GAP ACCEPTANCE AT NON-STANDARD STOP-CONTROLLED INTERSECTIONS

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CHAPTER 1
PROBLEM CONCEPT

The common or standard arrangement found at stop-controlled T-intersections consists of a minor approach forming a right angle with the through street, and minor roadway traffic stops for or yields to through street vehicles. Conversely, intersections at which the right-of-way is assigned in a different manner, such as giving priority to a left turn movement and requiring the opposing through-street movement to stop, can be called "non-standard intersections". Through repeated experience, drivers anticipate and expect the standard stop-controlled pattern--drivers are more likely to be confused or surprised at a non-standard intersection.

A variety of scenarios may justify assigning right-of-way priority to the left-turning traffic. Perhaps the left-turning movement has high traffic volume and is considered one of the major traffic streams. Or, an approach to the intersection may have only a single lane, and vehicles waiting to turn left may block and create undesirable delays for through traffic following behind. Traffic engineers seldom use non-standard stop-controls to address traffic needs at intersections.

Engineers need guidelines to assess the performance (safety, delay) of such intersections, to determine when these non-standard patterns are no longer suitable, and to know when changes in right-of-way assignment should be made. With such guidelines, engineers can make changes before intersection operation problems become severe. This report presents gap- and lag-acceptance findings from an examination of one non-standard stop-controlled intersection.

1.1 DESCRIPTION OF A NON-STANDARD T-INTERSECTION

Two-way stop-controlled (TWSC) intersections are the most prevalent type of intersection in the United States. The *Highway Capacity Manual (HCM)* noted that a three-leg intersection could be considered as a special type of TWSC intersection as long as the single minor street approach is controlled by a stop sign *(1)*. *HCM* indicates that the procedures for a TWSC analysis do not address non-standard forms of unsignalized control, where one or more left-turning movements are allowed to travel unimpeded through the intersection. This non-standard form of intersection control also includes three-leg intersections where two of the three approaches are controlled by stop signs.

Figure 1.1, adapted from *HCM* Figure 10-2, illustrates the right-of-way priority held by various traffic streams at a "standard" unsignalized T-intersection with a stop sign on the minor approach. Theoretically, only movements #1 and #3 are the true major street traffic streams that have the first rank priority (i. e., the priority over all other movements). However, movement #4 is also granted the first priority rank because the only conflicting traffic stream, namely #2, must yield to #3.

FIGURE 1.1 *HCM* Priority Traffic Streams

At non-standard intersections, the stop and yield signs are placed in such a way as to assign first priority to movements other than #1 and #3. At a non-standard stop-controlled T-intersection, the first priority rank may be assigned to movements #1 and #2. This arrangement can violate the expectations of many drivers. The following problems could result.

1. Drivers may need a gap different from that of standard two-way stop-controlled (e. g., *HCM* recommends 5.0 to 7.0 seconds) to cross traffic having the right-of-way.
2. Without knowing the needed gap size and the capacity/delay associated with given intersection volumes, the engineer does not have the tools (i.e., standard values) to estimate delay or otherwise analyze the intersection.
3. Even if there was good justification for the original pattern, as conditions change (e.g. volumes grow), the engineer has no way of knowing when it is time to convert such

intersections to a standard traffic control pattern (either unsignalized or signalized).

1.2 PROJECT OBJECTIVE

This study investigated the traffic flow characteristics at one non-standard stop-controlled T-intersection. The preliminary research activities included observing gap acceptance (or rejection) patterns and developing field data collection and reduction procedures. Various methods were employed to estimate the critical gap value, which is defined by *HCM* as the minimum gap size that allows a single side street vehicle to cross or merge into the main stream traffic *(1)*. This information could help determine when the non-standard right-of-way assignment at stop-controlled intersections is inadequate and if a change in right-of-way assignment should be considered.

1.3 RESEARCH SCOPE

The main activities of this research were to collect and analyze lag and gap acceptance data at a non-standard stop-controlled intersection. This data could subsequently be used to build a non-standard T-intersection lag and gap acceptance model. Several textbook methods were employed to analyze field data and define the size of the critical gap. The research scope was defined as follows.

1. To conduct literature reviews of the current lag and gap modeling techniques, the theoretical aspect of lag and gap modeling, discussions of various aspects (difficulties, assumption, etc.) of lag and gap modeling, etc.
2. To identify a study site that fit the description of a non-standard stop-controlled intersection.
3. To collect lag and gap rejection and acceptance data.
4. To derive lag and gap acceptance values based on a number of selected deterministic and probabilistic models.
5. To report critical lag and gap values.

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CHAPTER 2
LITERATURE REVIEW

This chapter relates some of the past research and relevant writings about unsignalized intersection traffic control, definitions (lag, gap, critical gap, etc.), gap acceptance modeling, driver behavioral aspects of gap acceptance modeling, critical gap modeling techniques, and traffic data collection methods using video technology.

2.1 TWO-WAY STOP-CONTROLLED TRAFFIC TERMS

Researchers rely on many specific definitions to describe the performance of traffic operation systems. The clear understanding of such terminology is an important element is studying two-way stop-controlled (TWSC) traffic operation system characteristics.

2.1.1 Designation of Intersection Approaches

A TWSC intersection is an unsignalized intersection with the right-of-way assigned to one of the two streets that intersect. The prioritized street is called the major street. Vehicles on the non-priority streets, also known as minor streets, must stop at the intersection. The other minor street approach is then named as the opposing approach (not applicable at a T-intersection). The two major street approaches are known as the conflicting approaches *(2)*.

2.1.2 Special Conditions

In most situations, stop or yield signs are posted only on the minor street to stop the lesser flow of traffic. However, conditions may arise where a stop or a yield sign is installed on what wold normally be called the major street. *HCM* noted that some TWSC intersections have unusual operating characteristics. For example, one or more left-turning movements may be given the right-of-way over opposing through movements. *HCM* recognized such operating conditions can legitimately and appropriately exist under special but relatively rare circumstances.

In the section on warrants for yield sign installation, *MUTCD* stated "yield signs may be installed to control a major traffic movement where a majority of drivers in that movement are making right turns." However, traffic engineers should note that at such intersections, only one yield sign should be erected and two stop signs installed on the other two legs (3). Figure 2.1, which is similar to *MUTCD*, Figure 2-2a, illustrates this special traffic control pattern.

FIGURE 2.1 *MUTCD* Special Condition Yield Sign Control

Victoria's Road Safety (Traffic) Regulations 1988 provided guidelines for installing a "Modified Intersection". This term is used specifically to describe a stop- or give way- (i.e., yield-) controlled intersection, where the priority route through the intersection goes around a curve or corner, rather than in a straight line *(4)*. A Modified Intersection is defined as

> "an intersection where two or more highways meet at which signs, traffic islands or road markings have been placed in a manner so as to indicate that the carriageway of one highway entering the intersection is continuous with the carriageway of another highway entering the intersection and the carriageways which are not continuous being so indicated by signs, traffic islands or road marking."

Also,

> "...all modified intersections require a control sign on each minor leg. All Stop and Give Way sign controlled intersections shall have exactly two uncontrolled legs which together form the major road through the intersection."

2.2 TIME SPACE VARIABLES IN HIGHWAY CAPACITY

The followings four terms define the time interval or time spacing between arrivals of vehicles.

1. Lag: The time interval from the arrival of a side street vehicle at an intersection until the arrival of the first major street vehicle *(5)*.
2. Gap: The time interval between passage of one vehicle and the arrival of the next vehicle. In strict technicality, the gap is measured from the back bumper of the front vehicle to the front bumper of the next vehicle (see Figure 2.2) *(6)*.

3. Headway: The time interval between the arrival of two successive vehicles. Headway differs from gap because it is measured from the front bumper of the front vehicle to the front bumper of the next vehicle (see Figure 2.2) *(6)*.
4. Minimum Headway: The minimum gap maintained by a vehicle in the major traffic stream.

FIGURE 2.2 Time-Space Interval

When entering an intersection, all drivers decide whether to accept or reject a lag or gap. A lag is accepted if the side street vehicle crosses or enters the main street before the arrival of the first main street vehicle. A gap is accepted if the side street vehicle crosses or enters between the arrivals of two main street vehicles that form a gap.

2.2.1 Critical Gap

The critical gap, t_g, is defined by Kyte et al. as the minimum gap in the major traffic stream needed by a minor stream vehicle to merge into or travel through the major stream gap *(7)*. Chapter 10 of the *HCM* defines the critical gap as the "minimum length time interval that allows intersection entry to one minor street vehicle" *(1)*. Both definitions use different wordings but convey similar meanings. These definitions may seem simple but are vague and difficult to apply in practice. The critical gap values measured by different people may be inconsistent, depending on the interpretation of "what is the minimum gap size". Figure 2.3 illustrates the concept of follow-up time and critical gap.

FIGURE 2.3 *HCM* Critical Gap and Follow-up Time

It is generally assumed in gap acceptance theory that drivers are both consistent and homogenous. Where gap size is likely to depend on many factors, this assumption is not entirely correct. The 1985 and 1994 *HCM* contained different critical gap values which recognize the effects of turning movement, speed, and number of lanes on major roadway. Table 2.1 presents values from 1994.

TABLE 2.1 1994 *Highway Capacity Manual* Critical Gap Values

	Critical Gap, t_g		
Vehicle Maneuver	Two-Lane Major Road	Four-Lane Major Road	Follow-Up Time t_f (sec)
Left turn, major street	5.0	5.5	2.1
Right turn, minor street	5.5	5.5	2.6
Through traffic, minor street	6.0	6.5	3.3
Left turn, minor street	6.5	7.0	3.4

Note: From HCM 1994 Table 10-2, Critical Gaps t_g and Follow-up Time t_f for TWSC Intersections

The critical gap and follow-up time values presented in this table reflect data obtained on roadways where the average approach speed on the major street through vehicles approximately 30 mph. In cases where no better data are available, these same values may be used to approximate t_g and t_f for roadways with approach other than 30 mph.

2.2.2 Follow-up Time

The follow-up time, t_f, is the minimum headway between first vehicle and the second vehicle, and subsequent vehicle pairs, as they enter the same major stream gap when a continuous queue exists on the minor street approach *(7)*. Follow-up gap refers to the move up time of the second vehicle in the subject approach to reach the stop line after the first vehicle has departed from the intersection *(2)*. *HCM* defined it as the time span between the departure of one vehicle and the departure of next vehicle under a continuous queue condition *(1)*.

Field measurements were conducted in Germany to estimate the value of follow-up time. As quoted by Panchavati *(2)*, Jessen assumed that there is a fixed depedency of t_f and t_g according to the following equation.

$$t_f = 0.6\ t_g$$

2.2.3 Zero Gap

In *HCM*, the zero gap is only stated as the summation of the critical gap and one half of follow-up time. Based on the interpretation of the example illustrated by Kyte et al. *(7)* for continuous queue conditions on a minor street approach, zero gap can be defined as the gap size in major street traffic that was not used by any minor street vehicles.

2.3 DIFFERENCES IN CRITICAL GAP MEASUREMENT

The 1985 *HCM* defined critical gap as the median time headway between two successive vehicles in the major street traffic stream that is accepted by a driver in a subject movement that must cross and/or merge with the major street flow *(8)*. Some researchers questioned this definition *(7)*, as the median value is a weak representation of the overall gap acceptance data. Kittelson and Vandehey said the correct approach is to consider both accepted and rejected gap data when estimating the size of the critical gap *(9)*.

The *HCM* changed definitions in the 1994 edition. However, the smallest acceptable gap size is difficult to determine, in part because the recorded size of the accepted gap is not necessarily the smallest gap size that the driver would have accepted.

Over the course of many years, various researchers have published different ideas of measuring the critical gaps. In the 1940s, Greenshields et al. called the gap that is chosen by half of the drivers the "minimum acceptable gap" *(10)*. Raff et al. defined critical gap as "the size of the gap whose number of accepted gaps shorter than it is equal to the number of rejected gaps longer than it" *(11)*. To avoid over-representing cautious drivers, Raff et al. decided to use only the first rejected gap instead of the largest gap *(12)*. As quoted by Kittelson et al., Bissell suggested in

1960 that the critical gap should reflect the median probability of accepting a gap of a given size *(9)*. Kittleson et al. also concluded that this definition is indeed more superior to 1985 *HCM* definition because it takes into account both acceptance and rejection characteristics.

2.3.1 Critical Gap Sensitivity Analysis

Aerde and Velan devised a computer simulation TWSC model to test the effects of various critical gap and follow-up sizes on minor street capacity *(12)*. With the major traffic flow set to 900 vehicles per hour (vph), the minor street capacity for critical gap size of 7 and 5 seconds was found to be 400 vph and 620 vph, respectively.

Their work showed that if the critical gap was estimated to be 7 seconds when the true critical gap was 5 seconds, then the capacity of the minor street was underestimated by 55%. If the follow-up time were reduced from 3 to 2 seconds, the minor street capacity increased by 39%.

2.3.2 The Practical Definition of Maximum Accepted Gap Size

Kittleson and Vandehey noted that it is intuitively obvious that most drivers will accept 15-second gaps, so large gap-size data do not provide an indication of how drivers will react to a 5- or 6-second gap *(9)*. It is usually logical to assume that drivers will accept gaps greater than 11 seconds. This suggests that there is no meaningful information regarding driver gap acceptance behavior when the accepted gap size is above 12 seconds. The inclusion of such data is also likely to skew the results of critical gap analysis, i. e., cause the calculated critical gap size to be larger than it really is. These data should either be excluded or adjusted to produce a more accurate critical gap size estimate.

2.4 BEHAVIORAL ASPECTS IN DRIVER GAP ACCEPTANCE

For practical purposes, *HCM* assumes that all drivers have consistent gap acceptance behavior; that is to say the accepted gaps are always greater than or equal to the critical gap *(1)*. According to Cassidy et al., this assumption is not always true because the gap acceptance process is probabilistic *(13)*. Each driver has his or her own perception of a critical gap and the value of this "minimum acceptable" gap may change with conditions at the intersection. For instance, a driver may not always act consistently and may accept a subsequent gap that is smaller than previously rejected gaps.

2.4.1 Differences in Lag and Gap Acceptance Behavior

By definition, lag and gap are different in the physical sense. However, there are conflicting conclusions of whether drivers' lag and gap acceptance behaviors differ from one another. Wagner concluded lag and gap acceptance differed at a 0.05 level of significance *(14)*. Other researchers such as Solbarg and Oppenlander, Miller, Adebisi, etc. chose to analyze lag and gap as a single group of data *(10, 15, 16)*.

Wagner found that except for very small sizes, a gap of a given size was more readily accepted than a lag of the same size. For example, a gap of 8 seconds was accepted by 60% of the waiting drivers but a lag of the same size was accepted by only 50% *(14)*. Miller concluded that the measurement of lags is usually less precise than that of gaps *(15)*. Adebisi assumed lag and gap acceptance values were similar if drivers come to a complete stop *(16)*.

In order to simplify work, lag and gap are generally not treated differently *(15, 16)*. For example, in *HCM*, lag and gap are treated as a single variable in the two-way stop-controlled intersection capacity formula *(1)*.

2.4.2 Factors Affecting Gap Acceptance Behavior

HCM recognized the unstable nature of critical gap by using different critical gap sizes based on turning movements, number of lane in the major roadway, and a fixed speed range *(1)*. *HCM* listed two more factors that may also affect driver gap acceptance characteristic: the adequacy of intersection sight distance and corner radii. Various traffic studies have listed the minor street drivers' waiting time, the major traffic flow, visibility (day or night), the existence of a queue on the minor street, the stop type (rolling or complete stop), and the vehicle type as possible elements that affect gap acceptance behavior.

Kyte et al. explained how a long queue-waiting time may reduce the driver's critical gap *(17)*. Drivers' frustration may increase as length of the queue and queue time increases. Also, the pressure on the driver that is first in line from other vehicles queued behind it will encourage the driver to accept a shorter gap. Finally, the longer the time a driver spends in queue, the better he or she will be able to estimate the size of upcoming gaps and the driver may come to accept a shorter gap. Some researchers have found evidence that supported the above reasoning *(9, 18)*.

In Nigeria, Adebisi investigated the effect of major traffic flow on drivers' gap acceptance behavior *(16)*. The data showed that the estimated critical gap was larger than the aggregated critical gap for low major traffic flow and conversely, the critical gap was smaller for high major traffic flow. He concluded that the mean critical gap will be constant only if the traffic flow is within half the standard deviation of the observed average flow. Wagner also found evidence that drivers accept smaller lags and gaps during peak periods than during off-peak hours *(14)*. For example, 6-second lags were accepted by nearly half the population of the peak-period drivers, but by only 20% of the off-peak hour drivers.

2.5 GAP ACCEPTANCE MODELING FUNDAMENTALS

According to *HCM*, gap acceptance modeling begins with the recognition that TWSC intersections give the minor street driver no positive indication as to when it is safe to leave the stop line and enter the major traffic stream. The driver must determine both when a gap in the major traffic stream is large enough to permit safe entry and when it is his or her turn to do so, based on the relative priority of the competing traffic streams. This decision making process has been formalized into what is known as gap acceptance theory, which relies on three basic elements:

1. the size and distribution (availability) of gaps in the major traffic stream;
2. the usefulness of these gaps to the minor stream drivers; and
3. the relative priority of traffic streams at the intersection.

2.5.1 Arrival and Departure Characteristics

The study of vehicle arrival and departure characteristics at an intersection is basically a microscopic examination of vehicles in motion. In this context, the microscopic examination means that every stage of a vehicle in-motion is analyzed in great detail. Minor street traffic arrivals and departures are more complicated and difficult to define than are those of major street traffic.

Wagner defined the arrival of a major street vehicle as the point in time when the vehicle crosses or enters the intersection area *(14)*. The arrival of a side street vehicle on an unoccupied stop-controlled minor street approach is considered as the point in time when the vehicle either stops or reaches its lowest speed before entering the intersection area. For an occupied minor street, the arrival time of the second-in-queue vehicle is the time coinciding with the complete entry of the first waiting vehicle into the intersection. This definition provides a beginning reference point for measuring the lag presented to the second-in-queue vehicle.

2.5.2 Impedance Effects

Impedance effects are the influences of one traffic stream that impedes the smooth movement of other traffic streams. The main reason for this effect is that the gaps in the major street traffic flow are used by a number of competing flows in a prioritized manner. Essentially, a gap used or taken by one minor street vehicle may not be available for use by another vehicle. *HCM* uses the probability of a queue-free state for major left-turning traffic and the minor street crossing traffic to quantify the magnitude of impedance upon low-priority movements *(1)*. In other words, the higher the probability that a queue-free state will occur, the higher the capacity of the minor street approach.

2.6 LAG AND GAP ACCEPTANCE MODELING TECHNIQUES

Madanat et al. offered two approaches to drivers' critical gap values: the deterministic and the probabilistic approach *(19)*. The deterministic critical values are treated as a single average value. The fundamental assumption is that drivers will accept all gaps that are larger than the critical gap and reject all smaller gaps. *HCM* has adopted the deterministic approach in the TWSC capacity formula.

As an alternative, probabilistic models solve some of the inconsistency elements in gap acceptance behavior by using a statistical treatment of minor street drivers' gap acceptance behavior. This means that drivers' perceptions of a minimum acceptable gap is treated as a random variable. Log-normal and Erlang functions are two commonly used probability distribution functions to model the critical gap *(5)*. According to Adebisi and Sama, probabilistic models can be further subdivided into two basic types of studies: queue acceptance studies and gap acceptance studies *(18)*. Queue acceptance studies are based on the length of each accepted gap in the main traffic stream to the number of minor road vehicles that enter the gap. Gap acceptance studies are related to the length of gaps in the main traffic and the minor street drivers' probabilities of accepting those gaps.

2.6.1 Acceptance Curve Bias or Lag Acceptance Bias

The phenomenon of acceptance curve bias (or lag acceptance bias) produces a slight distortion. According to Ashworth, this bias is introduced when data from drivers that reject multiple gaps are included *(20)*. Drivers with low acceptance thresholds are more likely to accept the first gap offered to them, whereas drivers who want long gaps will often reject the lag and several gaps before obtaining an acceptable gap. Considering all accepted and rejected gaps will produce a gap acceptance curve in which the percentage acceptance of a given gap size will be somewhat less than the percentage of minor road drivers prepared to accept a gap of that size. The resulting effect of this bias is that the reported critical gap is somewhat larger than the actual critical gap.

In other words, cautious drivers are overepresented compared with risk-taking drivers. Hewitt noted that drivers who will accept a short gap are also likely to accept a short lag *(21)*. Risk-taking drivers are more likely to accept the initial lag and thus not be represented in the subset of drivers whose gap acceptance behavior is observed. According to Ashworth, Raff and Hart realized this bias but many studies that were conducted later appeared to overlook it *(20)*. This is also the reason that Raff and Hart chose to use only lag data and excluded any subsequent gaps.

2.6.3 Deterministic Models

The deterministic model has been the conventional approach of gap acceptance studies. Several critical gap definitions have been used, such as the median, the mean, or a particular gap size where the percentage of rejection and acceptance are the same. Common examples include Greenshields, Raff, and acceptance curve methods that involve data compilation and manipulation techniques.

2.6.3.1 Greenshields Method

The classical Greenshields method employs a histogram to represent the total number of acceptances and rejections for each gap-range. The vertical axis of the histogram represents the number of gaps accepted (positive value) or rejected (negative value) of a certain gap-range, and the horizontal axis represents the gap size range. The critical gap is identified as the gap-range that has an equal number of acceptances and rejections. As a reminder, Mason et al. noted that certain results from Greenshields' analysis must be interpreted with caution because of small sample sizes *(22)*.

2.6.3.2 Raff Method

Raff defined critical gap to be the size of the gap whose number of accepted gaps shorter than it is equal to the number of rejected gaps longer than it. This definition takes the form of the intersection of the two cumulative curves on a number-of-acceptances versus gap-range graph. The rejection curve is obtained by using the total number of rejected gaps with gap size larger than the given gap size. The acceptance curve is formed by a cumulative curve that represents the total number of accepted gaps with gap size less than the given gap size.

The original Raff definition only uses lag acceptance and rejection data. This approach is considered statistically wasteful by some researchers, since useful gap acceptance and rejection data are omitted *(15, 19)*. There are two approaches to remedy this shortcoming. Fitzpatrick decided to combine the gap and lag data based on the notion that there is no statistical significance between lag and gap data

(11). An alternative approach is to separate the lag and gap data into "lag only" and "gap only" curves.

2.6.3.3 Acceptance Curve Method

Both theoretical and empirical considerations suggest that when the dependent variable is a binary variable, the shape of the response function will frequently be curvilinear. This also means that the response function for such binary variables is noted to shape as a tilted *"S"*, with y = 0 and y = 1 as asymptotes. The dependent variables of this response curve are the cumulative probability of accepting a gap of a specific length. The x-value corresponding to the 0.5 probability may be used as critical gap size. Maze illustrates the probability calculation as follows *(23)*.

Install Equation Editor and double-click here to view equation.

P_i = cumulative probability of accepting a gap of time length i.

d_i = number of gaps accepted of time length i or less, and

N = total number of events.

2.6.4 Probabilistic Modeling

Probabilistic modeling is more complex than deterministic modeling. Three probabilistic modeling techniques (logit, probit, and Siegloch) are discussed.

2.6.4.1 Logit Method

The logit method is basically a weighted linear regression model. As opposed to the fitted least squares model, the weighted least square provides efficient estimates when the error variances are unequal *(24)*. It can only be used, however, when the error variance is known completely or at least known up to a proportional constant. The mathematical model for the logit method follows.

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P = probability of accepting a gap (referred to acceptance curve)

$ß_0$, $ß_1$ = regression coefficient

x = variable related to the gap acceptance decision (i. e., gap length)

The logit function can be transformed into a linear equation.

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P' = transformed probability

The critical lag and gap is the x-value, obtained by substituting *P* with 0.5.

2.6.4.2 Probit Analysis

Probit analysis is a statistical technique used to treat the percentages of a population making all-or-nothing (binomial) responses to increasingly severe values of a stimulus *(5)*. In the context of gap acceptance studies, the value of stimulus is the size of gap. The probit transformation equation follows.

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Y = the probit of x

μ = the population mean

s = the standard deviation of the population

A probit transformation table shows the transformation of cumulative percentage to probit. This allows the plotting of data based on the transformation of the percentage of acceptance and gap size. A fitted linear line can then be plotted on the chart to identify the value of gap that produces probit of 5.0. This value is considered as the median value of the stimulus, i. e., the critical gap.

2.6.4.3 Siegloch Method

To use the Siegloch method as a queue acceptance model, the minor road should be saturated with queued traffic. Kyte et al. illustrated a method developed by Siegloch which provides a direct link between gap acceptance theory and the definitions of these parameters. In this method, both the size of the major traffic stream gap and the number of minor stream vehicles (*n*) using each major stream gap during periods of continuous queuing are recorded. The mean gap size used by *n* vehicles is computed and is plotted against *n*. The resulting regression line that best fits these points is used to calculate the critical gap and the follow-up time. The value of zero gap (t_o) is obtained as the X-axis intercept. The slope of the regression line is the reciprocal of the follow-up time (t_f). The critical gap (t_g) is then obtained by the summation of zero gap plus one-half of the follow-up time.

Maher and Dowse also illustrated an example that is similar to the Siegloch method *(25)*. However, the Maher and Dowse example differed in that the gap data with zero acceptances were also included.

2.7 TRAFFIC DATA COLLECTION USING VIDEO-BASED SYSTEMS

Video-based technology offers advantages and is gaining popularity as a data collection method. Video data constitutes a permanent record--by replaying the video data, researchers can observe special problems or review specific operational situations several times. Video data can be entered directly into the computer, eliminating errors that often occur when researchers transcribe field data sheets. Video data collection methodology may produce higher quality traffic data than manual methods. Researchers can easily obtain event-times data with accuracy of 0.1 second (*26*). Also, by using the frame-by-frame replaying feature, a researcher can exerecise careful and unhurried judgement when unusual, complicated, or rapid events occur. Data from video records may be reduced by frame-by-frame viewing or by replaying at normal speed while recording events with computer software.

2.7.1 Calibration Procedure of Video-Based System

Researchers using video methods need to be aware of a systematic error known as tape drag. Tape drag causes video data events to take more time than the actual real-time event. Bonneson and Fitts explain that this phenomena is due to the internal conversion of 1 second to 30 frames, where the more accurate ratio is about 1 second to 29.970 frames for color images *(26)*. The authors illustrate a procedure to improve the precision in measuring traffic event time. An in-picture generator can be used to superimpose a digital time image over the camera's video data. These generators typically provide a precision to 0.01 second and exceed the precision of a video frame, i. e., 1/30 second.

Bonneson and Fitts also noted that consumer-grade VHS videotape recorders have -0.0016 sec/sec drag, while the professional-grade Hi8 recorder has -0.00020 sec/sec drag. The formula to calculate tape drag follows.

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T_r = true event time (second)

T_t = event time measured with an external time clock during tape playback (second)

t_d = tape drag adjustment factor (second/second)

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CHAPTER 3
DATA COLLECTION AND REDUCTION PROCEDURES

The objective of the field research was to record the arrival and departure times of vehicles on each intersection leg, for use in the calculation of lag and gap size. After data was collected, it was reduced into arrival and departure times. This chapter provides information about the non-standard unsignalized T-intersection study site and the procedures used in field research and field data reduction.

3.1 SITE DESCRIPTION

The unsignalized T-intersection of Drake Street and Gregg Avenue in Fayetteville, Arkansas, was suitable for this study. Both were two-lane roadways with 45 mph (approximately 72 km/h) posted speeds and were also designated as SH 180 (Figure 3.1). In February 1997, after field data collection was completed, this intersection was converted into a standard two-way stop-controlled T-intersection.

FIGURE 3.1 Non-Standard T-intersection Priority Traffic Streams

This T-intersection was considered a non-standard T-intersection because it had a stop sign on one through approach and a yield sign on the perpendicular approach. This traffic control pattern assigned first rank priority over all traffic streams to the south approach (northbound through and left-turning) traffic streams. West approach (eastbound) traffic streams were controlled by a yield sign; they yielded to northbound traffic when making left turns but had first rank priority when making a right turn. North approach (southbound) right-turning traffic had the same priority rank as the eastbound left-turning traffic, yielding only to northbound left-turning traffic. North approach (southbound) through traffic stopped for both northbound and eastbound traffic. The eastbound approach radius allowed right-turning vehicles to pass by waiting left-turning vehicles. The north approach (southbound intersection leg) did not have a separate right-turn lane.

3.2 PRELIMINARY CONSIDERATIONS

It was important to identify and analyze site attributes when designing the field research and data reduction procedures. The situations identified could be divided into two categories, the observational and the conceptual. Literally, the observational problems were those identified by observation during preliminary studies. The conceptualized problems were those identified by conceptualization when field data was examined closely. Generally, the field research procedures were designed specially to address some of the observational problems and the data reduction procedures were designed to solve the remaining observational and conceptualized problems.

3.2.1 Initial Traffic Operation Observations

Two characteristics of this intersection affected the major street traffic flow and consequently the traffic operation characteristics. First, a signalized intersection approximately 2.5 km (1.5 mi) south of this intersection created some platooning in northbound traffic. Second, the railroad track parallel to and on the west of Gregg Avenue is higher than the roadway, restricting the vision of southbound through drivers trying to monitor eastbound traffic.

During high volume periods (e. g., 4 p.m. to 6 p.m.), this non-standard T-intersection experienced excessive delay on the southbound approach. In many cases the total delay per vehicle exceeded 45 seconds, which is the delay defined as level-of-service F for two-way stop-controlled intersections *(1)*.

3.2.2 Observational Problems

Four problems were noticed during the preliminary studies of traffic patterns. The first problem was driver confusion, perhaps among drivers that were either new to the area or wary of other road users. There were many instances that indicated drivers were confused by the right-of-way pattern. For example, northbound left-turning and eastbound right-turning drivers stopped and yielded to southbound through traffic as if they were at a standard intersection. During this indecisive moment, some aggressive southbound drivers entered the intersection.

The second problem was that southbound through drivers would sometimes underestimate the size of the upcoming lag or gap. Based on their perception of speed and distance, southbound drivers estimated if the interarrival times between northbound vehicles would be large enough; this is done by estimating or projecting the future arrival time of northbound vehicles. Because northbound vehicles (especially left-turning vehicles) often slowed when they got close to the intersection, the actual interarrival time between two northbound vehicles at the intersection could be greater than what a southbound drivers had estimated when the northbound vehicle were upstream of the intersection.

The third problem was the inefficiency in traffic operations. This situation is very similar to the impedance effects described in *HCM*, where otherwise adequate northbound gaps can not be used by southbound traffic because eastbound left-turning traffic is present. However, by the nature of this non-standard T-intersection, the impedance effects do not prevent southbound traffic from entering the intersection in a physical sense. In other words, southbound through drivers were not strictly bound by the designated traffic operating rules, i. e., stop and wait for eastbound left-turning to clear. Southbound through drivers, in the absence of eastbound right-turning and northbound left-turning traffic, sometimes proceeded through the intersection when there was a constant flow of northbound through traffic to hold back eastbound left-turning vehicles. Northbound through traffic was creating a temporary window for southbound through drivers to enter the intersection.

The fourth problem involved aggressive eastbound left-turning drivers occasionally entering the intersection without an adequate-size gap. When this happened, northbound drivers were forced to slow in order to avoid a rear end collision.

3.2.3 Conceptualized Problems

While reviewing the field data, three additional traffic operations problems were conceptualized. The first problem was that some minor street drivers intentionally or unintentionally violated some traffic operating rules. For instance, many drivers only slowed and did not come to a full or "wheel locked" stop at the stop sign before entering the intersection. During this deceleration, southbound drivers were monitoring the priority traffic flows while approaching the intersection. If drivers were convinced that the lag was large enough for them to proceed, some would enter the intersection without coming to a full stop.

The second problem was that some eastbound left-turning and southbound drivers did not wait at the stop line before entering the intersection. In other word, vehicles in these two traffic streams did not have a consistent stopped position. On some occasions, drivers stopped and moved forward more than once while waiting for an adequate gap size. One possible explanation for this behavior is that drivers' hesitated when deciding to accept or reject the gap(s) offered. This multiple stop scenario made it more difficult to consistently identify the intersection arrival times of eastbound left-turning and southbound traffic.

The third problem was that southbound drivers' arrival behavior might not be totally independent of the major traffic streams, particularly northbound traffic. If a priority flow was blocking the intersection but the southbound driver could see an upcoming sizeable gap, some southbound drivers slowed their approach to the intersection and delayed their arrival time at the stop line, therefore minimizing the amount of time actually stopped. Or, southbound drivers might perceive that stopping at the intersection was unavoidable and they might as well arrive at the intersection in an unhurried manner. Ashworth pointed out that this behavior makes it more difficult to calculate the precise length of a rejected lag *(20)*.

3.3 DATA COLLECTION PROCEDURES

The field procedure was designed to address some of the previously identified problems. A traffic classifier and a video camera were the two major equipment items used in field research. Figure 3.2 shows data collection in progress.

A traffic classifier was placed 46 m (150 ft) south of the intersection to collect northbound traffic speeds and arrival times. Two flexible road tubes spaced 3 m (10 ft) apart were laid perpendicular to the northbound traveled way. The classifier was located upstream in order to record the passage time and speed of northbound traffic in advance of the actual intersection, hopefully mimicing the decision process exercised by eastbound left-turning and southbound drivers. The collected northbound traffic arrival times were later projected to what they would have been at the intersection, had the northbound vehicles maintained constant speed. The projected arrival times were expected to often be earlier than the actual arrival times.

To obtain southbound and eastbound arrival and departure times, a video camera was aimed to cover north (southbound) and west (eastbound) intersection approaches. Figure 3.3 depicts field locations of the video camera and traffic classifier.

One person operated the traffic classifier and another the video camera. Both persons simultaneously started their data collection devices when northbound traffic was absent. This step was designed to simplify the data reduction process by making it easier to establish a common reference or global time frame for data collected by both video and the traffic classifier.

FIGURE 3.2 Data Collection at Intersection

FIGURE 3.3 Field Equipment Setup

3.4 DATA REDUCTION PROCEDURES

The data stored in the classifier was downloaded to a computer, then converted to ASCII text format before being imported into a spreadsheet. Appendix A contains summary descriptors such as traffic volumes and proportions of vehicles turning.

3.4.1 Video Data Reduction

There were five 60 to 90 minute video sessions, with each session marked by either the starting of a videocassette or a startup after replacing a video camera battery. This research procedure involved time consuming manual data recording. However, this procedure was systematic and created numerous opportunities for reviewing and correcting erroroneous data entry.

The traffic data collected by the classifier was validated to eliminate incorrect data. Hard copies of data files were printed and the existence of each northbound vehicles was verified by viewing the video replay. The process of classifying northbound traffic turning movements (left turn or through) was performed at the same time.

All the incorrect data was adjusted accordingly. For instance, an incorrectly-recorded 4-axle vehicle was changed to 2 vehicles with the same speed and a 1 second headway. Using the same approach, the sensor-miss data was inserted with the same speed and 1 second difference in arrival time of either the preceding or the following vehicle. The frequency of the "4-axle" and "sensor-miss" events was about 3 times and 1 time respectively in every video session.

3.4.2 Three Types of Time Data

There were three categories of time data in this research. Only two of the three time data represented a true event time.

The first true event time data was the "video time" which was inserted automatically into the videotape by the video camera. This video internal clock was a regular clock and was not affected by tape drag. The second true event time data was the "classifier time", which was also regular clock time and represented the actual event time. The main challenge was to correlate these two different time records by using one of them as the reference (global) time.

The time units inserted by the video camera were in hours and minutes; this was not sufficiently precise for this study. Another time code (the third time data used in this study) with higher accuracy was added to the video data. Video production technology allows the insertion of a second time window by duplicating the video data while connecting to a time encoder. The accuracy of the second time code in this study was 1/30 second which assumed the conversion rate of 1 second to 30 frames.

The "tape drag" problem causes the time code stamped by the encoder to be slower than the real time (the video or classifier time). To illustrate the impact of tape drag deviation to the real time and the time code, the inserted time code window was used to record the arrival times of northbound traffic at the intersection. This time data was then compared to the projection time (travel time of 150 feet added to the classifier time) of the northbound vehicle. The logical expectation was that the projected time was to be slightly earlier than the time code data, but after a 57 minutes video replay session, the recorded arrival time of northbound vehicle from time code turned out to be earlier than the projected time by approximately 4 seconds.

The following formula was used to calculate tape drag (*D*).

Install Equation Editor and double-click here to view equation.

D = tape drag (most likely a small, negative value)

TL = time lapse of time code window in second

TLV = time lapse of video camera internal time code in second

The "second-to-frame" relationship is found as follows.

1 second = 30 * (1 + *D*) frames

3.4.3 Tape Drag Correction

There were two ways to correct tape drag. The first option was to deduct the magnitude of tape drag from the classifier time. This meant the northbound traffic arrival event time would be brought forward (i.e., to happen earlier) so as to be at the same pace as the inserted video time code. The second option was to add the magnitude of the tape drag to the time code data so the time code arrival time was brought forward. The first option was used in the data reduction process because only northbound arrival times were based on the classifier time and all the minor street event times were collected from time code data.

The magnitude of tape drag deviation was observed to increase as more video replay time had elapsed. This indicated that tape drag deviation accumulated over time, hence it was suitable to analyze with a linear regression model. The dependent variable was the magnitude of tape drag while the independent variable was the replay time. These two variables were collected by first identifying the earliest possible moment at each video reduction session when the video time (inserted by video internal clock) started a new minute. This task was accomplished by replaying video data using frame by frame replay mode. When this moment was identified, the readings of video time and time code were collected as time zero for independent and dependent variables, respectively. This step was then repeated to record the time code reading at five-minute intervals. The independent and dependent variables can be found by subtracting each time zero value from the value recorded at every five-minute interval.

For all five video data reduction sessions, the R^2 values were above 0.99. Bonneson and Fitts reported that the tape drag value (not the magnitude of tape drag) for consumer-grade cassette may increase with replay time *(26)*. However, the high R^2 values indicated that the tape drag value in this research was approximately linear or consistent throughout the video sessions.

FIGURE 3.4 Tape Drag Linear Regression Analysis

3.4.4 Event Time Reduction

To calculate minor traffic stream lag and gap acceptance (or rejection) data, one needs to know both minor street traffic arrival/departure times and major street traffic arrival times. Northbound traffic arrival time was the projected time obtained from classifier, while southbound and eastbound traffic arrival and departure times were obtained by viewing the video time code display window.

The arrival, departure, and "arrival-departure" times were recorded for eastbound left-turning and southbound vehicles. Arrival-departure describes an event where vehicles did not fully stop and did not have distinct arrival and departure events. Vehicles that both arrived and departed within a single two-second window were categorized as "arrival-departures".

3.4.5 Post Video Reduction

There was a need to address the intentional delay by southbound drivers approaching the intersection. This sometimes required the adjustment of southbound vehicle arrival times.

When southbound vehicles approached the intersection and joined pre-existing queue, the arrival time of the second-in-queue vehicle at the intersection was adjusted to be no later than the sum of the departure time of first-of-queue vehicle plus the follow-up time. The follow-up time used was 3.80 seconds (sec), obtained by the Siegloch method.

Unfortunately, there was no quick and easy solution for southbound vehicles arriving at an empty intersection. The only way to adjust this was during video reduction process, which was troublesome and introduced difficulty into the data reduction process.

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CHAPTER 4
DATA ANALYSIS AND RESULTS

After retrieving and reducing the video and the classifier data, the researchers analyzed the data. This chapter explains the data analysis procedures. The Siegloch, Greenshields, Raff, acceptance curve, and logit critical lag and gap modeling methodologies were used to derive critical lag and gap values.

4.1 ARRIVAL AND DEPARTURE TIMES

For those traffic streams that did not have to yield, only the arrival times at the intersection were collected. For others, arrival and departure or arrival-departure times were collected.

4.1.1 First-Priority Traffic Streams

The time-of-arrival for northbound vehicles was projected by recording the passage time at a point 46 m (150 ft) in advance of the intersection and adding to that the time needed to travel 46 m at the recorded speed. This projected arrival time was assumed to approximate the arrival time estimated by southbound and eastbound left-turning drivers.

The eastbound right-turning vehicle arrival time was defined as the moment a vehicle entered the intersection area. To ensure consistency, the arrival time was further defined as when the front axle of the vehicle or less than half of the front portion of the vehicle's body entered the intersection area.

4.1.2 Southbound and Eastbound Left-Turning Traffic Data

Both arrival and departure times were collected for eastbound left-turning and the southbound vehicles. Wagner's definitions were used extensively *(14)* in defining these arrival times. According to Wagner, for a minor street vehicle that arrived at an empty intersection with no pre-existing queue, the arrival time was when this vehicle either stopped or reached its lowest speed. If an intersection leg had an existing queue, the arrival time of second-of-queue vehicle was set to coincide with time of complete entry into the intersection area of the head-of-queue vehicle. In this research, the departure time was the moment when vehicles began to enter the intersection area. The recording of these event times was accomplished by replaying the video record in slow motion.

Many minor street vehicles did not come to a wheel-locked stop before entering the intersection. As previously noted, these vehicles either did not have distinctive departing characteristics or the departure time was very close to the arrival time. This situation was often associated with drivers accepting the lag. Since lag is the time interval from the arrival time of a minor street vehicle at an intersection to the arrival of the first major street vehicle, departure time information was not needed to calculate the lag. Therefore, only the stop line crossing time, termed the "arrival-departure" time, was recorded as the time when vehicles arrived at the intersection and accepted the lag offered. Again, to promote consistency, the determining factor for classifying the arrival-departure time as a single event was when the arrival and departure times of a particular vehicle were less than 2.0 seconds apart.

In some cases, the difference between the arrival time of the second-in-queue vehicle and departure time of the head-of-queue vehicle was less than one second. At first glance, this seemed wrong because the arrival time of the second-in-queue vehicles was supposedly coinciding with the time when the head-of-queue vehicle completely entered the intersection. However, this situation could occur when the head-of-queue vehicle stopped beyond the designated stopped line, with part of the vehicle body within the intersection area. Hence, the second-in-queue vehicle needed little time to arrive at the stop line.

The numerous southbound "multiple stop" situations created ambiguity. These situations occurred when southbound head-of-queue drivers stopped and moved forward more than once while they were evaluating the lag or gaps in the major traffic streams. The fact that the arrival time was needed only to calculate the lag also implied that the effort to select the correct minor street arrival time was only necessary before the arrival of the first major street vehicle. Possible options included:

1a. using the time of the first southbound arrival, as defined by the first "wheel locked" moment;
1b. using the time that coincided with the complete entry of the preceding southbound vehicle into the intersection; or
2. using the last time that southbound drivers hesitated and stopped before actually proceeding.

To partly address the issue that southbound drivers deliberately delayed their time-of-arrival at the stop-line, the first option was adopted. During the post video data procedure, the data was adjusted so that for southbound vehicles queued at the stop bar, the time of arrival for a southbound vehicle could be no later than the previous vehicle's time-of-departure plus the follow-up time (which had been found from the data).

4.2 SEQUENCING THE FIELD DATA

Two needs arose while manipulating the field data. The first was to correctly identify the major traffic flow vehicle that interacted with a given minor vehicle, in order to obtain lag and gap data. The second need was identifying and minimizing sources of ambiguity when determining lag and gap sizes. The researchers employed several BASIC programs to screen data and to calculate the lag and gap sizes.

4.2.1 Major Traffic Streams for Second Rank Priority Minor Street Traffic

At this intersection, eastbound left-turning and southbound right-turning traffic were second rank priority streams, and as such only needed to monitor the first rank priority traffic stream(s).

Eastbound left-turning vehicles had to consider the combined northbound traffic streams as major traffic flow. On the other hand, the major traffic flow for southbound right-turning traffic was only the northbound left-turning traffic stream.

4.2.2 Major Traffic Streams for Southbound Through Traffic

As the only third rank priority traffic stream at this intersection, southbound through drivers yielded to northbound left-turning, eastbound right-turning, and eastbound left-turning traffic streams. However, for the following reasons, southbound-through versus eastbound-left-turning traffic interactions were not modeled. To overcome a small set of one movement combination and to avoid ambiguity, the absence of eastbound left-turning traffic was a prerequisite for using data from southbound-through interactions with northbound.

Inclusion of the eastbound left-turning traffic flow as a major traffic stream presented a technical difficulty because the lag and gap values between southbound through traffic and eastbound left-turning traffic were difficult to establish. There were relatively few eastbound left-turning vehicles. When there were both southbound and eastbound left-turning traffic interactions, northbound traffic was usually present. Since eastbound left-turning vehicles had to yield to the northbound flow, gaps between southbound and eastbound simply did not exist.

The researchers decided to employ two separate ways of reporting southbound through drivers' lag and gap sizes. The first method involved effectively eliminating all northbound through vehicles (making "phantoms" out of northbound through vehicles) from the data set; therefore, all lags and gaps faced by southbound drivers were calculated from intervals between the combined northbound left-turning and eastbound right-turning traffic streams. Data from those time periods during which an eastbound left-turning vehicle was present was deleted. The other method considered all intervals (lags or gaps) involving any northbound vehicle, but deleted data from those time periods during which any eastbound vehicle was present.

4.2.3 Process to Exclude Eastbound Traffic Effects on Southbound Through Traffic

A series of steps were taken to exclude from the data those southbound vehicles that were influenced by eastbound traffic. The first step was to identify the various scenarios of eastbound traffic affecting southbound through drivers. The second step was to develop algorithms to identify the affected southbound through drivers based on these predetermined scenarios. The last step was to deploy several BASIC programs to exclude the affected southbound through drivers from the remainder of the southbound through traffic stream.

Two scenarios of southbound through drivers being affected by eastbound left-turning traffic were identified. These were based on a sequence of arrival and departure events. The first scenario was when a southbound through vehicle arrived or departed after the arrival of an eastbound left turning vehicle, but before the eastbound vehicle departed. The second scenario was when a southbound vehicle arrived before the arrival of an eastbound left-turning vehicle and departed after the eastbound vehicle had departed. The sequences are as follows.

First scenario: eastbound arrival – either southbound arrival or departure – eastbound departure

Second scenario: southbound arrival – eastbound arrival – eastbound departure – southbound departure

For both lag/gap calculation methods, the following situations triggered the exclusion of data by means of a screening algorithm.

1. For an eastbound left-turning vehicle with arrival-departure characteristics (did not come to a full stop), the interval of 8 seconds before to 6 seconds after the eastbound's arrival-departure was eliminated.
2. For an eastbound left-turning vehicle that came to a full stop, the interval between the eastbound's arrival and its departure was excluded.
3. For the scenario of southbound arrival–eastbound arrival–eastbound departure–southbound departure, all data involving the one affected southbound vehicle at the head-of-queue was deleted.

In addition, for the lag/gap calculation method based on both northbound through and left intervals, the following situation also caused the exclusion of data.

4. For an eastbound right-turning vehicle, the interval of 8 seconds before to 6 seconds after the eastbound's arrival was eliminated.

This "8 seconds and 6 seconds" zone was derived after viewing traffic behaviors on tape. The conservative screening standard was needed to eliminate those southbound vehicles that violated traffic rules by taking advantage of slow responding eastbound drivers. Figure 4.1, a graphical illustration of the “8 seconds and 6 seconds” zone, follows.

4.2.4 Largest Lag and Gap Size

As suggested by Kittleson and Vandehey, accepted gap sizes above 12 seconds do not produce meaningful critical gap information. For this research, lag and gap sizes larger than 12 seconds were converted to 12.01 second. This step facilitated the task of excluding them from the critical gap modeling processes.

FIGURE 4.1 8 Seconds and 6 Seconds Zone

4.2.5 Turning Movement-Based Lag and Gap Data Classification

The researchers performed two separate investigations of lag and gap acceptance traits, by classifying lag and gap data into "movement" based lag and gap data. All southbound lag and gap data was classified as either:

1. "northbound through" and "northbound left-turning", or
2. "northbound left-turning" and "eastbound right-turning" lag and gap data.

This step also addressed bias caused by the predominance of one movement pattern. For example, the northbound traffic was comprised of more than 80% through traffic, which also implied that most of the lags and gaps that southbound drivers faced involved northbound through vehicles. If northbound through and northbound left-turning data were combined and analyzed, the resulting critical lag and gap values would be weighed or biased toward values of an interaction with only a northbound through stream.

The following guidelines were employed to classify "turning movement based" lag and gap data. First, the lag data were classified based on the turning movement of the first major street vehicle encountered by a southbound through driver. For instance, a classification of "northbound through lag" reflected a case where the first northbound vehicle was a through vehicle. The subsequent gaps were categorized according to the paths of the following vehicle of the pair that formed that gap. For example, a through vehicle that was followed by a left-turning vehicle constituted a "left-turn gap". This principle was applied to also classify "northbound left-turning" and "eastbound right-turning" lag/gap data.

4.2.6 Algorithms for Lag and Gap Calculation

After establishing the relationship between each minor street traffic stream and its respective major traffic flow, the next step was to develop algorithms for lag and gap data calculation.

This algorithm began with identification of the arrival and departure time of a minor street vehicle. This was followed by identifying the arrival time of the first major street vehicle ($n = 1$). The lag was calculated by deducting the arrival time of the minor street vehicle from the major street vehicle arrival time. The lag was accepted by the minor street vehicle if the minor street vehicle departure time was earlier than the arrival time of the first ($n = 1$) major street vehicle. Conversely, if the departure time was later than the arrival time of major traffic, the lag was rejected.

Only if the lag was rejected was there a need to calculate the gaps rejected (if any) and gap accepted. Theoretically, an infinite number of gaps could be rejected but only one gap could be accepted. The next step was to identify the first major street vehicle (n = N) whose arrival time was later than the departure time of the minor street vehicle. All gaps from the first (n = 1) to the second last vehicle (n = N -1) were rejected. The sizes of rejected gaps were then calculated by deducting the $n\text{-}1^{th}$ major street vehicle's arrival time from the n^{th} vehicle's arrival time. Finally, the size of the accepted gap was calculated as the arrival time of N^{th} subtracting the arrival time of $N\text{-}1^{th}$ vehicle.

These sequences are as follows.

1. Algorithm for Accepted Lag

   Southbound Arrival:

      Lag Accepted = First Northbound Arrival – Southbound Arrival

   Southbound Departure:

      First Northbound, n = 1 = N

2. Algorithm for Rejected Lag

   Southbound Arrival:

      Lag Rejected = First Northbound – Southbound Arrival

      First Northbound, n = 1

      First Gap Rejected = Second Northbound – First Northbound

      Second Northbound, n = 2

      … if more northbound …

      Third Last Northbound, n = N –2

      Last Gap Rejected = Northbound, N-1 – Northbound, N-2

      Second Last Northbound, n = N –1

   Southbound Departure

      Gap Accepted = Last Northbound – Southbound Departure

      Last Northbound, n = N

All the algorithms were incorporated into a numbers of BASIC programs. By deploying these programs, all the field data were converted into lag and gap rejection and acceptance data for critical gap modeling.

4.3 LAG AND GAP ACCEPTANCE MODELING

Lag and gap acceptance values were calculated according to a number of alternative modeling techniques. The Siegloch, Greenshields, Raff, acceptance curve, and logit methods were used.

4.3.1 Siegloch Method

The project researchers first used the Siegloch method to obtain values for southbound movement follow-up time. This method reports the mean gap size that allows one side street vehicle to merge into or travel through the major stream gap. The implementation of this method required input that somehow reflected the information of a gap size versus the total number of minor street vehicles that had accepted this gap.

The input data compilation involved three steps. The first step was to arrange all major traffic arrival times in a “gap-pair” sequence. In other words, the two major street vehicles' arrival times that formed a gap were paired. For example, the first gap-pair was the first arrival time and the second arrival time, the second gap-pair was then the second arrival time and the third arrival time, and so forth. The second step was to assume that the minor street driver's acceptance of an offered gap was when he or she departed. This meant that there was a need to gather all minor street departure times into one input file as the total number of minor street acceptances. Finally, the third step was to find the total number of departures in between a gap-pair, then calculate the respective gap size by subtracting the first arrival time from the second arrival time.

The hypothesis that eastbound traffic could affect southbound driver's gap acceptance behavior also prevailed in this method. The effects of eastbound traffic on southbound traffic were removed, based on the major flow combination used. For example, if all northbound traffic streams were considered as the major traffic flow, then those gap-pairs that occurred when eastbound traffic was also present were discarded. The same concept was also applied to filter-out the effect of eastbound left-turning traffic when northbound left-turning and eastbound right-turning traffic streams were used as major traffic flow.

Two points were noted when implementing this method. First, this research did not differentiate the turning movement of southbound traffic stream when analyzing the total number of southbound vehicles’ acceptance. In other words, when gathering southbound drivers’ departure event times, southbound through and southbound right-turning traffic streams were treated as the same traffic stream. However, the inclusion of southbound right-turning traffic was not expected to distort the final output because the southbound right turning comprised only about 20% of the total southbound traffic flow. Second, as to be consistent with the example illustrated by Kyte et al. *(7)*, those gap-pairs that were not accepted by any southbound through vehicles (zero number of acceptance) were excluded.

After all the data points were obtained, the next step was to calculate the average gap size for each category of gap, based on the number of acceptances. These mean values were then plotted with gap size in seconds as the X-axis and the number of acceptances on the Y-axis. A least-squares linear regression line was plotted through these data points. Appendix B shows two graphs for the respective major traffic flows, and Table 4.1 the results. The zero gap (t_0) was obtained as the X-axis intersection of the linear regression, the follow-up (t_f) time was the reciprocal of slope of the linear regression line, and critical gap (t_g) was the summation of zero gap and half follow-up gap.

TABLE 4.1 Siegloch Method Values

Major flow	t_0	t_f	$t_g = t_0 + 0.5\ t_f$
Northbound through and left	1.54	3.75	3.42
Eastbound right and Northbound left	4.92	4.88	7.36

4.3.2 Greenshields Method

The classical Greenshields method employs a histogram with the gap-range as the X-axis and the number of acceptances (positive value) and rejections (negative value) along the Y-axis. The histogram allows an analyst to view the plot showing the critical gap-range that has the equal number of acceptances and rejections.

In this research, the total number of acceptances and rejections was reported in 0.5 second increment lag/gap-ranges. Appendix C contains this data. If there was no lag/gap-range that had the same number of acceptances and rejections to qualify as critical lag/gap- range, the lag/gap-range that had the closest number of rejection and acceptance was used as the critical lag/gap-range. The mid-point of the critical lag/gap-range was used as the representation of the value of critical lag or gap.

For southbound-through versus northbound-only traffic, northbound left-turning critical gap data was not reported due to having few data points. Table 4.2 lists critical lag and gap values for southbound through traffic.

4.3.3 Raff Method

The modified Raff method used in this research included gap acceptance and rejection data. As previously noted, the compilations of rejection and acceptance data were implemented with separate procedures. The acceptance data values were obtained by accumulating the total number of acceptances for a particular lag (gap)-range and other smaller lag/gap-ranges. The rejection data values were obtained in an inverse

TABLE 4.2 Greenshhields Method Values

Movement combination		Number of rejections/ acceptances for the given 0.5 sec interval	Lag/Gap size (sec)
Southbound through versus all northbound			
Critical Lag			
	Northbound through	31/36	2.25
	Northbound left-turn	3/4	4.25
Critical Gap			

Northbound through	19/16	3.25
Northbound left-turn	n/a	n/a
Southbound through versus northbound left-turn and eastbound right-turn		
Critical Lag		
Eastbound right-turn	9/11	6.25
Northbound left-turn	10/10	5.75
Critical Gap		
Eastbound right-turn	2/0	7.75
Northbound left-turn	0/1	6.25

manner, i.e., summing the number of lags (gaps) rejected of a specified range or larger. Thus, the acceptance curve could be viewed as an cumulative curve with the rejection curve as an inverse-cumulative curve.

All the data points were plotted with the Y-axis as the number of acceptances and rejections, and the X-axis as gap-range size in 0.5 second increments (see Appendix D). The intersection of the acceptance and rejection curves constituted the critical lag or critical gap values, listed in Table 4.3.

4.3.4 Acceptance Curve Method

The acceptance curve method identified the lag (gap) size with a 0.5 probability (50% chance) of acceptance by southbound through drivers. The probability of acceptance was calculated by dividing the total number of acceptances by the total number of lags or gaps offered. In preparing the input data, lag (gap) data were grouped into the optimum lag/gap-range. In this context, the optimum lag (gap) range was referred to the increment size that produced at least 3 continuous non-zero data points. Generally, a few trials of different increment size were required to identify the optimum lag/gap-range.

TABLE 4.3 Raff Method Values

Movement combination	Critical lag (sec)	Critical gap (sec)
Southbound through versus all northbound only		
Northbound through	1.8	2.6
Northbound left-turn	4.2	5.6
Southbound through versus northbound left-turn and eastbound right-turn		
Eastbound right-turn	6.2	7.4
Northbound left-turn	5.3	5.8
Southbound right-turn versus northbound left-turn	3.9	3.3

Eastbound left-turn versus all northbound only	3.6	6.6

In the analysis of southbound-through versus all northbound traffic, the optimum lag/gap-range was 1.5 seconds. On the other hand, the optimum lag/gap-range was 3.0 seconds for the analysis involving northbound left-turning and eastbound right-turning traffic (see Appendix E). Table 4.4 lists the critical lag and gap values found by the acceptance curve method.

TABLE 4.4 Acceptance Curve Method Values

Movement combination	Critical Lag (sec)	Critical Gap (sec)
Southbound through versus all northbound only (1.5-second range)		
Northbound through	2.2	3.2
Northbound left-turn	4.6	5.6
Southbound through versus northbound left-turn and eastbound right-turn (3.0-second range)		
Eastbound right-turn	6.2	8.0
Northbound left-turn	5.2	5.8

4.3.5 Logit Method

Inputs for the logit method were obtained by modifying the input data used in the acceptance curve method. The optimum lag- or gap-ranges of 1.5 and 3.0 seconds identified in acceptance curve method were also

used. Weighted linear regression analyses were performed on the mid-point value of lag/gap-range versus the natural logarithm of *P/(1-P)*, where P is the probability of acceptance for a particular lag/gap-range. The calculations for this method are illustrated in Appendix F, and the results are in Table 4.5.

TABLE 4.5 Logit Method Values

Movement combination	Critical Lag (sec)	Critical Gap (sec)
Southbound through versus all northbound only (1.5-second range)		
Northbound through	2.5	3.7
Northbound left-turn	5.4	9.0
Southbound through versus northbound left-turn and eastbound right-turn (3.0-second range)		
Eastbound right-turn	6.9	8.3

Northbound left-turn	5.9	6.9

4.4 SUMMARY OF CRITICAL LAG AND GAP VALUES

The summary of critical lag and gap values for the southbound through traffic stream (i.e., vehicles on the through road, but required to stop and having the lowest priority) is listed in Table 4.6.

TABLE 4.6 Summary of Southbound Through Critical Lag/Gap Values

Movement	Greenshields	Raff	Acceptance curve	Logit	Siegloch
Southbound through versus northbound only (through and left)					
Northbound through					
Critical Lag	2.25	1.8	2.2	2.5	n/a
Critical Gap	3.25	2.6	3.2	3.7	3.42
Northbound left-turn					
Critical Lag	4.25	4.2	4.6	5.4	n/a
Critical Gap	n/a	5.6	5.6	9.0	3.42
Southbound through versus northbound left-turn and eastbound right-turn					
Eastbound right-turn					
Critical Lag	6.25	6.2	6.2	6.9	n/a
Critical Gap	7.75	7.4	8.0	8.3	7.36
Northbound left-turn					
Critical Lag	5.75	5.3	5.2	5.9	n/a
Critical Gap	6.25	5.8	5.8	6.9	7.36

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CHAPTER 5
CONCLUSION

The use of different critical gap modeling techniques produced results for various movement combinations that varied widely. This makes the task of selecting the proper critical gap size more difficult. This chapter focuses on selecting the southbound through driver critical lag and gap values to use.

From field observations and data analysis, the researchers concluded that for some movement combinations, unusually small critical lag and gap values may be realistic. When interpreting northbound (i.e, through) lag and gap data, the conventional notion that drivers who accepted smaller lags or gaps were risk-taking drivers may not be true. A southbound driver accepting a very small lag or gap could have assumed that all approaching northbound vehicles (i.e., those with the right-of-way) were going to proceed straight and not turn left in front of the southbound vehicle. The stopped southbound driver may have assumed this because the oncoming northbound vehicle was almost in the intersection and had not yet slowed. Another factor contributing to small critical lags or gaps is the use of northbound arrival times projected from an upstream speed. If the actual northbound vehicles' arrival times at the intersection had been used instead of their projected arrival times, the lag and gap values would probably have been greater.

It was noted that the majority of the critical gap values were greater that the critical lag values. Two possible explanations for this phenomenon are apparent. The first explanation is that drivers were more willing to accept a lag than a gap of the same size. The second explanation was that the proportion of lag acceptance data was relatively larger than the rest of the data. In both combinations of major traffic flow, it was noted that approximately 50% of the total data were lag acceptance data, while about 20% of the total data were lag rejection data. Also, by definition, the summation of lag acceptance and rejection data was the total number of southbound through-street vehicles being analyzed. In other words, this meant that 70% of southbound through vehicles accepted the lag offered. According to Hewitt, drivers who have low critical gap size are also likely to accept the initial lag *(21)*. This large proportion of lag acceptances probably caused the critical lag values to be lower than the critical gap values.

In "movement" based lag and gap data, the northbound left-turning values were noted to be higher than the northbound through values. This was not surprising, because southbound drivers were required to yield to northbound left-turning traffic but not to northbound through traffic. On the other hand, the eastbound right-turning critical lag (gap) values were noted to be higher than northbound left-turning critical lag (gap) values. This may have been caused by the more restricted intersection sight distance to monitor eastbound traffic.

5.1 COMPARISON WITH HCM CRITICAL GAPS VALUES

The *HCM* critical gap values for minor street through and left-turning vehicles crossing two-lane major roads are 6.0 and 6.5 seconds respectively. Most of the lag/gap values from the "southbound through versus northbound left-turn and eastbound right-turn" combinations were of similar magnitude; however, the critical gap with the eastbound right-turn movement was higher for all calculation methods.

The lag/gap values from the "southbound through versus northbound only" combinations were smaller than those found in the *HCM*. This difference is more pronounced for the interactions between southbound through and northbound through vehicles. A possible explanation for this, southbound drivers assuming that oncoming northbound vehicles that had not slowed were going to proceed straight through, has been previously discussed. Low critical lag/gap values may suggest that the minor street capacity at a non-standard T-intersection may be higher than capacity at a "standard" TWSC intersection. For example, critical gap value for the northbound only major traffic flow were found to be in the 2.6 to 3.7 second range. The *HCM* values are considerably higher than this, which would imply that non-standard T-intersection minor street approach capacity is higher. However, this critical gap value was meant to represent only the interaction between southbound through and northbound only traffic flow. So, the only valid conclusion was that a non-standard stop-controlled pattern might increase the intersection capacity only under some traffic flow patterns. Coincidentally, the need to accommodate an unusual traffic flow pattern is a primary reason for the use of non-standard stop-control.

5.2 NON-STANDARD T-INTERSECTION CRITICAL GAP VALUES

A review of the outcomes shows that the values found according to the Raff method often were lower than others, and the Logit method produce values that were usually higher than others. Again, it should be noted that data for this study was collected at an intersection with an unbalanced flow pattern; that is, some movements had much more volume than did other movements. Additional study would be required to ascertain if these lag/gap values were affected by proportions-of-flow in a given movement.

This following recommended lag and gap values for the straight-but-subordinate movement (in this case, the southbound through) at non-standard stop-controlled T-intersections were derived from the weighted outcomes of the various methods used to analyze the data. Since the Siegloch and the logit methods are probabilistic models that involved more rigorous computational efforts than some others, outcomes from these methods were given higher credence.

Considering Lags/Gaps with Northbound only (through and left-turn) northbound through critical lag = 2.2 seconds

northbound through critical gap = 3.3 seconds

northbound left-turning critical lag = 4.8 seconds

northbound left-turning critical gap = 6.0 seconds

Considering Lags/Gaps with Northbound left-turn and Eastbound right-turn eastbound right-turning critical lag = 6.5 seconds

eastbound right-turning critical gap = 7.8 seconds

northbound left-turning critical lag = 5.6 seconds

northbound left-turning critical gap = 6.6 seconds

REFERENCES

1. Special Report 209: Highway Capacity Manual, 3rd ed. TRB, National Research Council, Washington, D. C. 1994. pp. 10-3--10-12.
2. Panchavati, S. G. V. Traffic Operations At Two-Way Stop-Controlled Intersections, Volume III, Evaluation and Testing of Theoretical Models for Analysis. Report TNW91-07.3. Transportation Northwest (TransNow), University of Washington. December 1991. pp. 6-7, 9-14.
3. Manual On Uniform Traffic Control Devices For Streets And Highways, 1988 ed. U. S. Department of Transportation Federal Highway Administration. Washington, D. C. pp. 2A-16, Figure 2-2a.
4. Jordan, P. Fewer Stop Signs: More Safety, Less Cost. Proceedings - Part 5 - Traffic engineering and planning. 15th ARRB Conference - 1990. Australian Road Research Board. pp. 57-67.
5. Gerlough D. L., and Huber, M. J. Traffic Flow Theory, A Monograph. Special Report 165. TRB, National Research Council. Washington, D. C. 1975. pp. 41, 145, 206.
6. Traffic Control System Handbook, Implementation Package 76-10. U S Department of Transportation Federal Highway Administration Office of Development Implementation Division. Washington, D. C. June 1976. p 54, Figure 23
7. Kyte, M., Kittelson, W., Tian, Z, Brilon, W., Troutbeck, R., and Mir, S. New Measurements for Saturation Headways and Critical Gaps at Stop-Controlled Intersections. Proceeding of Second International Symposium on Highway Capacity, 1994, Volume 1. pp. 345-64.
8. Special Report 209: Highway Capacity Manual, 2nd ed. TRB, National Research Council, Washington, D. C. 1985, pp. 10-5 - 10-7.
9. Kettelson, W. K., and Vandehey, M. A. Delay Effects on Driver Gap Acceptance Characteristics at Two-Way Stop-Controlled Intersections. Transportation Research Record 1320, TRB, National Research Council, Washington, D. C. 1991. pp. 154-9.
10. Solberg, P., and Oppenlander, J. C. Lag and Gap Acceptances at Stop-Controlled Intersections. Highway Research Record 118, HRB. 1966. pp. 48-67.
11. Fitpatrick, K. Gaps Accepted at Stop-Controlled Intersections. Transportation Research Record 1303, TRB, National Research Council, Washington, D. C. 1991. pp. 103-12.
12. Velan, S. M., and Aerde, M. V. Gap Acceptance and Approach Capacity at Unsignalized Intersections. Institute of Traffic Engineers. March 1996. pp. 40-5.

13. Cassidy, J. M., Madanat, S. M., Wang, M., and Yang, F. Unsignalized Intersection Capacity and Level of Service: Revisiting Critical Gap. Transportation Research Record 1484, TRB,

National Research Council, Washington, D. C. 1995. pp. 16-23.

14. Wagner, F. A. An Evaluation of Fundamental Driver Decision and Reaction at an Intersection. Highway Research Record 118, HRB. 1966. pp. 68-84.

15. Miller, A. J. Nine Estimators of Gap-Acceptance Parameters. Traffic Flow And Transportation Proceedings. International Symposium on the Theory of Traffic Flow and Transportation (5th: 1971). Newell, G. F., ed. American Elsevier Pub. Co., New York, 1972. pp. 215- 35.

16. Adebisi, O. Driver Gap Acceptance Phenomena. Journal of Transportation Engineering. ASCE, 108(6). November 1982. pp. 677-688.

17. Kyte, M., Zegeer, J., and Lall, K. B. Empirical Models For Estimating Capacity and Delay at Stop-Controlled Intersections in the United States. Intersection without Signals II, Proceeding of an International Workshop, Bochum, Germany. Brilon, W., ed. Springer-Verlag. New York. 1991 pp. 335-61.

18. Adebisi, O., and Sama, G. N. Influence of Stopped Delay on Driver Gap Acceptance Behavior. Journal of Transportation Engineering. ASCE, 115(3). November 1989. pp. 305-15.

19. Madanat, S. M., Cassidy, M. J., and Wang, M. Probabilistic Delay Model At Stop-Controlled Intersection. Journal of Transportation Engineering. ASCE, 120(1). January/February, 1994. pp. 21-36.

20. Ashworth, R. The Analysis and Interpretation of Gap Acceptance Data. Transportation Science Vol. 4, No. 3. 1970. pp. 270-80.

21. Hewitt, R. H. Measuring Critical Gap. Transportation Science Vol. 17, No. 1. 1983. pp. 87-109.

22. Mason, J. M., Fitzpatrick, K., and Hardwood, D. W. Field Observations of Truck Operational Characteristics Related to Intersection Sight Distance. Transportation Research Record 1280, TRB, National Research Council, Washington, D. C. 1990. pp. 163-72.

23. Maze, T. H. A Probabilistic Model of Gap Acceptance Behavior. Transportation Research Record 795, TRB, National Research Council, Washington, D. C. 1981. pp. 8-13.

24. Neter, J., and Wasserman, W. Applied Linear Statistical Models. Homewood, Illinois, R. D. Irwin, Inc., 1974. pp. 135, 330-34.

25. Maher, M. J. and Dowse, R. J. Estimating parameters in models of gap acceptance by queues. Traffic Engineering & Control. May 1983. pp. 252-8.

26. Bonneson, J. A. and Fitts, J. W. Traffic Data Collection Using Video-Based Systems. Transportation Research Record 1477, TRB, National Research Council, Washington, D. C. 1995. pp. 31-40.

APPENDIX A Traffic Data Collected at Non-Standard Stop-Controlled T-intersection

Date	12/30/96	12/31/96		1/2/97	
Session	I	II	III	IV	V
Time Begin	13:45	12:57	14:19	12:46	14:10
Time End	14:41	14:18	15:27	14:10	15:11
Total Time (hour:minute)	0:56	1:21	1:08	1:24	1:01
Total Time (hour)	0.93	1.35	1.13	1.40	1.02
Total Entering Vehicles	1182	1590	1354	1735	1259
Total Entering Volume (vehicle per hour)	1266	1178	1195	1239	1238
Northbound (total) (%Tot)	583 (49%)	765 (48%)	673 (50%)	869 (50%)	623 (49%)
Northbound Volume (vehicle per hour)	625	567	594	621	613
Northbound Through (total) (%TM)	493 (85%)	641 (84%)	550 (82%)	732 (84%)	519 (83%)
Northbound Left-turning (total) (%TM)	90 (15%)	124 (16%)	123 (18%)	137 (16%)	104 (17%)
Eastbound (total) (%Tot)	166 (14%)	260 (16%)	212 (16%)	265 (15%)	199 (16%)
Eastbound Volume (vehicle per hour)	178	193	187	189	196
Eastbound Right-turning (total) (%TM)	121 (73%)	178 (68%)	162 (76%)	183 (69%)	152 (76%)
Eastbound Left-turning (total) (%TM)	45 (27%)	82 (32%)	50 (24%)	82 (31%)	47 (24%)
Southbound (total) (%Tot)	433 (37%)	565 (36%)	469 (34%)	601 (35%)	437 (35%)
Southbound Volume (vehicle per hour)	464	419	414	429	430
Southbound Through (total) (%TM)	385 (89%)	473 (84%)	370 (79%)	496 (83%)	367 (84%)
Southbound Right-turning (total) (%TM)	48 (11%)	92 (16%)	99 (21%)	105 (17%)	70 (16%)

%Tot = (Total of intersection approach / Total Entering Volume)%

%TM = (Total of Turning Movement / Total of Intersection Approach)%

APPENDIX B The Siegloch Method

APPENDIX C The Greenshields Method

with Southbound Through Versus Northbound Through and Left Traffic

	Lag/Gap with Northbound Through				Lag/Gap with Northbound Left-turn			
Range (sec)	Through LAG Reject	Through LAG Accept	Through GAP Reject	Through GAP Accept	Left LAG Reject	Left LAG Accept	Left GAP Reject	Left GAP Accept
0.0 - 0.5	40	22	0	0	8	1	0	0
0.5 - 1.0	38	26	6	1	5	0	0	0
1.0 - 1.5	43	36	27	7	6	1	4	0
1.5 - 2.0	39	25	47	20	9	1	8	0
2.0 - 2.5	**31**	**36**	30	21	7	1	14	1
2.5 - 3.0	24	34	20	22	6	1	4	0
3.0 - 3.5	11	33	**19**	**16**	6	3	1	0
3.5 - 4.0	5	22	7	16	5	1	6	1
4.0 - 4.5	3	38	7	13	**3**	**4**	3	0
4.5 - 5.0	2	35	2	16	3	2	2	0
5.0 - 5.5	7	30	0	6	2	4	1	0
5.5 - 6.0	3	33	1	9	3	6	2	1
6.0 - 6.5	1	31	1	10	0	6	0	0
6.5 -7.0	0	29	0	9	0	2	0	2
7.0 - 7.5	0	22	0	5	0	3	0	2
7.5 - 8.0	0	29	0	7	0	9	0	2
8.0 - 8.5	0	22	0	5	0	6	0	0
8.5 - 9.0	0	20	0	7	0	5	0	3
9.0 - 9.5	0	14	0	10	0	4	0	1
9.5 - 10.0	0	17	0	2	0	4	0	3
10.0 - 10.5	1	21	0	5	0	6	0	1
10.5 - 11.0	0	16	0	1	0	5	0	0
11.0 - 11.5	0	20	0	6	0	2	0	4
11.5 - 12.0	0	15	0	2	0	3	0	0
12.0 - ++	0	160	0	56	0	40	0	17

APPENDIX C, con't. The Greenshields Method

with Southbound Through Versus Eastbound Right-turn and Northbound Left-turn

	Eastbound Right-turn Lag and Gap	Northbound Left-turn Lag and Gap

Range (sec)	Right LAG Reject	Right LAG Accept	Right GAP Reject	Right GAP Accept	Left LAG Reject	Left LAG Accept	Left GAP Reject	Left GAP Accept
0.0 - 0.5	10	4	6	0	19	1	5	0
0.5 - 1.0	11	2	5	0	11	0	7	0
1.0 - 1.5	10	3	8	0	11	1	9	1
1.5 - 2.0	13	0	18	1	17	1	8	1
2.0 - 2.5	20	0	25	4	13	2	10	0
2.5 - 3.0	21	2	18	0	14	2	6	0
3.0 - 3.5	21	2	12	0	12	4	4	1
3.5 - 4.0	17	2	10	0	10	2	6	2
4.0 - 4.5	14	4	7	2	11	7	9	1
4.5 - 5.0	10	6	5	2	5	2	4	4
5.0 - 5.5	16	5	2	3	6	11	4	0
5.5 - 6.0	14	6	10	2	**10**	**10**	4	2
6.0 - 6.5	**9**	**11**	3	2	4	10	**0**	**1**
6.5 -7.0	9	15	1	1	3	10	2	6
7.0 - 7.5	6	14	6	1	3	7	1	3
7.5 - 8.0	4	11	**2**	**0**	0	16	0	3
8.0 - 8.5	2	15	4	5	1	17	1	6
8.5 - 9.0	5	11	1	4	1	10	0	4
9.0 - 9.5	0	14	2	6	4	10	1	7
9.5 - 10.0	0	20	0	2	0	13	0	4
10.0 - 10.5	1	17	2	5	0	15	1	1
10.5 - 11.0	2	11	0	2	0	11	1	3
11.0 - 11.5	2	15	1	7	0	14	0	3
11.5 - 12.0	0	7	0	2	0	13	0	5
12.0 - ++	2	555	1	155	0	414	1	107

APPENDIX D The Raff Method

Southbound Through Versus Northbound Only

APPENDIX D, con't. The Raff Method

Southbound Through Versus Eastbound Right and Northbound Left

APPENDIX E The Acceptance Curve Method

APPENDIX F The Logit Method

for Southbound Versus Northbound Only Traffic

EQ1 :WY = Y-Intercept*sum(W) + Slope*sum(WX)

EQ2 : WXY = Y-Intercept*sum(WX) + Slope*sum(WX^2)

Lag with Northbound Through (Southbound vs. Northbound Only Traffic)

X	Through LAG Reject	Through LAG Accept	N	P	P/(1-P)	Y	W
0.75	121	84	205	0.41	0.69	-0.36	49.58
2.25	94	95	189	0.50	1.01	0.01	47.25
3.75	19	93	112	0.83	4.89	1.59	15.78
5.25	12	98	110	0.89	8.17	2.10	10.69
6.75	1	82	83	0.99	82.00	4.41	0.99

Y = LN(P/1-P)   W = N*P(1-P)

	WY	W	WX		WXY	WX	WX^2
	-18.10	49.58	37.19		-13.57	37.19	27.89
	0.50	47.25	106.31		1.12	106.31	239.20
	25.06	15.78	59.16		93.96	59.16	221.86
	22.45	10.69	56.13		117.87	56.13	294.67
	4.35	0.99	6.67		29.39	6.67	45.01
EQ1	34.27	124.28	265.45	EQ2	228.77	265.45	828.63

Factor = -(sum(WX)/sum(W)) = -2.14

EQ1*Factor	-73.19	-265.45	-566.97
EQ1+EQ2	155.58	0.00	261.66

Slope = 0.59   Y-Intercept = -0.99   Critical Through Lag = 2.51

Gap with Northbound Through (Southbound vs. Northbound Only Traffic)

X	Through GAP Reject	Through GAP Accept	N	P	P/(1-P)	Y	W
0.75	33	8	41	0.20	0.24	-1.42	6.44
2.25	97	63	160	0.39	0.65	-0.43	38.19
3.75	33	45	78	0.58	1.36	0.31	19.04
5.25	3	31	34	0.91	10.33	2.34	2.74
6.75	1	24	25	0.96	24.00	3.18	0.96

Y = LN(P/1-P)   W = N*P(1-P)

	WY	W	WX		WXY	WX	WX^2
	-9.12	6.44	4.83		-6.84	4.83	3.62
	-16.48	38.19	85.94		-37.09	85.94	193.36
	5.90	19.04	71.39		22.14	71.39	267.73
	6.39	2.74	14.36		33.54	14.36	75.39
	3.05	0.96	6.48		20.59	6.48	43.74
EQ1	-10.26	67.37	183.00	EQ2	32.34	183.00	583.84

Factor = -(sum(WX)/sum(W)) = -2.72

EQ1*Factor	27.88	-183.00	-497.11
EQ1+EQ2	60.23	0.00	86.72

Slope = 0.69   Y-Intercept = -2.04   Critical Through Gap = 3.66

Lag with Northbound Left-turn (Southbound vs. Northbound Only Traffic)

X	Left LAG Reject	Left LAG Accept	N	P	P/(1-P)	Y	W
0.75	19	2	21	0.10	0.11	-2.25	1.81
2.25	22	3	25	0.12	0.14	-1.99	2.64
3.75	14	8	22	0.36	0.57	-0.56	5.09
5.25	8	12	20	0.60	1.50	0.41	4.80

Y = LN(P/1-P)
W = N*P(1-P)

	WY	W	WX		WXY	WX	WX^2
	-4.07	1.81	1.36		-3.06	1.36	1.02
	-5.26	2.64	5.94		-11.84	5.94	13.37
	-2.85	5.09	19.09		-10.68	19.09	71.59
	1.95	4.80	25.20		10.22	25.20	132.30
EQ1	-10.24	14.34	51.59	EQ2	-15.36	51.59	218.27

Factor = -(sum(WX)/sum(W)) = -3.60

EQ1*Factor	36.82	-51.59	-185.58
EQ1+EQ2	21.47	0.00	32.69

Slope = 0.66   Y-Intercept = -3.08   Critical Left Lag = 5.45

Gap with Northbound Left-turn (Southbound vs. Northbound Only Traffic)

X	Left GAP Reject	Left GAP Accept	N	P	P/(1-P)	Y	W
2.25	26	1	27	0.04	0.04	-3.26	0.96
3.75	10	1	11	0.09	0.10	-2.30	0.91
5.25	5	1	6	0.17	0.20	-1.61	0.83

Y = LN(P/1-P)   W = N*P(1-P)

	WY	W	WX		WXY	WX	WX^2
	-3.14	0.96	2.17		-7.06	2.17	4.88
	-2.09	0.91	3.41		-7.85	3.41	12.78
	-1.34	0.83	4.38		-7.04	4.38	22.97
EQ1	-6.57	2.71	9.95	EQ2	-21.95	9.95	40.63

Factor = -(sum(WX)/sum(W)) = -3.68

EQ1*Factor	24.17	-9.95	-36.60
EQ1+EQ2	2.22	0.00	4.03

Slope = 0.55   Y-Intercept = -4.46   Critical Left Gap = 8.99

APPENDIX F, con't. The Logit Method
for Southbound Versus Eastbound Right and Northbound Left

EQ1 :WY = Y-Intercept*sum(W) + Slope*sum(WX)

EQ2 : WXY = Y-Intercept*sum(WX) + Slope*sum(WX^2)

Lag with Eastbound Right-turn (SB vs. EB right + NB Left Traffic)

X	Right LAG Reject	Right LAG Accept	N	P	P/(1-P)	Y	W
1.5	85	11	96	0.11	0.13	-2.04	9.74
4.5	92	25	117	0.21	0.27	-1.30	19.66
7.5	35	77	112	0.69	2.20	0.79	24.06
10.5	5	84	89	0.94	16.80	2.82	4.72
13.5	2	555	557	1.00	277.50	5.63	1.99

Y = LN(P/1-P)   W = N*P(1-P)

	WY	W	WX		WXY	WX	WX^2
	-19.92	9.74	14.61		-29.87	14.61	21.91
	-25.61	19.66	88.46		-115.26	88.46	398.08
	18.97	24.06	180.47		142.29	180.47	1353.52
	13.31	4.72	49.55		139.80	49.55	520.28
	11.21	1.99	26.90		151.35	26.90	363.19
EQ1	-2.03	60.17	359.99	EQ2	288.31	359.99	2656.98

Factor = -(sum(WX)/sum(W)) = -5.98

EQ1*Factor   12.15   -359.99   -2153.74

EQ1+EQ2   300.46   0.00   503.24

Slope = 0.60   Y-Intercept = -3.61   Critical EB Right Lag = 6.88

Gap with Eastbound Right-turn (SB vs. EB right + NB Left Traffic)

X	Right GAP Reject	Right GAP Accept	N	P	P/(1-P)	Y	W
1.5	80	5	85	0.06	0.06	-2.77	4.71
4.5	46	9	55	0.16	0.20	-1.63	7.53
7.5	17	13	30	0.43	0.76	-0.27	7.37
10.5	5	24	29	0.83	4.80	1.57	4.14
13.5	1	155	156	0.99	155.00	5.04	0.99

Y = LN(P/1-P)   W = N*P(1-P)

	WY	W	WX		WXY	WX	WX^2
	-13.05	4.71	7.06		-19.57	7.06	10.59
	-12.28	7.53	33.87		-55.26	33.87	152.43
	-1.98	7.37	55.25		-14.82	55.25	414.38
	6.49	4.14	43.45		68.15	43.45	456.21
	5.01	0.99	13.41		67.65	13.41	181.08
EQ1	-15.80	24.73	153.04	EQ2	46.15	153.04	1214.68

Factor = -(sum(WX)/sum(W)) = -6.19			
EQ1*Factor	97.79	-153.04	-947.07
EQ1+EQ2	143.94	0.00	267.61
Slope = 0.54	Y-Intercept = -3.97		Critical EB Right Gap = 8.31

Lag with Northbound Left-turn (SB vs. EB Right + NB Left Traffic)

X	Left LAG Reject	Left LAG Accept	N	P	P/1-P	Y	W
1.5	85	7	92	0.08	0.08	-2.50	6.47
4.5	54	36	90	0.40	0.67	-0.41	21.60
7.5	12	70	82	0.85	5.83	1.76	10.24
10.5	4	76	80	0.95	19.00	2.94	3.80

Y = LN(P/1-P) W = N*P(1-P)

	WY	W	WX		WXY	WX	WX^2
	-16.15	6.47	9.70		-24.22	9.70	14.55
	-8.76	21.60	97.20		-39.41	97.20	437.40
	18.07	10.24	76.83		135.50	76.83	576.22
	11.19	3.80	39.90		117.48	39.90	418.95
EQ1	4.35	42.11	223.63	EQ2	189.35	223.63	1447.12

Factor = -(sum(WX)/sum(W)) = -5.31			
EQ1*Factor	-23.10	-223.63	-1187.58
EQ1+EQ2	166.25	0.00	259.54
Slope = 0.64	Y-Intercept = -3.30		Critical NB Left Lag = 5.93

Gap with Northbound Left-turn (SB vs. EB right + NB Left Traffic)

X	Left GAP Reject	Left GAP Accept	N	P	P/1-P	Y	W
1.5	45	2	47	0.04	0.04	-3.1	1.91
4.5	31	10	41	0.24	0.32	-1.13	7.56
7.5	4	23	27	0.85	5.75	1.75	3.41
10.5	3	23	26	0.88	7.67	2.04	2.65
13.5	1	107	108	0.99	107.00	4.67	0.99

Y = LN(P/1-P) W = N*P(1-P)

WY	W	WX	WXY	WX	WX^2
-5.96	1.91	2.87	-8.94	2.87	4.31
-8.55	7.56	34.02	-38.50	34.02	153.11
5.96	3.41	25.56	44.70	25.56	191.67
5.41	2.65	27.87	56.76	27.87	292.59
4.63	0.99	13.38	62.50	13.38	180.56

EQ1	1.48	16.53	103.69	EQ2	116.52	103.69	822.23

Factor = -(sum(WX)/sum(W)) = -6.27

EQ1*Factor	-9.28	-103.69	-650.55
EQ1+EQ2	107.24	0.00	171.69

Slope = 0.62 Y-Intercept = -3.83 Critical NB Left Gap = 6.93