Gap Acceptance Studies and Critical Gap Times for Two-Way Stop Controlled Intersections in the Mayagüez Area

by

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A project submitted in partial fulfillment of the requirements for the degree of

MASTERS OF ENGINEERING
in
CIVIL ENGINEERING

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
2006

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Abstract

Traffic analyses of priority intersections in Puerto Rico are currently performed using parameters obtained from the Highway Capacity Manual (HCM). These values were obtained from studies performed in other environments that not necessarily represent traffic conditions in Puerto Rico. The main purpose of this study was to determine critical gap times for left turns from the minor road, right turns from the minor road and left turns from the major road on two-way stop controlled intersections in the Mayagüez area. During the study period, it was observed that drivers, especially in right turn maneuvers in the minor stream, did not come to a complete stop before entering the intersection. If the lag was large enough for acceptance, then drivers continued without stopping. For left turns from the minor road, the study determined that the majority of drivers (55.5%) will accept gaps in the range of 5 seconds or greater. For this maneuver the critical gap obtained is 5.1 seconds. The gap acceptance study for right turn maneuvers from the minor road determined a critical gap of 4.7 seconds. In addition, the critical gap for left turns from the major road was determined to be 3.95 seconds. Critical gaps from the HCM were compared to those obtained from field studies. It can be clearly seen that Puerto Rican drivers in the Mayagüez area accept gaps that are smaller than those presented in other regions.

Resumen

Los análisis de tráfico en Puerto Rico utilizan tiempos de brecha crítica obtenidos directamente del Manual de Capacidad de Carreteras (HCM por sus siglas en inglés). Estos valores fueron obtenidos de estudios desarrollados en condiciones que no necesariamente representan las de Puerto Rico. El propósito principal de este estudio es determinar tiempos de brecha crítica para virajes a la izquierda y derecha desde la vía secundaria y virajes a la izquierda desde la vía primaria en intersecciones controladas por PARE en el área de Mayagüez. Durante el periodo de estudio se observó que los vehículos en la vía secundaria que hacen maniobras de viraje a la derecha, no se detienen completamente antes de entrar a la intersección. Si la brecha es lo suficientemente grande, los conductores continúan sin detenerse. Para los virajes a izquierda desde la vía secundaria, el estudio determinó que la mayoría (55.5%) de los conductores que realizan esta maniobra, aceptarán brechas mayores a 5 segundos. Para esta maniobra la brecha crítica que se obtuvo es de 5.1 segundos. El estudio de aceptación de brecha para virajes a la derecha desde la vía secundaria determinó que la brecha crítica es de 4.7 segundos. Además, la brecha crítica para virajes a la izquierda desde la vía principal resultó ser 3.95 segundos. Las brechas críticas del HCM se compararon con las obtenidas en los estudios de campo. Se pudo observar que los conductores puertorriqueños en el área de Mayagüez aceptan brechas que son menores a las aceptadas por conductores en otras regiones.

To my loving family:

The persons who love me and support me unconditionally; Jorge A. Rivera Román, Rosaura Rodríguez Cuevas and Joari R. Rivera Rodríguez.

"Do not be overcome by evil, but overcome evil with good."

Romans 12:21

"...Everything is possible to the one who believes."

Mark 9:23

Acknowledgments

During my graduate studies in the University of Puerto Rico at Mayagüez several persons collaborated with my research. I wish to dedicate this section to recognize their support.

First I would like to thank God for giving me the health and strength needed to go on day by day. Also my parents Jorge A. Rivera (papi) and Rosaura Rodríguez (mami) and my sister Joari R. Rivera (Jo), for their prayers, unconditional love and support. They have always been there to help me when I needed it most, and always given me good advice. Also to my friends, they always make me see the sunnier side of things and bring laughter to the workplace.

Special thanks to all the students and administrative personnel working at the Transportation Technology Transfer Center (T2) for helping me throughout the project. To Dr. Benjamín Colucci Ríos, a professor that is always willing to lend a helping hand when one needs it even though he is not part of the graduate committee. In addition the University Transportation Research Center supported me with the 2005-2006 fellowship.

Last but not least, to Dr. Didier Valdés Díaz, president of the graduate committee, Dr. Felipe Luyanda Villafañe and Dr. Sergio González Quevedo for their help and guidance on the development of this project.

Table of Contents

List of Tables

List of Figures

1 Introduction

1.1 Problem Statement

Traffic analyses in Puerto Rico are currently performed using parameters obtained directly from the Highway Capacity Manual (HCM). These values are developed from studies performed in other environments that not necessarily represent traffic conditions in Puerto Rico and from experience doing traffic analysis in the field.

In this study, gap acceptance parameters are determined for Two-Way Stop Controlled Intersections (TWSC), for two cases in urban areas of Mayagüez. The results obtained can be applied to traffic models to achieve more realistic simulations. The main purpose of the study is to determine if driver behavior in the Mayagüez area results in gap acceptance parameters similar to those obtained in other parts of the United States. The Gap Acceptance study will determine if critical gap times used in the Highway Capacity Manual can be applied to traffic modeling of intersections in Mayagüez, Puerto Rico.

1.2 Project Objectives

The main objective of the study is to determine if driver behavior regarding gap acceptance in the Mayagüez area is similar to other environments that have been used in the past to determine gap acceptance parameters. The Gap Acceptance study will determine if critical gap times given in the Highway Capacity Manual should be used or not for traffic modeling in Mayagüez, Puerto Rico.

The specific objectives of this project are:

1. Study methodologies describing gap acceptance models.
2. Learn the methodology used to perform gap acceptance studies in priority intersections.
3. Select intersections suitable for gap acceptance studies.
4. Develop a gap acceptance study for the chosen Two-way Stop Controlled intersections.
5. Determine the critical gap for Puerto Ricans driving in the selected intersections.
6. Compare critical gap results with those established in the HCM and in the aaSidra modeling Program.

1.3 Scope of Work

This research project considers gap acceptance parameters in urban areas for Two-way Stop Controlled intersections in the Mayagüez area. Two types of TWSC intersections were used, the first one is a T-intersection in an urban area of Mayagüez and the second one is a Four-leg intersection in the urban area of Añasco. The criteria used to choose the intersections are described in chapter 3 section3.5. Both intersections have two lanes (one per direction) and are undivided. Also both intersections do not comply with intersection departure sight triangles according to the methodology described in chapter 9 of A Policy on Geometric Design of Highways and Streets from the American Association of State Highway and Transportation Officials (AASHTO). There are no traffic lights near the primary access that could cause platoons. The critical gap times obtained from the study apply only to passenger cars.

1.4 Organization

The document is organized in 7 chapters. Each chapter contains information regarding gap acceptance studies and its application to Puerto Rico, specifically the Mayagüez area. The literature review of variables, various parameters and models in gap acceptance studies are included in Chapter 2. Chapter 3 illustrates a flowchart of the methodology and a detailed description of all steps followed in the research. In Chapter 4 a description of the data reduction and analysis is presented as well as the criteria for selecting accepted gap times. Chapter 5 presents critical gap values for each maneuver and a comparison between field critical gaps and HCM critical gaps including a percent of difference of both values. In Chapter 6 two models with aaSidra representing a TWSC intersection in the city of Mayagüez are described, the models were developed using HCM critical gaps and field critical gaps for a queue comparison. Conclusions and recommendations regarding gap acceptance studies in Puerto Rico are presented in Chapter 7.

2 Literature Review

This section describes various parameters and variables used to determine gap acceptance capacity models. Definitions are based on those found in the Transportation Research Board's Highway Capacity Manual (HCM) of 2000. In addition, this section presents the methodology used to determine intersection sight distance for stop controlled intersections and the main characteristics of a Two Way Stop Controlled Intersection. The two major parameters for gap acceptance models are critical gap and follow-up time. Capacity is greatly affected by these two parameters. Puerto Rico is currently applying to its traffic models values from the HCM. The HCM values are developed from studies in the United States of America, which not necessarily represent conditions in Puerto Rico.

2.1 Variables

Three elements define gap acceptance studies: gap sizes, how useful are the gaps available to vehicles in the minor stream, and stream priority at the intersection. Gap acceptance studies generally assume all drivers are consistent. When in reality this is not true, driver reaction time changes with age and conditions on the road. Some of the variables used in the study are defined in this section.

2.1.1 Gap

Gap is a measure of time between two consecutive vehicles moving in the same direction on the same road. The Highway Capacity Manual glossary defines gap as follows: "the time, in seconds, for the front bumper of the second of two successive vehicles to reach the starting point of the front bumper of the first" (TRB, 2000 Chapter 5 – Glossary, pp. 5-6). Figure 2-1 shows a diagram describing gap time.

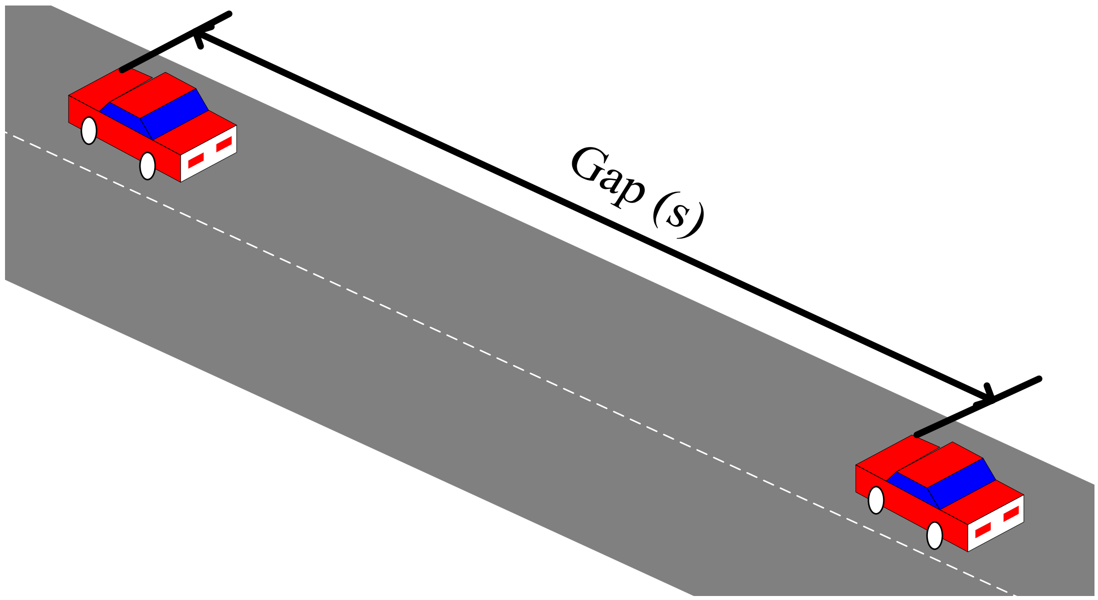

Figure 2-1 Gap Time Between Two Consecutive Vehicles.

This definition of gap has been used in the literature in several gap acceptance studies (May, 1990, pp 44-48). However it is important to note that this definition corresponds to the headway definition of microscopic variables used to represent the characteristics of a traffic stream. Appendix A presents those definitions as used in most of the text books of transportation engineering for the characterization of traffic streams. By using the relation between gap and headway defined in the appendix, they can be interchanged. According to Troutbeck and Werner (2001) gaps are measured in time and are equal to headways (TRB, 2001).

2.1.2 Lag

Differently from gap, this time measurement is between two vehicles on different roads. Lag is defined as the time it takes a vehicle in the major road to reach the front bumper of the vehicle in the minor road (see Figure 2-2).

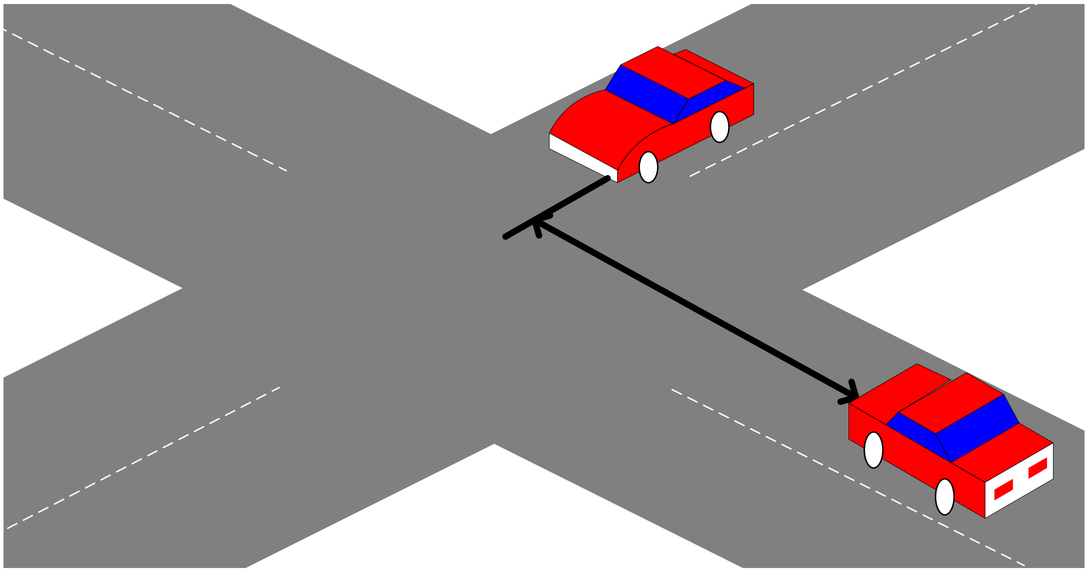

Figure 2-2 Lag Time Between Two Vehicles.

2.1.3 Critical Gap

Critical gap is the minimum time needed for a vehicle in the minor road to enter safely the major road stream. The critical gap is the median of the minimum accepted gaps. The median divides the data set into two parts of equal size. Another definition given by Raff and Hart (Salter, 1974) defines the critical gap as that gap of which the number of accepted gaps shorter than it is equal to the number of rejected gaps longer than it. Critical gaps are estimated by measuring gap acceptances and rejections of a minor road vehicle who wishes to cross or enter the major stream. Several models have been developed specifically to estimate the critical gap values at intersections.

2.1.4 Gap Acceptance

Gap acceptance is the process in which a vehicle in the secondary access accepts gaps available in the primary traffic stream.

2.1.5 Follow-up Time

This variable is defined as the time between the exit of a vehicle on the minor street and the exit of a second vehicle using the same gap. Follow-up time is measured only under continuous queue conditions.

2.2 Intersection Clear Sight Triangles

Intersection Clear Sight Triangles are areas in the intersection approaches and their corners that should be clear of obstructions that might block drivers view and cause a safety hazard in the intersection. Objects 3.5 ft (1,080mm) high are considered obstructions to drivers in passenger cars. The triangle dimensions are directly dependent on the design speed, traffic control and driver behavior. Two types of triangles are defined in the book A Policy on Geometric Design of Highways and Streets (AASHTO, 2001), approach sight triangle and departure sight triangle. Both figures are used depending on the intersection control. The decision point (for drivers in the minor street) presented in the figure symbolizes a point where any driver should start braking if a vehicle from the major road approaches to the intersection.

For approach sight distance Figure 2-3A is used. The geometry of the intersection should be in a way that both drivers, the minor and major road drivers, see each other before reaching the conflict zone. Approach sight triangles are not needed for STOP controlled intersections, although it is desirable to use it in high volume roads. The departure sight triangle shown in Figure 2-3B provides a stopped driver in the minor road sufficient sight distance to cross or enter the major stream. Departure Sight triangles are used in intersections with STOP or Yield control; its dimensions are based on driver behavior and their gap acceptances.

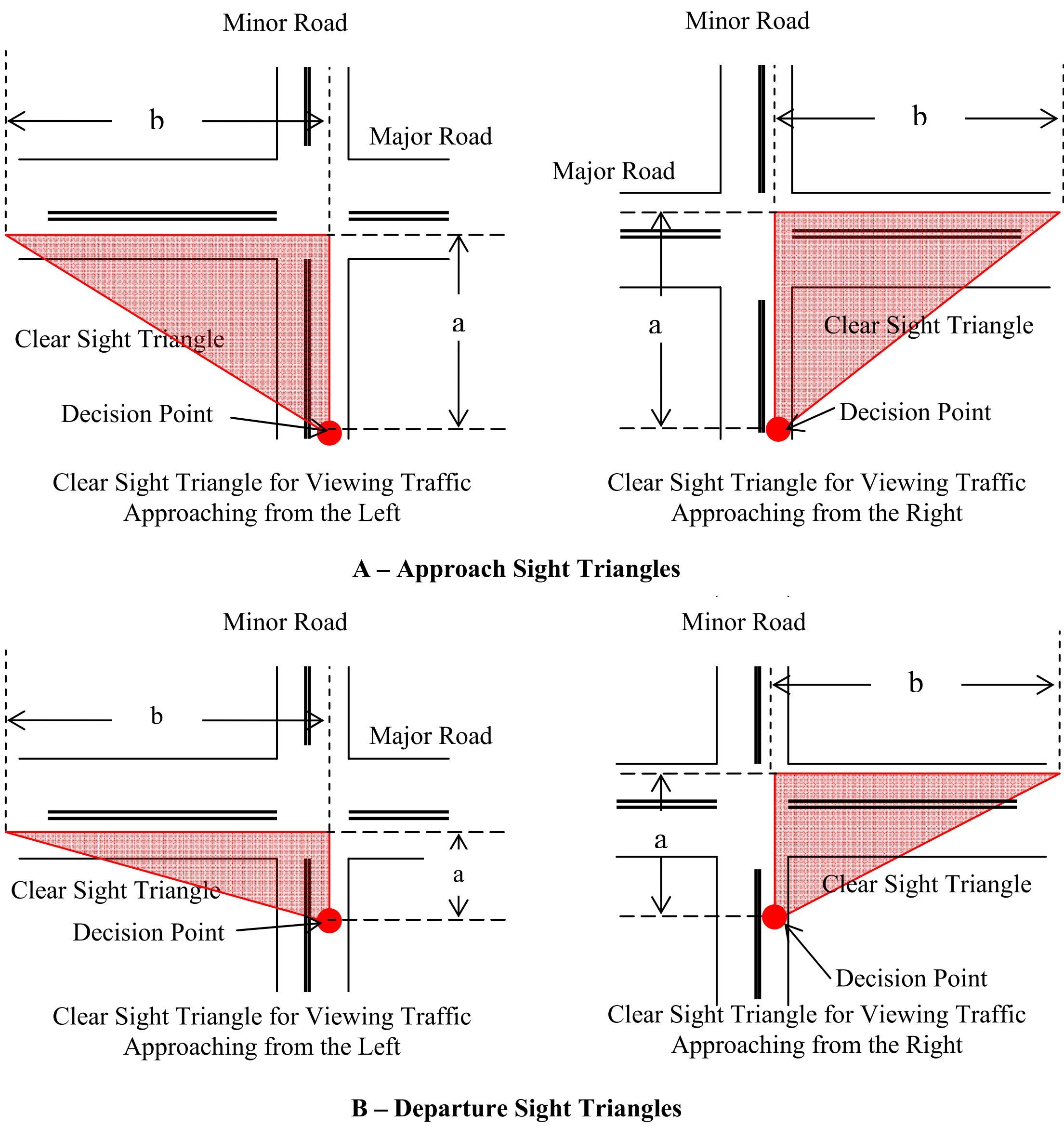

Figure 2-3 Intersection Sight Triangles Case (B).

Source: A Policy on Geometric Design of Highways and Streets 2001, AASHTO.

2.3 Intersection Control

Sight triangle dimensions are directly dependent on the type of control governing the intersection. The different cases are:

A. Intersection with no control

B. STOP control on the minor road

1. Left turn

2. Right turn
3. Crossing Maneuver

C. Yield Control on the minor road
1. Crossing Maneuver
2. Left turn or Right turn from the minor road

D. Traffic Signal Control

E. All Way Stop Control

F. Left turns from the major road

Even though the AASHTO's Greenbook, explains in detail all of theses cases, for the purpose of this project, the only case considered is the STOP control on the minor road (Case B), because all intersections studied have a STOP sign as traffic control.

2.3.1 Case B - STOP control on the minor road

The model for STOP control does not need Approach Sight Triangles to determine visibility. Case B is divided in three cases, left turn from the minor road, right turn from the minor road and crossing maneuver from the minor road. The intersection sight distance criteria from this type of intersection is larger than its stopping sight distance for it to operate more efficiently and vehicles entering from the minor road will not make vehicles, in the major stream, stop.

2.3.2 Case B1 – Left turn from the minor road

Left turn from the minor road use, departure triangles. This model requires a distance of 14.4ft (4.4m) from the major road to the decision point in the minor road. When practical, a distance of 17.8ft (5.4m) from the major road is recommended. By using this distance, the front bumper of the vehicle will be located 10ft (3m) from the major road, and a bigger sight triangle will be provided (AASHTO, 2001).

The distance along the minor road (distance "a" in Figure 2-3) for the departure sight triangle, is the sum between 14.4ft in the minor road, the total width of lanes crossed and one half (1/2) lane more.

The model assumes gaps presented in Table 2-1 provide sufficient time for a vehicle stopped in the minor road to enter the major road; also this gap can be used to determine the sight distance on the intersection and, finally, drivers reduce speed when a vehicle enters the intersection from the minor road. The equation used to determine Intersection Sight Distance is shown in the following figure.

Metric	US Customary
$ISD = 0.278\ V_{major}\, t_g$	$ISD = 1.47\ V_{major}\, t_g$ **(9-1)**
where: ISD = intersection sight distance (length of the leg of sight triangle along the major road) (m) V_{major} = design speed of major road (km/h) t_g = time gap for minor road vehicle to enter the major road (s)	where: ISD = intersection sight distance (length of the leg of sight triangle along the major road) (ft) V_{major} = design speed of major road (mph) t_g = time gap for minor road vehicle to enter the major road (s)

Figure 2-4 Intersection Sight Distance.

Source: A Policy on Geometric Design of Highways and Streets 2001 AASHTO.

The gap time used for the equation is given in Table 2-1. These values are adjusted depending on intersection geometry. If the leg of the intersection has an upgrade that exceeds 3% then; 0.2 seconds are added for each percent grade. There is also an adjustment in the gap if the number of lanes crossed is greater than one.

Table 2-1 Gap Times for Left Turn Maneuvers from a Stop.

AASHTO—Geometric Design of Highways and Streets

Design vehicle	Time gap (s) at design speed of major road (t_g)
Passenger car	7.5
Single-unit truck	9.5
Combination truck	11.5

Note: Time gaps are for a stopped vehicle to turn right or left onto a two-lane highway with no median and grades 3 percent or less. The table values require adjustment as follows:

For multilane highways:
For left turns onto two-way highways with more than two lanes, add 0.5 seconds for passenger cars or 0.7 seconds for trucks for each additional lane, from the left, in excess of one, to be crossed by the turning vehicle.

For minor road approach grades:
If the approach grade is an upgrade that exceeds 3 percent; add 0.2 seconds for each percent grade for left turns

Source: A Policy on Geometric Design of Highways and Streets 2001 AASHTO.

Gap times presented in Table 2-1 are for passenger cars on the minor road only. If the volume of the minor road has a high percentage of heavy vehicles, using gap acceptance times for this type of vehicles should be considered.

2.3.3 Case B2 – Right Turn from the minor road

This model is developed equally as Case B1. The only difference between the two models is the gap acceptance time for a driver in the minor road. Gap acceptance times are one (1s) second less than the gap needed for left turn maneuvers. This time is instead used in the ISD equation.

2.3.4 Case B3 – Crossing Maneuver from the Minor Road

Using intersection sight triangles for left turn and right turn maneuvers gives enough distance for vehicles crossing the main road. Sight distance for crossing maneuvers should be checked in the following cases: 1) if illegal right or left turns are seen in the intersection, 2) if the crossing distance is bigger than six lanes, 3) if there is a high percentage of heavy vehicles and steep grades are present in the intersection. The model uses the same ISD equation as case B1, but gap times are from case B2.

2.4 Intersection Classification

The Highway Capacity Manual (HCM) defines three types of unsignalized intersections: Two-way stop controlled (TWSC), All-way stop controlled (AWSC), and roundabouts.

2.4.1 Two Way Stop Controlled intersections

Two Way Stop Controlled (TWSC) intersections are characterized by the presence of STOP signs to control vehicle movements. The Stop controlled access is designated the secondary access, while the uncontrolled access is the primary. Three legged intersections (Type T) are considered TWSC if the secondary access, (typically the stem of the T) is controlled by a stop sign. Some variables, such as gaps, are specific to flows with interruptions, in this type of intersection, drivers in the minor road have to stop and accept gaps available on the major road. The intersection capacity depends upon gap distribution on the major road and the gap required by the driver on the minor road to enter the intersection. Gap availability in the major stream depends on the arrival of vehicles to the intersection, the street volume, traffic distribution, and number of lanes. Similar to the intersection geometry and characteristics, driver behavior also determines the gap time needed to enter the intersection. Some factors also affecting gap acceptance are age, reaction time, driver aggressiveness, eyesight and weather conditions, among others.

2.5 Intersection Priority

On priority intersections, some maneuvers have absolute priority, while others must allow higher ranking maneuvers to enter the intersection first. The HCM groups maneuvers in four different ranks, being one (1) the highest priority, and four (4) the lowest priority. All ranks are presented in Figure 2-5. Rank 1 is for those vehicles doing right and crossing maneuvers from the major road. Rank 2 maneuvers are left turns from the major road and right turns from the minor road. Rank 3 groups crossing maneuvers from the minor road for a four-leg Intersection and left turn from the minor road for a T-intersection. Rank 4 only occurs in left turn maneuvers from the minor road in four-leg intersections.

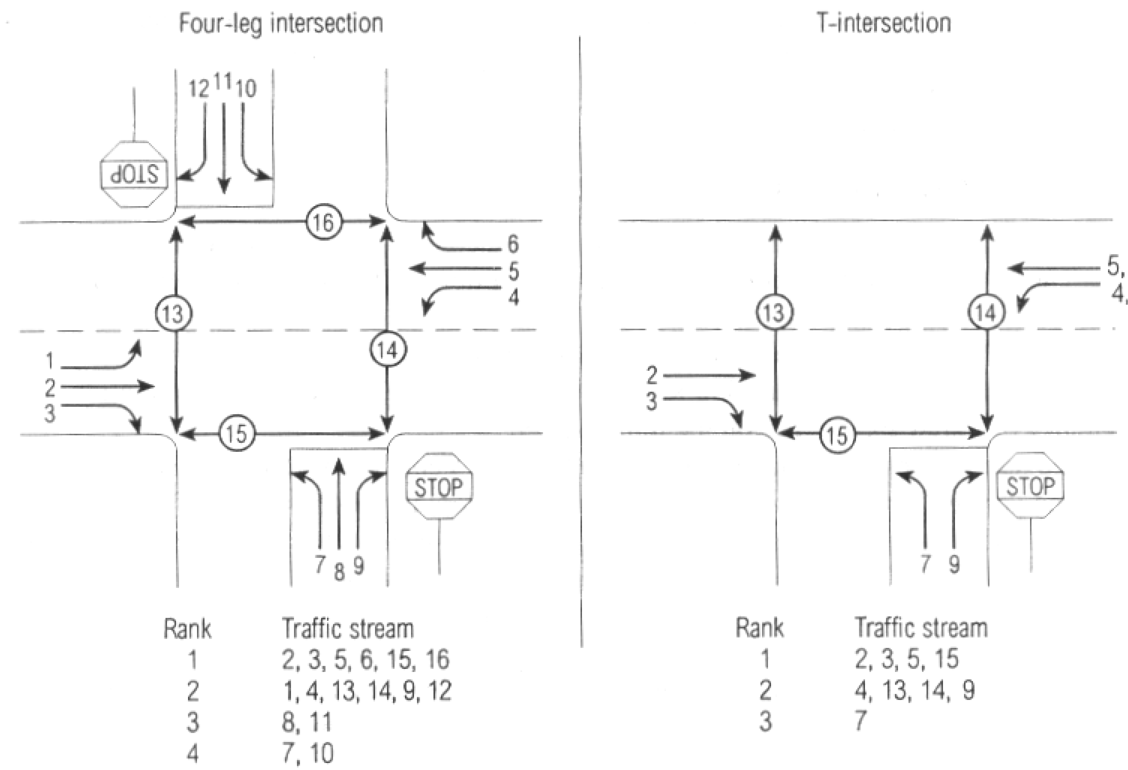

Figure 2-5 Intersection Priority Diagrams for a TWSC.
Source: TRB (2000). Highway Capacity Manual

2.6 Gap acceptance Models

Drivers on the minor road of a TWSC intersection do not have control over when it is safe to enter the intersection. The driver must determine his turn to enter depending on the intersection priority, and which gap is safe enough to make the maneuver. This decision is known as gap acceptance theory. Gap availability depends on generated gaps, vehicle arrival and the capacity of drivers to accept gaps. Gap acceptance is related to driver characteristics such as age, gender, and aggressiveness. Gap models assume that drivers on the major road are not affected by drivers on the minor road.

2.7 Critical Gap and Follow-up Time

Critical gap (t_g) is the minimum time, in seconds, needed for a vehicle in the minor road to enter safely the major road stream. All gaps less than the critical gap will be rejected by drivers. It is estimated by measuring gap acceptances and rejections of a minor road vehicle who wishes to cross or enter the major stream. Follow-up Time (t_f**)** is defined as the time between the exit of a vehicle on the minor street and the exit of a second vehicle using the same gap. Follow-up time is measured only under continuous queue conditions. Typical times for the United States are presented in Table 2-2.

Vehicle Movement	Base Critical Gap, $t_{c,base}$ (s)		Base Follow-up Time, $t_{f,base}$ (s)
	Two-Lane Major Street	Four-Lane Major Street	
Left turn from major	4.1	4.1	2.2
Right turn from minor	6.2	6.9	3.3
Through traffic on minor	6.5	6.5	4.0
Left turn from minor	7.1	7.5	3.5

Table 2-2 Base Critical Gaps for Stop Controlled Intersections.
Source: TRB (2000). Highway Capacity Manual

Critical Gap and Follow-up times presented in Table 2-2 should be adjusted for intersection characteristics and heavy vehicle volume when present.

Measurements conducted in Germany (Gattis and Low, 1998) to estimate follow-up time assumed that there is a fixed dependency of *tf* and *tg* according to the following equation.

$$t_f = 0.6\ t_g \qquad \text{Equation 2-1}$$

2.8 Maximum Accepted Gap Size

Studies about gap acceptance behavior done by Kittleson and Vandehey in 1991 noted that most drivers will accept 12 second gaps (Pollatschek, Polus, Livneh, 2002), so larger gaps do not represent how drivers will react to lesser gaps. It is logical to use only gap times that are less or equal to 12 seconds. The inclusion of big gap times makes the critical gap to be larger than it really is.

2.9 Impedance Effect

Gap acceptance in TWSC is in a prioritized manner. According to the HCM, the impedance effect occurs mostly during congested conditions when vehicles from minor road movements force their gaps through the intersection. This means that one traffic stream impedes the smooth movement of other traffic streams. Typically this impedance effect causes delays on maneuvers that have priority at the intersection, which is not the expected (normal) condition. Therefore, it is not advisable to perform gap acceptance studies during this period. Minor road drivers are not accepting gaps but forcing them.

3 Methodology

3.1 Introduction

The methodology presented in this chapter describes the research development and data collection for the selected intersections in Mayagüez and Añasco. The developed methodology is outlined in a flowchart to better understand all steps taken. Initially a literature review of theories and publications related to gap acceptance and critical gap studies was conducted. Then an assessment of intersections around the city of Mayagüez and Añasco was done by site visit evaluations. Suitable intersections were selected based on intersection geometry and traffic volume. Then, field data was gathered in both intersections using a video camera and a stop watch for the critical gap study. Results were compared using aaSidra® and analyzed to obtained conclusion and recommendations.

3.2 Description

The methodology followed in this study is presented in the flow diagram below and described in the next sections.

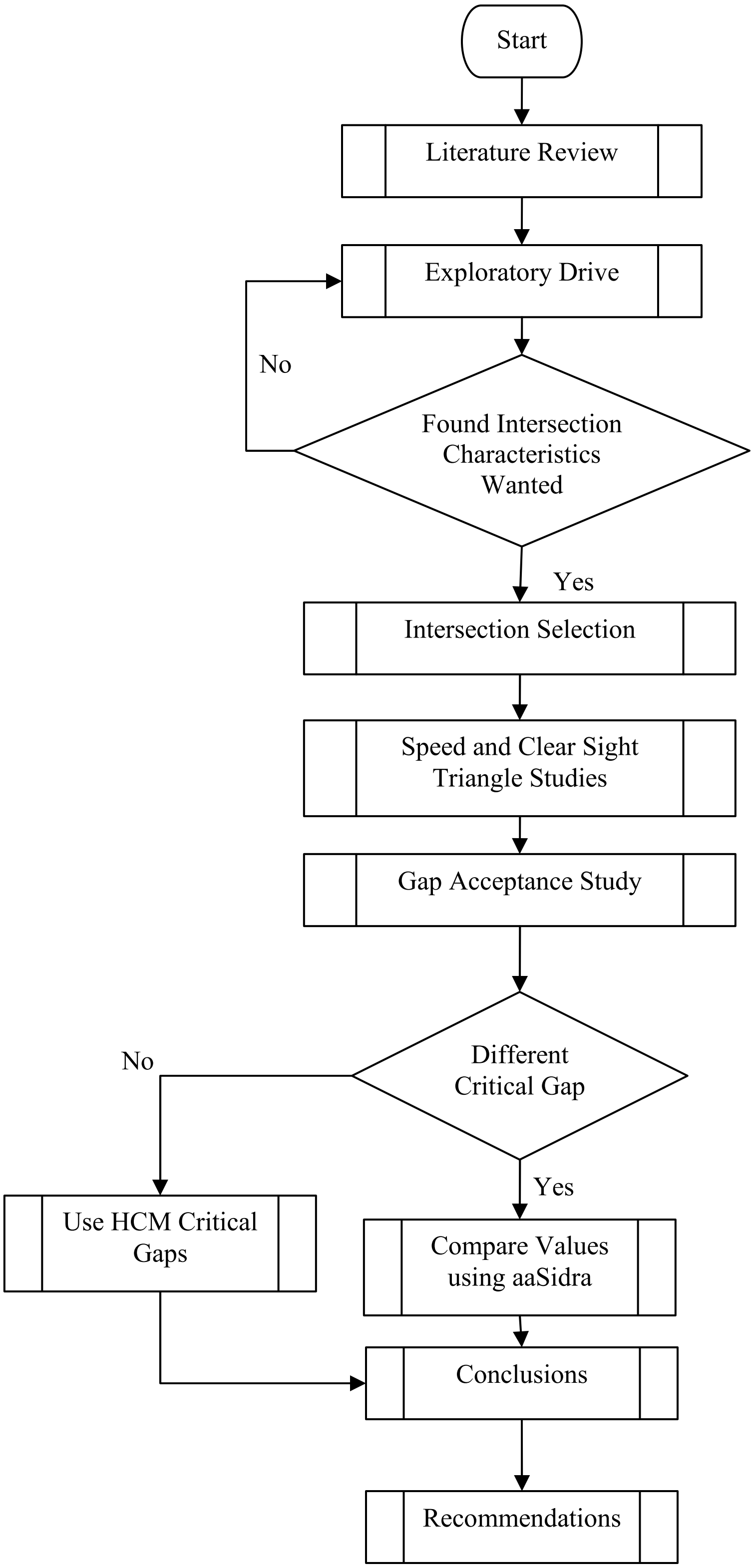

Figure 3-1 Flow Diagram for the Project's Methodology.

3.3 Literature Review

The first step taken for the development of this research project was researching publications about gap acceptance and critical gap studies. The internet, the library's electronic resource databases, books, manuals and magazine publications were used to find the information. The reviewed material consisted of various theories, definitions and methodologies for gap acceptance studies, also different critical gap models and their precision were identified. The most important findings from the review are discussed in chapter 2.

3.4 Exploratory Drive

To select intersections for the field study, it was necessary to perform exploratory drive through the area of study and identify intersections. A drive was done across the urban areas in the cities of Mayagüez and Añasco, looking for intersections that qualified different criteria or had certain characteristics, both operational and geometrical. The criteria used are presented below.

3.5 Intersection Selection

A really important step was to select the proper intersections for further field studies. Not all priority intersections have the same operation; it depends on the type of control and site characteristics. According to the criteria established, the characteristics of the selected intersections are presented in detail in this section. Both intersections are TWSC (two way stop control), one a T-type and the other a Four-leg intersection. The criteria used to select the intersections for this study are presented in Table 3-1

Table 3-1 Intersection Criteria.

Intersection control	TWSC
Major Street Volume	>400 vph
Minor Street Volume	> 100 vph
Number of lanes per direction	1
Zone	urban
Adjacent intersection Control	uncontrolled
Structure near the intersection	Yes
Lane divisions	Undivided
Access Grade	Flat
Speed	25 mph

Another characteristic necessary to obtain good field data was the availability of proper space to locate the video camera, preferably a structure. The camera has to be in an inconspicuous place to not affect driver behavior and high enough to see all movements simultaneously. Both intersections selected have a building close by, but the clear sight triangles for both intersections are not affected by the structure. The proximity of traffic signals was also taken into consideration; there are no traffic signals near the intersection primary access. Traffic signals cause platoons in the major traffic stream, therefore cars do not arrive randomly thus affecting gap generation.

Volume at the intersection is an important factor in the determination of gap acceptance; flows at the intersection should exceed 100veh/hr in the minor stream, and 400veh/hr in the major traffic stream (Salter, 1974). Geometrical characteristics such as one lane per direction, flat access grades and undivided lanes were also variables taken into consideration when selecting the study sites. Clear sight triangles use different variables to determine sight distances needed for drivers to enter the intersection safely. In order to simplify the work and not affect behavior, intersections selected have one lane per direction, flat grades and undivided lanes.

A few intersections in Mayagüez were identified that satisfy most of the characteristics mentioned above, but not all of them. The Four-leg intersection identified in Mayagüez had yield control signs and divided lanes. Therefore it does not comply with the desired intersection criteria. Because of this, it was necessary to move to Añasco, a city located about 9 miles to the north from the city of Mayagüez. There a Four-leg intersection with the desired characteristics was identified.

3.6 Gap Acceptance Study

Gap acceptance studies are used to determine the critical gap. Critical gaps are then used to evaluate level of service and capacity at priority intersections. This study measures gaps in the major stream and driver behavior on the minor road. Different types of drivers will accept different gaps, more aggressive drivers will accept smaller gaps and conservative drivers accept larger gaps.

3.7 Video and data collection

To determine gap acceptance times at an intersection, a field study must be performed. In this project a video camera was used to record maneuvers in the intersection, while recording, an observer had to indicate the arrival time and departure time of a vehicle to the intersection. The observer said “Major” each time a vehicle approached from the major road and reached the reference point selected. He said “Minor” when a vehicle in the secondary road stopped at the intersection. Also it is important to indicate in the video if a vehicle stopped in the intersection has accepted or rejected a gap. If a vehicle is not present, the gap is classified as untested. By using a stopwatch the times are recorded in the video. All data collection must be done in an inconspicuous manner to avoid any influence in driver behavior. Drivers get distracted when there are people doing any kind of work on the side of the roadway, thus adding another variable to the equation.

3.8 Raff Method

The method used to determine critical gap is similar to the one developed by Raff. Raff uses accepted and rejected lags only (Salter, 1974). Both gaps and lags where used to determine the critical gap. A lag was considered as the unaccepted gap if; only the lag was unaccepted, or gaps following the lag were not larger. To develop a gap acceptance graph, all accepted gaps chosen are sorted in ascending order and grouped in different classes. In other words, gap times from cero (0) to .99 seconds are one group, another from one (1.0) to 1.99 seconds, until 12 seconds are reached. The number of observations in each group is counted and written down on a table as number of observed acceptances. Finally all data is accumulated to create the graph for Total Accepted Gaps. The same process is done for rejected gaps, but the number of rejected observations is not accumulated; they are subtracted from the total number of observations until cero (0) is reached. The data obtained for the three maneuver's critical gap and tables for number of acceptances, number of rejections and accumulated gaps. Movement critical gaps are obtained from the graphical accumulated gap. This is explained in more detail in Chapter 4.

3.9 Use of MICROSOFT EXCEL®

Microsoft Excel® was the primary program used to reduce the field data and calculate gap acceptance or gap rejection times. A simple programming in Excel® was done to input arrival times and calculate gaps. By using a stopwatch during the recording, the arrival time of every vehicle can be easily noted on Excel. Everything is noted, the observer's commentary, the major vehicle arrival time and the minor vehicle arrival time. The input data sheet was also developed to write down if the minor vehicle accepted or rejected the gap and the arrival time for each car (major or minor). A much simpler table is created with only the accepted gap and rejected gap for each vehicle. The tables are presented and discussed in the section Gap determination using Microsoft Excel.

3.10 Akçelik's aaSidra

A model of both intersections was developed using Akçelik's aaSidra. This program is widely used for intersection analysis in Puerto Rico and accepted as an accurate model to represent field conditions at intersections. First, a model using HCM critical gap standard parameters were used. A second model was developed using critical gaps for left turn maneuvers from the minor road, right turn maneuvers from the minor road and left turn maneuvers from the major road calculated from field data. In the latter model, the critical gap for through maneuvers is considered to be the same as left turn maneuvers from the minor road. A comparison of queues from field observations and aaSidra outputs was conducted. The queue distance obtained from aaSidra's modeling was compared with the queue seen in the field during the study period.

3.11 Conclusions and Recommendations

A series of conclusions were drawn from data analysis and evaluation. The comparison between HCM critical gap times and those obtained in this study was established; reasons for possible differences are mentioned. Also recommendations regarding study procedures for future research are described.

4 Data Analysis

The analysis of the data obtained in this project, was performed by comparing the critical gap times calculated using field data with HCM standard critical gap times. Also a sensitivity analysis of critical gap times in aaSidra® was conducted.

4.1 Clear Sight Triangles

Clear Sight triangles were determined using the AASHTO methodology for Stop Controlled intersections. The study determined that both intersections (Añasco and Mayagüez) have obstructions inside the departure sight triangle for left turns such as those presented in Figure 4-1. These obstructions are, concrete utility post, chain link fences, and traffic signs. Because intersections were selected in urban areas, with no trees, proper care of green areas; grass and other natural obstruction did not have to be considered. In rural areas, objects like embankments, grass, and trees are common visibility problems and should also be considered in the analysis. Intersection sight triangle dimensions were calculated as described in the following section.

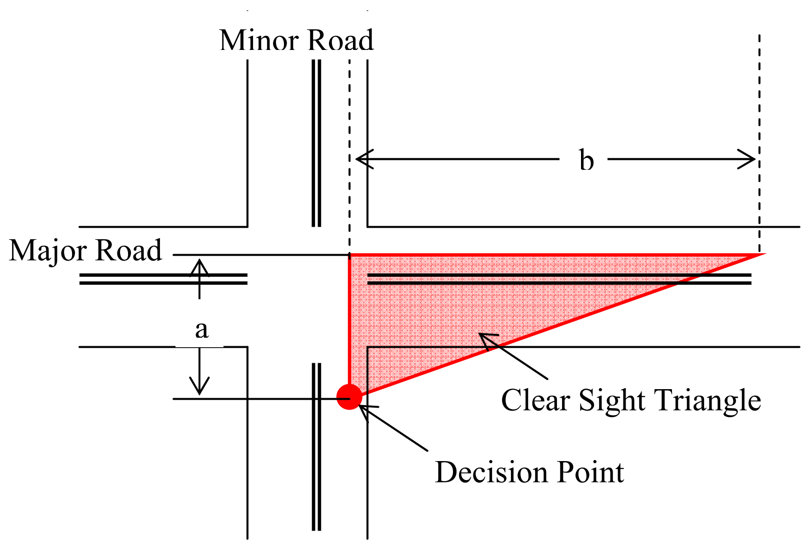

Figure 4-1 Departure Sight Triangle for Left Turns.

Traffic approaching from the right

4.2 Case B1-Left turn from the Minor Road

According to the AASHTO Greenbook (AASHTO, 2001), a passenger car turning left from the minor road in a two lane (one per direction), undivided highway, with flat grades has a critical gap of 7.5 seconds. Since the design speed for the major road is unknown, a speed study using a laser trap (radar) was performed to determine the major road's driving speed. The study found a mean driving speed of 25 mph; this speed was used to calculate intersection sight distance.

$$ISD = 1.47\,V_{major}\left(t_c\right) \qquad \text{Equation 4-1}$$

$$ISD = 1.47\,(25mph)(7.5s) \qquad \text{Equation 4-2}$$

$$ISD = 275.62\,ft \approx 276\,ft \qquad \text{Equation 4-3}$$

Distance along the major road is 276 ft from the point of conflict. The lane width was measured in the field, to calculate the distance along the minor road. The distance of 14.4ft from the major road required by the model and the lane width was used to determine the distance to the decision point along the minor road. Figure 4-2 presents the intersection sight triangles for left turns.

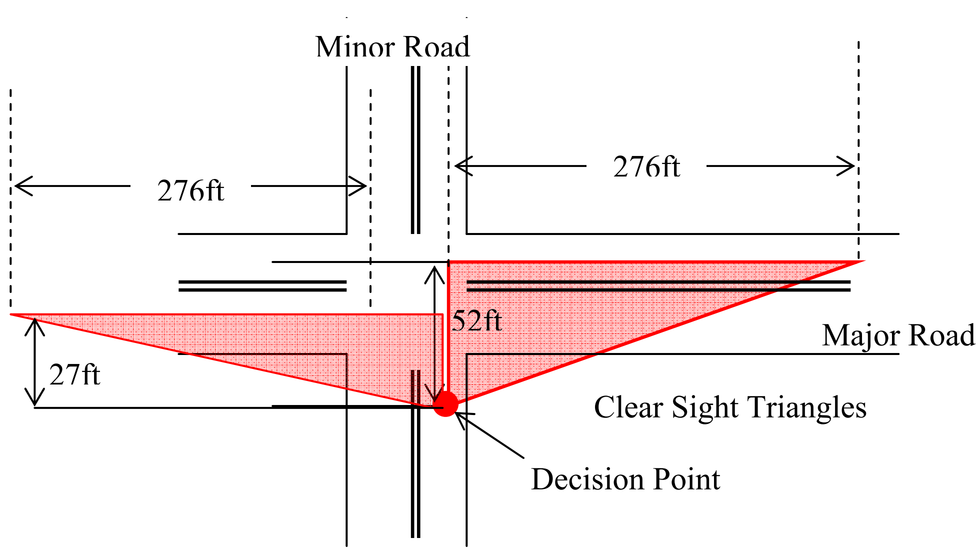

Figure 4-2 Intersection Sight Triangles for Left Turns from the Minor Road.

4.3 Case B2-Right turn from the Minor Road

According to the AASHTO's Greenbook, a passenger car turning right from the minor road with the same roadway conditions as the example above has a critical gap of 6.5 seconds (AASHTO, 2001). The calculated distance along the major road for a 25 mph running speed is 239 ft from the point of conflict. The lane width was measured in the field, to calculate the distance along the minor road. Since the intersection did not change, distances along the minor road stays he same. Figure 4-3 shows the sight triangles for right turns from the minor road.

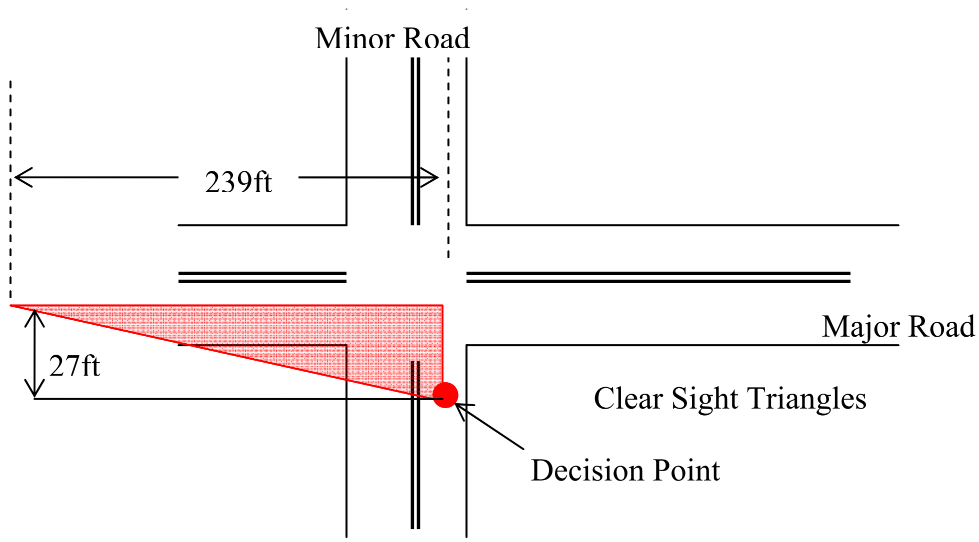

Figure 4-3 Intersection Sight Triangles for Right Turns from the Minor Road.

When both triangle cases were calculated and verified in the field, it was determined that both intersections, (Cross intersection and T-type intersection) had obstructions inside the triangle area.

When visibility problems are present, drivers entering the intersection do not stop at the specified stop line, instead they come closer to the major traffic stream. This makes it more difficult to determine the exact place vehicles stop and the gap it will accept. To reduce errors caused by driver variable stopping location, during the data analysis, vehicles conflict points were used to determine accepted or rejected gaps and lags.

4.4 Gap Determination using Microsoft Excel®

Microsoft Excel® was the primary program used to determine all gap acceptance or rejection times. A simple programming in Excel was done to input arrival times and calculate gaps. Every vehicle's recorded arrival time and the observer's commentary are noted in the data sheet. The input data sheet was developed to write down if the minor approach vehicle accepted, or rejected the gap, if there was a follow-up time and also the arrival time for each car (major and minor). The type of car was included in the table only as reference, but, if desired it can be used to determine critical gaps for other vehicle classes (i.e. heavy vehicles). Gap acceptance and critical gap studies for other vehicles different to passenger cars are out of the scope of the project.

The spreadsheet calculates gaps between every successive vehicle in the major road as the difference between the arrival of the second vehicle and the arrival of the first vehicle. Lags are the difference between the arrival of the vehicle in the minor road and the next vehicle arriving in the major road. Every gap is classified by the observer as not accepted ("not acc"), accepted ("acc") and untested. Lags area also classified depending on the drivers reaction.

From the observer's comments the spreadsheet classifies gaps as accepted or rejected. Lags are included manually. Table 4-1 shows a spreadsheet section with a simplified data example used to determine gap rejection and gap acceptance.

Table 4-1 Example of Data Reduction Sheet in the Gap Acceptance Study.

Gap Determination	Direction to WIPM				Calc. lag	Acc/ not acc	Accepted Gap	Unaccepted Gap
Car	Obs. Says	Arrival tmajor	Calc. Gap	Arrival t_{minor}				
Taxi	Major	0						
Explorer	Minor		3.93	0				
					3.93	not acc		3.93
Escort	Major	3.93						
	Not acc		11.97					11.97
Rav 4	Major	15.9						
	Not acc		3.27					3.27
Accent	Major	19.17						
	Not acc		5.78					5.78
Rav 4	Major	24.95						
	Acc		19.78				19.78	
Paseo	Minor			33.83				
G Corolla	Major	44.73			10.9			
	Acc		10.94				10.94	
American	Major	55.67						
Pathfinder	Minor		21.5	56.55				
					20.62			
SUT	Major	77.17						
F150	Minor		3.56	78.23				
	Not acc				2.5	not acc		2.5
Cherokee	Major	80.73						
	Acc		6.82				6.82	

After completing all data reduction, a much simplified table is used to calculate critical gaps. This table, instead of vehicle characteristics, uses numbers to identify each car; also the only data shown are, accepted gaps and rejected gaps. Table 4-2 is a simplified table of gap acceptance/rejection patterns for 25 vehicles in the study.

Table 4-2 Example of Gap Acceptance/Rejection Patterns for Each Car.

PR2R Intersection	***Accepted Gap***	***Rejected Gap***			
Car number	(s)	(s)	(s)	(s)	(s)
1	19.78	3.93	3.27	5.78	
2	10.94				
3	20.62				
4	6.82	2.5			
5	10.97				
6	25.86	3.2	4.04		
7	14.51				
8	18.52	11.38	6.28		
9	9.48				
10	17.6				
11	26.63				
12	38.43	1.96	1.8		
13	34.78				
14	25.89				
15	19.99				
16	14.82				
17	8.44	3.37			
18	9.91	2.11	1.76	1.7	3.69
19	15.42	4.19			
20	12.92				
21	8.3	7.64			
22	5.23				
23	18.87	1.62			
24	10.5	5.6			
25	12.37				

If one were to use only the data in Table 4-2, not all 25 accepted gaps and rejected gaps could be used. For the analysis, accepted gaps greater than 12 s were discarded.

Kittleson and Vandehey (Pollatschek, Polus, Livneh, 2002) noted that nearly most drivers will accept 12 second gaps. Also, to avoid bias, the first rejected gap for each vehicle in the minor stream is the one used to determine the critical gap.

5 Critical Gap

This chapter describes the gap data and the critical gap estimation procedure for all studied maneuvers. Critical gaps are estimated by measuring gap acceptances and rejections of a minor road vehicle who wishes to cross or enter the major stream. Several models have been developed specifically to estimate the critical gap values at intersections. Critical Gaps were obtained using Raff's Method.

Critical gap times were divided into three sections, left turns from the minor road, right turn from the minor road, crossing maneuvers and left turns from the major road. Crossing maneuvers are included in the left turn from the minor road data. Critical gap times for heavy vehicles are out of the scope of this project. During field studies it was observed that drivers who wanted to make a crossing maneuver use the same critical gap as those making left turn maneuvers from the minor road, vehicle majority doing a crossing maneuver was single unit trucks and a patrol car. Also the sample size available to determine critical gap for this type of maneuver is considerably less to make an acceptable estimate. According to the calculations shown below, a sample size of 138 vehicles was needed to perform the gap acceptance study: however during the data acquisition process the actual sample size used as larger than that number. Section 5.4 presents the margin of error calculation using the actual sample size for each maneuver. Sample size was determined using the following equation.

$$n = \left(\frac{z_{\alpha/2} * \sigma}{E} \right)^2 \qquad \text{Equation 5-1}$$

Where E is the margin of error equal to .5, this was used as a starting point to determine a sample size. Sigma (σ) is the theoretical standard deviation with a value of 3 and a critical value $z_{\alpha/2}$ for a 95% confidence level of 1.96.

$$n = \left(\frac{1.96 * 3}{.5} \right)^2 \quad \text{Equation 5-2}$$

$$n = 138 \quad \text{Equation 5-3}$$

Also critical gaps were determined for three different maneuvers; left turns from the minor road, right turns from the minor road and left turns from the major road. The following sections present results for each maneuver.

5.1 Left Turn from the Minor Road

The first maneuver studied was the left turn from the minor road. Gap acceptance studies for this type of maneuver are the most difficult one to develop. Left turn maneuvers have the lowest priority on an intersection. Therefore, gap acceptance studies for this type of maneuver should consider gaps available in both directions of the main traffic stream. Figure 5-1 shows the left turn maneuver and the conflicting maneuvers. The yellow arrow represents the studied maneuver, while the red arrows the conflicting streams.

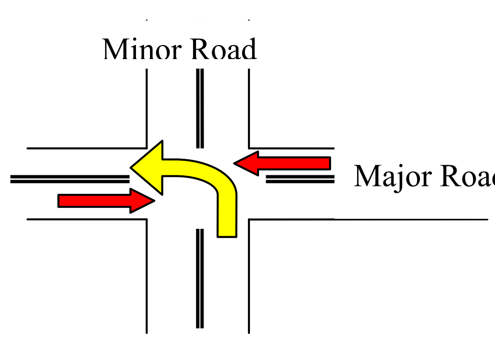

Figure 5-1 Left Turn from the Minor Road.

To develop the gap acceptance graph, all accepted gaps chosen are sorted in ascending order and grouped in different number classes. The number of observations in each group is counted and written down on a table as number of acceptances. Finally all data is accumulated to create the graph for Total Accepted Gaps. For rejected gaps, the number of rejected observations is subtracted from the total number of observations until cero (0) is reached. Table 5-1 and Table 5-2 present the number of acceptances, number of rejections and accumulated gaps for left turns from minor road maneuver. The critical gap for the maneuver is obtained from the graphical representation obtained for the data.

Table 5-1 Acceptances and Rejections for Left Turns from the Minor Road.

# of observations	*Number of Acceptances*	*Number of Rejections*
0	0	0
9	0	9
23	0	23
14	1	13
15	5	10
9	5	4
11	9	2
7	7	0
11	10	1
7	7	0
7	7	0
3	3	0

Table 5-2 Gap Acceptance/Rejection Pattern for Left Turns from the Minor Road.

Gap Class	*Number of Acceptances*	*Accumulated Acceptances*	*Number of Rejections*	*Accumulated Rejections*	*Percentage of Acceptances (%)*
0.0-.9	0	0	0	62	0
1.0-1.99	0	0	9	53	0
2.0-2.99	0	0	23	30	0
3-3.99	1	1	13	17	7.14
4-4.99	5	6	10	7	33.33
5-5.99	5	11	4	3	55.5
6-6.99	9	20	2	1	81.81
7-7.99	7	27	0	1	100
8-8.99	10	37	1	0	90.91
9-9.99	7	44	0	0	100
10-10.99	7	51	0	0	100
11-11.99	3	54	0	0	100
			62		

According to (Miller, 1970), critical gaps are those gaps that 50% of people will accept, or the median of the gap acceptance distribution. However the methodology used in this study to determine the value of the gap acceptance (Raff Method) does not calculate directly the median of the gap acceptance distribution only. It uses both the cumulative gap acceptance and cumulative rejected gaps using a graph to obtain the results. By calculating the percentage of acceptance for each class, this definition can be clearly seen. Table 5-2 shows the different percentages of acceptance for each gap class for right turns from the minor road. Critical gaps are located in the gap class whose percentage of acceptance is closer to fifty percent (50%). From the table, driver majority (55.5%) will accept gaps in the range of 5 or greater. Also, from the data all vehicles (100%) will accept gaps greater than 7 seconds. When accumulated gaps are plotted, a graph like the one presented below is obtained. The critical gap is the point where both graphs intersect each other. For left turn lane from the minor road maneuver the critical gap obtained from the graph in Figure 5-2 is 5.1 seconds. Again Miller's definition is confirmed, like on the table, the critical gap was between 5 and 5.99 seconds.

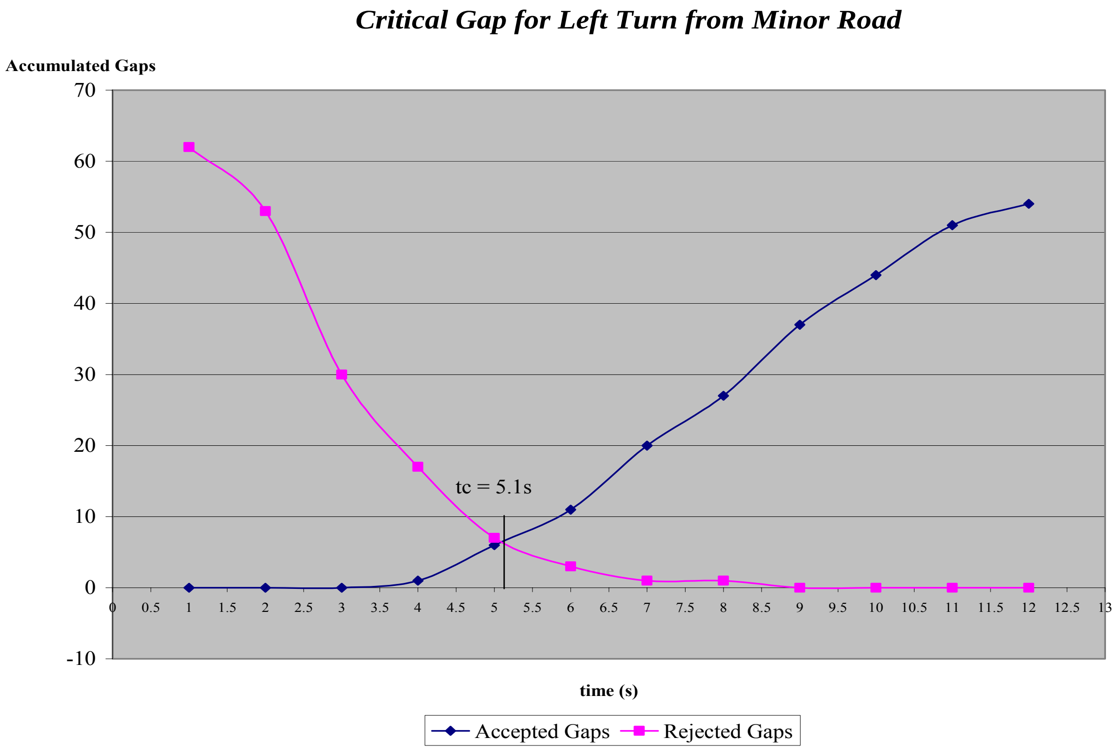

Figure 5-2 Critical Gap for Left Turns from the Minor Road.

5.2 Right Turn from Minor Road

The second maneuver studied was the right turn from the minor road. The gap acceptance study for this type of maneuver is the easiest one to develop. The study should consider gaps available in the nearest lane of the main traffic stream. Figure 5-3 shows the maneuver and its conflicting maneuver. The yellow arrow represents the studied maneuver, while the red arrow (darkest) the conflicting stream.

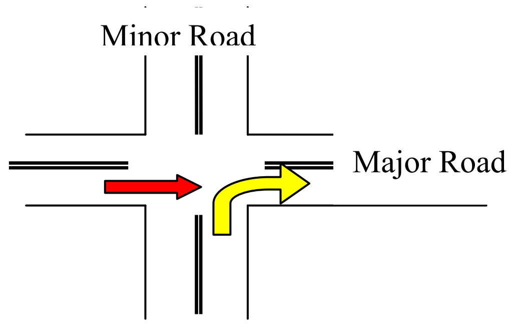

Figure 5-3 Right Turn from the Minor Road.

The gap acceptance graph was developed by sorting the acceptances in ascending order and grouped in different number classes from cero (0) to twelve (12). The procedure is the same described before for left turns from the minor road. The following tables (Table 5-3 and Table 5-4) present number of acceptances, number of rejections and accumulated gaps. The maneuver's critical gap is obtained from the graphical representation of the data.

Table 5-3 Acceptances and Rejections for Right Turns from the Minor Road.

# of observations	*Number of Acceptances*	*Number of Rejections*
10	0	10
13	1	12
6	1	5
10	4	6
7	4	3
10	7	3
10	9	1
4	4	0
9	9	0
10	10	0
2	2	0
7	7	0
1	1	0
		40

Table 5-4 Gap Acceptance/Rejection pattern for Right Turns from the Minor Road.

Gap Class	*Number of Acceptances*	*Accumulated Acceptances*	*Number of Rejections*	*Accumulated Rejections*	*Percentage of Acceptances (%)*
0.0-.9	0	0	10	40	0
1.0-1.99	1	1	12	30	7.69
2.0-2.99	1	2	5	18	16.67
3-3.99	4	6	6	13	40
4-4.99	4	10	3	7	57.14
5-5.99	7	17	3	4	70
6-6.99	9	26	1	1	90
7-7.99	4	30	0	0	100
8-8.99	9	39	0	0	100
9-9.99	10	49	0	0	100
10-10.99	2	51	0	0	100
11-11.99	7	58	0	0	100
12	1	59	0	0	100
			40	0	

Once again Miller's definition of critical gap can be clearly seen. Table 5-4 shows the different percentages of acceptance for each gap class for right turns from the minor road. From the table, driver majority (57%) will accept gaps in the range of 4.99 or less. According to the table all vehicles (100%) accept gaps greater than 7 seconds. The critical gap for right turns from the minor road was determined to be 4.7 seconds (See Figure 5-4).

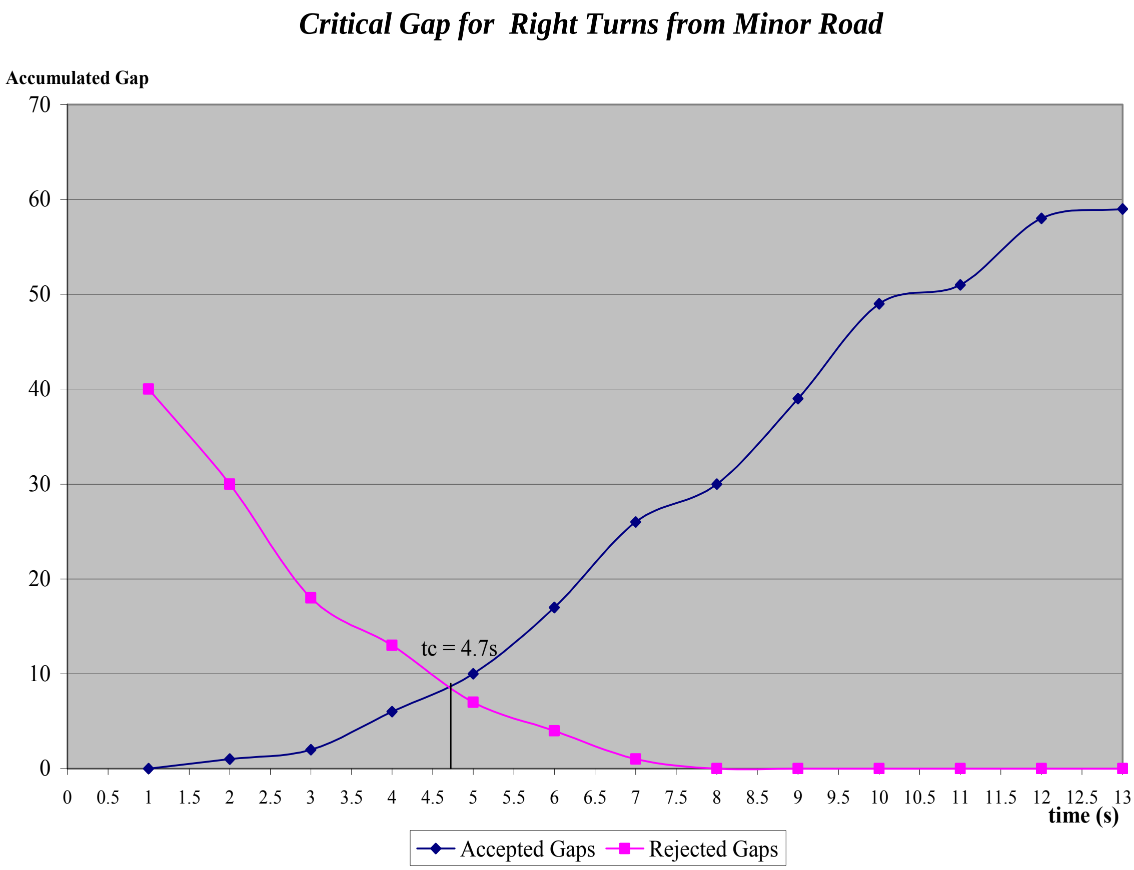

Figure 5-4 Critical Gap for Right Turns from the Minor Road

5.3 Left Turn from Major Road

The final maneuver studied was the left turn from the major road. Figure 5-5 shows the maneuver and the conflicting movement. The yellow arrow represents the studied maneuver, while the red arrow (darkest) the conflicting stream. This gap acceptance study should consider gaps available in the opposite direction on the major traffic stream.

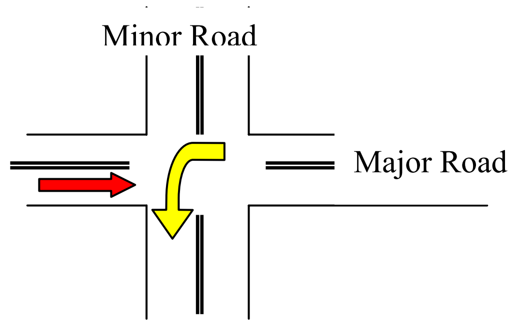

Figure 5-5 Left Turn from the Major Road

The gap acceptance graph was developed by using the same procedure as before. Table 5-5 and Table 5-6 presents number of acceptances, number of rejections and accumulated gaps for left turns from the major road. The percentage of acceptance to determine the critical gap's location in the graph is also presented in Table 5-6. The exact critical gap is obtained from the graphical representation of the data.

Table 5-5 Acceptances and rejections for Left Turns from the Major Road.

# of observations	*Number of Acceptances*	*Number of Rejections*
22	0	22
23	0	23
15	4	11
15	7	8
10	10	0
10	8	2
14	14	0
10	10	0
5	5	0
10	10	0
5	5	0
7	7	0
0	0	0
		66

Table 5-6 Gap Acceptance/Rejection Pattern for Left Turns from the Major Road.

Gap Class	*Number of Acceptances*	*Accumulated Acceptances*	*Number of Rejections*	*Accumulated Rejections*	*Percentage of Acceptances (%)*
0.0-.9	0	0	22	66	0
1.0-1.99	0	0	23	44	0
2.0-2.99	4	4	11	21	26.67
3-3.99	7	11	8	10	46.67
4-4.99	10	21	0	2	100
5-5.99	8	29	2	2	80
6-6.99	14	43	0	0	100
7-7.99	10	53	0	0	100
8-8.99	5	58	0	0	100
9-9.99	10	68	0	0	100
10-10.99	5	73	0	0	100
11-11.99	7	80	0	0	100
12	0	80	0	0	100
			66	0	

Table 5-6 shows the different percentages of acceptance for each gap class for left turns from the major road. From this table, gaps in the range of 4 or greater will be accepted by vehicles (100%) of the time. Although no group has a 50% of acceptance, but the 3-3.99 interval has a 46.67%, being close to the median. When the graph was plotted, the critical gap for left turns from the major road was determined to be 3.95 seconds (See Figure 5-6), inside the 3-3.99 interval.

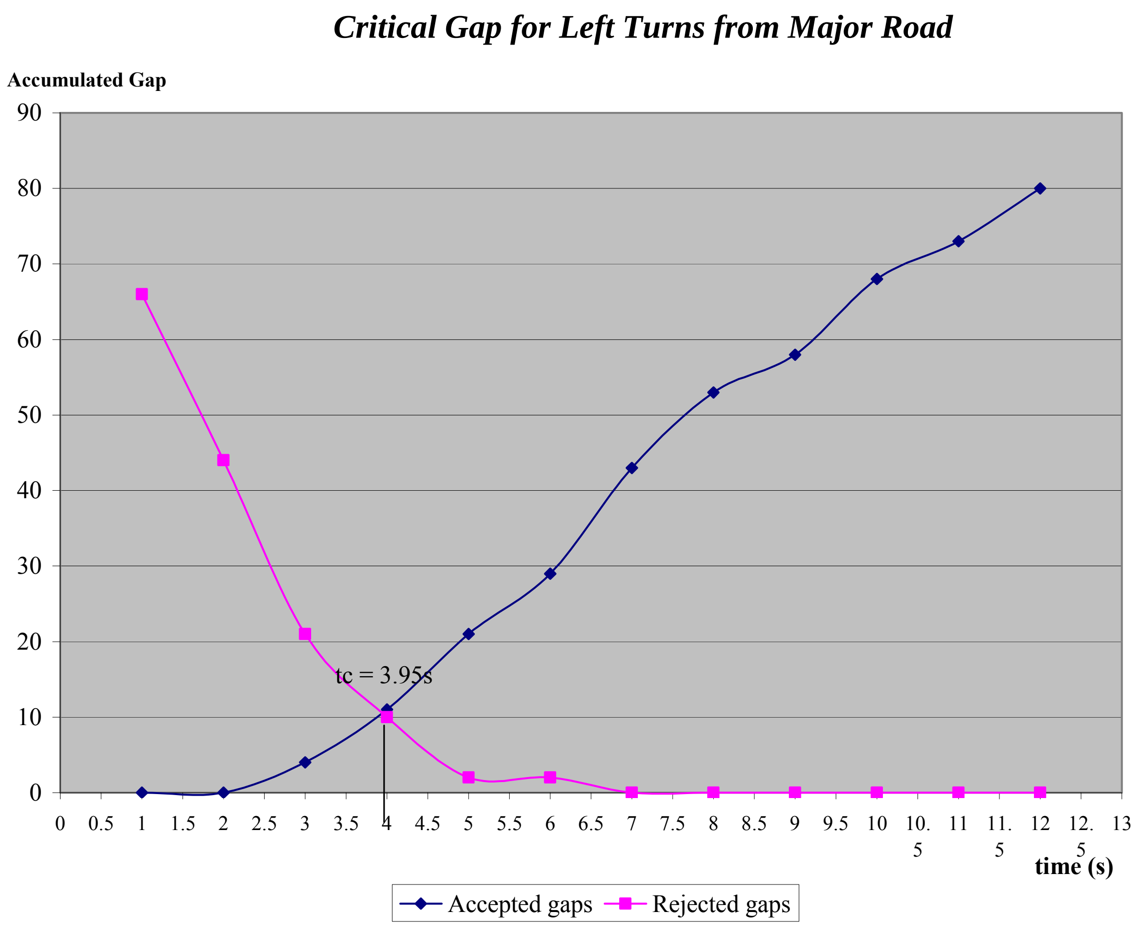

Figure 5-6 Critical Gap for Left Turns from the Major Road.

5.4 Calculated Margin of Error for the Data

When Equation 5.1 was used, a sample size of 138 vehicles was obtained. To determine the critical gap, the calculated sample size was used as the minimum sample size. The actual sample size used was larger than 138 vehicles per maneuver. Actual sample sizes and Margins of Error for every maneuver are presented in Table 5-7. Equation 5-4 is derived from Equation 5-2. The error was calculated using Equation 5-4.

$$E = \left(\frac{1.96 * 3}{\sqrt{n}} \right) \qquad \text{Equation 5-4}$$

Table 5-7 Margin of Error per Maneuver

Maneuver	n (vehicles)	E
Left turn from major	161	0.46
Left turn from minor	301	0.34
Right turn from minor	150	0.48

All maneuvers had a Margin of Error smaller than the .5 selected to calculate the original sample size. Left turns from the minor road have the biggest sample size because; vehicles traveling in both directions had to be considered in the gap acceptance study.

5.5 HCM Critical Gap Comparison

One of the project's main objectives is to compare the critical gaps obtained from field studies with the critical gaps found in the Highway Capacity Manual (TRB, 2000). The tables presented in this section compare HCM critical gap times with the ones found in the field.

Table 5-8 Critical Gaps.

Vehicle Movement	*HCM Critical Gap (s)*	*Calculated Critical Gap (s)*
Left turn from major	4.1	3.95
Right turn from minor	6.2	4.7
Left turn from minor	7.1	5.1

Time difference between critical gaps can be up to two (2) seconds depending on the maneuver. The critical gap for the left turn from the major road HCM and Experimental have a time difference of 0.15 seconds for a 3.8 %. This difference is less than the margin of error for the sample size used; therefore in this case the difference might be attributed to the variability of the gap acceptance process. On the other hand, the other two critical gaps have changes from 1.5 seconds to 2 seconds. These differences are larger than the margin of error used. Therefore, these two maneuvers represent major differences in behavior. Right turn from the minor road has a percent of difference of approximately 30%; also the critical gap for left turns from the minor road has a percent of difference of almost 40% (See Table 5-10). It can be clearly seen that Puerto Ricans in the Mayagüez area need less time to enter the intersection. Table 5-9 presents critical gap time difference between HCM and Experimental critical gap.

Table 5-9 Critical Gap Time Difference.

Vehicle Movement	***HCM Critical Gap (s)***	***Critical Gap (s)***	***Time difference (s)***
Left turn from major	4.1	3.95	***0.15***
Right turn from minor	6.2	4.7	***1.5***
Left turn from minor	7.1	5.1	***2.0***

5.6 Percent of Difference

The following equation was used to determine the percent of difference between the experimental critical gaps obtained from field data and critical gaps obtained from HCM.

$$\% d = \left| \frac{Experimental\,Critical\,Gap - HCM\,Critical\,Gap}{Experimental\,Critical\,Gap} \right| * 100 \qquad \text{Equation 5-5}$$

Table 5-10 Percent of Difference Between Critical Gap Times.

Vehicle Movement	***HCM Critical Gap (s)***	***Experimental Critical Gap (s)***	***% of difference***
Left turn from major	4.1	3.95	***3.8***
Right turn from minor	6.2	4.7	***31.9***
Left turn from minor	7.1	5.1	***39.2***

5.7 Proximity of critical gap of left turn from major road and HCM

When doing the study and video reduction, it was clearly seen that there was two different behaviors for Left turns from the major road. One type of driver (cautious one) stopped or reduced the car's speed and continued slowly until having the necessary gap to maneuver. The second type of driver was the aggressive driver; this driver accelerated and made the maneuver early to enter the intersection. Also, critical gap depends on stopped vehicles. If drivers stop or move slowly until a proper gap is provided, the accepted gaps are greater than six (6) seconds. On the other hand, if drivers accelerate, accepted gaps are under 6 seconds. In short, drivers were looking for an acceptable gap in the intersection.

5.8 Intersection Sight Triangle Recalculation

After obtaining new critical gap values, a recalculation of sight triangle dimensions was conducted. When using critical gaps from AASHTO's Greenbook, it was found that both intersections do not comply with sight triangle dimensions, (there are obstructions inside the driver field of vision). The equation used for intersection sight distance is the following:

$$ISD = 1.47\, V_{major}(t_c) \qquad \text{Equation 5-6}$$

All variables are in English units. The major road speed (V_{major}) used, was 25 mph as measured in the field, and t_c is the critical gap for the desired movement. To compare the sight distance needed, the critical gap is the only variable that changes. Table 5-11 (a) and (b) present the triangle dimension along the major road using HCM critical gaps and the one obtained from the study.

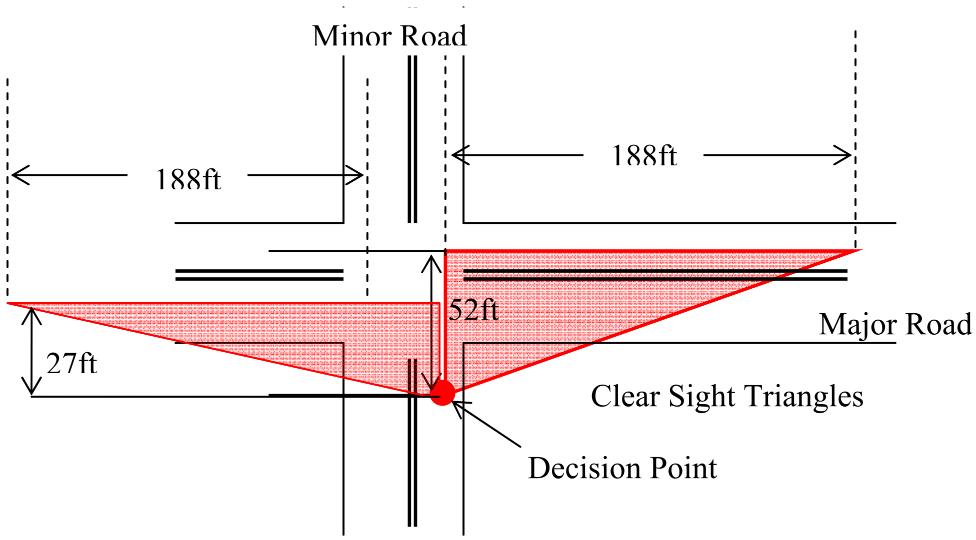

Figure 5-7 Clear Sight Triangles for Left Turns from the Minor Road at Añasco.

Table 5-11 (a) Triangle Dimension on the Major Road for Case B-1, (b) Case B-2.

Case B-1 Left turn from minor	***HCM critical gap***	***Calculated Critical Gap***
Triangle dimension along the major road	276 ft	188 ft

(a)

Case B-2 Right turn from minor	***HCM critical gap***	***Calculated Critical Gap***
Triangle dimension along the major road	239 ft	173 ft

(b)

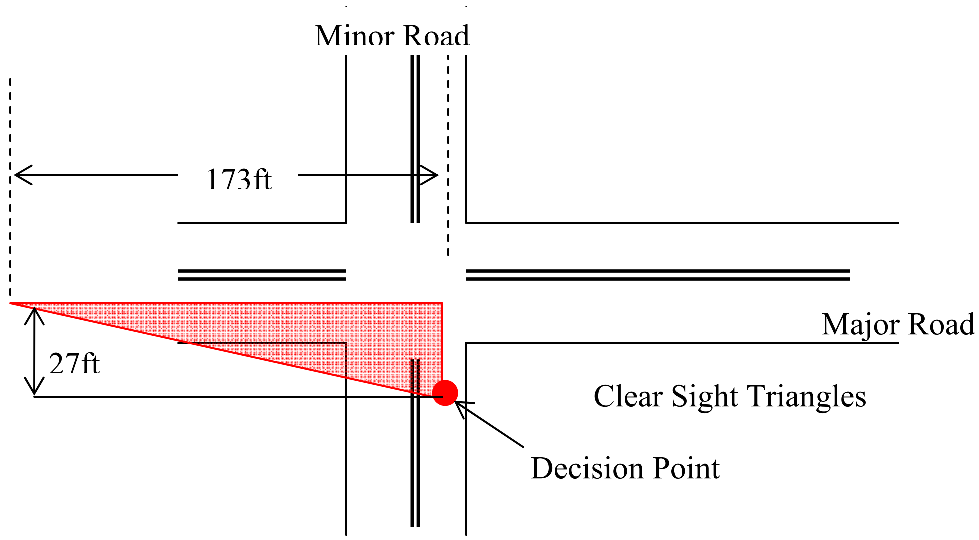

Figure 5-8 Intersection Sight Triangles for Right Turns from the Minor Road.

Even though the code requires a distance of 276 ft on the major road for Left turn from the minor road, if critical gaps found in the study are used instead; Puerto Ricans on the studied intersection only require 188 ft on the major road. This distance represents 69 % of the total 276 ft per AASHTO. Right turn from minor road requires a distance on the major road of 239 ft, but with the critical gap this distance is reduced to 173 ft, 72% of the total.

5.9 Problems encountered in the field

During the study and field data analysis, four problems were identified. The first problem encountered was that, drivers (especially in right turn maneuvers) in the minor stream did not come to a complete stop before entering the intersection. Left turn maneuvers do not have an adequate sight triangle in neither one of the intersections studied. While decelerating, minor street drivers were monitoring gaps provided in the major traffic streams before arriving at the intersection. If the lag was large enough for acceptance, then drivers continue without stopping.

The second problem encountered was that even during periods with low traffic flow (valley periods) drivers on the minor traffic stream force their own gaps (those forced gaps were not considered for the calculations). Drivers wait at the stop line. However after waiting for some time and having to reject several gaps, drivers become impatient, block the incoming flow of the nearest traffic stream, and wait to accept gaps available in the farthest lane. The Highway Capacity Manual describes this behavior as impedance effect. That should occur during congested conditions, however it was observed during not congested conditions as well.

Also, drivers who did stop at the intersection did not have a consistent stop position, even though there was a marked stop line at the intersection. On occasions vehicles made a full stop and moved forward to asses the situation and wait for an adequate gap. This minimizes the time actually stopped at the intersection.

The fourth problem observed in the intersection, regards major traffic stream driver behavior. When southbound drivers in the major traffic stream wanted to make a left turn maneuver with northbound vehicles arriving, they arrived slowly to the intersection, delaying their arrival time, having to wait less time at a full stop for a sizeable gap before actually stopping. The opposite also occurred, drivers accelerated before entering the intersection in order to “beat” the gap. Both behaviors made it more difficult to determine the reference point for data collection and calculate the rejected gap. Conflict points for each case were used as reference for time collecting.

5.10 Gap Fishing Phenomenon

When vehicles in the minor traffic stream arrived slowly to the intersection, delaying their arrival time and avoiding coming to a full stop while waiting for a sizable gap, this was defined as “Gap Fishing”. This phenomenon was observed in the intersections with a critical gap less than those found in the HCM. Even roadway accesses with a STOP sign as traffic control device have this phenomenon, because Puerto Ricans do not make full stops at an intersection unless available gaps in the major roadway are less than the critical gap.

Figure 5-9 presents two scenarios, (1) the vehicle accelerates and enters the intersection aggressively, or (2) the vehicle decelerates until a desirable gap is provided. Figure 5-10 shows scenario (1) in which the car enters the intersection before the upcoming vehicle arrives at the intersection. Figure 5-11 represents scenario (2), in this figure the vehicle at T decelerates until a sizable gap is provided in the major road, an undefined number of gaps are provided before doing the turning maneuver. The decision point is where the driver on the major road starts to accelerate or decelerate to beat the gap. For vehicles accelerating and performing the turn maneuver, the gap for that vehicle is less than the critical gap. For vehicles decelerating, the gap accepted by the vehicle is greater than the critical gap.

$$g_v < g_c \qquad \text{(Scenario 1, vehicles accelerating),} \qquad \text{Equation 5-7}$$

$$g_v > g_c \qquad \text{(Scenario 2, vehicles decelerating),} \qquad \text{Equation 5-8}$$

All variables in the equations can be obtained from field studies. The decision point presented in the figures can be taken from the intersection sight triangles on the AASHTO methodology.

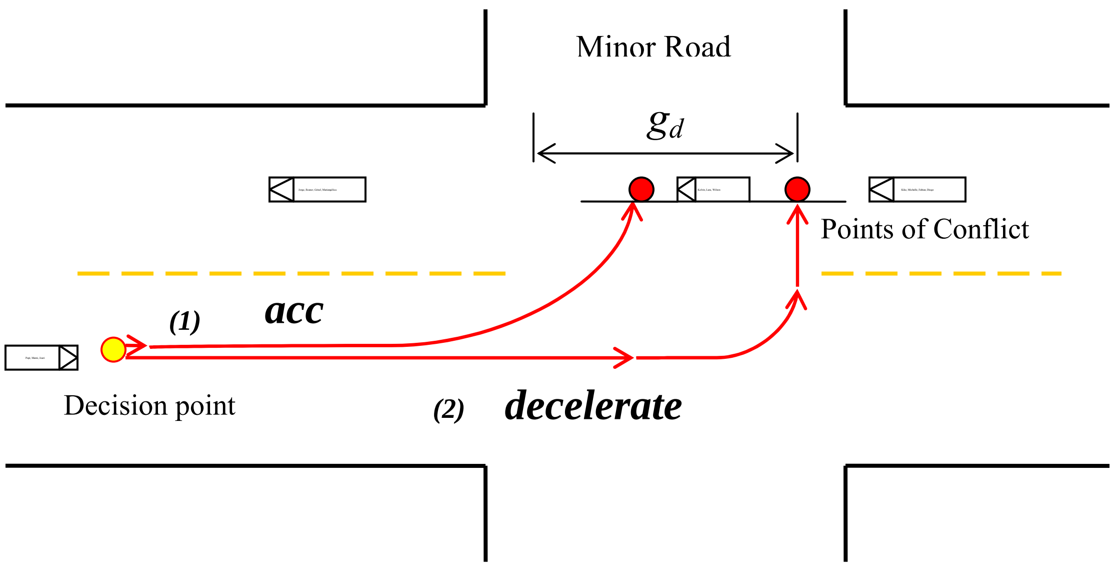

Figure 5-9 Driver Behavior.

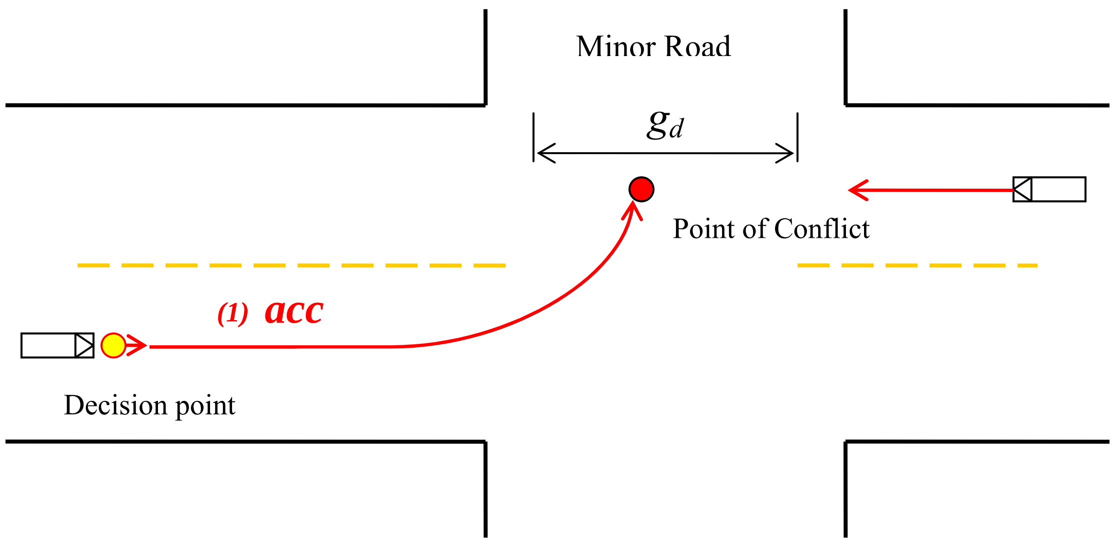

Figure 5-10 (1) Vehicle Accelerates and Enters the Intersection Aggressively.

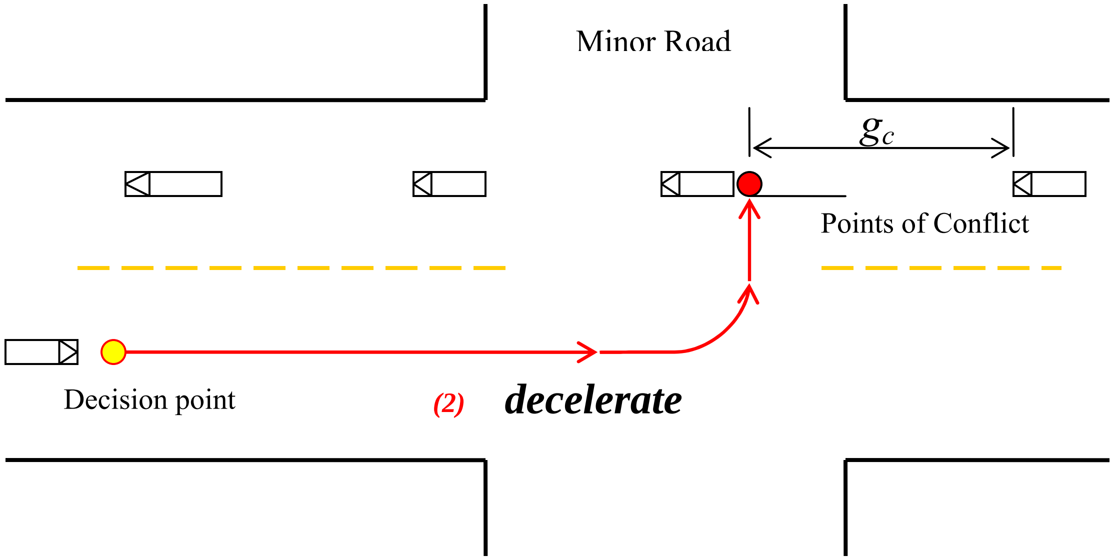

Figure 5-11(2) Vehicle Decelerates Until a Desirable Gap is Provided.

5.11 Case Characterization

The estimated time vehicle T needs to arrive at the intersection while accelerating at a rate a_T is less than the time it takes vehicle S to arrive at the conflict point. The distance d_1 and d_2 are defined by the following equations.

$$d_1 = v_o * t_1 + \frac{1}{2} * a_T * t_1^2 \qquad \text{Equation 5-9}$$

$$d_2 = v_o (t_1 + g_c) \qquad \text{Equation 5-10}$$

Where t_1 is the time it takes the vehicle to arrive at the conflict point and v_o is the approximation speed. The distance d_2 is the sum of d_1 plus the distance vehicle S moves in a time equal to the critical gap. The 25 mph approximation speed was the average speed measured at the intersections.

For example, if a vehicle with a speed of 25 mph is used in the equations, an acceleration of 4 ft/s^2 and a critical gap of 3.95s for left turn maneuver from the major road, a graphical representation for both approaching vehicles can be obtained. Figure 5-14 presents the graph of both equations for a time of up to 15 seconds using a critical gap of 3.95 seconds. Figure 5-15 shows the same graph for the minimum gap of 2.3 seconds. A gap of 2.3 seconds was the minimum gap accepted by a vehicle during the study period.

Both figures show the distance needed in order to enter the intersection without having to stop for a vehicle accepting the gap. The vehicle providing the gap is always the control vehicle; all decisions to enter the intersection and perform any maneuver (gap acceptance) depend on its distance to the intersection.

The next subsections describe in more detail the two cases in gap fishing. Case (I) describes how the driver accepting gaps will react if he is at a distance less or equal to d_1. Case II presents the case when the vehicle accepting the gap is at a distance grater than d_1

5.11.1 Case I $d_1 \leq d_2$

The first case in the gap fishing phenomenon represents when the vehicle accepting the gap (vehicle at T in Figure 5-12) is at a distance equal or less than the distance d_1 calculated using the equation and presented on the graph in Figure 5-14.

Assuming that vehicle at S, traveling at 25 mph (Figure 5-12), will reach the intersection in 10 seconds, the critical gap is 3.95 s, then the calculated distance traveled from the conflict point to the intersection using the equation or the graph in Figure 5-14 is d_1 = 566 ft, d_2 = 511 ft. The vehicle at T will enter the intersection if d_1 is less or equal to the distance calculated with the equation, because sufficient time is provided to perform the maneuver. In other words, the vehicle at S will travel 511 ft but it gives an extra 3.95 s of gap to the vehicle at T in order to enter the intersection.

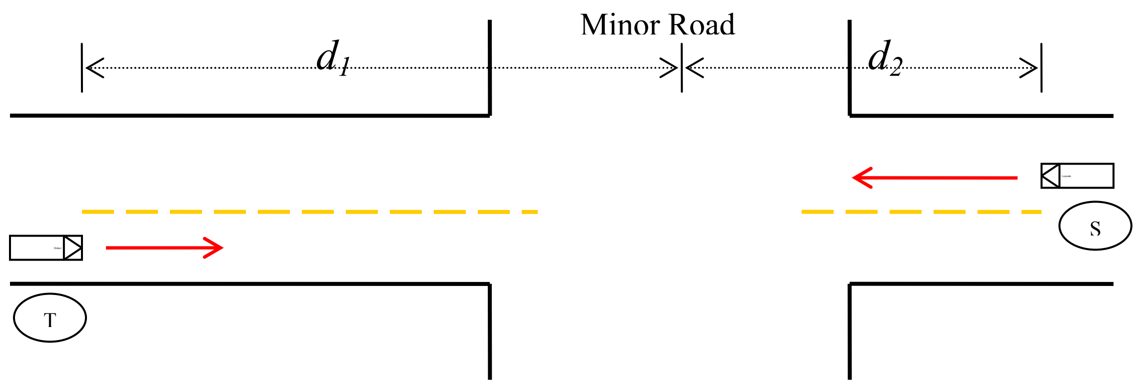

Figure 5-12 Vehicles Approaching the Intersection.

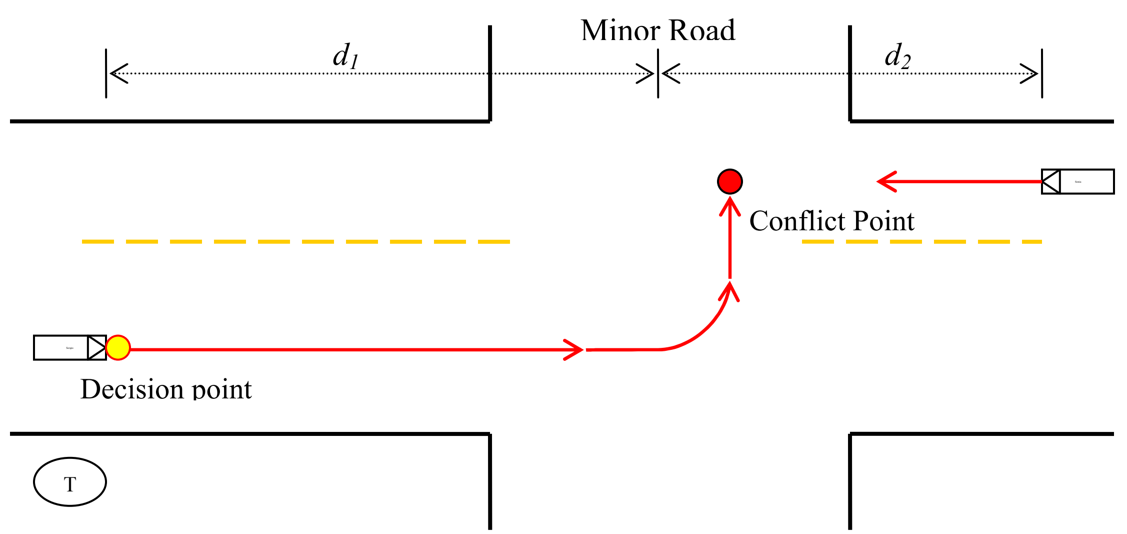

Figure 5-13 Case I $d_1 \leq d_2$

The vehicle at T will enter the intersection without having to stop because the distance provided is equal or less than the distance presented in the graph.

5.11.2 Case 2 $d_1 > d_2$

Gap Fishing phenomenon also presents a case when the vehicle accepting the gap (vehicle at T in Figure 5-12) is at a distance grater than distance d_1 (equation for graph in Figure 5-14).

The vehicle at T will not enter the intersection if d_1 is grater to the distance calculated with the equation, because sufficient time is not provided to perform the maneuver. The vehicle at S will travel 511 ft but the vehicle at T will arrive at the intersection during the 3.95s Critical Gap and will not accept the provided gap. This is assuming the driver's critical gap is 3.95s or lower.

During the data analysis, the minimum gap accepted was 2.3 seconds. If the capacity of an urban street is 3200 vph (1600 vph per lane) and assuming a uniform arrival distribution, then cars would arrive at a rate of almost 2.3 seconds per car. Vehicles accepting the minimum gap would not need to make a stop because a sizable gap would always be present.

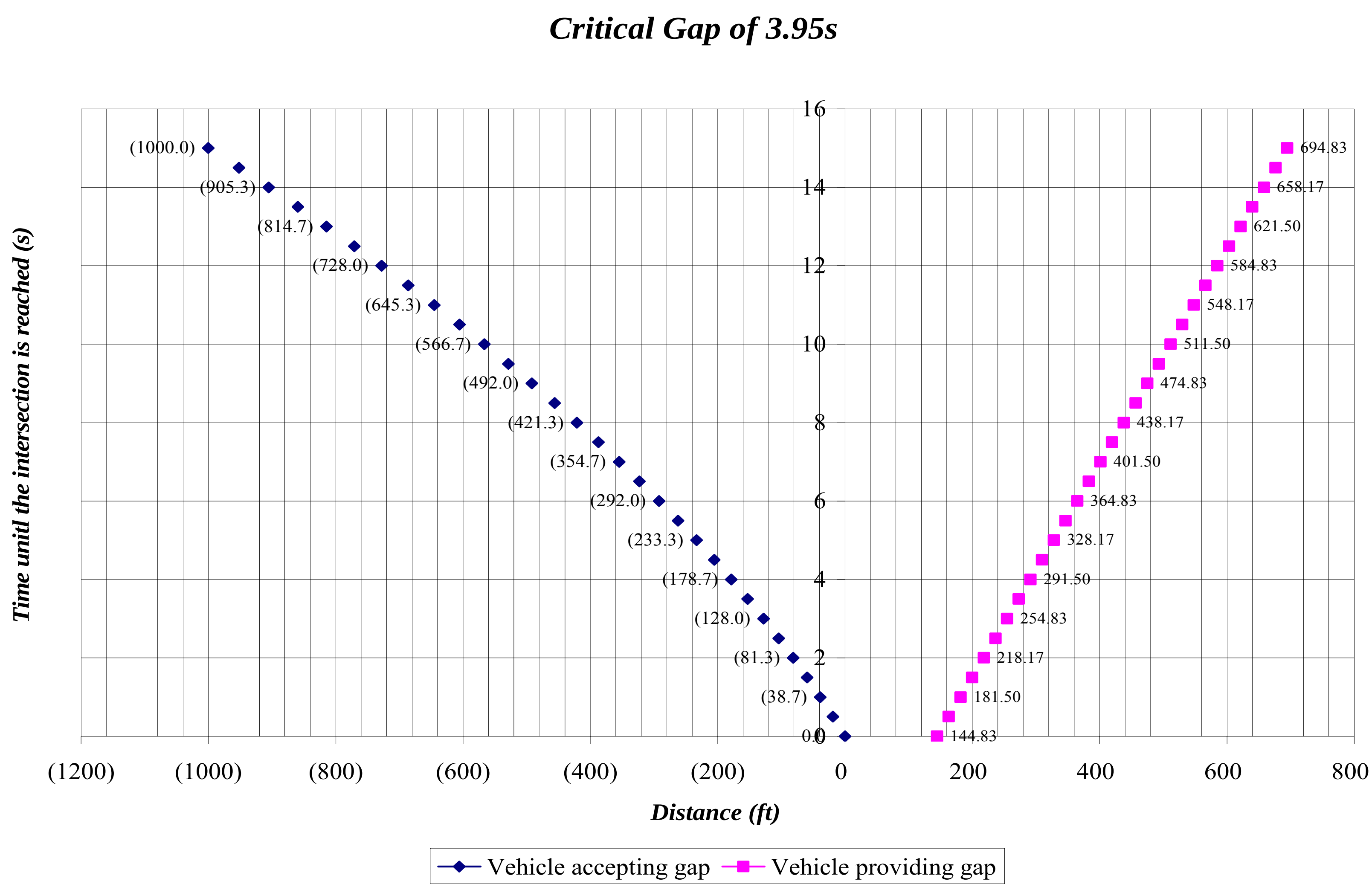

Figure 5-14 Distance traveled by vehicles approaching the intersection from opposing access stream for a Critical Gap of 3.95s

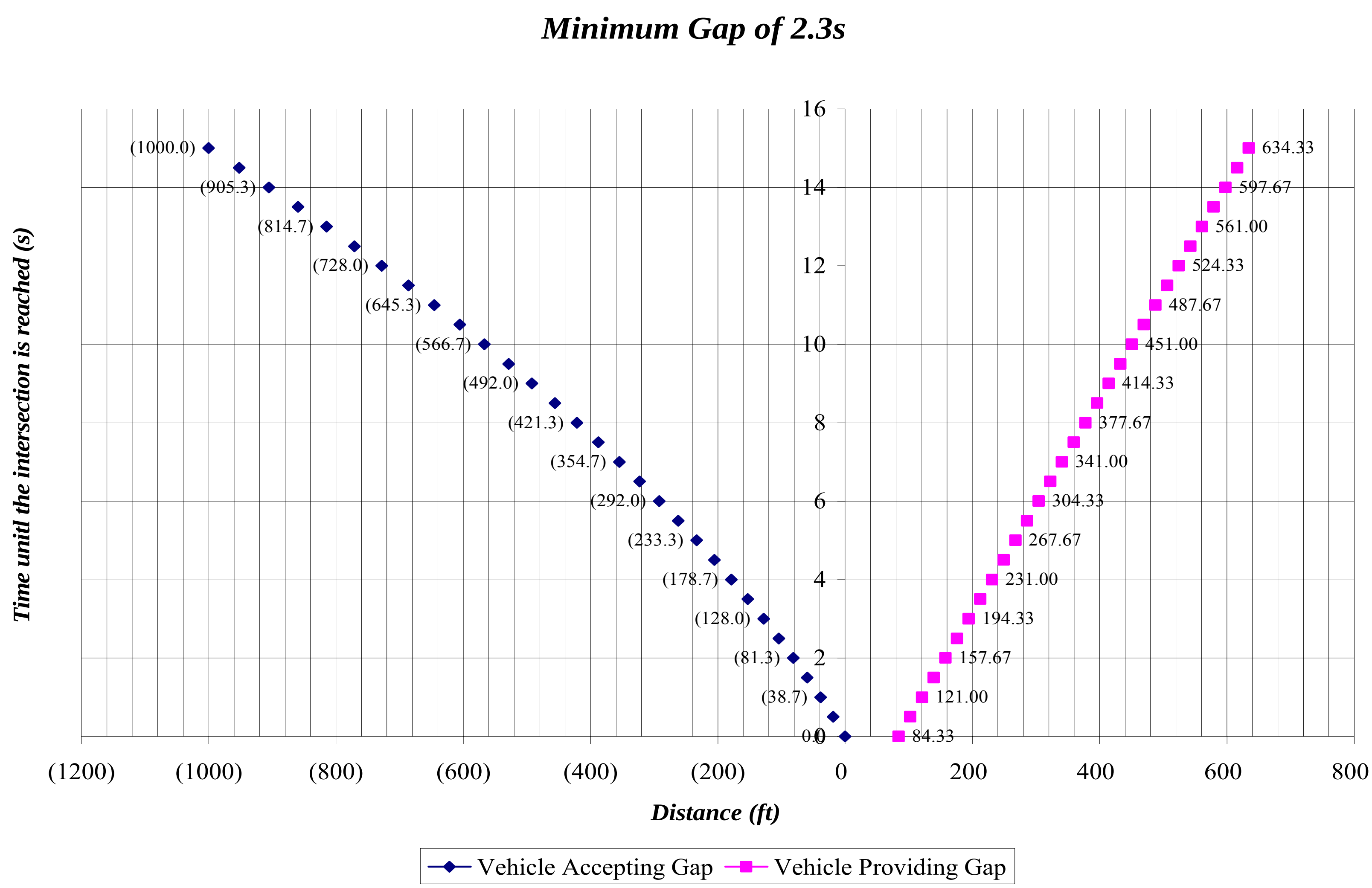

Figure 5-15 Traveled Distance of vehicles approaching the intersection from opposing streams for a Minimum Gap of 2.3s

6 Modeling with aaSidra

This chapter presents the input variables entered in the aaSidra program. The most important variables are the input volumes for each maneuver and the critical gaps. Two models were developed to do the sensitivity analysis, one with critical gap default values and a second with critical gaps found from field studies. A comparison was made by queues calculated by aaSidra and queues seen on the field during the study period. All the other parameters remained the same for both models.

6.1 Three leg intersection

The three leg intersection consists of one approach from Carolina Street and two approaches from Post Street. This intersection is located at the city of Mayagüez parallel to the major arterial PR-2. Figure 6-1 presents an aerial photo of the three leg intersection. The circle in the photograph indicates the exact point of the intersection. The intersection has two lanes per access with a lane with of 10 ft. An onsite picture of the intersection taken during the study is shown in Figure 6-2.

Figure 6-1 Aerial Photograph showing the Three Leg intersection at Mayagüez.

Source: Google Maps 2006

Figure 6-2 On site picture of the Three Leg Intersection.

Conditions of the PR-2R (Post-Carolina) intersection during the period of study are shown in Table 6-1. Volumes are presented for each maneuver, per approach and finally the total volume for the intersection. Major road volumes are greater than 400vph per approach, also the minor roadway (West Approach), has a volume greater than 100 vph. Figure 6-3 shows a diagram of the intersection with each input volume.

Table 6-1 Volume Per Maneuver in Vph.

	North Approach		***South Approach***		***West Approach (minor)***		
Maneuver	*Thru maneuver*	*Right turn maneuver*	*Thru maneuver*	*Left turn maneuver*	*Left turn maneuver*	*Right turn maneuver*	
Volume	348	350	311	16	205	43	Total
Volume for each approach	690		327		248		1265

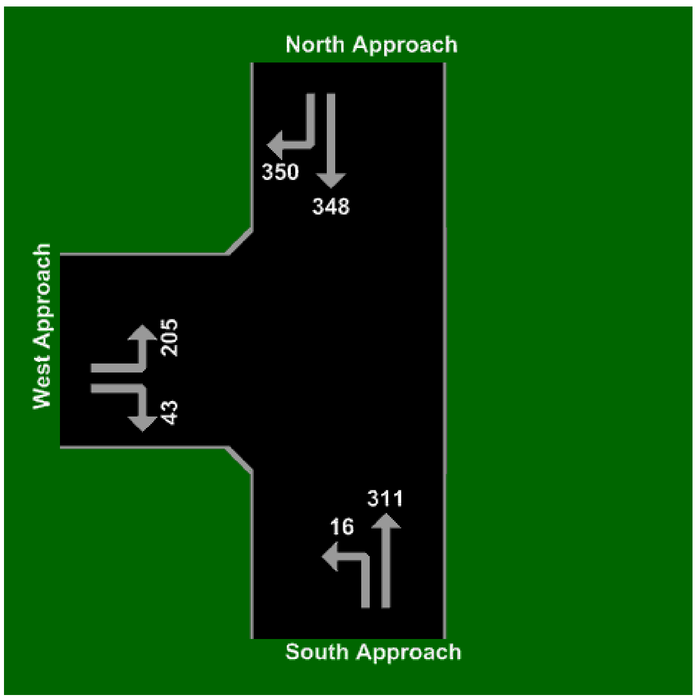

Figure 6-3 Input Volumes in the Three Leg (T) Intersection.

Even though aaSidra can be installed with standards for other countries, this project is focused on HCM. The default critical gap values (when installed as HCM standard) provided in aaSidra are shown in Table 6-2.

Table 6-2 Default Critical Gaps.

Vehicle Movement	***HCM Critical Gap (s)***
Left turn from major	4.1
Right turn from minor	6.2
Left turn from minor	7.1

To perform the critical gap sensitivity analysis, the output queue was used and compared with the queue seen during the field study. The modeling gave a queue of 532 ft (See Figure 6-4) in the west approach (minor road). The queue storage provided is 500 ft in length. The queue storage ratio (Figure 6-5) found was 1.06, meaning there is a 1.06 times more queue than space provided for storage. A queue of 532 ft was not present in the field during the study.

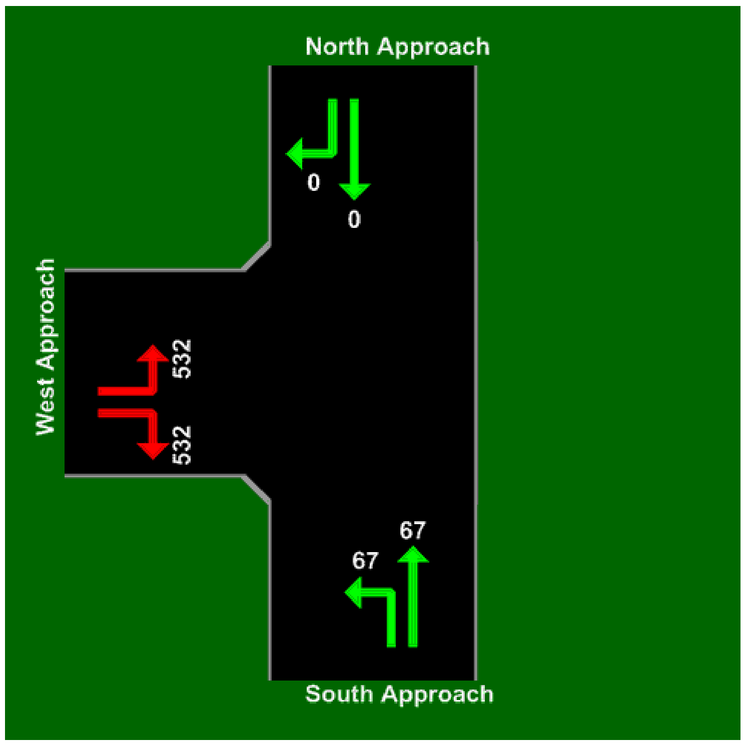

Figure 6-4 Queue Distance.

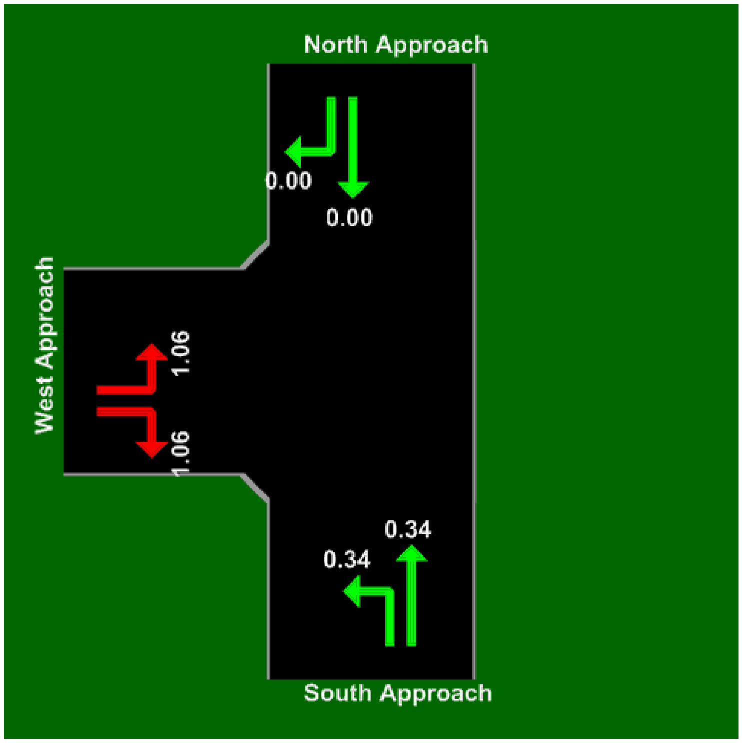

Figure 6-5 Queue Storage Ratio.

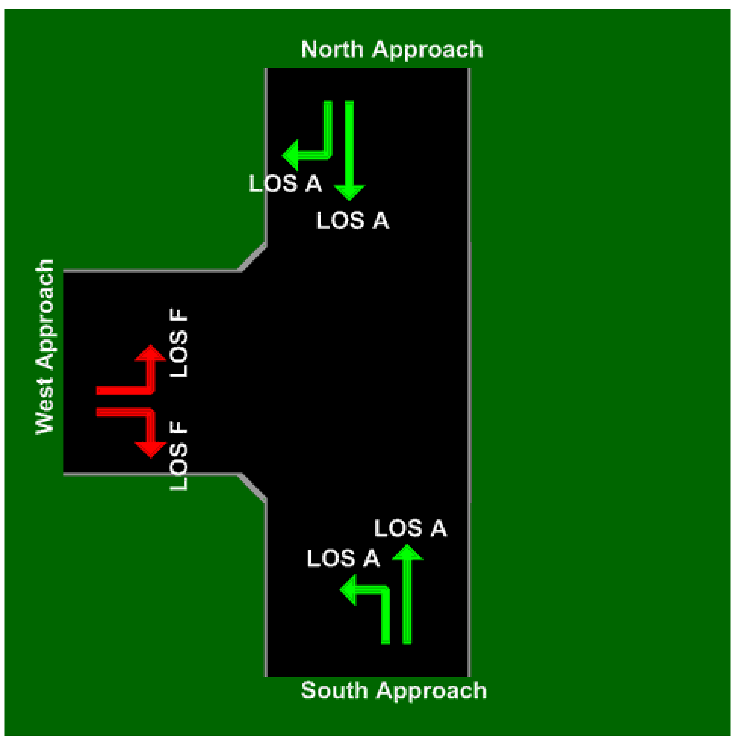

Figure 6-6 Level of Service.

According to the modeling results (See Figure 6-6), the minor road has a level of service (LOS) F. For this intersection a LOS F (over capacity) occurs when queues begin to form on the PR-2 segments. Queues did not reach the freeway during the study period.

6.1.1 Calculated Critical Gaps for Three Leg Intersection

The same volumes and intersection characteristics as the previous model were used to perform this model. The program has the option to change critical gap and follow up times. This option allows for a more accurate representation of roadway conditions. Table 6-3 presents the input critical gaps, which substitute HMC standards.

Table 6-3 Input Critical Gaps.

Vehicle Movement	***Experimental Critical Gap (s)***
Left turn from major	3.9
Right turn from minor	4.7
Left turn from minor	5.1

The queue obtained from aaSidra was compared with the field queue seen during the study period. The modeling gave a queue of 109 ft (See Figure 6-7) in the west approach (minor road). Like before, the queue storage provided is 500 ft in length. The queue storage ratio (Figure 6-8) found is now .22, meaning there is a queue equal to 22 percent of the space provided for storage.

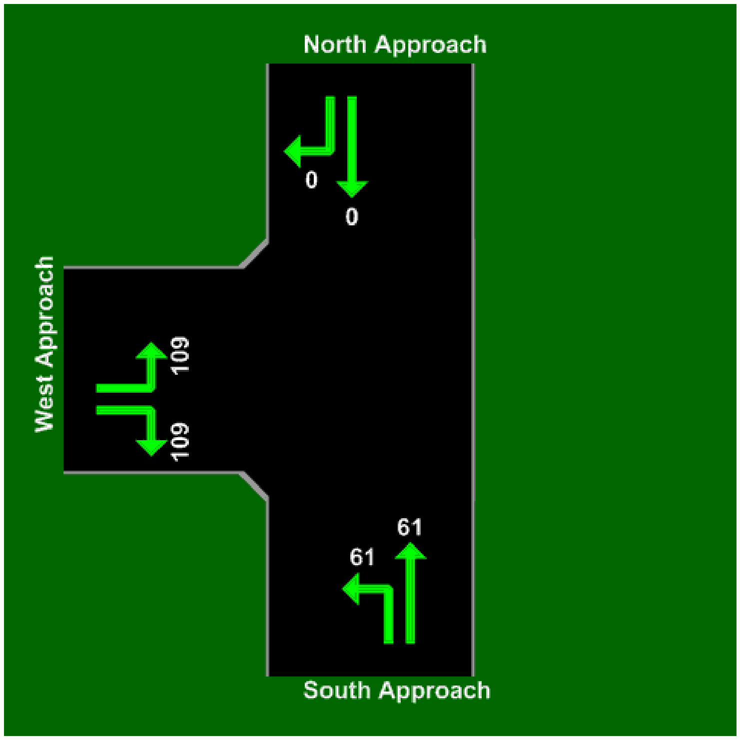

Figure 6-7 Queue Distance for Critical Gaps Found in the Field.

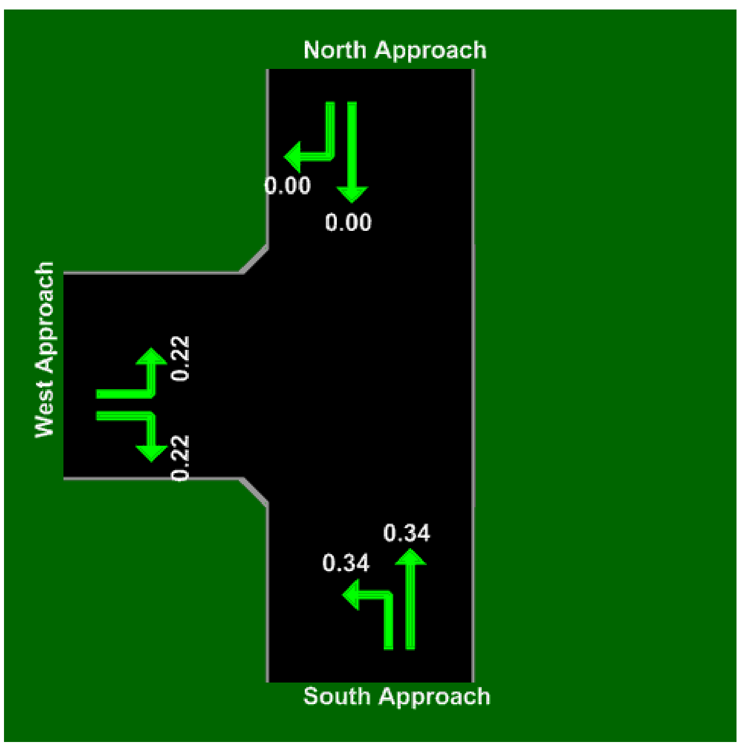

Figure 6-8 Queue Storage Ratio for Critical Gaps Found in the Field.

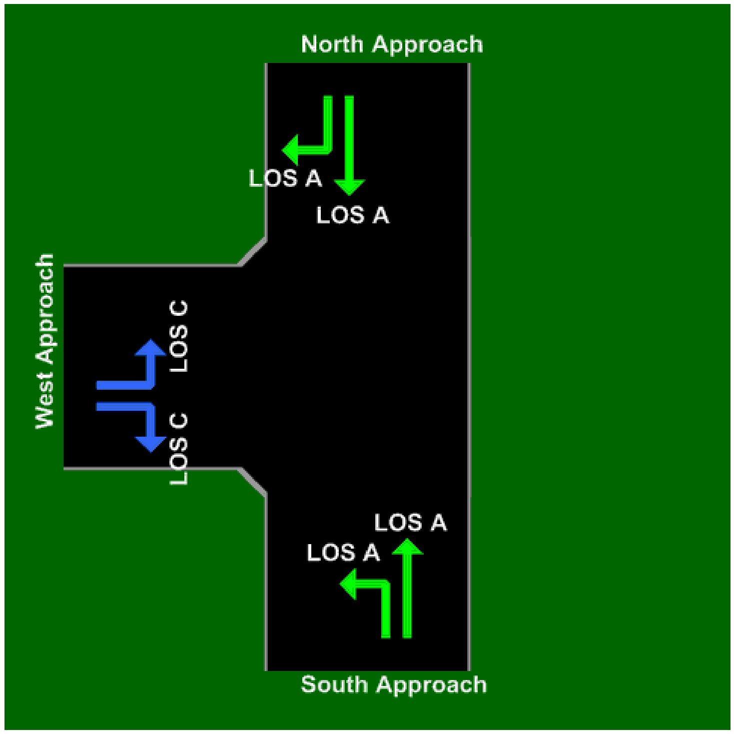

Figure 6-9 Level of Service for Critical Gaps Found in the Field.

Modeling results (See Figure 6-9) gave a LOS C to the minor road. Queues did not reach the major arterial PR-2 during the study period. The LOS C occurs when the intersection is operating below capacity conditions, therefore it has a more realistic representation of the period studied.

After seeing the modeling results, it can be concluded that default critical gaps (HCM) cause an overestimation of queues in the intersection. Also, performance measures are affected negatively; the program presents an intersection with worst conditions than those seen on the field.

6.2 Four leg intersection

The Four Leg Intersection consists of one approach from and two approaches from Post Street. This intersection is located at the city of Mayagüez parallel to the major arterial PR-2. Figure 6-1 presents an aerial photo of the three leg intersection. The circle in the photograph indicates the exact point of the intersection.

Figure 6-10 On site picture of the Four Leg Intersection at Añasco.

Conditions of the PR-402 intersection in Añasco during the period of study are shown in Table 6-4 and Table 6-5. Volumes are presented for each maneuver, per approach and finally the total volume for the intersection (See Table 6-6). The major road volume is 605 vph greater than the 400vph needed for the study, also the minor roadway, has a volume of 241vph complying with the 100vph minimum. Figure 6-11 shows a diagram of the intersection with each input volume.

Table 6-4 Volume Per Maneuver in vph for the Major Road.

	North Approach maneuvers			***South Approach maneuvers***			
Turn	*Thru*	*Left*	*Right*	*Thru*	*Left*	*Right*	***Major road total***
volume	225	127	7	226	10	10	
Volume of approach	359			246			605

Table 6-5 Volume Per Maneuver in vph for the Minor Road.

	East Approach (minor) maneuvers			***West Approach (minor) maneuvers***			
Turn	*Thru*	*Left*	*Right*	*Thru*	*Left*	*Right*	***Minor road total***
volume	12	9	188	10	12	10	
Volume of approach	209			32			241

Table 6-6 Volume Per Approach in vph for the Intersection.

	North Approach maneuvers	***South Approach maneuvers***	***East Approach (minor) maneuvers***	***West Approach (minor) maneuvers***	***Intersection Total***
Volume of approach	359	246	209	32	846

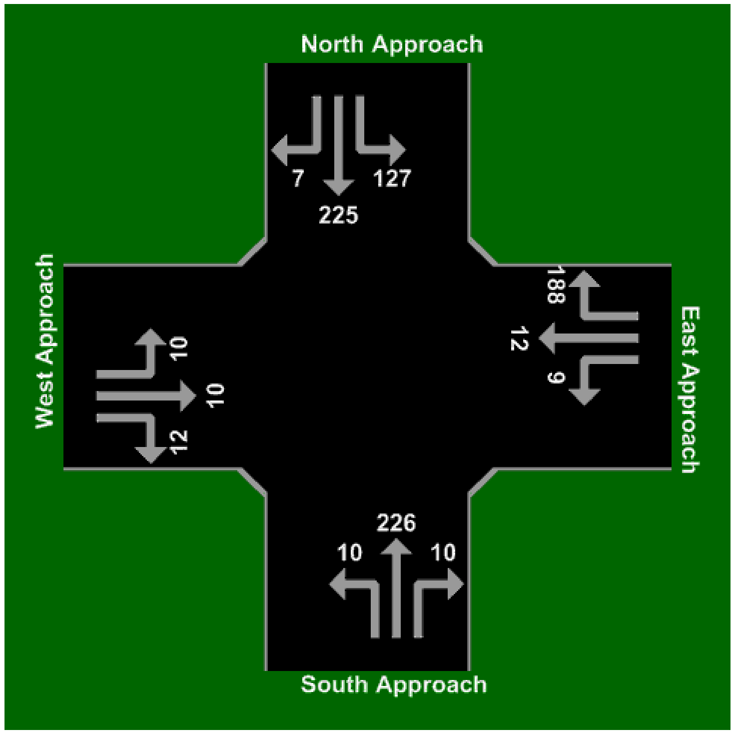

Figure 6-11 Input Volumes in the Four Leg Intersection.

The default critical gap values (when installed as HCM standard) provided in aaSidra are the same used for the three leg intersection shown in Table 6-2. To perform the critical gap sensitivity analysis, the output queue was used and compared with the queue seen during the field study. The modeling gave a queue of 64 ft for the east approach and 14 ft for the west approach (minor road). Also the major road had a queue of 47 ft on the north approach and 30 ft on the south approach (See Figure 6-12). If the average car length is 16 ft, when compared to the queue length given by aaSidra, it can be concluded that the longest queue of 64 ft is equal to 4 cars. During the study period a queue of four (4) cars on the minor road was never seen. The biggest one seen was a queue of (2) two cars. The queue storage provided for every approach is 300 ft in length. The queue storage ratio (Figure 6-5) found was .21, meaning the queue covers 21% of the space provided for storage. The longest queue in the major road is 47 ft, equivalent to 3 cars. During the field study, vehicles who wanted to make a left turn maneuver from the major road, slowed down and caused a queue behind.

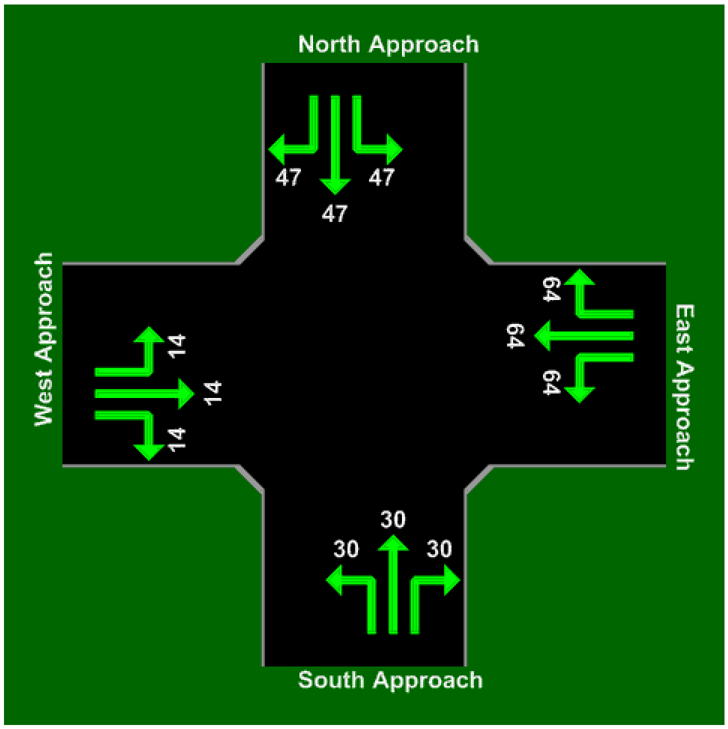

Figure 6-12 Queue Distance for the Four Leg Intersection.

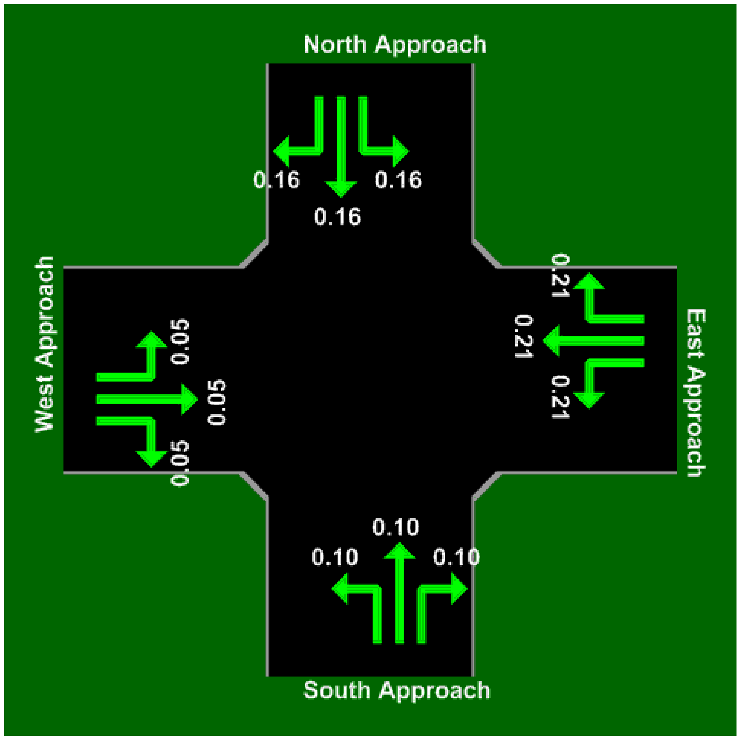

Figure 6-13 Queue Storage Ratio for the Four Leg Intersection.

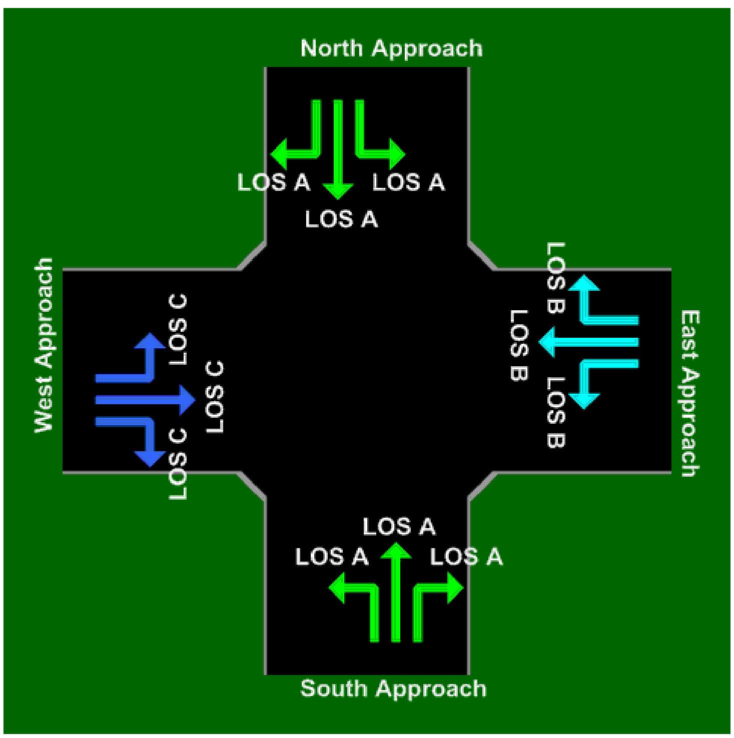

Figure 6-14 Level of Service for the Four Leg Intersection.

According to the modeling results (See Figure 6-14), the minor road has a level of service (LOS) C on the west approach and LOS B on the east approach. According to the HCM, a level of service LOS C has a delay from 15 s to 25 s, and the LOS B has a delay of 10 s to 15 s (HCM, 2000). No vehicle on the west access to wait in the stop line of more than 15 seconds. The longest waiting time of a vehicle was almost 15 seconds.

6.2.1 Calculated Critical Gaps for Four Leg Intersection

The same volumes and intersection characteristics as the previous model were used to perform this model. The program gives the user the option to change critical gap times and follow up times, allowing a more accurate roadway conditions representation. Table 6-3 presents the input critical gaps, which substitute HMC standards.

The queue obtained from aaSidra was compared with the field queue seen during the study period. The modeling gave a queue of 32 ft for the east approach and 7 ft for the west approach (minor road). Also the major road had a queue of 43 ft on the north approach and 27 ft on the south approach (See Figure 6-15). Like before, the queue storage provided for every approach is 300 ft in length. Figure 6-16 shows the queue storage ratio for every intersection approach. Again if the average car length is 16 ft, the longest queue distance given by aaSidra (43 ft) is equal to 3 cars. The longest queue seen in the major road was equivalent to 3 cars. The longest queue on the minor road is 32 ft, equivalent to (two) 2 cars.

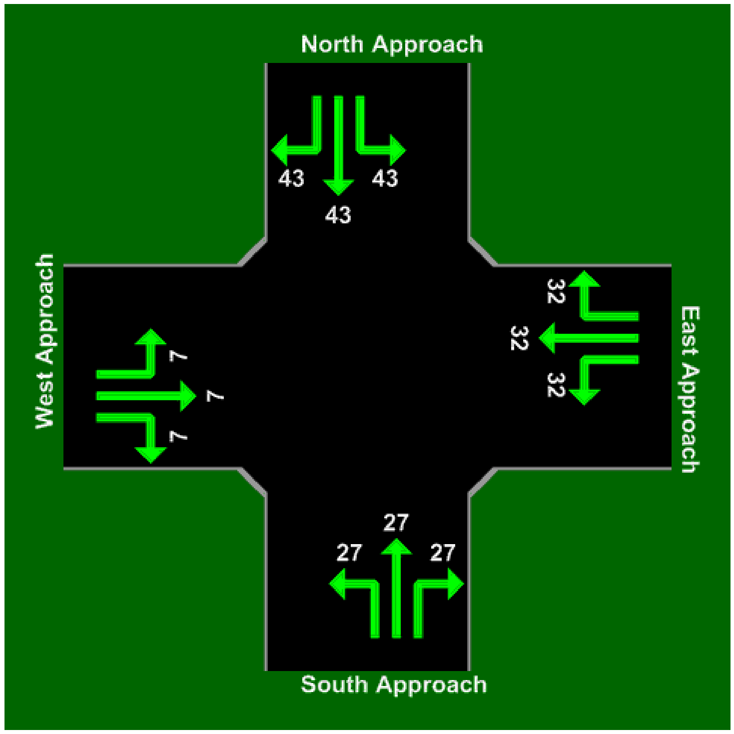

Figure 6-15 Queue Distance for Critical Gaps Found in the Field.

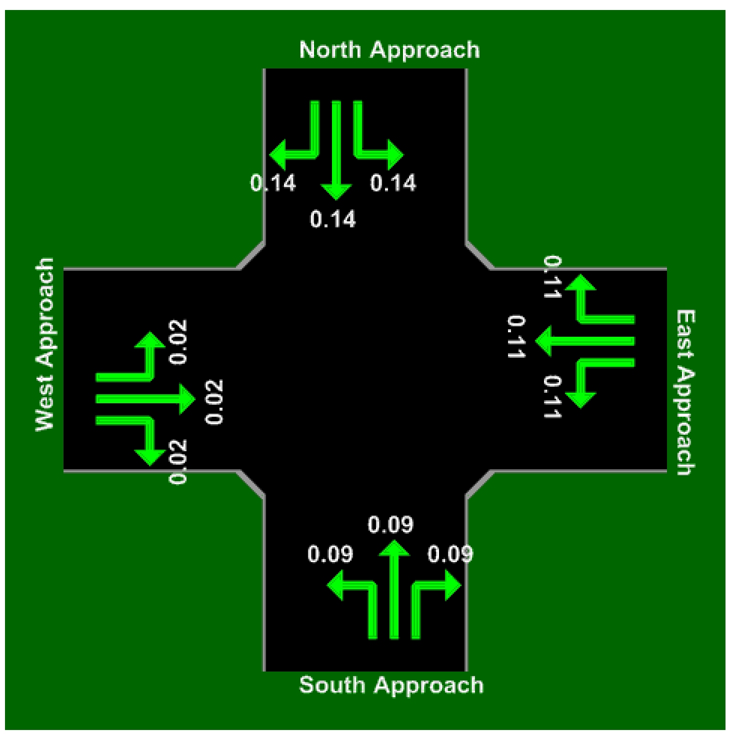

Figure 6-16 Queue Storage Ratio for Critical Gaps Found in the Field.

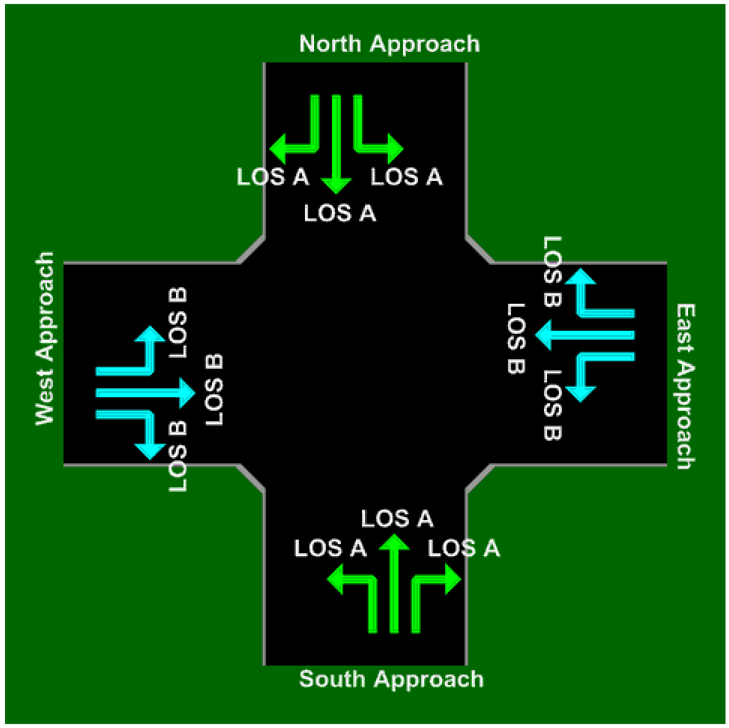

Figure 6-17 Level of Service for Critical Gaps Found in the Field.

Modeling results (See Figure 6-17) gave a LOS B to the minor road. As mentioned before, LOS B is equivalent to a delay of up to 15 s; this model represents the intersection more accurately.

After seeing the modeling results, it can be concluded that default critical gaps (HCM) cause an overestimation of queues in the intersection. Also, performance measures are affected negatively; the program presents an intersection with worst conditions than those seen on the field.

7 Conclusions and Recommendations

This chapter presents the conclusions achieved from field observations and the gap acceptance study, and also the recommendations for future studies. Conclusions are given for observations done during field studies, critical gaps for every maneuver, and also modeling results. During the intersection video recording, a series of driver behaviors made it more difficult to select a reference point to determine the gap. Drivers, did not come to a complete stop before entering the intersection, drivers force their own gaps even during non-peak hour periods, between others. The most important conclusion drawn from the study is if simulation programs with incorporated deterministic models are used, there should be a calibration of parameters, such as gaps, in order to develop a more accurate simulation.

7.1 Conclusions

The main purpose of this study was to determine critical gap times for intersections in the Mayagüez area. It is important to emphasize that the critical gap times obtained in the study can not be generalized to all of Puerto Rico. The island has different characteristics and driving behavior depending on the geographical location. Drivers in the San Juan metropolitan area tend to be more aggressive than drivers in Mayagüez area. After studying different gap acceptance methodologies, the most simple was Raff's method. This method was developed originally considering only lags, for this study gaps were also considered. Even though is not the most accurate model to determine critical gaps, is accurate enough. When researching gap acceptance studies, all theories for gap acceptance studies are defined as a straight forward study. They do not mention driver behavior considerations and problems defining reference points. To ease data collection, intersection conflict points were taken as reference for gap acceptance. Two suitable intersections were found in the Mayagüez area. Both have similar geometrical characteristics.

A gap acceptance study for chosen Two-way Stop Controlled intersections was developed successfully. During the intersection video recording a series of driver behaviors made it more difficult to select a reference point to determine the gap. Drivers, especially in right turn maneuvers in the minor stream did not come to a complete stop before entering the intersection. While decelerating, minor street drivers were monitoring gaps provided in the major traffic streams before arriving at the intersection. If the lag was large enough for acceptance, then drivers continued without stopping.

During the study periods (non peak hour), drivers on the minor traffic stream force their own gaps. When drivers wait at a stop for some time and reject several gaps, drivers become impatient, block the incoming flow of the nearest traffic stream, and wait for available gaps. This behavior should occur during congested conditions, however it was observed during not congested conditions. Drivers who did stop at the intersection did not have a consistent stop position, even though there was a marked stop line at the intersection. On occasions vehicles made a full stop and moved forward to asses the situation and wait for an adequate gap. This minimizes the time actually stopped at the intersection.

When drivers in the major traffic stream wanted to make a left turn maneuver with vehicles arriving in the opposite direction, they delayed the arrival time, having to wait less time at a full stop for a sizeable gap. Drivers also accelerated before entering the intersection in order to “beat” the gap.

All of these behaviors made it more difficult to determine the reference point for data collection and calculate the rejected gap. Conflict points for each case give better reference for time collecting.

Critical gaps for two TWSC intersections in the Mayagüez area were determined successfully. Critical gap times were divided into three sections, left turns from the minor road, right turn from the minor road, crossing maneuvers and left turns from the major road. Crossing maneuvers are included in the left turn from the minor road data. During field studies it was observed that drivers who wanted to make a crossing maneuver use the same critical gap as those making left turn maneuvers from the minor road.

7.1.1 Left Turn from the Minor Road

The first maneuver studied was the left turn from the minor road. Gap acceptance studies for left turn from the minor road maneuver are the most difficult one to develop. Left turn maneuvers have the lowest priority on an intersection. Therefore, gap acceptance studies for this type of maneuver should consider gaps available in both directions of the main traffic stream. The study determined that driver majority (55.5%) will accept gaps in the range of 5 or greater. Also, all vehicles (100%) will accept gaps greater than 7 seconds. For left turn lane from the minor road maneuver the critical gap obtained from the graph is 5.1 seconds.

7.1.2 Right Turn from Minor Road

The gap acceptance study for right turn from the minor road maneuver should consider gaps available in the nearest lane of the main traffic stream. Analysis determined that 57% of the drivers will accept gaps in the range of 4 or greater and all vehicles (100%) accept gaps greater than 7 seconds. The critical gap for right turns from the minor road was found to be 4.7 seconds.

7.1.3 Left Turn from Major Road

The final maneuver studied was the left turn from the major road. This study should considered gaps available in the opposite direction on the major traffic stream. Gaps in the range of 4 or greater will be accepted by vehicles (100%) of the time. Although no group has a 50% of acceptance, but the 3-3.99 interval has a 46.67%, being close to the median. The critical gap for left turns from the major road was determined to be 3.95 seconds, inside the 3-3.99 interval.

7.1.4 HCM Critical Gap Comparison

Critical gaps from the Highway Capacity Manual gap and the critical gaps obtained from field studies were compared. The Following tables compare HCM critical gap times with the ones found in the field. The time difference between critical gaps can be up to two (2) seconds depending on the maneuver. The critical gap for the left turn from the major road HCM (4.1 seconds) and the calculated from intersection data (3.95 seconds) have a time difference of 0.15 seconds for a 3.8 % change. The right turn from the minor road critical gap is 4.7 seconds and the left turn from the minor road has a critical gap of 7.1 seconds. Critical gaps for, Right turn from the minor road and Left turn from the minor road respectively are 1.5 seconds and 2 seconds less than the HCM critical gaps. Right turn from the minor road has a percent of difference of approximately 30%; also the critical gap for left turns from the minor road has a percent of difference of 40%. It can be clearly seen that Puerto Ricans in the Mayagüez area need less time to enter the intersection. Table 5-9 presents critical gap time difference between HCM and Experimental critical gap.

7.1.5 Critical Gap inputs in aaSidra

To determine how critical gap times affect modeling, the program's output queue was compared with the queue seen during field study. The modeling gave a queue of 532 ft (approximately 29 passenger cars) for a 500 ft storage length. The queue storage ratio was 1.06, meaning there is a 1.06 times more queue than space provided for storage. The 532 ft queue was not present in the field during the study period. The maximum number of passenger vehicles counted in the longest queue was 10 cars (approximately 180 ft).

After substituting the default critical gaps with those found in the filed, the modeling gave a queue of 109 ft in the minor road. The queue storage ratio found was .22, meaning there is a queue equal to 22 percent of the space provided for storage. During the period studied, queues did not reach the freeway (PR-2).

After seeing the modeling results, it can be concluded that default critical gaps (HCM) cause a queue overestimation in the intersection. Also, performance measures are affected negatively; the program presents an intersection with worst conditions than those seen on the field.

When simulation programs with incorporated deterministic models are used, there should be a calibration of parameters, such as gaps, in order to develop a more accurate simulation. The program user can iterate the critical gap until the queue given by the model resembles the observed field queue. This study has clearly revealed the fact that gap acceptance parameters in the Mayagüez area of Puerto Rico are different from those used by default in the HCM and commercial simulation models. Therefore, the best practice for using these simulation models should include the application of a thorough methodology for the analysis of a traffic system like an intersection. The methodology should include data collection for both performance analysis and model calibration. In the case of unsignalized intersections the model calibration should be produce the gap acceptance parameters suitable for the intersection under study.

Such methodology has been developed previously by Silva (1990), Valdes and Pipicano (1990) and has been used for the analysis of complex signalized intersections in previous works by Buitrago (1992), Diaz Godineaux (2004) and several good practitioners in their professional practice.

7.2 Recommendations

Gap acceptance studies rely on how efficiently field data is gathered from the intersections. To make the study more accurate, more cameras should be used in every access to record the exact moment the vehicle passes the reference point.

Driver behavior models representing aggressiveness and impedance effects should be compared using critical gaps found in studies performed in Puerto Rico.

Recommendations for Future Research

The following recommendations are done, in order to attain a critical gap that could be used for any intersection in Puerto Rico.

1. Conduct field studies on intersections representative of all areas of Puerto Rico. Studies in the San Juan metropolitan area, and other parts of the Island.
2. Use other critical gap models for a more accurate analysis and compare it with Raff method.
3. Use different modeling programs to compare how gap acceptance behavior cause changes in intersection capacity.
4. Make a more in depth study using more priority intersections to determine if Puerto Rican drivers use the same critical gap for both left turn maneuvers and crossing maneuvers.
5. Evaluate and determine the impact of driver behavior in critical gaps for left turn maneuvers from the major road.
6. Evaluate how gender, roadway conditions, geometry and vehicle type affect gap acceptance and critical gap times. Male drivers have a tendency to drive differently to female drivers; critical gaps should be different for both sexes. Also, the automotive industry is always manufacturing better and more responsive cars. It would be interesting to explore the following questions: Are drivers taking more risks and entering the intersection with a smaller critical gap because of the vehicle driven? And what differences are in accepted critical gaps if the vehicle providing the gap is a heavy vehicle?

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Appendix A

Clearance-Gap and Spacing Headway Concept

The difference between spacing and clearance is the vehicle length. Similarly the difference between gap and headway is the time equivalence of the vehicle length. The following equations give the relation between the microscopic variables and vehicle speed (Khisty and Lall, 1998).

$$g = h - \left(\frac{L}{v}\right)$$

$$c = g \times v$$

$$\begin{aligned} &g = gap\ (s) \\ &L = length\ of\ vehicle\ (ft) \\ &c = clearance\ (ft) \\ &h = headway\ (s) \\ &v = speed\ (ft/s) \end{aligned}$$

Clearance-Gap and Spacing Headway Concept