalized intersections. Gap-acceptance theory has been extensively used to model drivers waiting to cross the major street, or involved in merging or passing maneuvers. Daganzo (1982) has formulated the driver gap-acceptance problem in a multinomial probit framework for a single-lane crossing. This work applies his methodology to study the pedestrian gap-acceptance behavior and further extends it from single-lane crossing to a crossing on multi-lane approaches. A pedestrian can follow one of four possible types of crossings as follows. He/she may cross in one stage by seeking either a gap in the entire traffic stream, or a separate gap each in the near stream and in the far stream. Another option is to cross in two stages by considering the near stream first and then the far stream. This is a strong possibility at intersections with medians. The last possibility is a multi-stage crossing where the pedestrian crosses the street lane by lane. This work presents a formulation for each of these modes using a multinomial probit approach. Individual gap-acceptance behavior is influenced when pedestrians arrive and cross as a group. Also, the presence of a push-button is likely to affect gap-acceptance behavior. The modeling framework is extended to incorporate these interactions.

A data collection methodology was designed using a stratified random sampling approach. A stratification based on land use was adopted because one of the main objectives of the survey was to obtain information on pedestrian arrival rates. Five land uses in the quarter-mile zone and four land uses in the one-mile zone were identified. Intersections were classified using this nomenclature. If either of the zones has more than one land-use type, the dominant pedestrian-generating land use was used. A total of twenty intersections, one for each land-use combination, were selected for a survey from the city of Austin, Texas. Data was obtained through on-site observation and video recording techniques. Lane-by-lane gap information was obtained from the video using a continuous event-time recorder. A program was written to extract gaps for each of the crossing modes discussed earlier. The analysis was restricted to the first two modes because of insufficient data for the other two modes.

The estimation was conducted using a program based on Monte Carlo simulation developed earlier on the Cray Y-MP environment at The University of Texas at Austin. It was assumed in the analysis that all pedestrians look for gaps when they arrive at the intersection. The following cases were estimated:

a) One-stage crossing, pedestrian looks for an overall gap in the traffic, i.e., mode (a)
   - i) no push-button or group interactions,
   - ii) push-button but no group interactions,
   - iii) group interactions but no push-button interactions;

b) One-stage crossing, but the pedestrian looks for a gap in the near and far streams, i.e., mode (b)
   - i) no push-button or group interactions.

From a preliminary analysis, it was found that the sample does not have a sizable representation of groups in it, and, also, only a small fraction of these groups had a push-button option. So, a model with both push-button and group interactions was not estimated. From mode (a) estimation results, it was found that these interactions were very small. The model specification to the estimation program is more complicated for mode (b), and, since these interactions are not significant, they were not considered for this case.

The estimation results generally confirmed a priori expectations. The initial mean critical gap was greater than the initial mean critical lag because the lags could not be measured with the perception component. These critical values decreased as the waiting time increased. At busy or wide intersections, the critical values were found to be higher, implying that pedestrians are more cautious at these intersections. Also, on turn phases, the pedestrians were found to accept smaller gaps or lags than at through phases. Regarding push-buttons, it was found that pedestrians have an inherent tendency to avoid using these devices. However, push-buttons were likely to be used at busy or wide intersections. The results indicate that group interactions and push-buttons do not affect the gap-acceptance behavior significantly. It may not be conclusive, as the sample has no sufficient representation of these interactions in it. Comparing across modes, it was found that pedestrians are more likely to look for an overall gap (i.e., mode (a)) rather than two gaps (i.e., mode (b)).

6.2 Future Research

Some additional issues which could be explored are stated below:

1) It was assumed that all pedestrians look for gaps in the traffic. However, this assumption may not realistic as discussed in Chapter 3 (Figure 3.1) in the comparison of the gap size distributions for pedestrians crossing on "walk" and "don't walk," respectively. As a result of this assumption, the critical lag and gap may be overestimated, and the effect of waiting time may be underestimated. More accurate estimates could be obtained if repeat observations were available on each pedestrian. This would require observing select intersections on a frequent basis. The gap-acceptance study could then be limited to those who cross on a "don't walk" at least once.

2) Due to the small sample size, it was not possible in this study to compare the gap-acceptance behavior between signalized and unsignalized intersections. A study could be pursued in this direction. It would help identify population and intersection characteristics which contribute to the effectiveness of signalization. This study could help devise measures to educate the public, and also determine the need to develop new traffic control devices.

3) The current study is concerned only with intersection crossings. The gap-acceptance behavior can also be observed at unprotected mid-block crossings by jaywalkers. One would expect smaller values of critical lag and gap for jaywalkers. A comparison of other gap-acceptance parameters would not only reveal more insights into jaywalking characteristics, but would also help devise strategies to prevent jaywalking. One could also compare the crossing behaviors at signalized mid-blocks and signalized intersections.

APPENDICES

APPENDIX A
Gap-Acceptance Data

The data is presented in the following manner. The first part contains the gaps faced by each pedestrian. The second part contains information on individual, intersection, and arrival characteristics used in this study. Each part is stored in a separate file. The program in Appendix B uses the two files as input and generates gaps for the desired mode.

(a) Gap Information

```
Dummy       Wait time
Lane number   gap   thro/left  gap   thro/left  gap   thro/left  gap   thro/left...
Lane number   gap   thro/left  gap   thro/left  ...
Lane number   gap   thro/left  gap   thro/left  gap   thro/left...

Dummy       Wait time
Lane number   gap   thro/left  gap   thro/left  ...
Lane number   gap   thro/left  gap   thro/left  ...
```

A dummy value of 0 indicates the beginning of a new record to the program. A value of -1 indicates end of input.
In the data set, lane number is always multiplied by 100. It suggests to the program that for the same pedestrian, gaps are being read for the next lane with vehicles in it. If a lane has no vehicles during the crossing maneuver, it is not stated in the data set (redundant information). If the lane number is negative, it indicates a lane in the far stream.

```
0   8.1
200    2.77    0
0   3.5
200    3.5     0
0   6.2
100    4.03    0
200    4.92    0
0   24.9
200    20.881     2.32    1
0   24.8
```

```
100     1.78    0   2.65    0   2.22    0
200     2.92    0   2.29    0   2.18    0   4.49    0   10.761
0   18
200     9.09    1   3.46    1   1.8     1
0   18
200     9.09    1   3.46    1   1.8     1
0   44.2
200     2.33    0   6.99    0   3.83    0   5.95    0   7.02    0   1.51    0
0   44.2
200     2.33    0   6.99    0   3.83    0   5.95    0   7.02    0   1.51    0
0   14.5
300     2.21    1   2.82    0   10.191      4.79    1
0   14.5
300     2.21    1   2.82    0   10.191      4.79    1
0   31.8
100     4.69    0   9.72    0   5.08    0
200     4.64    0   1.58    0   6.49    0   1.99    0   4.88    0   7.86    0   2.26    0   0.99    0
0   31.8
100     4.69    0   9.72    0   5.08    0
200     4.64    0   1.58    0   6.49    0   1.99    0   4.88    0   7.86    0   2.26    0   0.99    0
0   17.6
100     7.24    0   1.47    0
0   17.6
100     7.24    0   1.47    0
0   12.3
100     7.24    0   1.47    0
0   8.3
100     3.12    0
200     12.440
0   25.2
100     1.42    0   5.02    0   1.95    0   11.550
200     0.6     0   2.8     0   1.76    0   1.41    0
0   25.2
100     1.42    0   5.02    0   1.95    0   11.550
200     0.6     0   2.8     0   1.76    0   1.41    0
0   23.2
```

```
200    14.641    0.98  1   2.78  1   1.44  1   1.82  1
0   77.8
100    39.040    1.44  0   2.1   0   2.05  0   2.06  0   1.67  0   1.3   0   3.25  0   1.59  0   1.47  0   1.72  0   4.77  0
    0.99
200    35.3  0   1.67  0   1.48  0   1.53  0   1.81  0   2.25  0   2.24  0   1.34  0   1.38  0   2.2   0   1.35  0   1.33  0
    3.35     0   3.46  0   3.05  0   2.61  0
300    24.590    2.41  0   1.46  0   2.11  0   2.45  0
0   77.8
100    39.040    1.44  0   2.1   0   2.05  0   2.06  0   1.67  0   1.3   0   3.25  0   1.59  0   1.47  0   1.72  0   4.77  0
    0.99   0
200    35.3  0   1.67  0   1.48  0   1.53  0   1.81  0   2.25  0   2.24  0   1.34  0   1.38  0   2.2   0   1.35  0   1.33  0
    3.35     0   3.46  0   3.05  0   2.61  0
300    24.590    2.41  0   1.46  0   2.11  0   2.45  0
0   30.9
100    14.341
200    29.111
0   5.9
100    11.65  1
0   0
100    9.66   1
0   5.9
100    1.71  0   4.15  0
0   24.2
100    9.33  0   9.98  0
0   36.64
100    1.27  0   4.3   0   3.57  0   1.37  0   1.93  0   2.94  0   3.3   0   1.45  0   1.51  0   1.89  0   7.61  0   1.35  0
    1.15            0
200    1.26  0   2.55  0   2.65  0   4.64  0   5.86  0   1.13  0   1.33  0   1.68  0   1.63  0   1.79  0   1.51  0   1.15  0
          1.92   0   2.51   0   1.08   0
-300   0.49  0   0.88  0   4.93  0   3.3   0   1.88  0   4.03  0   3.52  0
-400   1.65  0   5.6   0   1.6   0   1.34  0   6.04  0
0   20.61
-300   2.66  0   6.75  0   7.44  0
-400   14.120
0   7.83
100    2.47  0   1.95  0
```

```
200     6.32    0
0   15.44
-300    9.44    0
-400    9.46    0
0   20
200     6.07    0
-300    17.440
0   0
-300    3.75    0
0   36.77
100     1.51    0   3.11    0   1.89    0   1.19    0   2.63    0   0.79    0
200     1.26    0   3.07    0   2.72    0   1.85    0   1.68    0   8.59    0
-300    2.6     0   1.92    0   2.1     0
-400    0.8     0   1.08    0   1.37    0   2.43    0   1   0   1.38    0   2.38    0
0   7.95
-300    5.81    0
0   39.89
200     20.920      2.22    0   2.91    0   1.28    0
0   0
-400    4.17    0
0   0
-400    4.17    0
0   8.13
-400    1.92    0
0   0
-400    9.16    0
0   34.53
100     4.69    0   2.48    0   7.7     0   6.48    0   6.65    0   4.34    0
200     3.72    0   5.24    0   1.57    0   9.74    0
-300    14.520      2.61    0   2.65    0   2.87    0
-400    15.730      1.28    0   2.41    0   1.93    0   3.28    0   4.08    0
0   34.53
100     4.69    0   2.48    0   7.7     0   6.48    0   6.65    0   4.34    0
200     3.72    0   5.24    0   1.57    0   9.74    0
-300    14.520      2.61    0   2.65    0   2.87    0
-400    15.730      1.28    0   2.41    0   1.93    0   3.28    0   4.08    0
```

```
0   23.7
-300    6.03    1   5.89    1
0   23.7
-300    6.03    1   5.89    1
0   23.7
-300    6.03    1   5.89    1
0   10.5
-400    0.69    0   2.95    0   2.02    0
0   60.7
100     1.99    0   5.33    1   3.53    0   5.81    1   12.36   0   1.75    0   2.36    0   3.32    0   5.53            0   1.93    0

200     9.53    0   1.36    0   13.74   0   9.46    0   3.42    0   5.67    0   3.21    0
-300    48.86   0   3.03    0
-400    6.55    0   1.38    0   4.42    0   2.7     0   1.9     0   2.55    0   4.04    0   3.75    0   6.72    0           13.69   0   5.67    0   6.03
    0
-500    6.45    0   3.41    0   2.32    0   1.83    0   1.16    0   2.41    0   6.28    0   3.49    0   7.56        0   9.38    0   2.94    0   5.77    0
    6.62    0
0   30
100     2.38    0   4.96    0   7.22    0   3.49    0   2.4     0   8.32    0
200     3.42    0   2.52    0   2.23    0   3.11    0
0   51.6
100     0.57    0   1.74    0   1.67    0   1.41    0   3.13    0   1.37    0   1.25    0   8.74    0   1.74            0   14.17   0   2.53    0   5.44
    0   1.52    0   4.41    0   2.99    0
200     0.45    0   1.74    0   5.82    0   3.16    0   5.84    0   2.63    0   1.94    0   2.78    0   3.38            0   16.04   0   5.07    0
0   7.1
100     0.69    0   3.36    0   1.86    0   1.88    0
200     0.6     0   13.97   0
0   34.2
200     1.2     0   2   0   9.23    0   1.95    0
-300    15.72   0   2.1     0   2.22    0   2.07    0   2.56    0   1.99    0   3.55    0   1.68    0
-400    6.09    0   10.14   0
0   8.9
100     0.89    0   2.25    0   1.43    0   2.02    0
200     0.56    0   3.5     0   2   0
300     0.39    0   5.54    0
0   17
```

```
200    4.08   0  3.91   0  6.27   0
300    0.44   0  1.6    0  2.04   0  2.55   0  3.24   0  1.43   0
0  0
200    5.24   1
0  18.7
200    2.9    0
300    8.54   1  1.52   1  3.16   1
0  18.5
400    4.48   0  2.24   0  2.69   0  1.45   0
0  48.2
100    1.77   0  2.07   0  4.54   0  13.23  0  10.88  0
200    2.5    0  1.42   0  1.95   0  2.39   0  2.08   0  10.86  0  9.19   0  9.22   1  2.83   1  2.11   1
-300   0.45   0  1.91   0  1.11   0  2.11   0  1.03   0
-400   2.38   0  2.18   0  1.87   0
0  48.2
100    1.77   0  2.07   0  4.54   0  13.23  0  10.88  0
200    2.5    0  1.42   0  1.95   0  2.39   0  2.08   0  10.86  0  9.19   0  9.22   1  2.83   1  2.11   1
-300   0.45   0  1.91   0  1.11   0  2.11   0  1.03   0
-400   2.38   0  2.18   0  1.87   0
0  11.1
200    1.44   0  1.1    0  2.17   0
0  14.6
100    2.69   0  2.16   0  1.39   0  1.74   0  1.71   0  2.87   0  2.22   0  4.94   0  3.2    0  1.43   0  4.5    0  2.93   0
6:77   0
-300   2.89   0  2.28   0  1.67   0  1.27   0  2.4    0  2.6    0  2.45   0  3.05   0  1.88   0  1.61   0  2.24   0  2.13   0
1.97   0  2.46   0  2.46   0  2.06   0  8.58   0
0  8.68
100    0.83   0  1.69   0  1.49   0  2.56   0  1.55   0  1.76   0  2.4    0  1.63   0  1.98   0  12.1   0
-300   5  0  0.98   0  19.45  0
0  10.15
100    4.65   0  1.75   0  1.62   0
0  0
100    3.08   0
-300   4.7    0
0  11.9
100    6.94   0  2.21   0
```

```
-300	3.15	0	2	0	2.2	0	2.36	0	2.03	0
0	8.52
100	1.72	0	6.8	0
0	27.6
100	12.79	0	3.71	0	3.78	0	1.29	0	1.3	0	2.13	0	1.97	0	1.56	0
-300	0.5	0	1.46	0	2.6	0	1.72	0	1.74	0	1.38	0	2.61	0	1.77	0	3.73	0
0	15.3
100	0.82	0	1.46	0	1.62	0	1.82	0	2.78	0	1.9	0	4.18	0	9.34	0
-300	1.32	0	1.6	0	1.84	0	1.89	0	2.58	0	2.57	0	2.34	0	1.56	0	1.37	0	1.39	0	6.03	0
0	3.43
100	6.25	0
0	13.4
100	5.61	0	11.33	0
-300	1.15	0	2.03	0	2.95	0	2.96	0	11.94	0
0	48.1
100	2.45	0	1.58	0	1.04	0	1.61	0	1.59	0	1.72	0	1.63	0	3.03	0	1.12	0	1.41	0	1.68	0	10.12	0	9.1
	0	4.91	0
200	2.97	0	1.79	0	2.95	0	2.39	0	3.11	0	2.25	0	2	0	1.45	0	9.22	0	3.21	0	2.87	0	1.78	0	2.32
	0	1.8	0	1.55	0
0	51.7
100	1.74	0	1.25	0	1.36	0	1.58	0	5.41	0
200	4.73	0	1.56	0	5.4	0	5.85	0	5.63	1	1.48	1	0.97	1	1.51	1	0.73	1	1.39	1	2.42	1	1.19	1	0.8
	1	1.45	1
0	37.8
100	2.39	0
200	11.4	1	2.45	1	1.5	1	1.77	1	1.69	1	1.7	1	1.37	1	1.24	1	1.91	1	1.48	1	1.84	1	1.12	1

0	22
100	0.55	0	1.36	0	0.7	0	6.32	0	1.25	0	6.86	0	1.24	0	1.44	0	1.88	0
0	22
100	0.55	0	1.36	0	0.7	0	6.32	0	1.25	0	6.86	0	1.24	0	1.44	0	1.88	0
0	14.62
200	9.43	1	1.37	1	2.75	1
0	14.9
200	21.75	1
-300	0.96	0	0.82	0	3.02	0	4.55	0
```

```
0   10.1
-400    2.81    0   7   0   2.74    0
0   66
-400    3.88    0   13.64   0   2.19    0   4.66    0   9   0
0   10
-300    18  0
0   0
200     1.7     0
0   26
100     1.03    0   1.54    0   5.62    0   7.43    0   1.49    0   4.46    0
200     0.65    0   7.98    0   3.95    0
0   7.1
-300    8.44    0
-400    4.53    0   2.34    0
0   7.1
-300    8.44    0
-400    4.53    0   2.34    0
0   11
100     5.55    0
200     2.83    0
-300    0.63    0   7.28    0
-400    3.5     0   3.88    0   12.4    0
0   17.2
100     1.89    0   1.91    0   2.93    0   2.15    0   2.69    0   1.23    0
200     2.19    0   1.89    0
0   10.7
100     7.66    1
-400    7.11    0
0   6.2
100     0.66    0
200     6   0
0   22.3
-300    9.52    0
-400    0.58    0   2.2     0   2.19    0   2.53    0
-500    2.36    0   2.85    0   1.46    0   2.36    0
0   15.4
```

```
100    0.46   0  1.43    0  2.75   0  1.5    0
200    0.78   0  25.351
-300   11.980    2.51    0  2.05   0
-400   4.37   0  1.49    0  2.12   0  2.98   0  1.88   0
-500   1.42   0  3.04    0  2.95   0  1.68   0  1.77   0
0  40.6
100    5.04   0
200    4.84   0  7.99    0  1.37   0  4.24   0  0.94   0
-400   24.440    2.54    0  6.23   0  1.88   0  2.7    0  2.62   0
0  11.5
-300   3.24   0  7.64    0  1.85   0  1.54   0  8.6    0
-400   3.91   0  2.49    0  5.48   0
0  4
-300   2.06   0
0  0
100    1.25   0  2.12    0
200    8.27   0
0  13.6
200    8.94   1
-500   6   1  15  1
0  28.4
100    6.58   0  19.351
200    33.471
-400   15.890
-500   15.090
0  2
200    1.94   0
0  37.3
100    2.94   0  2.08    0
200    2.8    0  2.24    0
-300   10.740
-400   1.85   0  3.34    0
-500   1.95   0  4.56    0
0  13
100    1.29   0  9.93    0
200    0.7    0  7.46    0  4.15   0
```

```
0   4.9
-400    4   0
0   24.3
100     1.36    0   1.38    0
200     0.92    0   1.36    0   2.05    0   25.681
-400    0.58    0   1.81    0   3.24    0   2.46    0   2.23    0
-500    0.4     0   1.78    0   2.44    0   2.2     0   1.7     0   2.5     0
0   20.2
100     1.15    0   1.39    0   3.04    0
200     1.67    0   1.5     0   2.58    0   1.77    0   16.660
-300    12.710
-400    1.4     0   2.34    0   2.13    0   3.65    0   2.42    0   1.71    0   2.98    0
-500    0.41    0   5.48    0   1.94    0   1.63    0
0   35.3
100     6.9     0   1.9     0   1.42    0   1.95    0   1.98    0   2.32    0
200     7.46    0   1.49    0   1.37    0   2.36    0   1.13    0   2.78    0   2.59    0   3.08    0
-400    19.980
-500    29.080
0   33.3
-300    4.51    0   1.83    0   2.52    0   3.56    0   1.97    0   12.081      4.49    1
-400    5.8     0   4.34    0   1.66    0   8.53    0
0   32.8
100     8.52    0   3.31    0   2.43    0   1.82    0   1.43    0   1.74    0   3.32    0   3.44    0   1.21    0   2.28    0
200     8.97    0   3.83    0   1.74    0   1.61    0   1.53    0   3.32    0   4.7     0   1.92    0   1.24    0
300     26  0   3.44    0   3.35    0
-400    0.82    0   2.05    0   2.07    0   2.05    0   1.61    0   2.75    0
-500    2.73    0   2.34    0   1.36    0   1.44    0   1.32    0
0   15.5
-300    8.28    0   2.13    0
-400    4.57    0   2.38    0   1.07    0
0   16.5
-300    4.28    0   3.35    0   1.74    0   7.12    0
-400    3.09    0   1.34    0   1.46    0   2.03    0   1.54    0   6.49    0
0   30.7
100     20.280      1.4     0   1.15    0   1.1     0   0.97    0   10.960
200     22.740      2.42    0   2.04    0   2.27    0   1.24    0   6.44    0
```

```
-300   5.58   0  1.19   0  1.2    0  3.53   0  0.97   0
-400   0.85   0  1.72   0  1.12   0  3.4    0  2.11   0  1.28   0  2.35   0  1.68   0  1.58   0  1.74   0
0  53.6
100    0.74   0  1.7    0  1.85   0  1.59   0  1.16   0  1.33   0  2.14   0  2.35   0
200    0.86   0  1.17   0  1.79   0  1.07   0  1.51   0
-300   17.02  2.69   0  2.17   0  2.35   0  0.9    0  5.89   0  5.83   0  1.68   0  2.38   0  4.12   0
-400   16.87  2.67   0  2.35   0  2.11   0  1.48   0  1.87   0  3.13   0  2.84   0  5.15   0  5.56   0
-1
```

Individual, Intersection,and Arrival Characteristics

The corresponding individual, intersection, and arrival characteristics are shown below. The values are given according to the following format:

Column Guide

1. Intersection status
2. Arrival instant (hrs. min)
3. Arrival instant (seconds)
4. Arrival Size (number in arriving group)
5. Crossing Size (number in crossing group)
6. Gender (1 = Male; 2 = Female)
7. Age (number in years)
8. Ethnicity (1 = White, 2 = Black, 3 = Hispanic, 4 = Other)
9. Hands (0 = Free, 2 = Baby held, 3 = Push-carriage, 4 = Holding hands, 11 = Package in one hand, 12 = Packages in two hands)
10. Pedestrian Signal On Arrival (0 = no pedestrian signal, 1 = Walk, 2 = Flashing Don't Walk, 3 = Steady Don't Walk
11. Traffic Signal on Arrival (1 = Green, 2 - Red)
12. Number of Lanes (number)
13. Crossing Manner (1 = Walk, 2 = Walk & Run, 3 = Run, 4 = Jog, 5 = Wheelchair, 6 = Skate & Other
14. Push Button (0 = No push button available, 1 = Yes, 2 = No)
15. Pedestrian Signal at Crossing (0 = No pedestrian signal available, 1 = Walk, 2 = Flashing Don't Walk
16. Traffic Signal at Crossing (1 = Green, 2 = Red)
17. Median Usage (0 = no median available, 1 = uses median, 2 = doesn't use median
18. Wait Time (seconds)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

1	8.42	28	1	1	2	20	1	0	3	2	6	1	2	3	2	2	8.1
1	9.00	10	1	1	1	25	2	0	3	2	6	1	2	3	2	2	3.5
1	9.00	36	1	1	1	25	2	0	3	2	5	1	2	3	2	2	6.2
1	9.10	39	1	1	2	20	1	0	3	2	5	1	1	1	1	2	24.9
1	10.13	52	1	1	1	50	1	0	3	2	6	1	1	1	1	2	24.8
1	10.30	31	2	2	1	25	3	0	3	2	5	1	1	1	1	2	18
1	10.30	31	2	2	1	25	3	0	3	2	5	1	2	1	1	2	18
1	10.57	0	2	2	2	45	1	4	3	2	6	1	1	1	1	2	44.2
1	10.57	0	2	2	1	10	2	4	3	2	6	2	2	1	1	2	44.2
1	11.04	39	2	2	1	20	1	0	3	2	6	1	1	3	2	1	14.5
1	11.04	39	2	2	2	10	1	0	3	2	6	1	2	3	2	1	14.5
1	11.26	30	2	2	2	35	1	4	3	2	6	1	1	1	1	2	31.8
1	11.26	30	2	2	1	8	2	4	3	2	6	1	2	1	1	2	31.8
1	11.32	33	3	2	2	12	1	0	3	2	6	6	1	1	1	1	17.6
1	11.32	33	3	2	1	12	1	0	3	2	6	6	2	1	1	1	17.6
1	11.32	33	3	1	2	12	1	5	3	2	6	3	2	1	1	1	12.3
1	11.48	40	1	1	1	50	1	11	3	2	5	1	2	3	2	2	8.3
1	11.56	48	2	2	2	10	1	0	3	2	6	1	1	1	1	2	25.2
1	11.56	48	2	2	2	35	1	0	3	2	6	1	2	1	1	2	25.2
1	12.09	38	1	1	2	25	1	0	3	2	5	1	1	3	2	2	23.2
1	12.17	47	2	2	2	60	1	11	2	1	6	1	1	3	2	2	77.8
1	12.17	47	2	2	2	60	1	11	2	1	6	1	2	3	2	2	77.8
1	12.22	35	1	1	1	25	1	0	3	2	5	1	1	1	1	2	30.9
0	12.04	43	1	1	1	25	1	11	0	2	5	1	1	0	2	2	5.9
0	2.29	58	1	1	1	30	1	0	0	2	5	1	2	0	2	1	0
0	2.54	16	1	1	2	25	1	0	0	2	5	1	1	0	2	1	5.9
0	4.06	28	1	1	2	15	1	11	0	2	6	1	2	0	2	1	24.2
0	8.11	35	1	1	1	30	2	11	0	2	5	1	0	0	1	0	36.64
0	8.22	29	1	1	1	60	2	5	0	2	5	1	0	0	1	0	20.61
0	8.25	39	1	1	1	40	3	11	0	2	5	1	0	0	1	0	7.83
0	8.26	7	1	1	1	40	3	11	0	2	4	1	0	0	1	0	15.44
0	9.12	15	1	1	2	45	2	0	0	2	4	1	0	0	2	0	20
0	9.17	38	1	1	1	40	2	11	0	2	4	1	0	0	2	0	0
0	9.28	45	1	1	2	30	2	0	0	2	5	1	0	0	1	0	36.77
0	9.29	41	1	1	2	30	2	0	0	2	4	1	0	0	1	0	7.95
0	9.38	30	1	1	2	55	2	11	0	2	4	1	0	0	1	0	39.89

0	10.21	21	2	2	1	25	3	11	0	2	4	1	0	0	2	0	0
0	10.21	21	2	2	1	25	2	11	0	2	4	1	0	0	2	0	0
0	10.24	25	1	1	1	50	2	11	0	2	4	1	0	0	2	0	8.13
0	10.32	30	1	1	1	25	2	11	0	2	5	2	0	0	2	0	0
0	11.07	11	2	2	1	35	2	0	0	2	5	1	0	0	2	0	34.53
0	11.07	11	2	2	1	30	2	11	0	2	5	1	0	0	2	0	34.53
0	12.42	56	3	3	1	60	2	11	0	2	4	1	0	0	2	0	23.7
0	12.42	56	3	3	2	60	2	0	0	2	4	1	0	0	2	0	23.7
0	12.42	55	3	3	1	5	2	11	0	2	4	1	0	0	2	0	23.7
0	9.17	38	1	1	1	40	2	11	0	2	4	1	0	0	2	0	0
1	1.30	59	1	1	1	40	1	11	0	2	4	1	0	0	1	0	10.5
1	1.31	25	1	1	1	40	1	11	0	2	5	2	0	0	1	0	60.7
1	1.37	20	1	1	1	45	1	11	0	2	4	1	0	0	1	0	30
1	2.01	18	1	1	2	20	3	11	0	2	5	1	0	0	2	1	51.6
1	4.47	45	1	1	2	25	2	0	0	2	5	2	0	0	2	1	7.1
1	5.35	12	1	1	2	35	3	11	0	2	4	2	0	0	1	0	34.2
1	1.12	42	1	1	2	35	1	0	0	2	5	1	0	0	2	1	8.9
1	2.08	8	1	1	1	30	2	11	3	2	5	1	1	3	2	0	17
1	2.57	46	1	1	1	60	1	11	0	2	5	2	0	0	2	2	0
1	2.59	50	1	1	2	35	1	0	0	2	5	1	1	0	1	2	18.7
1	3.16	46	1	1	1	30	1	0	3	2	5	1	2	1	1	0	18.5
1	3.17	43	2	2	1	25	1	0	3	2	5	1	1	1	1	0	48.2
1	3.17	43	2	2	1	25	1	0	3	2	5	1	2	1	1	0	48.2
1	3.40	41	1	1	1	35	1	5	3	2	5	1	2	3	1	0	11.1
0	9.12	20	1	1	2	25	1	0	3	2	5	4	0	3	2	0	14.6
0	9.13	48	1	1	2	25	1	0	3	2	5	4	0	3	2	0	8.68
0	9.19	20	1	1	1	20	1	0	3	2	5	1	0	1	1	0	10.15
0	9.21	8	1	1	1	20	4	0	3	2	5	4	0	3	2	0	0
0	9.24	16	1	1	1	20	1	0	3	2	5	1	0	1	1	0	11.9
0	9.28	5	1	1	2	20	1	0	3	2	5	4	0	1	1	0	8.52
0	9.57	40	1	1	2	20	1	11	3	2	5	1	0	1	1	0	27.6
0	11.18	10	1	1	1	20	1	0	3	2	5	4	0	3	2	0	15.3
0	12.21	8	1	1	2	20	1	0	3	2	5	2	0	3	2	0	3.43
0	12.44	6	1	1	1	20	1	0	3	2	5	1	0	3	2	0	13.4
0	4.20	35	1	1	2	25	1	11	3	1	5	1	1	3	2	1	48.1
0	4.42	23	1	1	1	40	3	11	3	2	3	1	2	1	1	0	51.7

0	5.09	32	1	1	1	35	3	11	3	2	3	2	2	1	1	0	37.8
0	5.58	59	2	2	2	35	3	0	3	2	5	1	1	3	2	1	22
0	5.59	0	2	2	2	35	3	0	3	2	5	1	2	3	2	1	22
1	5.06	21	1	1	1	35	1	0	3	2	4	1	0	3	2	0	14.62
1	8.50	4	1	1	1	40	1	0	3	2	4	1	0	3	2	0	14.9
1	9.21	20	1	1	1	40	3	0	3	2	4	1	0	3	2	0	10.1
1	10.06	1	1	1	30	2	13	0	2	14	1	2	0	1	0	2	0
1	10.07	1	1	2	30	2	14	0	2	21	2	0	0	2	0	2	0
0	1.02	1	1	2	30	1	0	0	2	23	1	2	0	2	5	2	0
0	1.41	1	1	1	40	1	0	0	2	32	1	0	0	1	0	2	1.1
0	3.47	2	2	1	25	1	0	0	2	23	1	2	0	2	0	1	0.6
0	3.47	2	2	2	25	1	0	0	2	23	1	2	0	2	0	1	0.6
0	4.11	1	1	1	25	1	0	0	2	23	2	1	-99	2	0	2	0
1	11.44	17	1	1	1	50	1	0	3	2	4	1	0	1	1	0	17.2
1	12.09	3	1	1	2	20	1	0	3	2	5	1	0	1	1	0	10.7
1	12.09	32	1	1	2	20	1	0	3	2	4	1	0	1	1	0	6.2
1	12.44	50	1	1	1	50	1	0	3	2	5	1	0	3	2	0	22.3
1	12.57	20	1	1	2	20	1	0	3	2	5	1	0	3	2	0	15.4
1	1.07	37	1	1	2	20	1	0	3	2	4	1	0	1	1	0	40.6
1	1.29	16	1	1	1	20	1	0	3	2	4	4	0	3	2	0	11.5
1	1.49	30	1	1	1	50	1	1	3	2	4	1	0	1	1	0	4
1	2.07	24	1	1	1	40	1	0	3	2	4	1	0	3	2	0	0
1	2.07	35	1	1	1	40	1	0	3	2	5	1	0	3	2	0	13.6
1	2.23	33	1	1	1	20	1	0	3	2	5	1	0	3	2	0	28.4
1	2.26	25	1	1	1	20	1	0	3	2	5	1	0	3	2	0	2
1	3.07	20	1	1	2	35	2	0	3	2	5	1	0	1	1	0	37.3
1	3.16	51	1	1	1	20	1	1	3	2	4	1	0	1	1	0	13
1	3.18	14	1	1	1	30	1	0	3	2	4	1	0	1	1	0	4.9
1	3.37	18	1	1	1	40	1	1	3	2	5	1	0	3	2	0	24.3
1	3.42	18	1	1	1	40	1	0	3	2	5	2	0	3	2	0	20.2
1	3.48	18	1	1	2	20	1	0	3	2	5	1	0	3	2	0	35.3
1	3.54	13	1	1	1	35	1	0	3	2	4	1	0	1	1	0	33.3
1	4.09	14	1	1	1	20	1	0	3	2	5	2	0	3	2	0	32.8
1	4.40	30	1	1	1	20	1	1	3	2	4	1	0	2	1	0	15.5
1	5.01	19	1	1	1	20	1	0	3	2	4	1	0	3	2	0	16.5
1	5.06	0	1	1	1	40	1	0	3	2	4	1	0	3	2	0	30.7
1	5.25	20	1	1	1	25	2	0	3	2	4	2	0	2	1	0	53.6

APPENDIX B
Gap Pre-Processor: Program to Generate Gaps for Mode (a)

This program is written in Turbo C. It can generate gaps for mode (a) crossing. For mode (b), the logic is slightly different and is not presented here. The output of this program is directly fed to the probit estimation package.

```
#include <stdio.h>
#include <string.h>

#define fnabs(x)          (x>0?x:-x)
float w;
struct z
{       int lane,thro,fsd;
        float wt,g;
        struct z *next;
} *q1;

main()
{       float x,x1,totwt,tempwt;
        int lan,tro,nf,i,j,k,a1,count,accept,kk,kkk,agsx,index,pbdelta;
        int delta;
        int iid,ist,no,sec,garvs,gcs,sex,age,race,pid,pstat,hands,warea,pa,
        pc,aw,ag,stdir,nofl,mode,pb,pbseq,cw,cg,conf,med,jw,yn,dist,comp;

        float time,wt,st,xt;
        char s[13];
        char s1[13],s2[13];
        char *sa="o.dat",*sb="g.gap";

        char *fs="%1d %1d %1d %1d %1d %1d";
        char *fs1=" %1d %1d";
        char *fs2="  %5.2f %1d %5.2f %d %1d %1d";

        struct z *l,*a;
        FILE *inp1,*inp2,*inp3,*out;

        void fn_create(int ,int ,int ,float );
        void fn_sort(void);

        inp3=fopen("g1.dat","r+");
        out=fopen("gcg1.dat","w+a");
        strcat(fs1,fs2);
        strcat(fs,fs1);

do
{       fscanf(inp3,"%s",s);
        if(!strcmp(s,"*")) break;
        strcpy(s1,"");
        strcpy(s2,"");
```

```
          strcat(s1,s);
          strcat(s1,sa);
          strcat(s2,s);
          strcat(s2,sb);
          inp1=fopen(s1,"r+");
          inp2=fopen(s2,"r+");
          count=0;
          kkk=0;
          index=0;

do
{         i=0;
          lan=0;
          nf=0;
          delta=0;

          fscanf(inp1,"%d %f %d %d %d %d %d %d %d %d %d %d %d %d %d %d %d %d %d
                              %d %f",
          ,&ist,&time,&sec,&garvs,&gcs,&sex,&age,&race,&hands,&pa,&pc,&aw,&ag,&nofl,
                    &mode,&pb,&cw,&cg,&med,&wt);
          fprintf(out,"1 ");
          fprintf(out,fs,0,0,0,0,0,0,0,0,0.0,0,0.0,0,0,0,0);
          fprintf(out," 0\n");

          if(index>0) index--;
          if(index==0)
          {         pbdelta=0;
                    if(pb==1 && garvs>1)
                       index=garvs;
          }
          else if(index>0 && index<garvs)
          pbdelta=1;

          if(nofl<5) nofl=0;
          else nofl=1;
          if(hands>0) hands=1;
          if(pb==2) pb=-1;
          if(race==1) race=0; /*Non-whites*/
          else race=1;
          if(age>18 && age<51 & sex==1) agsx=1;
          else agsx=0;


          do
          {         if(i==0)
                    {         fscanf(inp2,"%f",&totwt);
                              if(totwt != wt)
                              {         printf("Error totwt=%5.2f wt=%5.2f iid=%2d no=%3d
                                                  time=%5.2f\n",totwt,wt,iid,no,time);
                                        exit(0);
                              }
                              q1=(struct z *)malloc(sizeof(struct z));
                              q1->lane=9;q1->thro=q1->fsd=2;
                              q1->wt=q1->g=totwt;
```

```
                    q1->next=NULL;
            }
            i=1;
            fscanf(inp2,"%f",&x);
            if(fnabs(x)>99) {lan=fnabs(x)/100; w=0;if(x<0) nf=1;}
            else if(x>0)
            {       fscanf(inp2,"%d",&tro);
                    if( !(tro==1 || tro ==0))
                    {       printf("Error in data input");exit(0); }
                    fn_create(lan,tro,nf,x);
            }
            else if(x<=0 && x>-10) break;
            else continue;
} while(1);

    fn_sort();

    l=q1;
    x1=0.0;
    if(l->next==NULL) { a1=1;}
    else l=l->next;
    i=0;
    kk=0;
    accept=1;
    while(a1!=1)  /*a1=1 => l==NULL & a2=1 => a==NULL*/
    {       k=0;
            if( (l->g > 2.75 ))
            {       fprintf(out,fs,ist,garvs,gcs,agsx,race,
                            hands,nofl,pb,
                            l->wt,delta,l->g,l->lane,l->thro,l->fsd);
                    k=1;
                    kk++;
   }
            delta=1;
            x1+=l->g;
            if(l->next==NULL)
            {       l->g=totwt-x1;
                    if(l->g<0)
                    {       accept=-1;
                            if(k==1) fprintf(out," %1d\n",accept);
                            i=1;
                    }
                    else
                    {    if(k==1) fprintf(out," %1d\n",accept);
                            accept=0;l->lane=9;l->thro=l->fsd=2;
                    }
                    break;
            }
            else if(x1 > totwt)
            {       accept=-1;
                    if(k==1) fprintf(out," %1d\n",accept);
                    i=1;
                    break;
            }
```

```
            else
            {       if(k==1) fprintf(out," %1d\n",accept);
                    l=l->next;
            }
    }
    if(i==0)
    {       if(l->lane==9) accept=0;
            if(l->lane !=9) accept=-1;
            if(l->g > 2.75)
            {       fprintf(out,fs,ist,garvs,gcs,agsx,race,
                            hands,nofl,pb,
                            l->wt,delta,l->g,l->lane,l->thro,l->fsd);
                    fprintf(out," %1d\n",accept);
                    kk++;
   }
    }

    if(kk<=6)
            while(kk<6)
            {       fprintf(out,fs,0,0,0,0,0,0,0,0,0.0,0,0.0,0,0,0,0);
                    fprintf(out," 0\n");
                    kk++;
            }
    else printf("More than 6 gaps available. Change 6 in the prog.\n");

    fprintf(out,fs,ist,garvs,gcs,agsx,race,hands,nofl,pb,totwt,pbdelta,0.0,0,0,0);
    fprintf(out," 0\n");
    kkk+= kk+2;
    if(garvs==1)
    {       while(kkk<8*3)
            {       fprintf(out,fs,0,0,0,0,0,0,0,0,0.0,0,0.0,0,0,0,0);
                    fprintf(out," 0\n");
                    kkk++;
            }
            kkk=0;
    }
    else if(garvs==2)
    {       if(kkk==8) continue;
            else
            {       while(kkk<8*3)
                    {       fprintf(out,fs,0,0,0,0,0,0,0,0,0.0,0,0.0,0,0,0,0);
                            fprintf(out," 0\n");
                            kkk++;
                    }
                    kkk=0;
            }
    }
    else if(garvs==3)
    {       if(kkk<=16) continue;
            else
            {       while(kkk<8*3)
                    {       fprintf(out,fs,0,0,0,0,0,0,0,0,0.0,0,0.0,0,0,0,0);
                            fprintf(out," 0\n");
                            kkk++;
```

```
                        }
                        kkk=0;
                }
        }
        else printf("Error; Group size > 3. Change 45 to 15*new group size");
        q1->next=NULL;
        free(q1);
        count++;
}while(x>=0);
        printf("%s\n",s);
        printf("# of Obsv: %3d \n",count);
        fclose(inp2);
        fclose(inp1);

}while(1);
        fclose(out);
        return;
}


void fn_create(int lan,int tro,int nf, float x)
{       struct z *l;

        l=q1;
        while(l->next!=NULL)
                l=l->next;

        l->next=(struct z *)malloc(sizeof(struct z));
        l->next->wt=w;
        l->next->g=x;
        l->next->lane= lan;
        l->next->thro=tro;
        l->next->fsd=nf;
        l->next->next=NULL;
        w+=x;

        return;
}

void fn_sort()
{   int lan,nf;
        float temp,x1;
        struct z *a,*l;

        l=q1->next;
        if(l==NULL) return;

        do
        {       if(l->next!=NULL) a=l->next;
                else return;
                do
                {       if( ((a->wt+a->g) <= (l->wt+l->g)) )
                        {       if((a->wt+a->g) != (l->wt+l->g))
                                {       temp=a->wt;
```

```
                                        a->wt=l->wt;
                                        l->wt=temp;
                                        temp=a->g;
                                        a->g=l->g;
                                        l->g=temp;
                                        lan=a->lane;
                                        a->lane=l->lane;
                                        l->lane=lan;
                                        lan=a->thro;
                                        a->thro=l->thro;
                                        l->thro=lan;
                                        nf=a->fsd;
                                        a->fsd=l->fsd;
                                        l->fsd=nf;
                                }
                                else if(a->lane < l->lane)
                                {       lan=a->lane;
                                        a->lane=l->lane;
                                        l->lane=lan;
                                        lan=a->thro;
                                        a->thro=l->thro;
                                        l->thro=lan;
                                        nf=a->fsd;
                                        a->fsd=l->fsd;
                                        l->fsd=nf;
                                }
                                else ;
                        }
                        a=a->next;
                }while(a!=NULL);
                l=l->next;
        } while(l->next!=NULL);

        l=q1->next;     /*this part obtains the "true gaps" for the approach*/
        if(l==NULL) return;
        x1=0.0;
        do
        {       l->g=l->wt+l->g-x1;
                l->wt=x1;
                x1=l->wt+l->g;
                l=l->next;
        } while(l!=NULL);

        return;
}
```

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