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Safety and Operational Assessment of Gap Acceptance Through Large-Scale Field Evaluation

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SAFETY AND OPERATIONAL ASSESMENT OF GAP ACCEPTANCE THROUGH LARGE-SCALE FIELD EVALUATION

A Thesis Presented

By

STEVEN M. TUPPER

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
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Civil and Environmental Engineering

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Approved as to style and content by:

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ABSTRACT

SAFETY AND OPERATIONAL ASSESMENT OF GAP ACCEPTANCE THROUGH LARGE-SCALE FIELD EVALUATION

May 2011

STEVEN M. TUPPER, B.S.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST

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Directed by: Professor Michael A. Knodler, Jr.

Given that "driver error" is cited as a contributing factor in 93 percent of all crashes, understanding driver behavior is an essential element in mitigating the crash problem. Among the more dangerous roadway elements are unsignalized intersections where drivers' gap acceptance behavior is strongly correlated to the operational and safety performance of the intersection. While a basic understanding of drivers' gap acceptance behavior exists, several unanswered questions remain.

Previous work has attempted to address some of these questions, however to date the research has been somewhat limited in scope and scale due to the challenges of collecting high fidelity gap acceptance data in the field. This research initiative utilized software newly developed for this project to collect gap acceptance data on 2,767 drivers at 60 sites, totaling 10,419 driver decisions and 22,639 gaps in traffic. This large-scale data collection effort allowed many of these remaining questions to be answered with an improved degree of certainty.

This research initiative showed that naturalistic driver gap acceptance behavior can realistically be observed and accurately recorded in the field in real time using a

newly developed software tool. This software tool and study methodology was validation using high fidelity video reduction techniques.

This research compared different methods of analyzing gap acceptance data, in particular determining critical gap, seeing that the method used significantly affects the results. Conclusions were draw about the merits of each of the ten analysis methods considered.

Through the analysis of the large data set collected, the research determined that there exist appreciable and identifiable differences in gap acceptance behavior across drivers under varied conditions. The greatest differences were seen in relationship to wait time and queue presence. If a driver has queued vehicles waiting behind them and/or has been waiting to turn for a long period of time, they will be more likely to accept a smaller gap in traffic.

Additionally, an analysis of gap acceptance as it relates to crash experience identified critical situations where a driver's gap acceptance behavior contributes to the occurrence of a crash. Characteristics of the driver such as gender and approximate age associated with specific crashes were examined. Teen drivers were identified as exhibiting aggressive gap acceptance behavior and were found to be overrepresented in gap acceptance related crashes. Ultimately, a better understanding of the driver and environmental factors that significantly contribute to increased crash risk will help guide the way to targeted design solutions.

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CHAPTER 1

INTRODUCTION

In the field of transportation safety it is well understood that crashes can be attributed to failures of the road, the vehicle, the user, or some combination thereof. One common driving task that requires each of these elements exists when drivers are required to make a gap acceptance decision either merging into or crossing a lane of traffic. Such a maneuver is depicted in Figure 1 where the black vehicle is attempting to make a right turn and the driver must decide whether or not to accept the 5 second gap that they face.

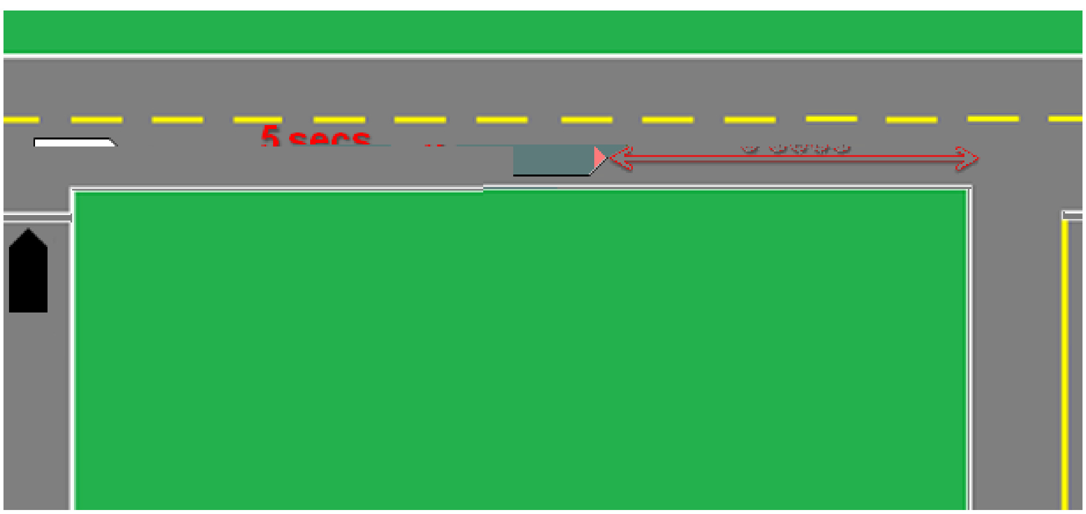


Figure 1. Depiction of Typical Gap Acceptance Situation

Given that "driver error" is cited as a contributing factor in 93 percent of all crashes, understanding driver behavior is an essential element in mitigating the crash problem (1). Among the more dangerous roadway elements are unsignalized intersections where driver behavior is directly related to the operational and safety performance (1). More specifically, drivers' gap acceptance decisions have serious consequences, and in many situations, the result of a poor gap acceptance decision is a crash.

The process of a driver's gap acceptance decision is driven by an individual's goals and attitudes and is affected by stimuli from their surroundings. It is widely accepted that the best method of observing naturalistic driver behavior is through field investigation (2). The difficulty is that current data collection methods are limited in the quality and quantity of data that can be reasonably gathered.

Problem Statement

A need exists to foster a greater understanding of drivers' gap acceptance behavior based upon real-world empirical data. Understanding this aspect of driver behavior is critical to transportation professionals dealing with roadway design and safety.

The mostly commonly used metric of drivers' gap acceptance behavior is critical gap: "the minimum time interval in the major-street traffic stream that allows intersection entry for one minor-street vehicle (3)." In practice, transportation professionals look up standard values of critical gap, as reported in the *Highway Capacity Manual 2000,* and apply a few basic corrections factors to reflect the site specific conditions. The problem with this current method is two-fold. First, the correction factors only account for a few basic factors that are likely to affect gap acceptance behavior. Some of the arguably most influential factors, such as local driver demographics, are not included. Many studies have found that factors such as driver age and sex (4; 5; 6; 7; 8) have a significant effect on drivers' gap acceptance behavior. Second, the standard values of critical gap, as well as the correction factors, are based on a relatively limited number of small-scale studies. In order to develop a greater understanding of drivers' gap acceptance behavior a large-scale field investigation must be undertaken.

Inaccurate or incorrectly used information on how drivers utilize gaps in traffic can lead to inappropriate design decisions. If overly passive gap acceptance behavior is assumed (large critical gap), roadway elements will be overdesigned wasting money, compromising efficiency, and possibly have deleterious effects on other elements of the roadway system. If overly aggressive gap acceptance behavior is assumed (small critical gap), the results will be a design that has insufficient capacity for turning movements and can even force drivers to make gap acceptance decisions in dangerous situations. Having access to a more accurate estimate of critical gap that accurately reflects the conditions under which it is be applied would lead to safer and more efficient roadway design.

When drivers make poor gap acceptance decisions there is a strong likelihood that the result will be a crash. The resulting crashes, often angle crashes, are some of the most severe crashes (1). Few studies exist on crashes related to poor gap acceptance decisions, but those that have been completed have begun to shed light at some of the underlying causes (9). Ultimately, a better understanding of the driver and environmental factors that significantly contribute to increased crash risk will help guide the way to targeted design solutions.

Despite the critical nature of this data, to date, there have not been any large-scale studies due mostly to the inherent challenges of collecting such data. To this end, the research initiative proposed uses of a new data collection tool that allows for the collection of large, high-fidelity data sets on gap acceptance behavior. Having access to this tool, transportation researchers will have the ability to collect larger, more detailed samples in the field in a relatively cost effective and timely manner.

Scope of Research

This research examined drivers' gap acceptance behavior in a real-world setting. Desired driver interactions occurred without any outside stimulus to make sure naturalistic behavior is observed. Drivers had no knowledge that their behavior was being observed and therefore did not alter their normal behavior patterns during the experiment. Careful selection of experiment locations ensured all factors being analyzed as contributing factors to drivers' gap acceptance behavior were captured. Although even larger-scale data collection is possible, the intended scope of this research will be limited to locations in Massachusetts and Oregon. Having validated the research methodology, future research initiatives could be replicated in other states.

Research Goals

Based upon the existing research needs and the potential application of a new data collection data relating to drivers' gap acceptance behavior, a series of proposed goals were proposed. The overarching goal of this research effort was to improve the understanding of driver behavior elements as related to gap acceptance. The research approach proposed herein is multifaceted and includes many facets of the gap acceptance issue in the form of supporting secondary goals. The following goals were established to address aims of this research initiative:

- Determine if naturalistic driver gap acceptance behavior can feasibly be observed and accurately recorded in the field in real time;
- Compare different methods of analyzing gap acceptance data, in particular determining critical gap, to see if the method significantly affects the results;
- Identify differences in gap acceptance behavior across drivers under varied conditions in the field; and
- Determine if differences in drivers' gap acceptance have implications on safety that can be seen in crash data.

These proposed research goals are organized into four research objectives detailed in the following sections.

Research Objectives

Four research objectives have been developed to address the goals of this research initiative. Background material supporting the four developed research objectives are presented later in this section. The four research objectives are:

1. *Detailed data on driver gap acceptance behavior can be accurately and efficiently collected in the field with the aid of computer software, and the results can be validated using parallel field video recording.*
2. *The method in which gap acceptance data is analyzed can have profound and identifiable effects of the conclusions of the analysis.*
3. *There exist appreciable and identifiable differences in gap acceptance behavior across drivers under varied conditions.*

4. *Differences in gap acceptance behavior across drivers under varied conditions have effects on safety that can be seen in the analysis of gap acceptance related crashes.*

The following sections provide background information on the research objectives and the context in overall examination of gap acceptance behavior.

Research Objective 1 - Develop and Validate Data Collection Tool

- *Detailed data on driver gap acceptance behavior can be accurately and efficiently collected in the field with the aid of computer software, and the results can be validated using parallel field video recording.*

As was discussed in greater detail in the previous chapter, up until now, given current technologies, large-scale gap acceptance studies have been infeasible. The challenges resulting from the complex nature of syncing multiple data inputs by multiple users, including timing devices, results in a field collection process that is infeasible for all but the smallest sample sizes. If video capture is used, the tremendous, time-consuming effort required to reduce the data results in a process that is equally infeasible for sample sizes necessary to draw conclusions with a high degree certainty. To address this particular research objective, a software application that can handle some of these time and labor intensive tasks was developed and tested. This software functions in a similar fashion to commercial products that are used for gap availability study, but is able to collect both gap availability and gap acceptance data. The tasks that relate to this objective include field testing of the new software and a video validation to make sure that the data collection can accurately reflect what occurs in the field. This software can fulfill a much needed role in the data collection toolbox.

Research Objective 2 - Analysis by Method

- *The method in which gap acceptance data is analyzed can have profound and identifiable effects of the conclusions of the analysis.*

Many different methodologies have been proposed and utilized for the purpose of analyzing gap acceptance data. There is an inherent desire to understand the possible impact of differing conclusions being drawn based upon the method employed. As with other aspects of transportation engineering, uniformity could lead to more consistent analysis nationwide. The question that remains is whether a single method can prove to be the "best" or is it dependent upon individual situations. While some research has compared different methods, it has traditionally been undertaken for the express purpose of proving that a particular author's new method is superior to old methods. Answering the research objective will compare methodologies, with the benefit of data from a large-scale field investigation, without bias as to the most effective and efficient method.

Research Objective 3 - Analysis by Factor

- *There exist appreciable and identifiable differences in gap acceptance behavior across drivers under varied conditions.*

As discussed in the previous chapter, differences in gap acceptance behavior across drivers under varied conditions appear to exist. A detailed description of such factors, including those related to the type of maneuver, site characteristics, visit characteristics, and vehicle/driver characteristics are included in later sections. Drawing conclusions about the effects of many of these factors are important to fully understanding gap acceptance behavior. Unfortunately, given the small sample size of previous experiments, the conclusions have at times been questionable. The large-scale field study conducted as part of this research initiative allowed these characteristics to be observed in a natural setting with a large number of individuals.

Research Objective 4 - Connecting Driver Behavior to Crash Experience

- *Differences in gap acceptance behavior across drivers under varied conditions have effects on safety that can be seen in the analysis of gap acceptance related crashes.*

It is important to understand the differences that exist across drivers under varied conditions, however knowing if these differences translate into safety risks is equally important. Looking at crashes where poor gap acceptance decisions contributed to a crash helps develop a better understanding of when this complex decision making process breaks down. Ultimately, a better understanding of the driver and environmental factors that significantly contribute to increased crash risk will help guide the way to targeted design solutions.

CHAPTER 2

BACKGROUND

Gap acceptance is a task that drivers perform so regularly that it occurs nearly at a subconscious level. However, being able to successfully complete this task is essential in order to drive safely. Not all drivers display the same gap acceptance behavior and even the same driver can react differently in different locations and under different conditions. Researchers have always sought to better understand this behavior. The following section provides a review of the pertinent literature as it relates to the scope of this research initiative. Specifically, it is important to consider several relevant areas of previous research, including:

- Gap availability studies;
- Gap acceptance studies;
- Critical gap;
- Factors affecting gap acceptance behavior; and
- Safety implications.

Each of these topics is discussed in detail throughout this chapter.

Gap Availability Studies

To most transportation professions, the term "gaps study" refers to a gap availability study. This field study tells the profession the number and size of gaps available to drivers or other road users such as bicyclists or pedestrians. The most common data collection method is to use a handheld count board, such as Jamar® TDC-8, where buttons are held when there is a gap in the traffic stream (10). This is a fairly simple way to gather information on the size and frequency of traffic gaps. This study does not however provide any information about how these gaps are being utilized by drivers. This knowledge is based on results of previous gap acceptance studies and applied to the current location.

Gap Acceptance Studies

Gap acceptance data can be collected and analyzed in a number of different ways; however, the principles of each method are quite similar. The best way to collect data on drivers' gap acceptance behavior is through direct field observations. (2) Drivers will exhibit their normal behavior patterns only when they have no knowledge that their behavior is being observed. The most basic method of data collection involves multiple observers located in the field with different pieces of equipment including stopwatches working in unison to collect data. This method is logistically challenging and impossible with large traffic volumes due to the human element. Given the large number of observers required and the amount of time required for data reduction, this method is infeasible for all but the very small sample sizes. Currently, the most common way to observe gap acceptance behavior in the field is to set up video surveillance equipment at the site and then process the data off-site. Processing the data generally involves slowly advancing the recording and capturing time stamps of each vehicle passing through the intersection. This is a very time consuming process, however the results are generally thought to be quite accurate. Unfortunately, the time it takes to reduce the data makes this method equally infeasible for large data sets.

A newer alternative to field studies are simulator studies where researchers have the ability to prescribe the gaps the driver will observe (11). While simulator studies have been conducted for a number of years with promising results (6), questions remain about the drivers' perceived realism of this complex behavior.

Critical Gap

The concept of critical gap has evolved over time, but, in general, as referenced in the *Highway Capacity Manual 2000*, the critical gap is "the minimum time interval in the major-street traffic stream that allows intersection entry for one minor-street vehicle. (3) Greenshields made early reference to critical gap referring to it as the "acceptable average minimum gap". (12) His definition of the critical gap is the gap that is accepted by 50 percent of drivers. This interpretation of critical gap was popularized by Raff in the late 1940's. His method of analysis of gap acceptance data, as shown below, is still one of the most common.

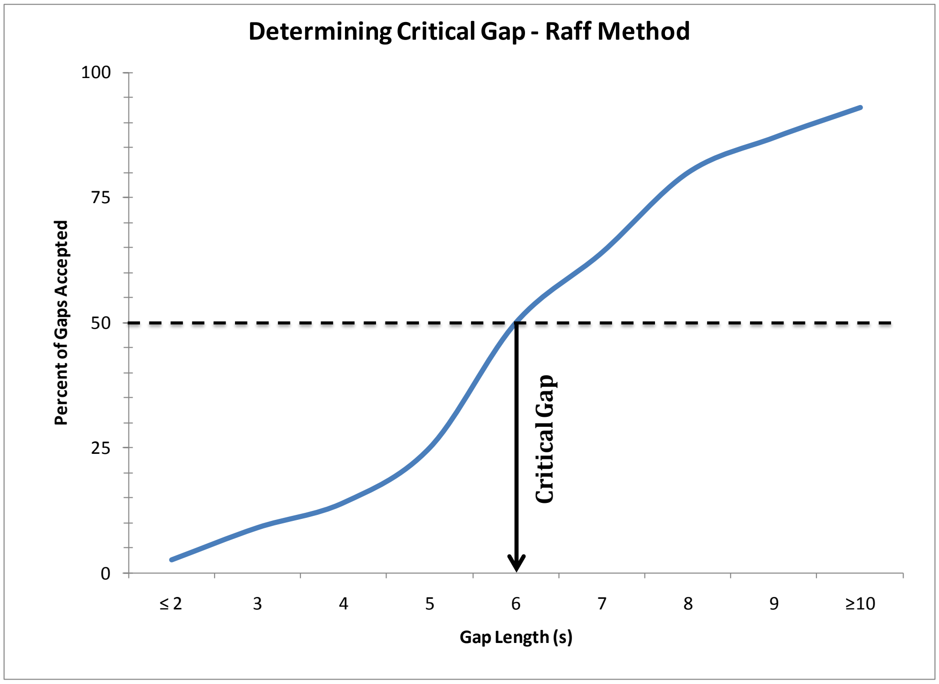


Figure 2. Determining Critical Gap Using the Raff Method

Other models including Ashworth (1970), Siegloch (1973), Harders (1968), Hewett (1983), and Troutbeck (1992) have also been suggested as alternative methods for gap acceptance analysis. More recently, models have been proposed using many different methodologies such as maximum likelihood and Logit models. (13; 14; 5; 15; 16). Of these, Troutbeck (1992) has seen the most use, although due to its relative complexity compared to Raff et al. (1950), it remains less utilized. While today there exist more than 20 models worldwide for estimating critical gaps, in practice the most common models are that of Raff et al. (1950) and Troutbeck (1992).

For most practicing engineers, critical gap is determined not through field study but by applying a formula, most often as presented in the *Highway Capacity Manual 2000*. The formula that applies to two-way stop controlled intersections (as will be studied in this research initiative), draws on past research efforts to develop a formula for critical gap that takes into account the type of turning maneuver, number of lanes on the major street, presence of heavy vehicles, approach grade, T-intersection geometry and two-stage gap acceptance (3).

Factors Affecting Gap Acceptance Behavior

Gap acceptance behavior is affected by many different factors. These include factors such as those relating to the site/location where the maneuver takes place, the conditions at the time of action, and driver/vehicle involved.

Many of the site characteristics have been studied such as number of lanes, speed limit (6; 17; 7), sightline restrictions (18), and unusual geometry (19; 20). At times there have often been conflicting results on the effects of these factors. Other site characteristics that may be a factor include roadway functional classification, type of traffic control device, excessive speeding, and crash experience. Some of these factors have been addressed, but in less formal setting.

Factors that have had less attention paid to them are the factors associated with the conditions at the time of the maneuver. These include the weather, road conditions, time of day, day of week, and gap availability at the time of the study.

Driver factors are some of the most commonly studied factors; however the results tend not to be used in practice. These factors most commonly studied include driver age and sex (4; 5; 6; 7; 8). Vehicle type, presence of a passenger in the vehicle, and presence of a queue behind the vehicle may also be important factors but have not been widely studied.

For all of the factors studied, the results have been far from conclusive. While some factors have shown strong effects across many studies, such as driver age, others, such as major street speed limit, have shown mixed effects. Some of these differences may be associated with regional differences or the relatively small sample sizes that the studies have relied on.

Safety Implications

One area where there is certainly consensus is that drivers' gap acceptance decisions have serious consequences. When drivers make poor gap acceptance decisions there is a strong likelihood that the result will be a crash. The resulting crashes, often angle crashes, are some of the most severe crashes (1). Few studies exist on crashes related to poor gap acceptance decisions, but those that have been completed have begun to shed light at some of the underlying causes (9). Ultimately, a better understanding of the driver and environmental factors that significantly contribute to increased crash risk will help guide the way to targeted design solutions.

CHAPTER 3

STUDY DESIGN AND METHODOLOGY

The study design and methodology chapter is divided into four section related to each of the four research objectives. The methodology employed in approaching each of these research objectives is detailed in the following sections.

Research Objective 1 - Develop and Validate Data Collection Tool

Two tasks relating to this objective were the large scale field study and the video validation.

Field Study

The field study required the most time and effort throughout this project. The field study consisted of visits to a wide variety of sites to collect data on drivers' gap acceptance behavior.

Experimental Protocol. This effort was carried out using a program developed at UMass and refined for this project on a Microsoft Access® platform. The programs will be referred to as the "GAPS," an acronym for Gap Acceptance Processing System. This GAPS programs can be operated by one person on a laptop computer in the field. A second observer is required if detailed vehicle and driver characteristics are to be simultaneously collected was done during the field study relating to this research initiative. All persons collecting data were thoroughly trained in proper data collection procedure and use of the software. A data collection packet detailing the collection procedure and containing supplemental data collection worksheets were also given to everyone in the field for their reference. The "Gap Acceptance Study Packet" given to observers in the field is presented on the following pages. The first page provides an overview of what the observers will be doing as part of the study. The second page explains the details of how to collect data using the GAPS program. The third page is a provided for the observer to record details about the site and conditions under which the observations are being made. The final page is a copy of the vehicle/driver data collection sheet that the second observer filled out for each vehicle exiting the minor street. Once the observation is complete, the data collection sheets and a copy of the electronic data were returned to the office for analysis.

Gap Acceptance Study Packet

Contents:

Instructions to Work "gap" Software

Site Description Form

Supplemental Vehicle Information Collection Sheet

This packet contains all of the information necessary to collect data for the Gap Acceptance Study. When you go out to collect data for the study you should have a one copy of the instructions, one copy of the site description form for every site you are visiting, and 10 supplemental vehicle information collection sheets for each site.

Most of the sites will be T-intersections although there may be some 4-leg-intersections as well. Picking busy locations and busy times of days with minimize the amount of time needed at each location. A minimum of 30 minutes should be spent at each site. Additionally, a minimum of 30 vehicles (although 50 is ideal) should be collected at each site. A viewing location with a clear view of the vehicles exiting the minor streets is crucial, but make sure you always keep safety in mind.

Figure 3. Gap Acceptance Study Packet - Collection Basics

Instructions to Work "gap" Software (must be run in Access 2007):

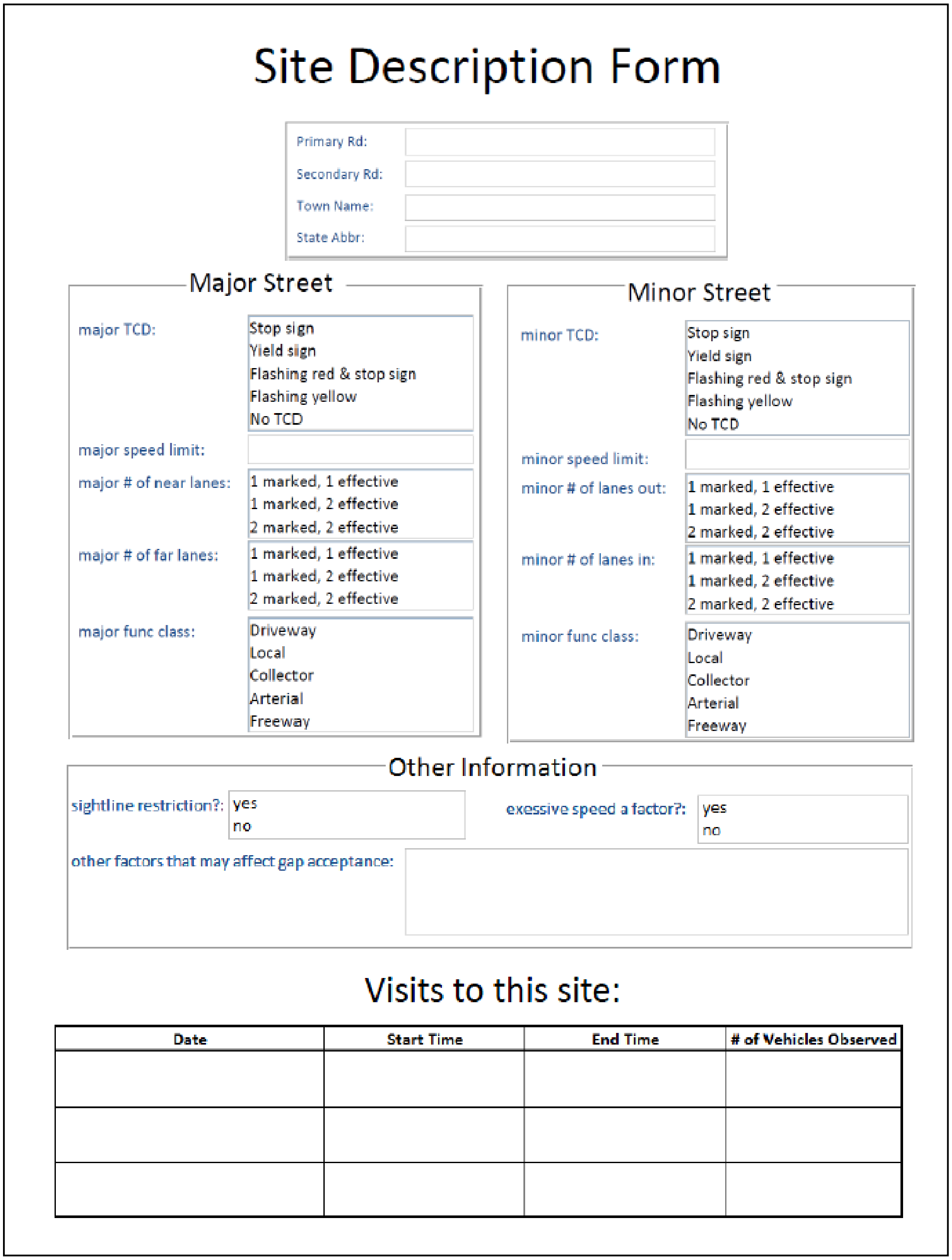
1. Enable macros.
2. When loading the database onto a new computer make sure to start with the "gaps - empty - user must enter new db_id" file. Open the 'db' table and enter a 5-digit number that must be unique to that machine. The ID will be linked to that machine and will allow for easy merging of datasets from different machines.
3. If this is the first study you have done you must open up the "observer" table (under "lookups" heading) and add your name.
4. Once you are at a site you must enter information about the site by clicking on the 'New Site' button on the 'main' form. Fill in the location, <u>the 'db_id'</u> and all other requested information. This information should also be recorded on the "Site Description Form" (attached) to keep things organized. If information on a site needs to be modified open up the 'site' table under the analysis heading and change it manually. Note: Speed limit exiting a parking lot is assumed to be 20 mph if not marked. Marked lanes are those designated by pavement markings or signs, whereas effective lanes are then number of lanes vehicles use (ie. a wide one lane road may be wide enough for left and right turning vehicles to be side by side).
5. Next, from the 'main,' select the site you are at in the top box and then click the 'Add New Visit' button. Fill in all of the information requested. Once you click 'Add Visit' a new row will appear in the bottom box of the 'main' window. Select that row and then click 'Record Observations'.
6. You will now see the "entry" form that will allow you to collect the data. The function of each button is labeled, but here is a basic overview:

   The 'S' and 'D' keys must be **held down** when the near and far side of the major road respectively are blocked by passing vehicles. If there are two lanes going the same directions the side if blocked if there is a vehicle in either lane. If a vehicle approaches on the near side and make a right turn into the minor street tap the "S" button as it turns since they inhibited any vehicle coming out of the minor street from making a turn.

   The 'J' and 'L' keys must be **tapped** when a vehicle arrives at the intersection from the minor approach in the left or right lane respectively. If there is vehicle on an opposing minor street that will likely interfere with the subject vehicle ignore that subject vehicle.

   The 'U', 'I', 'O', and 'P' keys must be **tapped** when the vehicle waiting on the minor street turns onto the major street by either turning left or right. **After** any of these keys is tapped the VID of that vehicle will be displayed next to the corresponding box. Call this number out (or have the second observer look at it) so that they can record that number along with the vehicle information collected on the "Supplementary Vehicle Information Collection Sheet." (copy attached) Be sure to check to make sure you are in sync with the other observer and that the vehicle IDs are matching up. Note that the ID for left lane vehicles are even and the right lane vehicles are odd, this can easily cause confusion if you are not careful.
7. Once you are finished recording observations you may close the 'entry' and 'main' forms. The data will be saved automatically.
8. If you collected supplementary vehicle information you must now enter that data. From the 'main' form click on the 'Add Vehicle Data' button. All vehicle records are now displayed. <u>Match up the VID recorded on your sheet to 'id' in the top left box</u> and input all of the information collect. Proceed to the next record and fill in data being sure to check that the VID is correct.
9. Repeat steps 4 – 8 for each location studied.

Figure 4. Gap Acceptance Study Packet - Software Instructions



Site Description Form

Primary Rd:	
Secondary Rd:	
Town Name:	
State Abbr:	

Major Street

major TCD:	Stop sign Yield sign Flashing red & stop sign Flashing yellow No TCD
major speed limit:	
major # of near lanes:	1 marked, 1 effective 1 marked, 2 effective 2 marked, 2 effective
major # of far lanes:	1 marked, 1 effective 1 marked, 2 effective 2 marked, 2 effective
major func class:	Driveway Local Collector Arterial Freeway

Minor Street

minor TCD:	Stop sign Yield sign Flashing red & stop sign Flashing yellow No TCD
minor speed limit:	
minor # of lanes out:	1 marked, 1 effective 1 marked, 2 effective 2 marked, 2 effective
minor # of lanes in:	1 marked, 1 effective 1 marked, 2 effective 2 marked, 2 effective
minor func class:	Driveway Local Collector Arterial Freeway

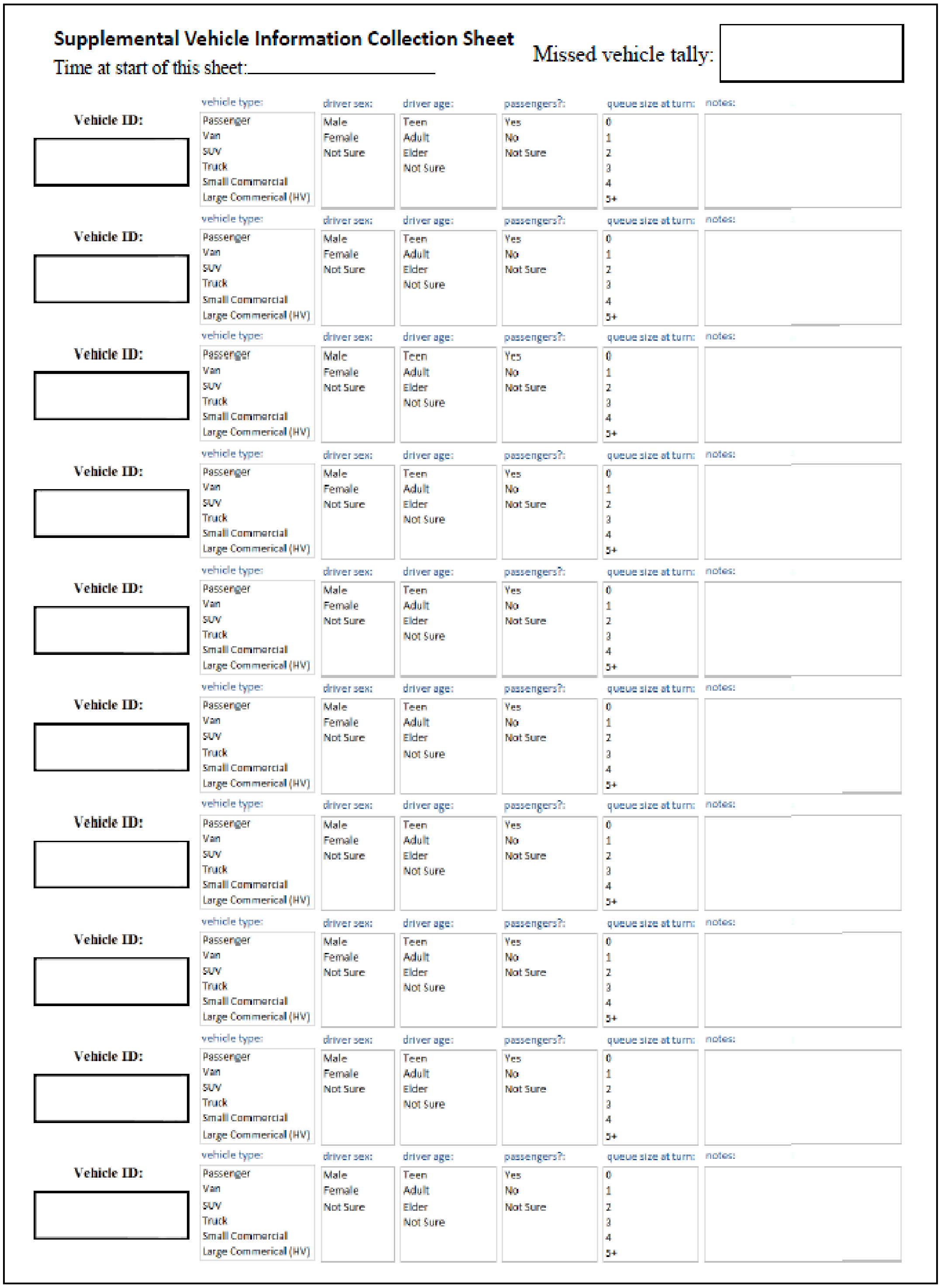
Other Information

sightline restriction?:	yes no	exessive speed a factor?:	yes no
other factors that may affect gap acceptance:			

Visits to this site:

Date	Start Time	End Time	# of Vehicles Observed

Figure 5. Gap Acceptance Study Packet - Site Description Form



Supplemental Vehicle Information Collection Sheet

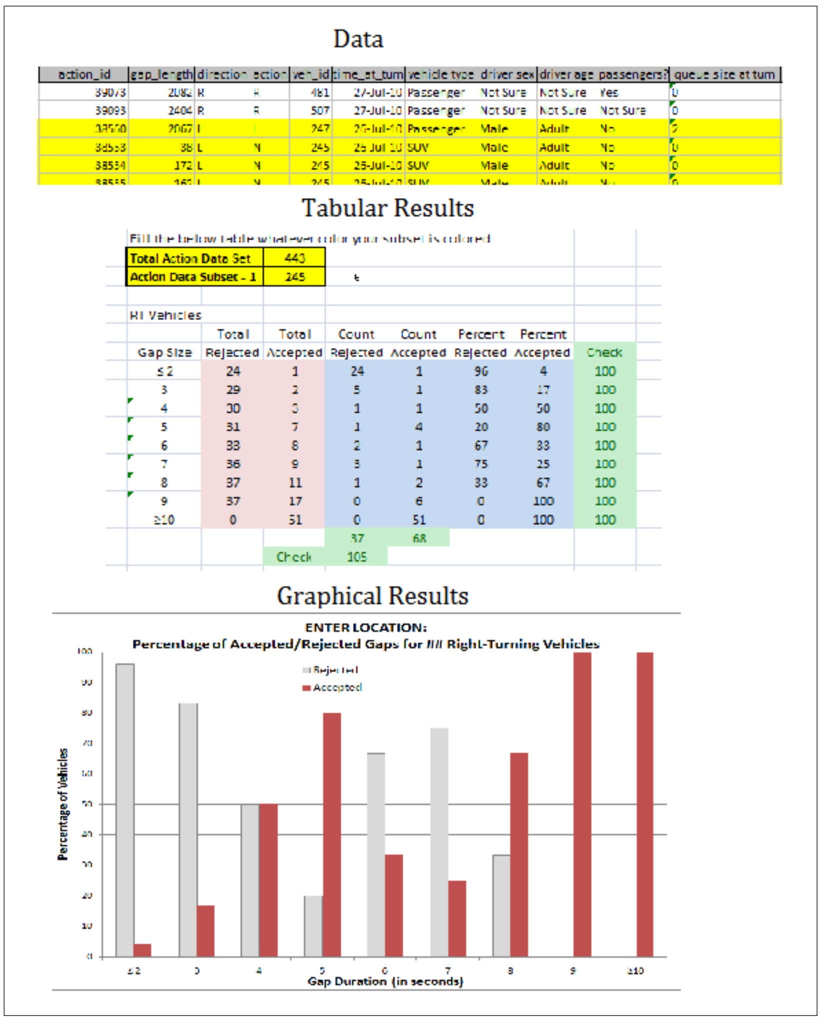
Time at start of this sheet:__________________

Missed vehicle tally:

	vehicle type:	driver sex:	driver age:	passengers?:	queue size at turn:	notes:
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	
Vehicle ID:	Passenger Van SUV Truck Small Commercial Large Commerical (HV)	Male Female Not Sure	Teen Adult Elder Not Sure	Yes No Not Sure	0 1 2 3 4 5+	

Figure 6. Gap Acceptance Study Packet - Vehicle Information Collection Sheet

Data Reduction and Analysis. Much of the data reduction and analysis was automated using the GAPS program in Microsoft Access® and in Microsoft Excel®. After the vehicle/driver data is entered into the GAPS programs it runs basic analysis and returns data in a form that can be exported into a Microsoft Excel® spreadsheet. This spreadsheet is programmed to take this data and run detailed analysis based on any desired characteristics using any analysis methods desired. The output is both tabular and graphic as seen in Figure 7.



Data

action_id	gap_length	direction	action	veh_id	time_at_turn	vehicle type	driver sex	driver age	passengers?	queue size at turn
39073	2082	R	R	481	27-Jul-10	Passenger	Not Sure	Not Sure	Yes	0
39093	2404	R	R	507	27-Jul-10	Passenger	Not Sure	Not Sure	Not Sure	0
38550	2067	L	[illegible]	247	26-Jul-10	Passenger	Male	Adult	No	2
38553	38	L	N	245	25 Jul 10	SUV	Male	Adult	No	0
38554	172	L	N	245	25-Jul-10	SUV	Male	Adult	No	0

Tabular Results

Fill the below table whatever color your subset is colored

Total Action Date Set	443
Action Data Subset - 1	245

RT Vehicles

Gap Size	Total Rejected	Total Accepted	Count Rejected	Count Accepted	Percent Rejected	Percent Accepted	Check
≤ 2	24	1	24	1	96	4	100
3	29	2	5	1	83	17	100
4	30	3	1	1	50	50	100
5	31	7	1	4	20	80	100
6	33	8	2	1	67	33	100
7	36	9	3	1	75	25	100
8	37	11	1	2	33	67	100
9	37	17	0	6	0	100	100
≥10	0	51	0	51	0	100	100
			37	68			
		Check	105				

Figure 7. Screenshots of Data Analysis Spreadsheet

Video Validation

A video validation component was incorporated into this research initiative to ensure that the data collection procedure accurately captured driver behavior.

<u>Experimental Protocol.</u> In order to validate the data collection process, a sampling of intersections was monitored by high-definition video recording equipment. The video cameras were mounted so that the views replicated what an observer in the field would

Figure 8. Intersection View from Video Footage

see. Figure 8 shows an example of the view the observer would have from the video footage. The video footage will then be played back for multiple observes who recorded data per the usual data collection procedure.

In order to account for challenges in data collection associated with different sites and different users of the software, the validation process was replicated under various conditions. Four locations were selected with different characteristics such as the number of lanes, approach speed, and traffic volume. Four different software users, one who in highly experienced with the software, one who had some experience with the software, and two who had never used the software before, were tested at each site. All users received identical instructions and basic training before validation testing. The observation period for each site was ten to fifteen minutes long.

Data Reduction and Analysis. The video collected on-site was played back in the office where time stamps of vehicle presence, arrivals, and departures could be a precisely recorded. These time stamps were recorded in a spreadsheet, similar to that shown in Figure 9, where analysis was run. The results of the experimental data collection and analysis process were then compared to those from the video reduction process and conclusions were drawn about the accuracy of data collection process. Similar results from the experimental method of collection and the video validated truth, for example the critical gap, would serve as validation of the experimental method.

Sample Video Validation Data Analysis

Data

Gap Availability				Gap Acceptance			
Near Lane Gaps		Far Lane Gaps		Veh. No	Turn Direction	Arrival Time	Departure Time
Start Time	End Time	Start Time	End Time				
0:02	0:08	0:13	0:16	1	L	0:15	0:45
0:12	0:19	0:29	0:37	2	R	1:25	1:42
0:35	0:48	0:42	0:51	3	R	3:05	3:12
0:59	1:20	0:57	1:15	4	L	3:14	3:26
...	...	...	...	...	...	...	...

Analysis

Gap Side	Length	Accpt/Rej
F	0:04	R
F	0:02	R
F	0:06	A
N	0:08	A
...	...	...

Results

LT Only Gap Size	Total Rejected	Total Accepted	Count Rejected	Count Accepted	Percent Rejected	Percent Accepted	Check
≤ 2	1017	15	1017	15	99	1	100
3	1222	45	205	30	87	13	100
4	1338	85	116	40	74	26	100
5	1410	137	72	52	58	42	100
6	1466	193	56	56	50	50	100
7	1489	259	23	66	26	74	100
8	1510	318	21	59	26	74	100
9	1517	374	7	56	11	89	100
≥10	31	1101	31	1101	3	97	100
			1548	1475			
		Check	3023				

Figure 9. Sample Video Validation Data Reduction

Research Objective 2 - Analysis by Method

A key parameter in the analysis of gap acceptance data is critical gap. As described in Chapter 2, there are a variety of different methods that can be used to determine critical gap. As part of this task, a number of different methods were used to determine the critical gap. The resulting critical gaps derived from each method were then compared. If there are differences of one second or greater in the critical gap as derived from different methods, then if can be said that the method of analysis can have profound effects on the conclusions of the analysis. When determining the overall utility of each method, characteristics such as ease of use, required sample size, and required site conditions were taken into consideration.

As part of this objective, the results of the different analysis methods were compared to the standard values reported in the *Highway Capacity Manual 2000*. These values were adjusted, per adjustment factors detailed in the *Highway Capacity Manual 2000*, to reflect the conditions under which the data was collected. Conclusions were drawn on how closely the numbers compare, and whether or not it would be advisable for the next version of the Highway Capacity Manual to consider more adjustment factors when determining critical gap.

Research Objective 3 - Analysis by Factor

There are a number of variables that influence a driver's gap acceptance behavior. Many factors are associated with the site such as the number of lanes, speed limit, functional classification, type of traffic control device, and traffic volume on the minor and major streets. Other factors are associated with the driver such as the driver's gender, age, the type of vehicle they are driving, and whether or not they have passengers. The final factors likely to affect gap acceptance behavior relate to other conditions at the time of the decision such as weather, time of day, presence of vehicles queued behind the turning vehicle, and length of wait time. As part of this research objective, gap acceptance behavior, in particular critical gap, were compared when considering a number of these different factors. Factors that could not be compared due to insufficient data of other complications were noted. For most of this analysis only data from Massachusetts locations were considered. The main reason for doing this was because, at the completion of this research initiative, only the Massachusetts data collection team had participated in the video validation methodology established for this research initiative. Where sample size necessitated and where commonality was seem between the data sets, both Massachusetts and Oregon locations were considered.

Research Objective 4 - Connecting Driver Behavior to Crash Experience

The results of the data reduction and analysis, particularly from third research objective, gave a great deal of insight into the differences in driving behavior between different driving populations. The question that arises is whether or not these differences in driving behavior result in different levels of driver risk on the roadway. For example, if driving group display particularly aggressive or erratic gap acceptance behavior does this correspond to an increased crash rate on the roadway?

To tackle this problem "gap acceptance related" crashes from were identified from crashes in the UMass Safety Data Warehouse. The crashes considered included those with characteristics that match the conditions under which the gap acceptance data was collected; occurring at an unsignalized T-intersection where a vehicle was making a left or right hand turn. The crashes were further narrowed by those where a driver was cited for an intersection right of way violation, an indication of inappropriate gap acceptance behavior (9). To ensure that the crashes were related to gap acceptance issues, the crash narratives, as written on the crash reports, were examined.

Analysis was performed to determine which driving groups were overrepresented in gap acceptance related crashes. Connections were made between the gap acceptance behavior of different driving groups and their relative representation in gap acceptance related crashes.

CHAPTER 4

DATA ANALYSIS AND RESULTS OF VIDEO VALIDATION

This chapter details the data collection effort that took place as part of this research initiative and the findings from the video validation.

Field Study

The large-scale field study was completed by over a dozen team members in Massachusetts and Oregon. In total 60 sites, 2,767 drivers, 10,419 driver decisions, and 22,639 gaps in traffic were observed. These observations represent a wide array of site conditions, with various traffic conditions, and many different driver types. To ensure that the results of the field study were accurate, video validation was performed.

Video Validation

The video validation component of this research initiative sought to determine if naturalistic driver behavior was being accurately collected by the research initiative. The video validation was performed at four sites with four observes recording data for each. In total the observers involved with the video validation cumulatively observed 538 drivers and 1,874 corresponding driver decisions.

There are many ways to determine if observers were using the software package to accurately collect data on driver behavior. The most basic metric of success is whether or not the observers captured data on all of the turning vehicles. This metric was used to

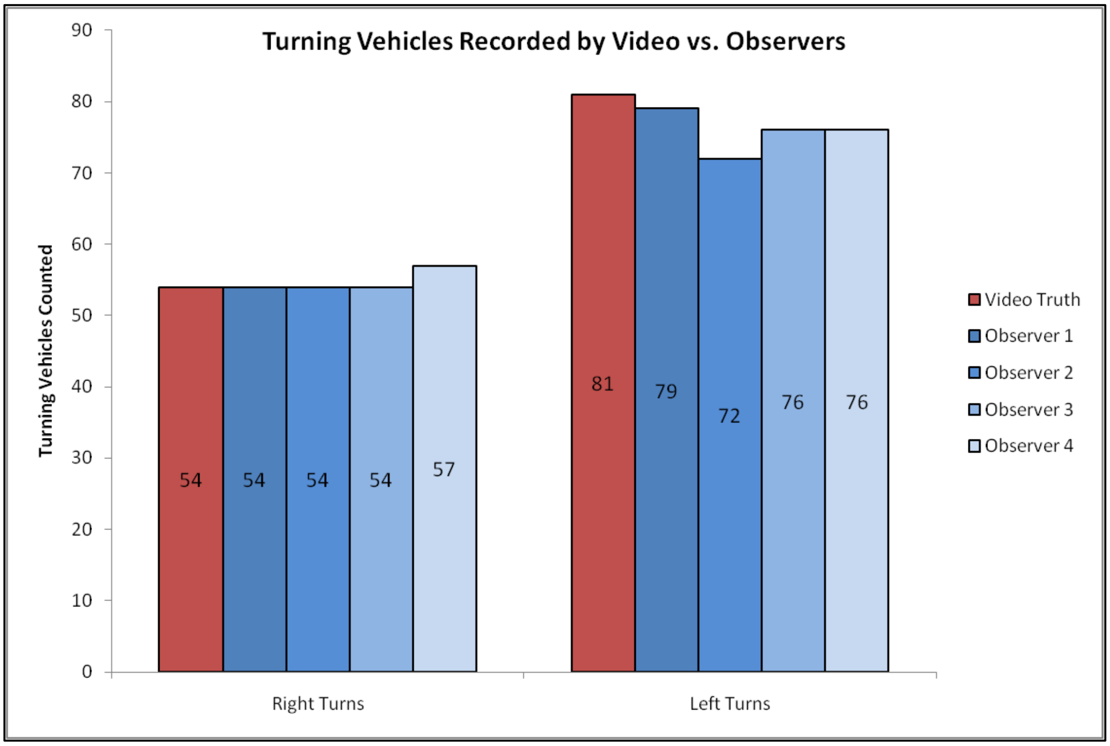


Figure 10. Video Validation - Turning Vehicles Recorded Comparison

compare each of the observers with the true number captured by the video reduction. The results of this comparison are presented in Figure 10.

In general the observers captured nearly all vehicles making turns during the observation period. The over counting of one right turn vehicle by Observer 4 was the result of misidentifying a vehicle as making a right turn when they in fact turned left. The undercounting of left turns by observer 3 was the result of computer issues unrelated to the GAPS program. This sample of the data was left in as, while such issues never encountered during the field study, there always exists the possibility of computer issues during any data collection effort.

Further analyzing the data, measures of gap availability and gap acceptance where compared. Less emphasis was placed on gap availability as the current methodology practiced for collecting gap availability in the field is almost identical to that used in the research initiative. While the collection usually utilizes a commercial count board, the user input actions are the same on the laptop base program used in this research initiative. Therefore the gap availability data collection using the GAPS software is no less accurate than that collected with existing technologies. Figure 11 presents gap availability distributions as captured by one of the observers and as determined by the video reduction for right and left turning maneuvers. The data from all four observers showed very similar trends that mirror the trends seen in the video reduced data.

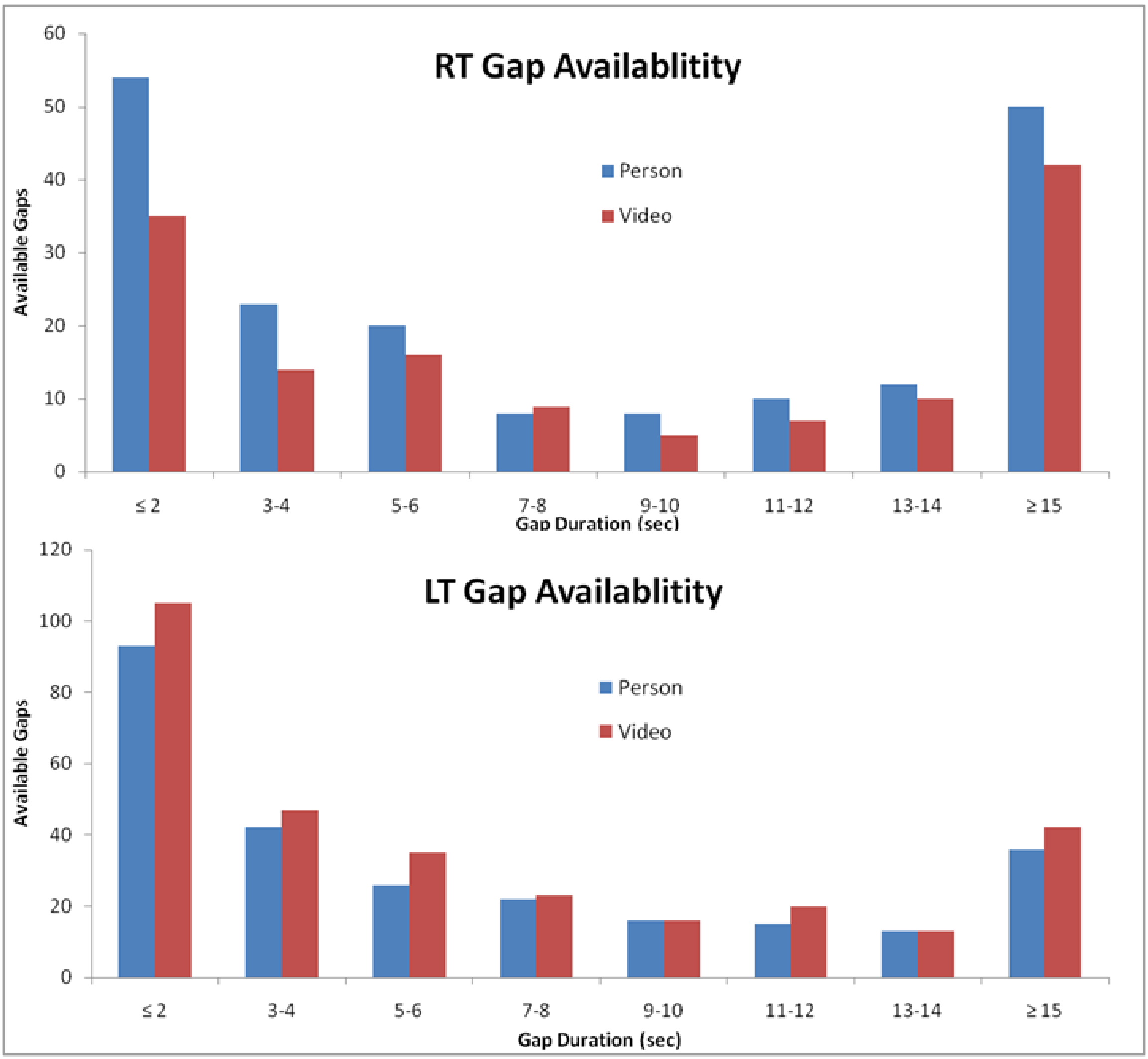


Figure 11. Video Validation – Gap Availability Comparison

The gap acceptance data collected by the observed and reduced from the video footage was more closely analyzed as gap acceptance is the focus of the research initiative. First, the distributions of accepted and rejected gaps were compared as shown in Figure 12.

As the figure shows, the distributions of the data collection from the observers

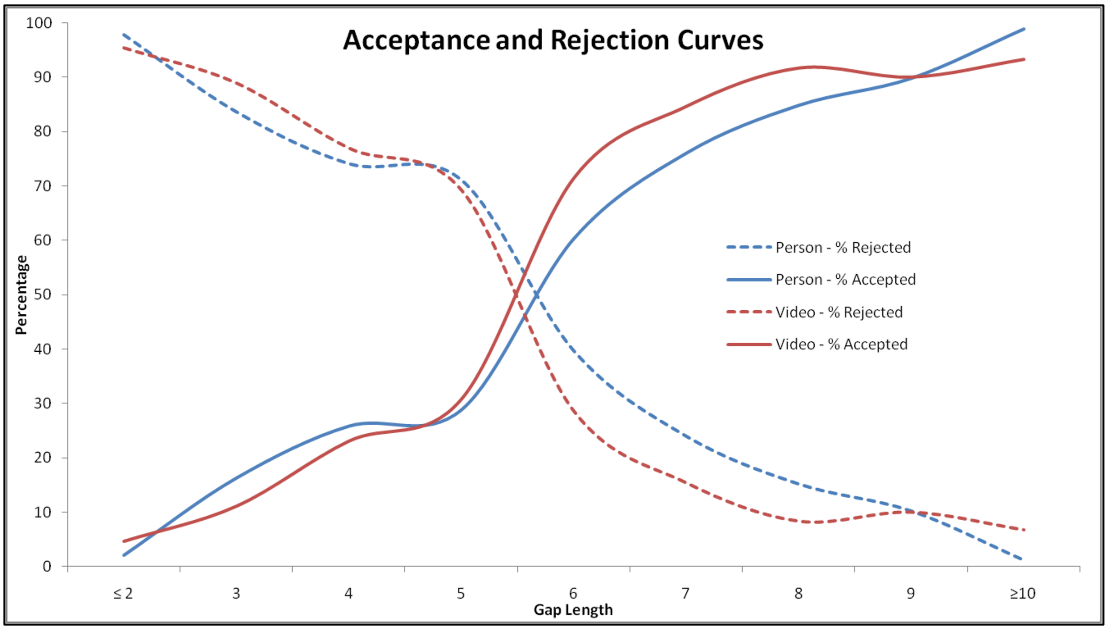


Figure 12. Video Validation - Acceptance and Rejection Curves

and the data reduced from the video are very similar. According to a chi square test on the binned rejected and accepted data, there is no statistically significant difference between the acceptance and rejection curves between the observer and the video.

As one of the ultimate goals of understanding gap acceptance behaviors is to determine metrics that can be used describe the behavior, such as critical gap, these metrics, estimated by the observer data and video data, were compared. A number of different analysis methods, which are described in greater detail in the following chapter, were used to compare the data sets. The resulting values are presented in Table 1.

Table 1. Video Validation - Gap Acceptance Metrics - Video versus Observer

	Video Truth	Observers	Difference
Average Accepted Gap	7.5 s	7.4 s	0.1 s
Raff Method	5.5 s	5.5 s	0 s
Cumulative Acceptance Method	6.25 s	6.25 s	0 s
Fit Maximization Method	5.0	5.25	0.25 s
Chi-Squared Value	p=0.462, no statistically significant difference		

Across all analysis methods there is little to no difference between the gap acceptance metrics from the video truth data and the observer data. With no practical or statistical differences between the gap acceptance data collected by the observers and the true conditions as captured by the video, it is reasonable to deduce that the observers are collecting data that accurately reflects the field conditions.

CHAPTER 5

RESULTS OF ANALYSIS BY METHOD

As discussed in the background section, there are a number of different methods that have been proposed to analyze gap acceptance data.

Some of these methods were eliminated from consideration in this research initiative because they were only applicable under certain traffic conditions. For example, the Siegloch (1973) method is only applicable under saturated conditions. For most situations in the field, and all of those studied in this research initiative, these methods are not appropriate.

Other methods were eliminated because they were two too computationally demanding to be implemented for most reasonable studies. These methods involved iteratively solving multiple equations and do not provide closed solution sets. One such method, proposed by Troubeck (1992), involves the principle of maximum likelihood analysis. This method has been approximated by more simple mathematical models that were incorporated in some of the methods utilized.

After eliminating methods that were inappropriate or impractical, five methods, each with two variations remained. The methods that were analyzed using the large data set collected in this research initiative are presented in Table 2.

.

Table 2. Gap Acceptance Analysis Methods Compared

Methods	Variation
Average Accepted Gap	All accepted gaps
	Accepted gaps < 12 seconds
Raff Method	All gaps
	All accepted gaps and maximum rejected gaps
Cumulative Acceptance	All accepted gaps
	Accepted gaps < 12 seconds
Equilibrium of Probabilities	All accepted gaps and rejected gaps
	All accepted gaps and maximum rejected gaps
Fit Maximization	All accepted gaps and rejected gaps
	All accepted gaps and maximum rejected gaps

Details on each of the methods used are discussed in following sections and the results are then compared between the methods.

Average Accepted Gap Method

This method is the most computationally simple of all the methods, however it is the only method does not provide an estimate of critical gap. The average accepted gap is often used as a proxy from critical gap to allow for comparison of different data sets or the effects of different characteristics.

Implementation

To employ this method the accepted gaps are tabulated and then averaged. With the second variation, accepted gaps over 12 second are excluded from analysis. The rationale behind this variation is that gaps in traffic over 12 seconds are universally accepted by drivers and therefore do not represent true gap acceptance decisions.

Sample Size Requirements

Since this method only uses accepted gaps and not rejected gaps as well as, a much large data set is required to reasonable conclusions to be drawn. The usable data from a sample further reduces when gaps over 12 seconds are excluded, necessitating an even larger sample size for meaningful results.

Results

The Average Accepted Gap Method was employed to analyze the data from the field study. Figure 13 presents the results for left and right turning maneuvers.

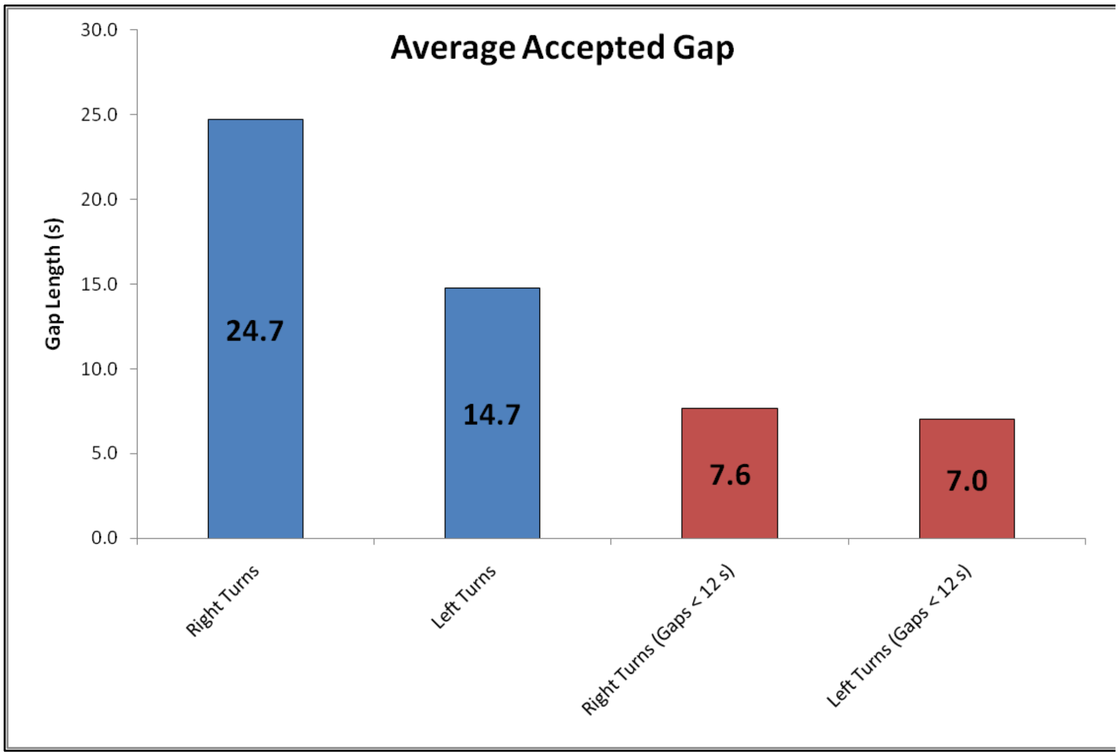


Figure 13. Results of Average Accepted Gap Method Analysis

As would be expected, excluding the gaps over 12 seconds significantly reduces the average accepted gap. With the gaps over 12 seconds excluded, the average accepted gap is relatively close to the critical gap estimated by the other methods utilized.

Overall, this method was usefully in quickly presenting results that could be used to compare different data sets. However, since rejected gaps are not utilized in the analysis a considerable amount of available information on driver decision making is wasted by using this method. The biggest drawback of this method is that critical gap is not estimated. As this is an important metric in many applications, this is a significant drawback.

Raff Method

One of the most commonly used analysis methods is the Raff Method. Proposed by Raff in the late 1940's, this method is both conceptually logical and computationally simple.

Implementation

To employ this method the accepted gaps and rejected gaps must be binned into set time intervals, such as 2 second intervals. For each interval the number of gaps accepted, number of gap rejected, percent of gaps accepted, and percent of gaps rejected must be tabulated. So for any gap length bin, the reduced data will show the percent of gaps accepted and percent of gaps rejected. Such a table of reduced data is presented in Table 3.

Table 3. Example of Raff Method Reduced Data

Gap Size	Total Rejected	Total Accepted	Count Rejected	Count Accepted	Percent Rejected	Percent Accepted	Check
≤ 2	1266	8	1266	8	99	1	100
3	1447	28	181	20	90	10	100
4	1556	65	109	37	75	25	100
5	1622	115	66	50	57	43	100
6	1662	160	40	45	47	53	100
7	1696	214	34	54	39	61	100
8	1716	271	20	57	26	74	100
9	1729	311	13	40	25	75	100
≥10	20	406	20	406	5	95	100
			1749	717			
		Check	2466				

By graphing the resulting percent accepted and percent rejected the critical gap can be determined. By the Raff definition, the gap length where the percent of gap rejected equals the percent of gap accepted is the critical gap. This corresponds to the point where 50 percent of gaps where rejected and 50 percent of gaps are rejected. Assuming the sample is representative of the driving population this would also be the gap length where a driver has a 50 percent probability of accepting the gap.

The variation on this method is to consider just the maximum gap rejected by each driver, not all gaps rejected by each driver. This variation removes the potential bias towards passive drivers who reject many gaps before accepting one.

Sample Size Requirements

Since this method utilizes both accepted gap and rejected gap data, a smaller sample size will give more meaningful results. All driver choices are reflected in this method of analysis.

With the maximum rejected gap variation some of the collected data in not used, thereby necessitating a larger sample size for meaningful results.

Results

The Raff Method was employed to analyze the data from the field study, the results are shown in Figure 14. Figure 15 present the results for the maximum gap accepted variation for right and left turning maneuvers respectively. The bars represent the percentage values as tabulated and the lines are used to interpolate between values. The critical gap value was estimated to the nearest 0.5 second interval from the graph.

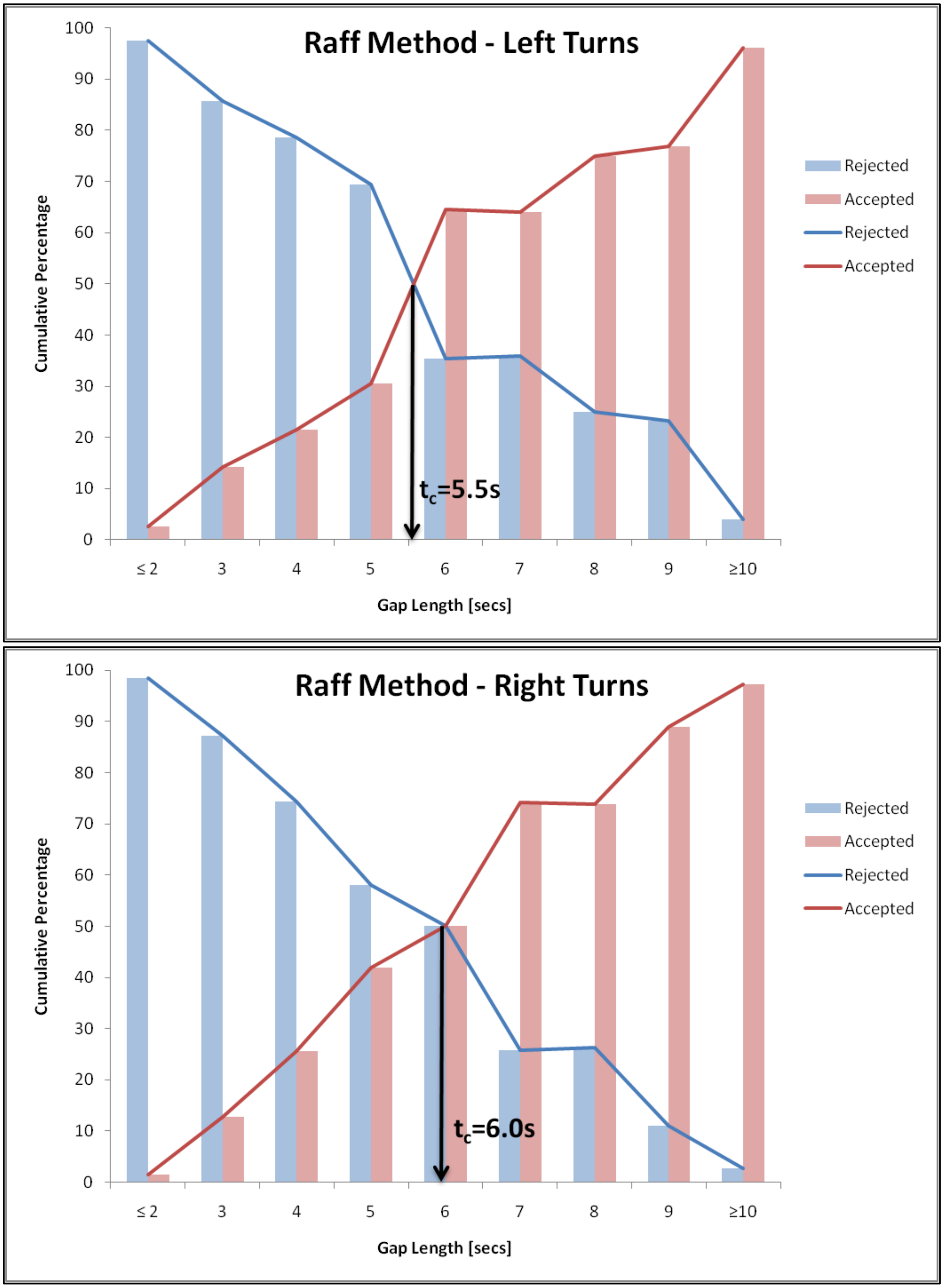
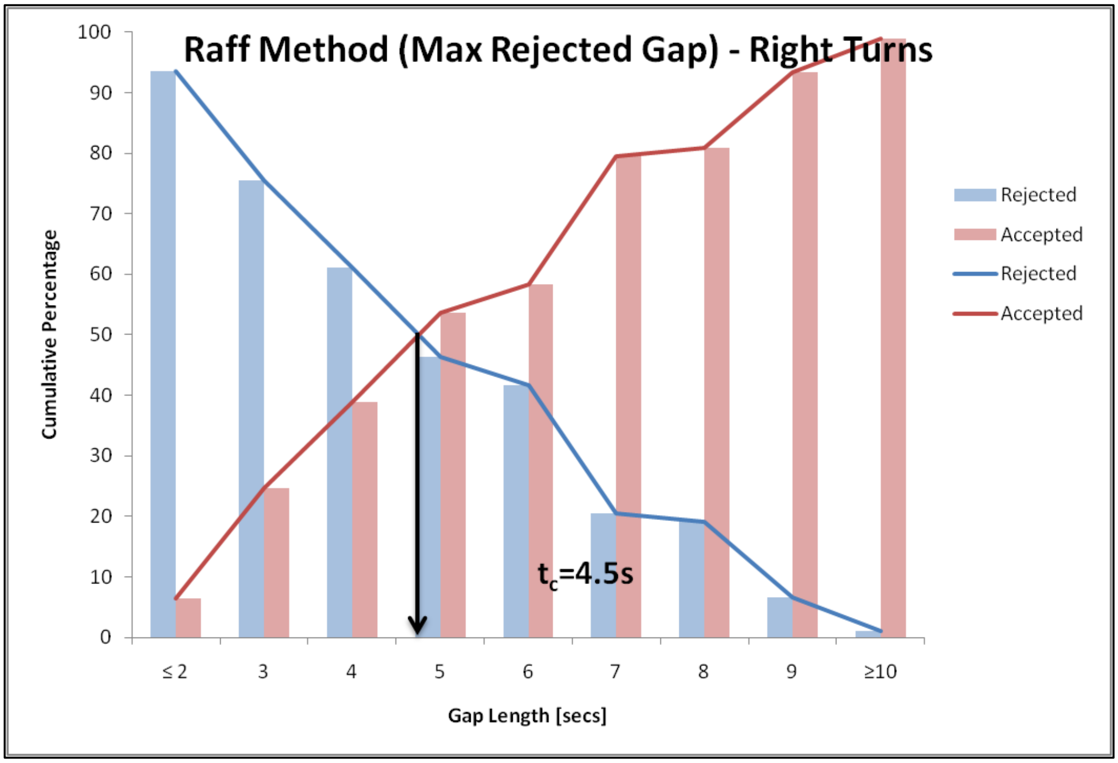


Figure 14. Raff Method



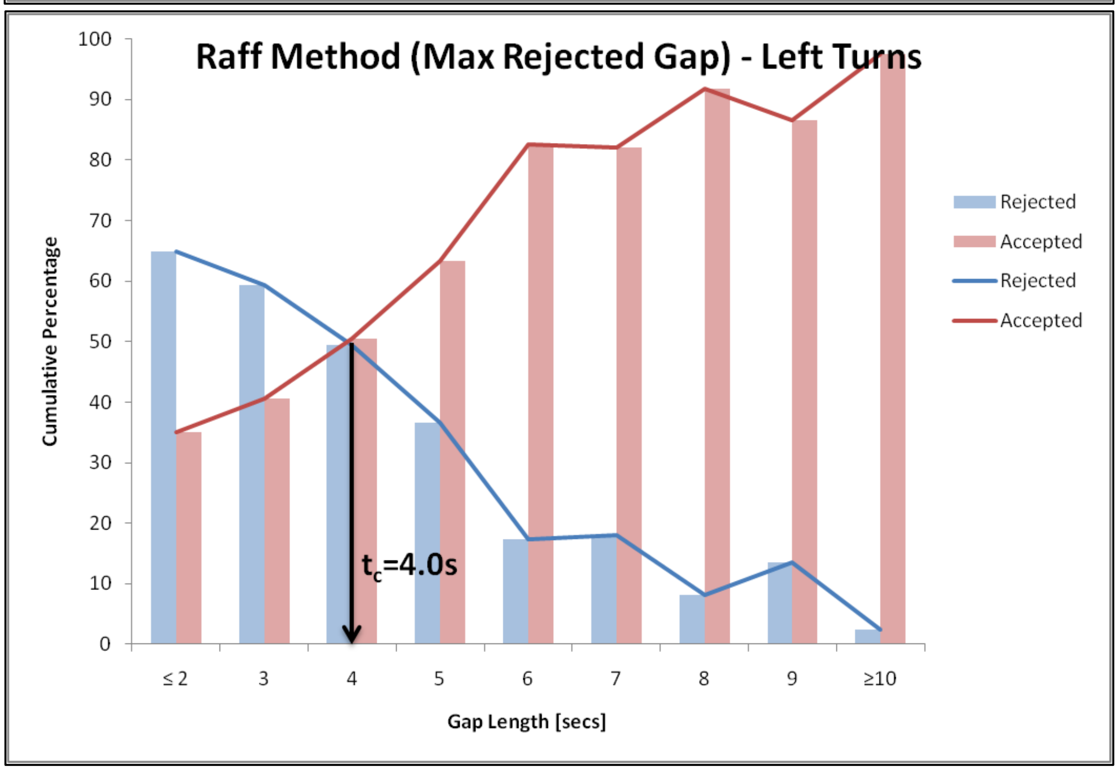


Figure 15. Raff Method (Max Gap Rejected Variation)

The results of the Raff Method are similar to those of the other methods. By using the maximum rejected gap variation the passive driver bias was eliminated thereby lowering the critical gap values. This method was both easy to implement and utilized all of the data available. This method has the added benefits of being easy to display graphically and easy to explain to those unfamiliar with gap acceptance theory. Describing the critical gap as the gap length corresponding to the 50-50 accept or reject decision point is easy to justify logically.

<u>Cumulative Acceptance Method</u>

The Cumulative Acceptance Method is the method described in the commonly used text entitled *Introduction to Traffic Engineering: A Manual for Data Collection and Analysis* by Thomas R. Currin (21). As this is an important resource for practitioners it was a method that warranted inclusion in this research effort.

Implementation

The underlying principle of this method is to identify a gap that would be acceptable to 85 percent of drivers. To do this the count of accepted gaps are binned by gap length. Gap length bins of 0.25 seconds were used as described in the aforementioned manual. Next, for each gap length, the cumulative percentage of accepted gaps is tabulated. According to this method, the critical gap is defined as the gap length where the cumulative percentage is greater than or equal to 15 percent. A table with binned gap accepted count and the cumulative percentage count is presented in Table 4. Note that the cumulative percent accepted first exceed 15 percent at a gap length of 7.25 seconds, so this is the critical gap as determined by this method.

Table 4. Example of Cumulative Acceptance Method Reduced Data

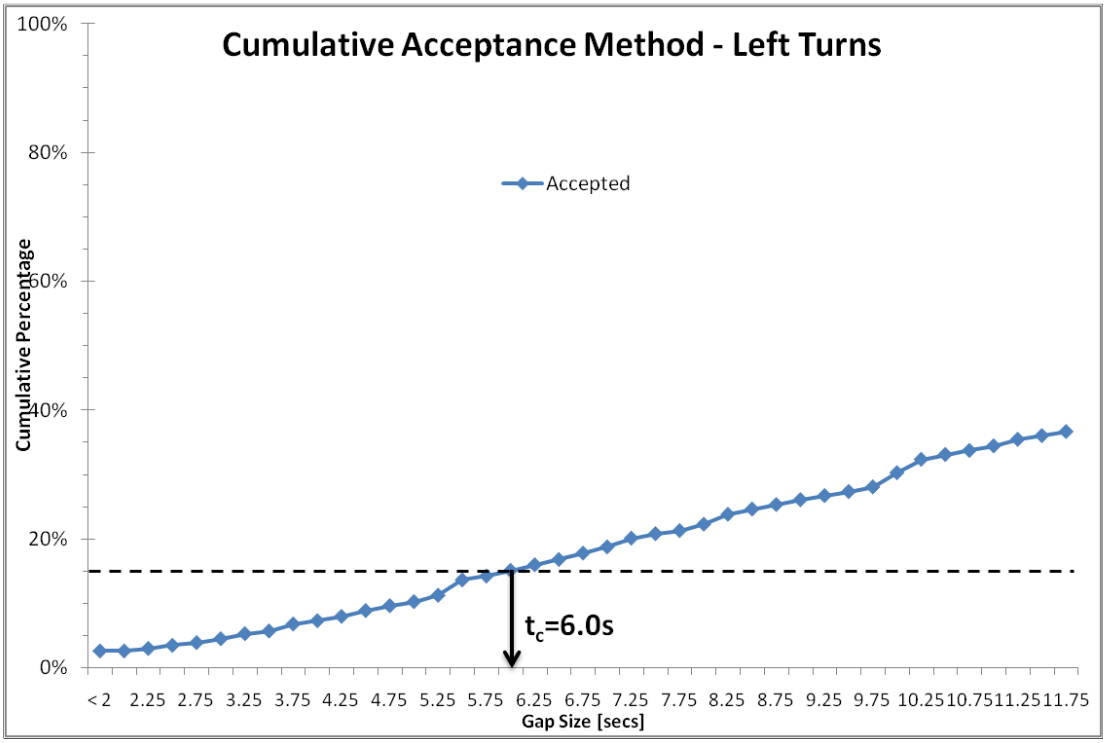
RT Vehicles	Critical Gap	7.25		
	Total	#		Cummulative
Gap Size	Accepted	Observed	Frequency	Frequency
< 2	5	5	0.01	0.01
2.0	5	0	0.00	0.01
2.25	9	4	0.00	0.01
2.50	11	2	0.00	0.01
2.75	15	4	0.00	0.02
3.00	19	4	0.00	0.02
3.25	22	3	0.00	0.03
3.50	24	2	0.00	0.03
3.75	28	4	0.00	0.03
4.00	36	8	0.01	0.04
4.25	41	5	0.01	0.05
4.50	49	8	0.01	0.06
4.75	54	5	0.01	0.07
5.00	61	7	0.01	0.07
5.25	68	7	0.01	0.08
5.50	76	8	0.01	0.09
5.75	80	4	0.00	0.10
6.00	86	6	0.01	0.10
6.25	98	12	0.01	0.12
6.50	112	14	0.02	0.14
6.75	114	2	0.00	0.14
7.00	120	6	0.01	0.15
7.25	128	8	0.01	0.15
7.50	132	4	0.00	0.16
7.75	138	6	0.01	0.17
8.00	145	7	0.01	0.18
8.25	156	11	0.01	0.19
8.50	163	7	0.01	0.20
8.75	167	4	0.00	0.20
9.00	175	8	0.01	0.21
9.25	180	5	0.01	0.22
9.50	187	7	0.01	0.23
9.75	201	14	0.02	0.24
10.00	209	8	0.01	0.25
>10	617	617	0.75	1.00
		826		

Sample Size Requirements

Since this method only uses accepted gaps and not rejected gaps as well as much, a larger data set is required to reasonable conclusions to be drawn. The usable data from a sample further reduces when gaps over 12 seconds are excluded, necessitating a large sample size for meaningful results.

Results

The Cumulative Acceptance Method was employed to analyze the data from the field study. Figure 16 presents the results for right and left turning maneuvers respectively. Figure 17 presents the results for the maximum gaps less than 12 second variation for right and left turning maneuvers respectively.



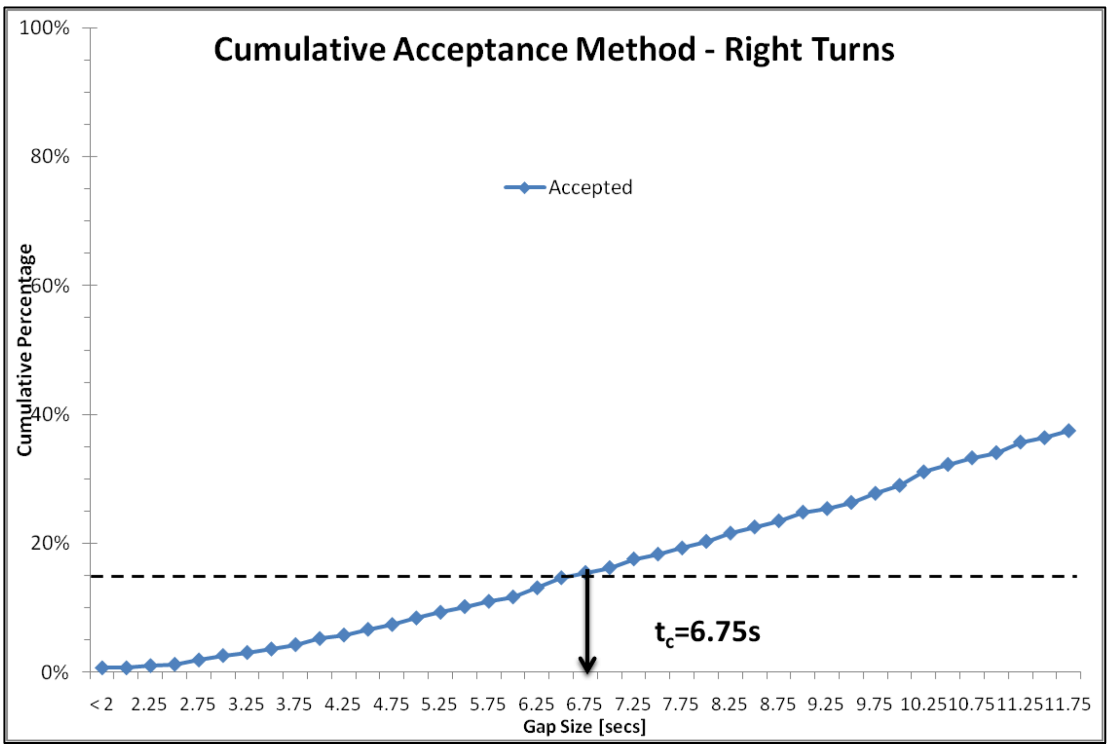


Figure 16. Cumulative Acceptance Method

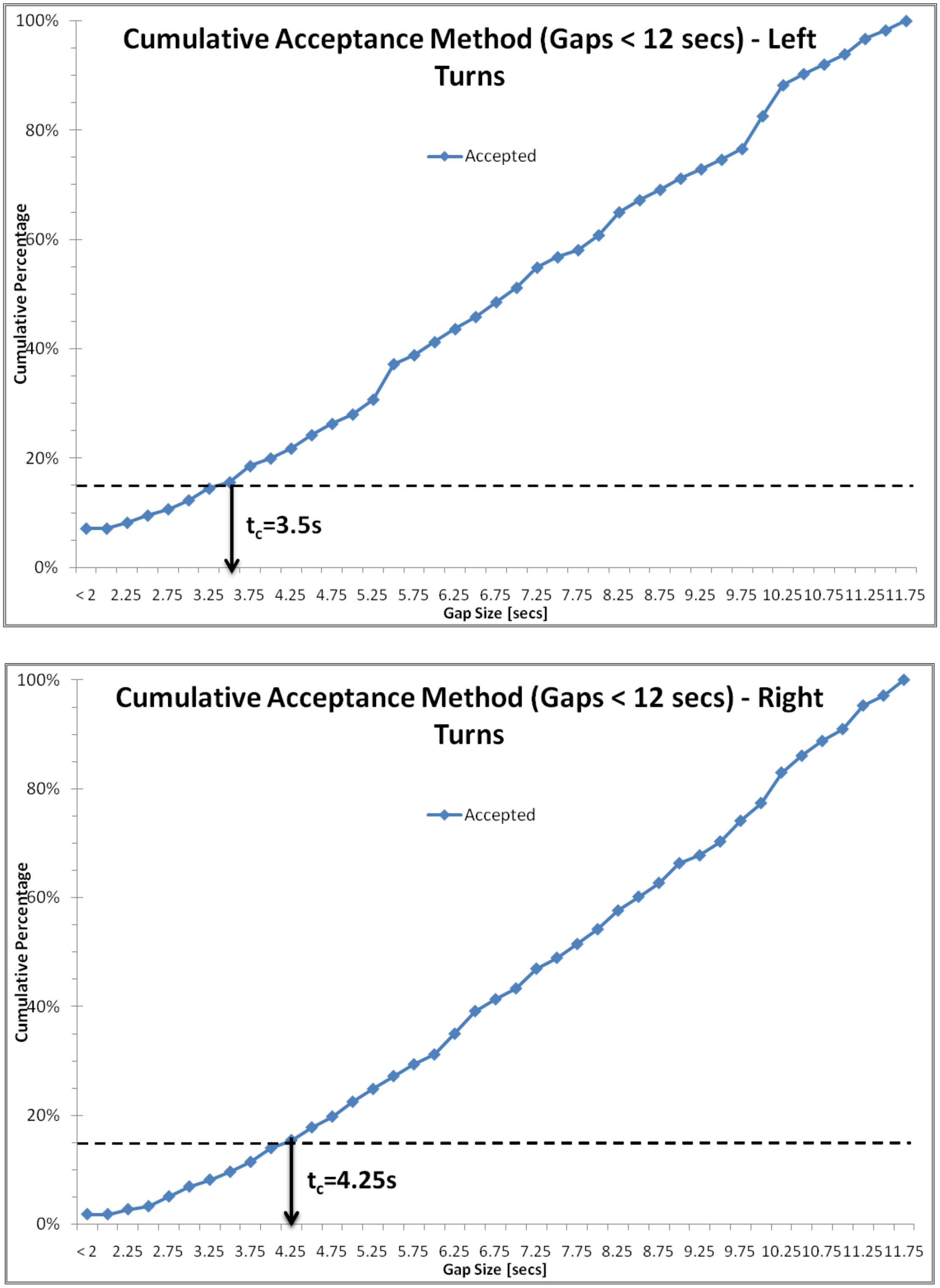


Figure 17. Cumulative Acceptance (Gaps < 12 seconds)

The variation of excluding gaps less than 12 seconds clearly makes a profound difference with this method. The cumulative percentage of accepted gap curves without the variation only approach 40 percent at 12 seconds as many of the recorded accepted gaps where greater than 12 seconds. This results in a much higher critical gap than with the variation. This variation is not included in the aforementioned manual, meaning that sites with a high proportion of large gaps will show skewed results if the methods outlined in the manual are followed.

Overall, this method gives results similar to those of other methods and is quite simple to implement. The drawback of this method is that the rejected gap data is not utilized meaning a large sample size is need for meaningful results.

Equilibrium of Probabilities

This method has a strong correlation to the fundamental reasoning behind the likelihood maximization logic used in the Troutbeck Method. The variation where only the maximum rejected gaps, not all rejected gaps, are used is almost identical to the Troutbeck Method but without the iterative calculations.

Implementation

The implementation of this strategy follows that proposed by Ning Wu in his paper published in 2006 (5). His tabular calculation of acceptance probabilities mirrors those used by Troutbeck without the iterative calculations. Using a spreadsheet based tabulation, the resulting critical gap value is very close to thought arrived at by the more computationally intensive Troutbeck Method (5). This is particularly true with the maximum excepted gap variation which more closely mirrors the Troutbeck variation (5).

To employ this method, all gaps, both accepted and rejected, are ordered by gap length. Based on whether each of these gaps was rejected or accepted, a model of the maximum likelihood of a gap acceptance decision for gap lengths is developed. This model is able to estimate the critical gap for the sample of gap data analyzed.

Sample Size Requirements

Since this method utilizes both accepted gap and rejected gap data, a smaller sample size will give more meaningful results. All driver choices are reflected in this method of analysis.

With the maximum rejected gap variation, some of the collected data in not used, so a larger sample size is required for meaningful results.

Results

The Equilibrium of Probabilities Method was employed to analyze the data from the field study. Figure 18 presents the results for left and right turning maneuvers.

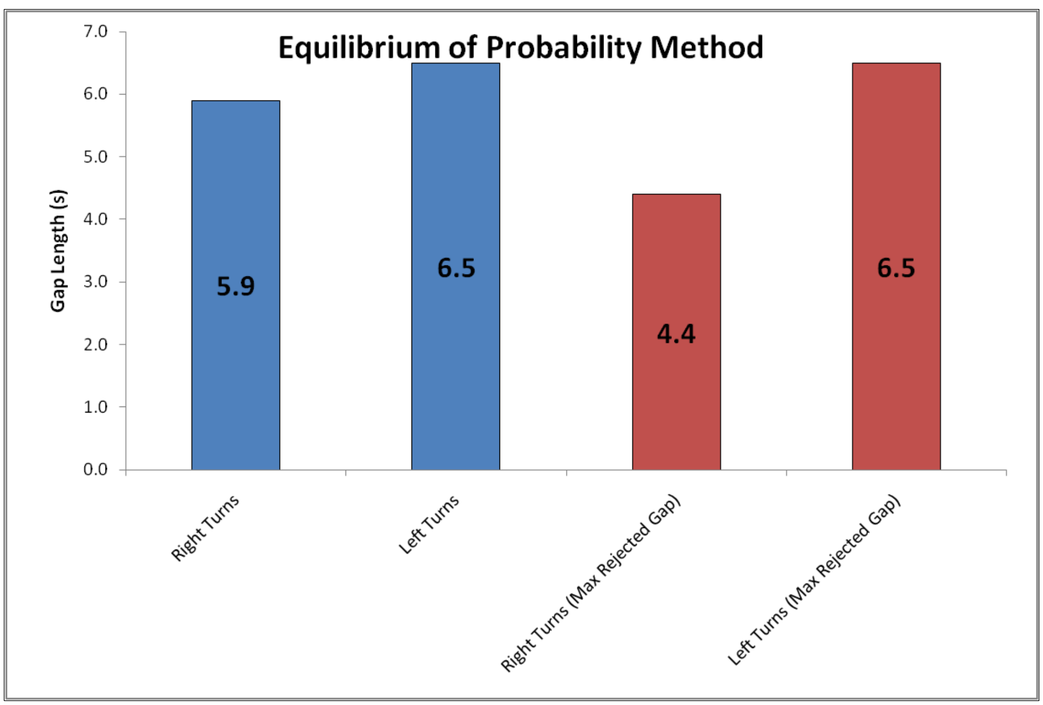


Figure 18. Results of Equilibrium of Probability Method Analysis

The results are similar to those of other methods of estimating critical gap. The maximum gap rejected variation showed mixed effects lowering the right turn critical gap, but no showing effect the left turn critical gap.

Overall, this method was computationally fairly simple although far more time consuming than some of the other methods previously described. Using both the accepted and rejected gap data this method makes good use of the all data on driver behavior collected in the field. Being a relatively new method it has not been widely used to this point, but given it computation advantages over the Troutbeck Method it may become more prevalent.

Fit Maximization Method

This method has been around a long time in principle, but the implementation as described below is new to this research initiative. The principle goes back to critical gap as described by D. R. Drew in his traffic flow theory book from the late 1960's (22). His suggestion was that critical gap should be defined as the gap length such that an equal percentage of the population would accept a large gap and reject a smaller gap. Under the assumption the study sample is representative of the entire population, this would correlate to an equal number of gaps smaller than the critical gap being rejected and larger than the critical gap being accepted. For this research initiative this statement was modified slightly to find the critical gap that would result in the most gaps larger than the critical gap being accepted and smaller than the critical gap being rejected. This is a bit of a departure from Drew's definition, but the resulting critical gap would be the one that maximizes the number of gap that fit into the correct position (ie. smaller gaps rejected and larger gaps accepted).

Implementation

The implementation of this method utilized a spreadsheet based algorithm that, for any guess at critical gap, returned the number of gaps that would have been fit that critical gap guess. By trying a variety of critical gaps, the one that maximized the logical gap fits could be pick. An example of such a spreadsheet is presented in Table 5.

Table 5. Example of Fit Maximization Reduced Data

tc	4	4.25	4.5	4.75	5	5.25	5.5	5.75	6	6.25	6.5	6.75	7	7.25	7.5	7.75	8
# < Rej	1279	1307	1336	1355	1378	1391	1408	1424	1440	1451	1464	1470	1478	1481	1487	1495	1499
# > Acc	1412	1398	1390	1375	1366	1350	1338	1325	1313	1303	1282	1258	1245	1235	1215	1204	1191
Sum	2691	2705	2726	2730	2744	2741	2746	2749	2753	2754	2746	2728	2723	2716	2702	2699	2690

A variation where only the maximum rejected gaps, not all rejected gaps was also considered. This variation is more closely related to Drew's definition of critical gap.

Sample Size Requirements

Since this method utilizes both accepted gap and rejected gap data, a smaller sample size will give more meaningful results. All driver choices are reflected in this method of analysis.

With the maximum rejected gap variation some of the collected data in not used, so a larger sample size is required for meaningful results.

Results

The Fit Maximization Method was employed to analyze the data from the field study. Figure 19 presents the results for left and right turning maneuvers.

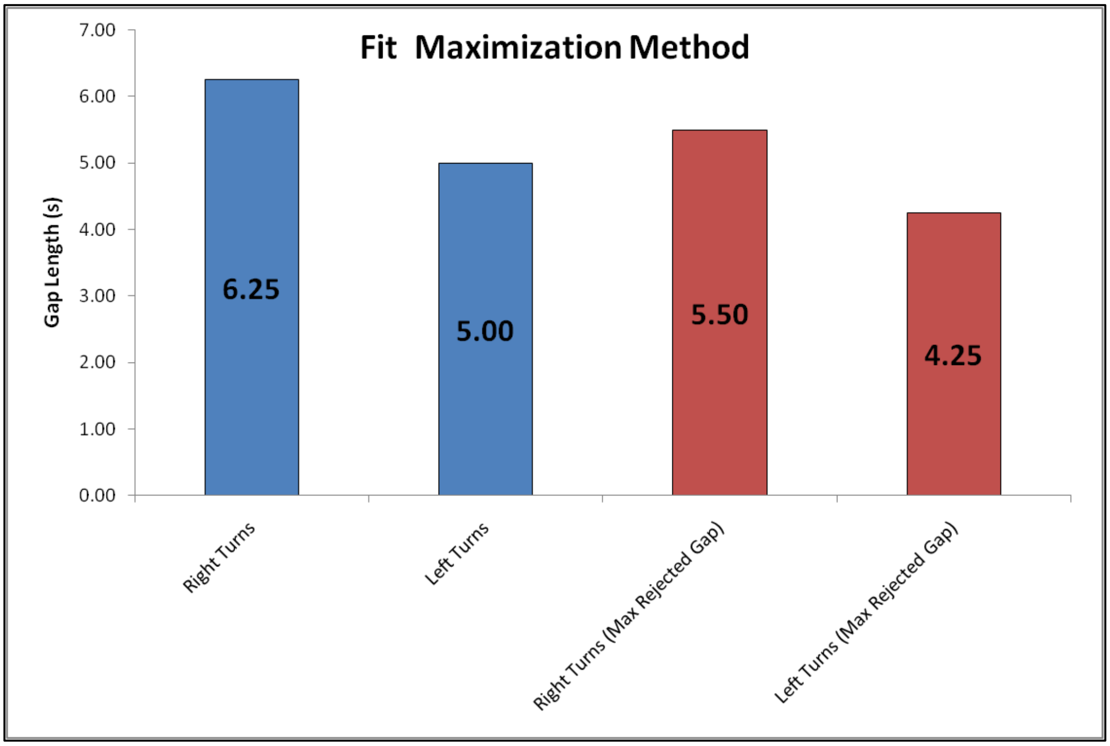


Figure 19. Results of Fit Maximization Method Analysis

The results are similar to those of other methods of estimating critical gap. The maximum gap rejected variation slightly reduced both the right turn and left turn critical gap estimates.

Overall, this method was computationally simple and based in sound logic. Using both the accepted and rejected gap data this method makes good use of the all data on driver behavior collected in the field. As this method, at least in this form, has never been used beyond the scope of this research initiative it should be tested under other, varied conditions to test its performance.

Comparison of Results by Method

The five methods, ten including variations, all had their relative merits. All methods except for the Average Accepted Gap Method resulted in estimates of critical gap. The Average Accepted Gap, Cumulative Acceptance, and Raff Methods were the most computationally simple followed closely by the Fit Maximization Method. Of the methods compared, the Equilibrium of Probabilities Method was the most computationally demanding. The Raff, Equilibrium of Probabilities, and Fit Maximization Methods utilized both the accepted and rejected gap data, requiring a smaller sample size. The Average Accepted Gap and Cumulative Acceptance Methods used only accepted gap data requiring a larger sample size for meaningful results. The variation of excluding gaps over 12 seconds seemed to make so of the resulting critical gap values more in line with expectations, but causes the loss of some of the data collected. Similarly, the maximum rejected gap variation seems to result in values that more accurately reflect the driver population, but causes the loss of some of the data collected. The relative merits of each of the method are presented in Table 6.

Table 6. Merits of Analysis Methods

Methods	Variation	Estimates Critical Gap	Ease of Use	Use of Data
Average Accepted Gap	All accepted gaps	No	Very Good	Poor
	Accepted gaps < 12 seconds			Very Poor
Raff Method	All gaps	Yes	Very Good	Very Good
	All accepted gaps and maximum rejected gaps			Good
Cumulative Acceptance	All accepted gaps	Yes	Very Good	Poor
	Accepted gaps < 12 seconds			Very Poor
Equilibrium of Probabilities	All accepted gaps and rejected gaps	Yes	Poor	Very Good
	All accepted gaps and maximum rejected gaps			Good
Fit Maximization	All accepted gaps and rejected gaps	Yes	Good	Very Good
	All accepted gaps and maximum rejected gaps			Good

To see whether or not different analysis methods lead to different results, the critical gaps estimated by each method were compared. For completeness, the average accepted gap as determined using the Average Accepted Gap Method was included as it is sometimes used as a proxy for critical gap. The values are presented in Table 7 and show graphically in Figure 20.

Table 7. Comparison of Critical Gap by Analysis Method

	Critical Gap Value [secs]	
Analysis Method	**Right Turns**	**Left Turns**
Average Accepted Gap[1]	24.7	14.7
Average Accepted Gap (Gaps < 12s)[1]	7.6	7.0
Raff Method[2]	6.0	5.5
Raff Method (Max Rejected Gap)[2]	4.5	4.0
Cumulative Acceptance[3]	6.75	6.00
Cumulative Acceptance (Gaps < 12s)[3]	4.25	3.50
Equilibrium of Probabilites[1]	5.9	4.4
Equilibrium of Probabilities(Max Rejected Gap)[1]	6.5	6.5
Fit Maximization[3]	6.25	5.50
Fit Maximization(Max Rejected Gap)[3]	5.00	4.25

[1]Rounded to nearest 0.1s

[2]Estimated to nearest 0.5 s

[3]Estimated to nearest 0.25 s

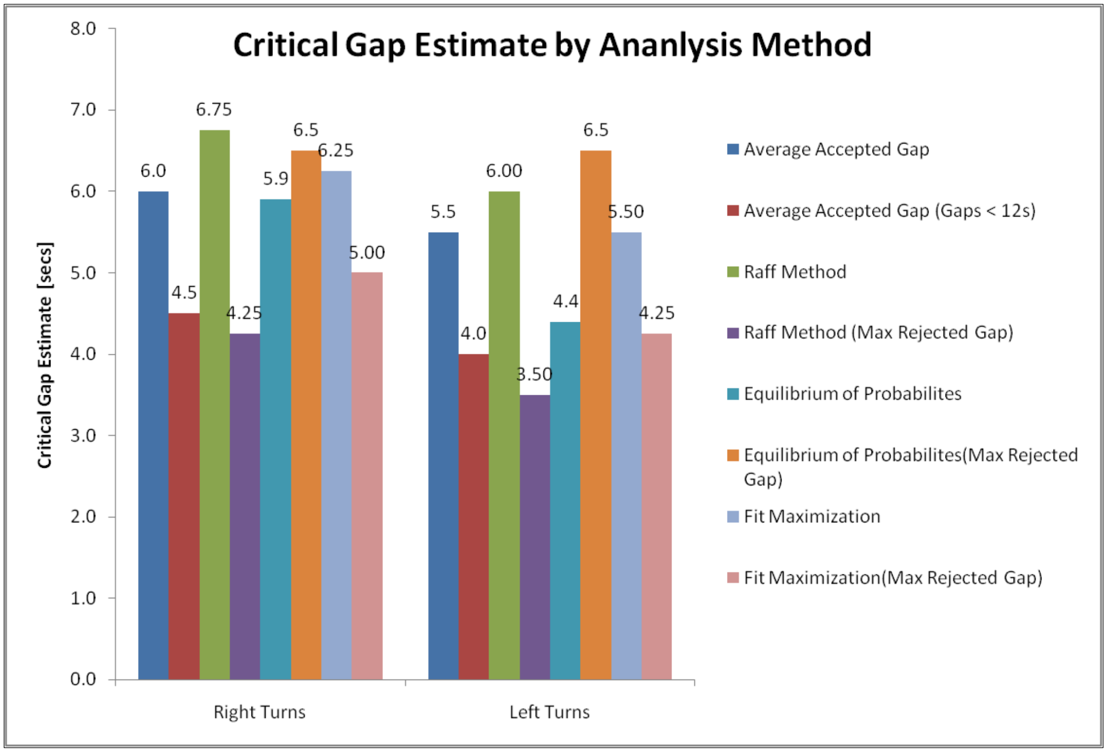


Figure 20. Comparison of Critical Gap by Analysis Method

As the table and figure show, there is a good deal of variation in the results of the analysis methods compared. The right turn critical gap estimate varied from 4.25 seconds to 6.75 seconds, and the left turn critical estimate varied from 3.5 seconds to 6.5 seconds. As the critical gap estimate depends of the definition of critical gap, there is no way to tell which values is "most correct," however general consensus between methods is a good indicator of a reasonable value. Additionally, the values are relatively close to values published in other literature.

HCM Comparison

One way of determine the validity of the results of the analysis methods is to compare them to the standard values reported in the *Highway Capacity Manual 2000*. Such a comparison is presented in Figure 21. However, it should be understood that the

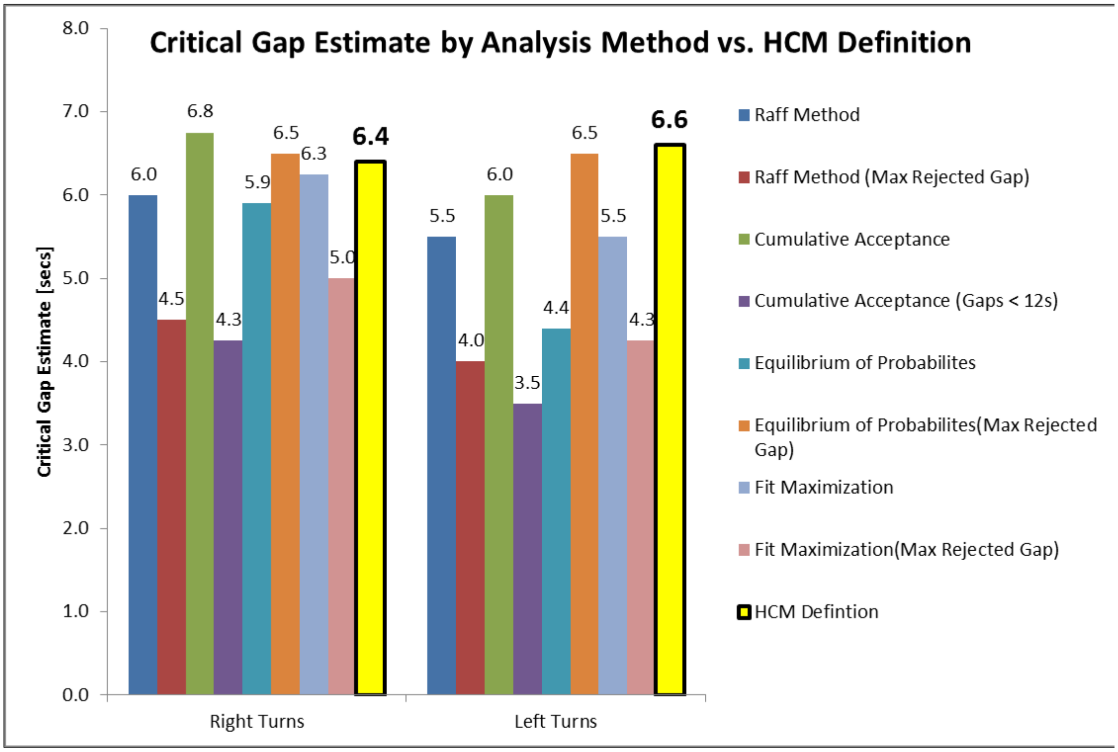


Figure 21. Comparison of Critical Gap by Analysis Method vs. HCM Definition

HCM definition value may not be applicable to all of the locations and conditions under which the study was conducted. The conditions that had the greatest impact were the intersection geometry which was a T-intersection for all locations and the number of lanes on the major street which was taken to be the weighted average between the actions recorded at two and four lane roadways. The HCM definition should therefore not be considered the "true value" but rather a value of critical gap worthy of comparison. For many methods, the critical gap estimates are quite close to the HCM value of critical gap. Overall, the method that most closely compared to the HCM definition was the Equilibrium of Probabilities method with the maximum rejected gap variation.

CHAPTER 6

RESULTS OF ANALYSIS BY FACTOR

There are a number of variables that influence a driver's gap acceptance behavior. Many factors are associated with the site such as the number of lanes, speed limit, functional classification, type of traffic control device, and traffic volume on the minor and major streets. Other factors are associated with the driver such as the driver's gender, age, the type of vehicle they are driving, and whether or not they have passengers. The final factors likely to affect gap acceptance behavior relate to other conditions at the time of the decision such as weather, time of day, presence of vehicles queued behind the turning vehicle, and length of wait time. As part of this research objective, gap acceptance behavior, in particular critical gap, were compared when considering a number of these different factors. Factors that could not be compared due to insufficient data of other complications were noted. For most of this analysis only data from Massachusetts locations were considered. The main reason for doing this was because, at the completion of this research initiative, only the Massachusetts data collection team had participated in the video validation methodology established for this research initiative. Where sample size necessitated and where commonality was seem between the data sets, both Massachusetts and Oregon locations were considered.

The following sections detail factors that appear to affect driver's gap acceptance decisions. The factors are organized into driver characteristics, site characteristics, and other factors related to conditions at time of the turn. The turning maneuvers were considered at the aggregate level including both left and right turning maneuvers as both maneuvers shows the same trends. By including both maneuvers the comparisons could be done in a more concise and easy to interpret manner while also drawing on the largest possible sample size for comparison. Where possible, the effects of different characteristics were compared using the Raff, Cumulative Acceptance, and Fit Maximization Methods that where discussed in the previous section. These methods were chosen because they are computationally simple, based in firm logic, and gave reasonable estimated of critical gap. Where possible, a Chi Square test was performed to compare the distributions of percentage of gaps accepted to see if the distributions showed statistically significant differences.

Driver Characteristics

The driver characteristics that appear to effect driver's gap acceptance behavior are driver gender, driver age, passenger presence, vehicle type, and driver decision making ability.

Driver Gender

Driver gender has shown mixed effects in other research initiatives, and the results were similarly unclear in this research initiative. While Table 8 shows differences between the critical gaps estimated by each method, the Chi-Square Test showed no statistically significant differences between the gap acceptance distributions.

Table 8. Effect of Driver Gender

Critical Gap Analysis Method	Male	Female	Difference
Raff Method [s]	5.5	6.0	0.5
Cumulative Acceptance Method [s]	6.0	6.25	0.25
Fit Maximization Method [s]	5.25	6.0	0.75
Chi-Square Test p-Value	p=0.573, no statistically significant difference		

However, while there may have been no statistically significant difference it does appear that, practically speaking, there may be a difference in driver gap acceptance behavior by gender. Figure 22 shows the gap acceptance curves for male and female drivers. While the distributions are very similar for large and smaller gaps, in the region where the most driver uncertainty occurs, between five and seven seconds, male drivers appear to be more aggressive. Further sampling across the nation should be conducted to see if these trends are representative of the entire driving population.

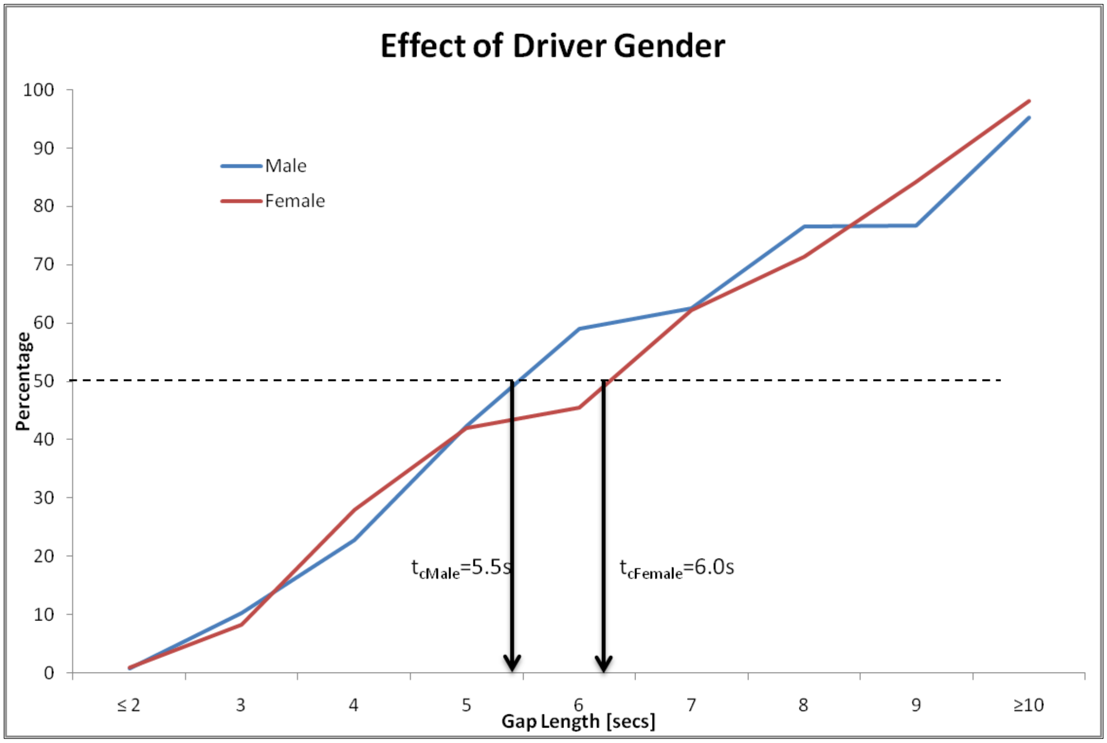


Figure 22. Effect of Driver Gender

Driver Age

This research initiative has shown significant differences in gap acceptance behavior between different age groups. As Table 9 shows, both practical and statistically significant differences exist in gap acceptance behavior between all age groups studied.

Table 9. Effect of Driver Age*

Critical Gap Analysis Method	Teen	Adult	Elderly
Raff Method [s]	5	6	5.5
Cumulative Acceptance Method [s]	3.75	5.25	6
Fit Maximization Method [s]	5	6.25	5.75
Chi-Square Test p-Value (Teen vs. Adult)	p<<0.05, statistically significant difference		
Chi-Square Test p-Value (Elderly vs. Adult)	p=0.021, statistically significant difference		

*included Oregon Data

The differences are most notable between the teen and adult driver. To a very high degree of certainty, the gap acceptance distributions are significantly different between these two age groups. The estimates of critical gap show similar differences between the teen and adult groups. All indications are that teen display more aggressive gap acceptance behavior than adults.

The differences are less notable between the adult and elderly driver groups. Additionally, it is unclear exactly what the overall difference is. Some analysis methods suggest the adult driver is more aggressive while others suggest the elderly driver is more aggressive. A larger sample of elderly drivers is required for definite conclusions to be drawn.

Figure 23 shows the gap acceptance curves for teen, adults, and elderly drivers. The same relative trends previously discussed are apparent with the gap acceptance distribution curves. The teen driver shows clearly more aggressive gap acceptance behavior than adult drivers. The difference between the adult and elderly driver groups is unclear.

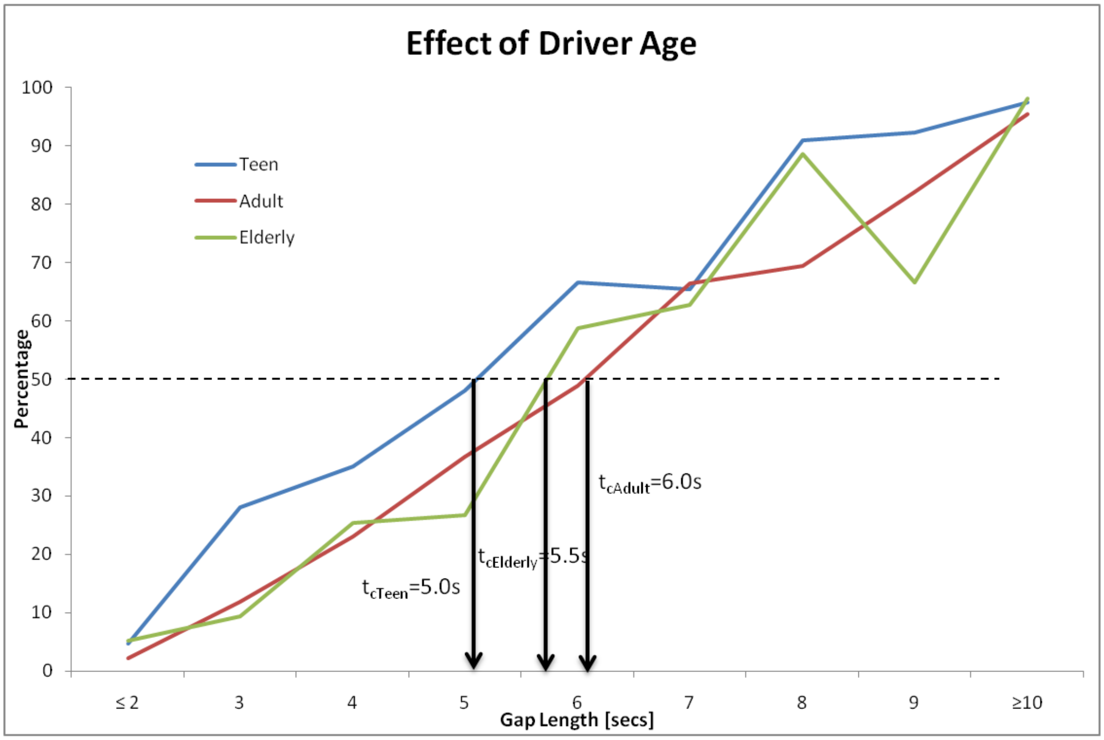


Figure 23. Effect of Driver Age

Passenger Presence

Whether or not a driver's gap acceptance behavior varies when there are passengers in the car has not been rigorously studied. One train of thought suggests that drivers may be more cautious knowing that they are responsible for more than one life in their car. Another would suggest that drivers, especially young drivers, may be distracted or pressured by passengers in the car to act more aggressively. In this research initiative the later was observed. As Table 10 shows, drivers act more aggressively, accepting smaller gaps, when passengers are present in the vehicle. While the difference in the gap acceptance distributions were not quite statistically significant, the differences in the critical gap estimate were practically significant. With differences in critical gap ranging from 1.0 to 1.5 seconds, this condition showed some of the greatest effects of the factors studied in this research initiative.

Table 10. Effect of Passenger Presence

Critical Gap Analysis Method	Passengers	No Passengers	Difference
Raff Method [s]	5.0	6.0	1.0
Cumulative Acceptance Method [s]	5.25	6.5	1.25
Fit Maximization Method [s]	4.5	6.0	1.5
Chi-Square Test p-Value p-Value	p=0.068, approaching statistical significance		

The gap acceptance curves for drivers with and without passengers in the vehicle, shown in Figure 24, clearly illustrate the difference in behavior between the two conditions. From three second to seven second, where almost all true gap acceptance decisions take place, drivers with one or more passengers were more aggressive than drivers without any passengers. Further sampling across the nation should be conducted

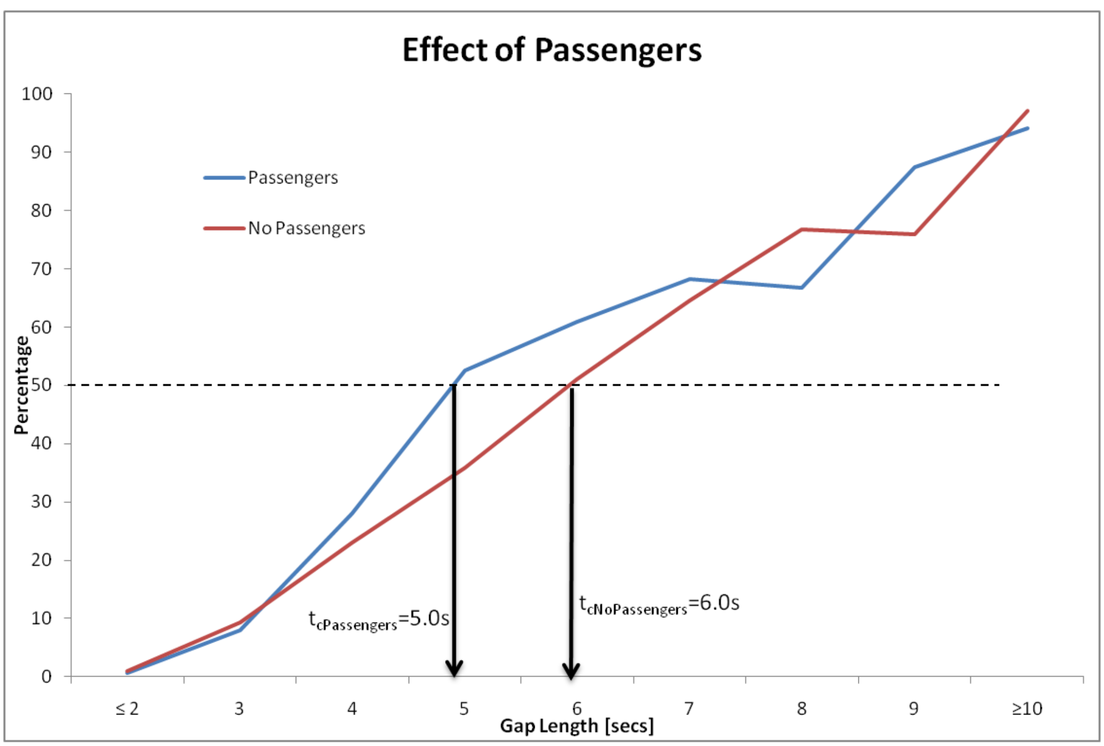


Figure 24. Effect of Passenger Presence

to see if these trends are representative of the entire driving population. The phenomenon seen this sample may be unique to the driving population studies in this research initiative, or there may be some underlying factors that are playing a role in these results.

Vehicle Type

The effect of vehicle type on a driver's gap acceptance decision is not easy to deduce. While passenger cars are certainly quicker and more maneuverable than a large commercial vehicles or even sport utility vehicles (SUVs), do these handling characteristics translate into driver behavior? In the field, data was collected on whether the driver was in a passenger car, van, SUV, truck, small commercial vehicle, or large commercial vehicle. In reducing the data, the trucks and both sizes of commercial vehicles categories were aggregated as their drivers displayed similar gap acceptance behavior. The results of the comparison of the effect of driver type on gap acceptance behavior are presented in Table 11.

Table 11. Effect of Vehicle Type

Critical Gap Analysis Method	Car	Van	SUV	Truck & Commercial
Raff Method [s]	7.0	6.0	5.0	5.0
Cumulative Acceptance Method [s]	6.25	7.0	5.5	5.5
Fit Maximization Method [s]	6.0	5.75	6.0	5.5
Chi-Square Test p-Value (Between All Sets)	p<<0.05, statistically significant difference			

Differences are seen between all sets of data in this analysis. These differences in gap acceptance distribution are at a statistically significant level. In general, the critical gap estimates suggest that trucks, SUVs, and commercial vehicles are more aggressive and passenger cars and van are more passive.

Figure 25 shows the gap acceptance curves by vehicle type. While some of the trends are difficult to distinguish, it is clear that drivers of vans are more passive in their gap acceptance behavior than drivers of other types of vehicles. Further sampling across the nation should be conducted to see if these trends are representative of the entire driving population.

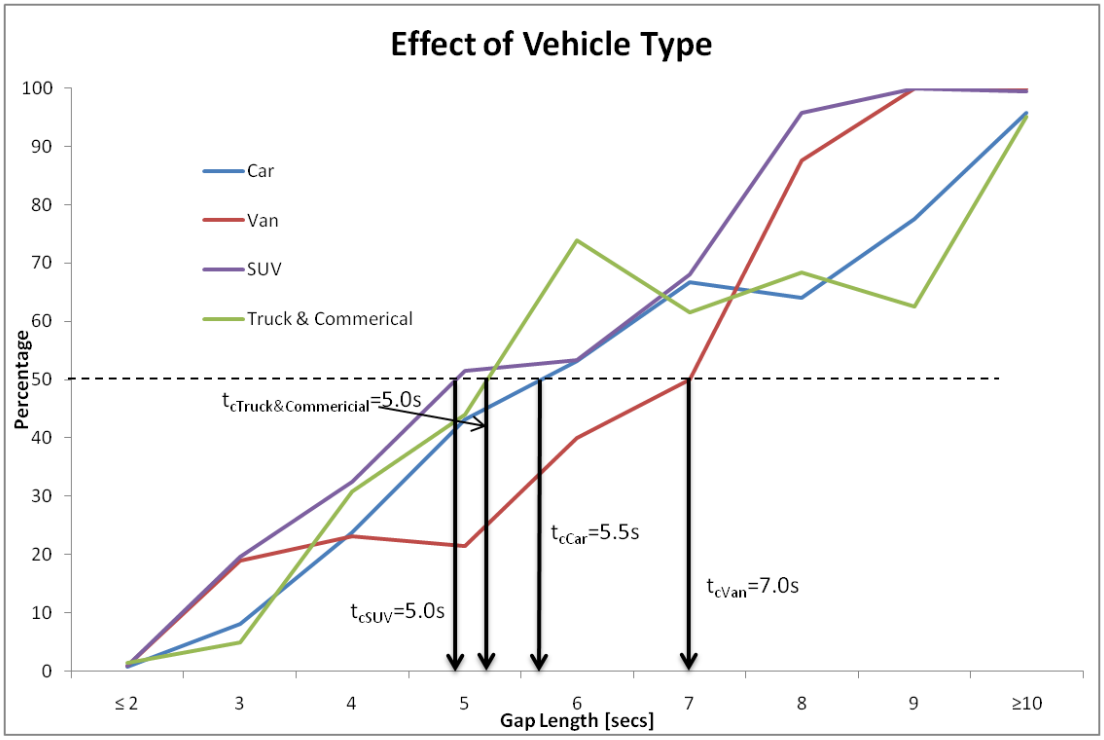


Figure 25. Effect of Vehicle Type

Driver Decision Making Ability

Assuming drivers are logical in their decision making process, after arriving at the intersection they will wait for a gap that they find suitably large and then accept it. In technical terms the will reject gaps until they are presented with a gap large than their individual critical gap. As a direct result, the gap that the driver accepts should be the largest that they see. This behavior however is not always exhibited by drivers. Some drivers observed in the study rejected gaps large than they ultimately accepted. This behavior, here forth referred to as illogical gap selection behavior, is worth investigating.

Using the data from the large-scale field study, the gap acceptance behavior of drivers who display illogical gap selection behavior was compared to drivers who display the more typical, logical gap acceptance behavior. The critical gap, as estimated by the Cumulative Acceptance Method, was compared for these two driver groups and is presented in Figure 26.

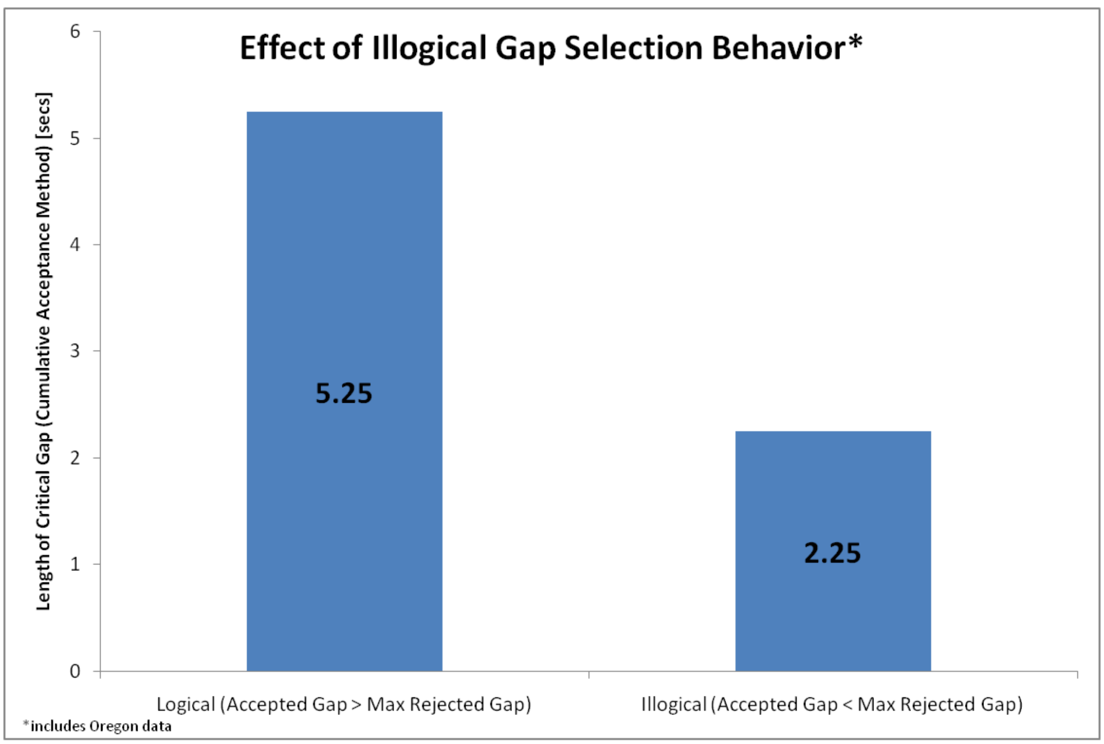


Figure 26. Effect of Illogical Gap Acceptance Behavior

Driver who displayed illogical gap selection behavior accepted much smaller gaps than drivers who displayed logical gap selection behavior. This may suggest that these drivers who displayed illogical gap selection behavior are having trouble selecting appropriate gaps and end up getting confused or frustrated and taking a much smaller gap than they would normally be comfortable with. Such a significant difference in the critical gap raising concerns about the potentially dangerous situations these drivers who displayed illogical gap selection behavior may be causing. A critical gap estimated by the Cumulative Acceptance Method of 2.25 seconds means that 15 percent of drivers who displayed illogical gap selection behavior accepted a gap less than or equal to 2.25 seconds. This is an extremely small gap that would normally be rejected by almost all drivers. These drivers are clearly exhibiting dangerous gap acceptance behavior. Further investigation into the nature of this problem should be considered.

Site Characteristics

In general, site characteristics appeared to have a less of an effect on drivers' gap acceptance behavior than other factors studied. This is interesting in that the *Highway Capacity Manual 2000* formula from determining critical gap relies heavily on site characteristics (23). The effects of major street speed limit, number of lanes on the major street, and number of lanes exiting the minor street will be discussed in this section.

Major Street Speed Limit

Major street speed limit has been show to both have a profound effect and have no effect at all depending on the study referenced (6; 17; 7). In this study the speed limit posted or the de facto speed limit when none was posted was recorded for the major street. For analysis, a comparison was made between speed limits 35 mph or less and speed limits 40 mph or greater. The results of this comparison are presented in
Table 12.

Table 12. Effect of Major Street Speed Limit

Critical Gap Analysis Method	35 mph or less	40 mph or greater	Difference
Raff Method [s]	6.0	5.5	0.5
Cumulative Acceptance Method [s]	6.25	7.0	-0.75
Fit Maximization Method [s]	5.25	5.8	-0.5
Chi-Square Test p-Value p-Value	p<<0.05, statistically significant difference		

While there are statistically significant differences in the gap acceptance distributions between the two conditions, it is unclear the overall effect on gap acceptance behavior. The estimates of critical gap are higher for the higher speeds by some methods, but lower for other methods. The reason for this apparent inconsistency can be explained by the gap acceptance curves shown in the Figure 27.

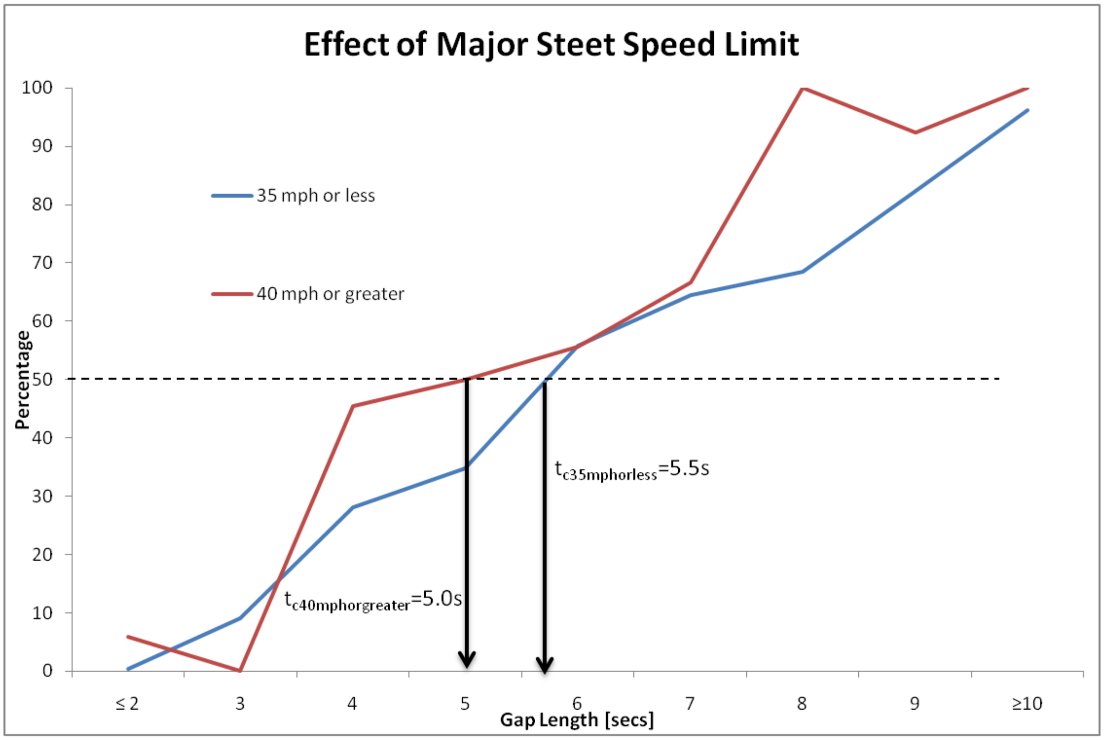


Figure 27. Effect of Major Street Speed Limit

While for most gap lengths, drivers are more aggressive at higher speed roads; this is not true for all gap lengths. The notable derivation from this trend around the three second range causes some of the analysis methods to return different results. To be certain of the effect of major street speed, more data should be collected are new sites.

Number of Lanes on Major Street

It is generally accepted that drivers wait for a larger gap in traffic to cross make a turn onto a four-lane roadway than a two-lane roadway. This however was not the case in the data analyzed in this study. The gap acceptance behavior of drivers at intersections with four-lane major streets and two-lane major streets are presented in Table 13.

Table 13. Effect of Number of Lanes on Major Street

Critical Gap Analysis Method	4 Lanes	2 Lanes	Difference
Raff Method [s]	5.5	5.5	0.0
Cumulative Acceptance Method [s]	4.8	6.25	1.5
Fit Maximization Method [s]	5.25	6.0	0.75
Chi-Square Test p-Value	p=0.02, statistically significant difference		

It is clear that the data shows that drivers display more aggressive gap acceptance behavior at intersections with four-lane major streets than at intersections with two-lane major streets. The differences in gap acceptance behavior at two-lane and four-lane major streets are both practically and statistically significant. This trend is not as clear when comparing the gap acceptance curves as shown in Figure 28.

A likely explanation for this seemingly counter intuitive result is that the nature of the two intersection types is different. The intersections with four-lane major streets tend to be busier with higher traffic volumes and fewer available gaps. Drivers may accept a smaller gap than they usually would because they know that it is the only way they will

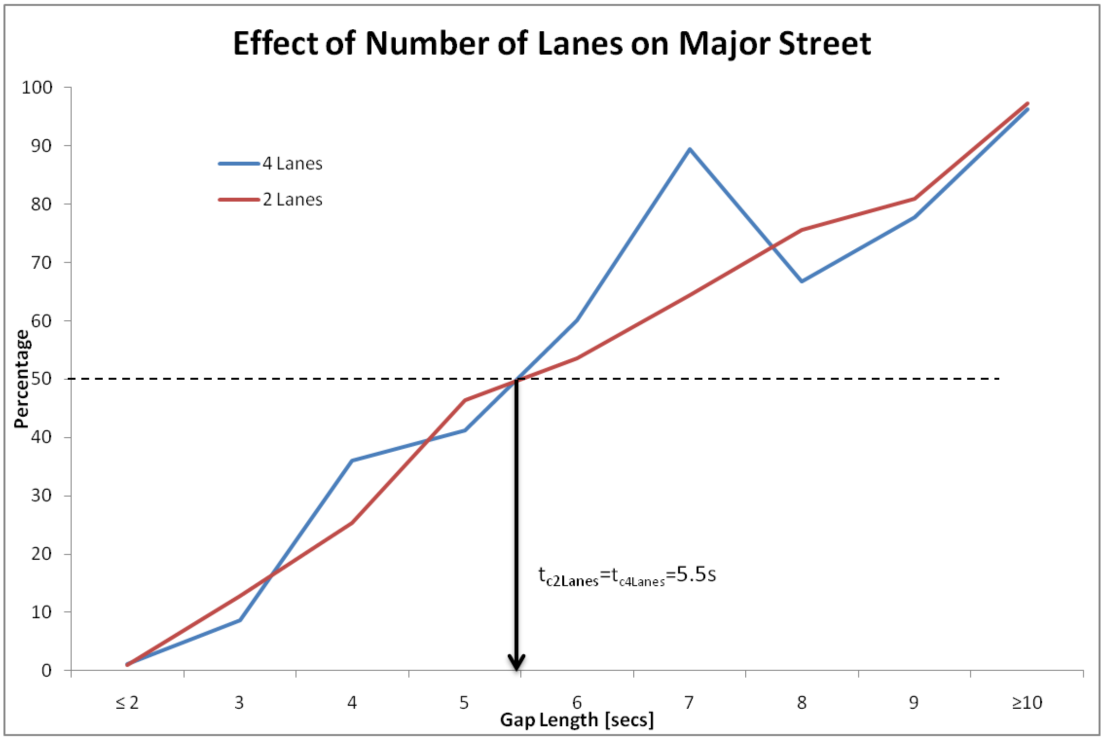


Figure 28. Effect of Number of Lanes on Major Street

get out. At the more quiet intersections with two-lane roadways drivers can wait for a large gap as they are expecting one to be available after a relatively short wait. Further research initiatives should compare gap acceptance behavior to the gap availability at the time of the turn to see if that is the underlying variable driving this phenomenon.

Number of Lanes Exiting Minor Street

The final site characteristic to be discussed in this section is the number of lanes exiting the minor street. This factor was included as a representative factor that had little impact on drivers' gap acceptance behavior. The gap acceptance behavior of drivers at intersections with one-lane and two-lane minor street exiting lanes is presented in Table 14.

Table 14. Effect of Number of Lanes on Major Street

Critical Gap Analysis Method	1 Lane Exiting	2 Lanes Exiting (Marked or Effective)	Difference
Raff Method [s]	5.5	5.5	0.0
Cumulative Acceptance Method [s]	6.0	6.25	0.25
Fit Maximization Method [s]	5.25	6.0	0.75
Chi-Square Test p-Value	p=0.888, no statistically significant difference		

There is no practical difference between the critical gaps estimated by the different analysis methods and there is no statistically significant difference between the gap acceptance distributions between the two intersection types.

This trend is even clearer looking at the gap acceptance curves presented in Figure 29. For almost any gap length, the percent of gap accepted by drivers is the same for both intersection types. This shows that drivers' gap acceptance decisions are not affected by the number of lanes exiting the minor street.

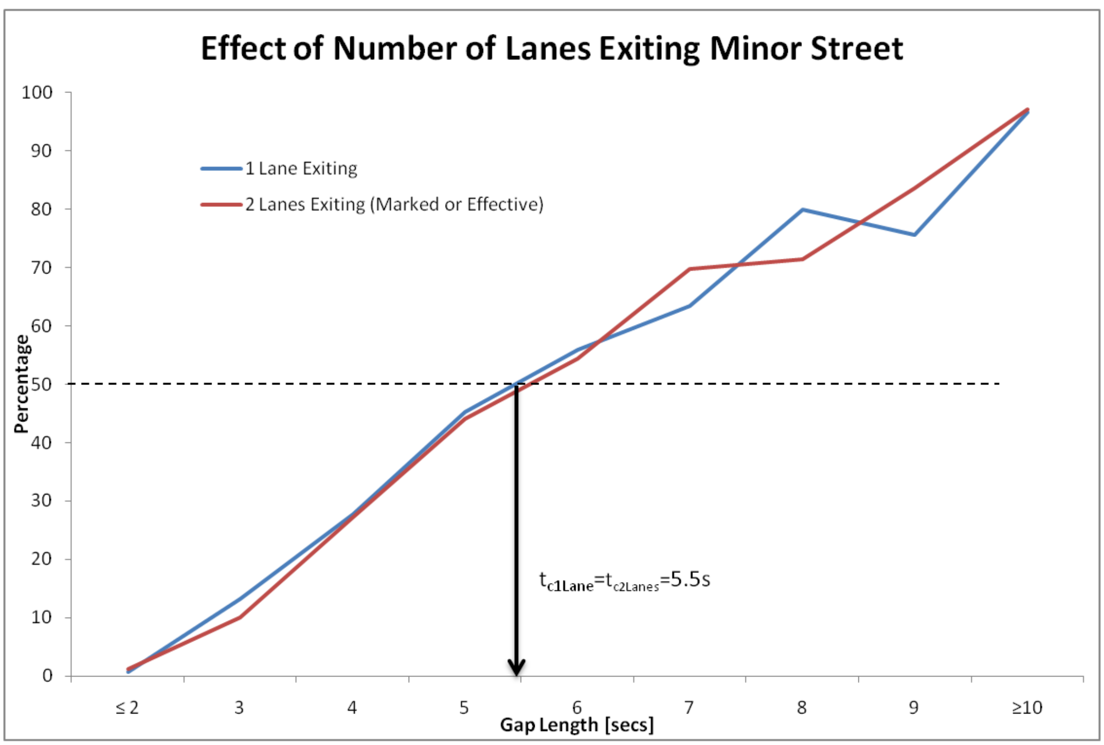


Figure 29. Effect of Number of Lanes Exiting Minor Street

Other Factors

The most compelling results of results were from factors not directly related to either driver or site characteristics. These factors are related to other conditions present when the driver is making the gap acceptance decision. The time of day and day of week are two such characteristics that showed some effect on drivers' gap acceptance behavior. The presence of a queue behind the driver, wait time, and number of gaps rejected had more profound effects on drivers' gap acceptance behavior.

Time of Day

There has long been a belief that drivers are more aggressive during the AM and PM peaks when they are commuting to and from work. As all actions observed during the field study were time stamped, they could be easily be organized by time period. The gap acceptance behavior was compared for the AM Peak, defined as 7-9 AM, the PM Peak, defined as 4-6 PM, and Midday, defined as 10 AM - 2 PM. These results of this comparison are presented in Table 15.

Table 15. Effect of Time of Day

Critical Gap Analysis Method	AM Peak (7-9 AM)	PM Peak (4-6PM)	Midday (10AM-2PM)
Raff Method [s]	6.5	6	5
Cumulative Acceptance Method [s]	4	4.25	6
Fit Maximization Method [s]	5	5.75	5.5
Chi-Square Test p-Value (Between All Sets)	p<<0.05, statistically significant difference		

As the estimates of critical value shown, drivers are most aggressive during the AM and PM Peaks than during the Midday time period. Figure 30 shows similar results, although though there is a dip in the AM Peak curve at six second that skews the Raff Method critical gap estimate; this is likely a sample size issue.

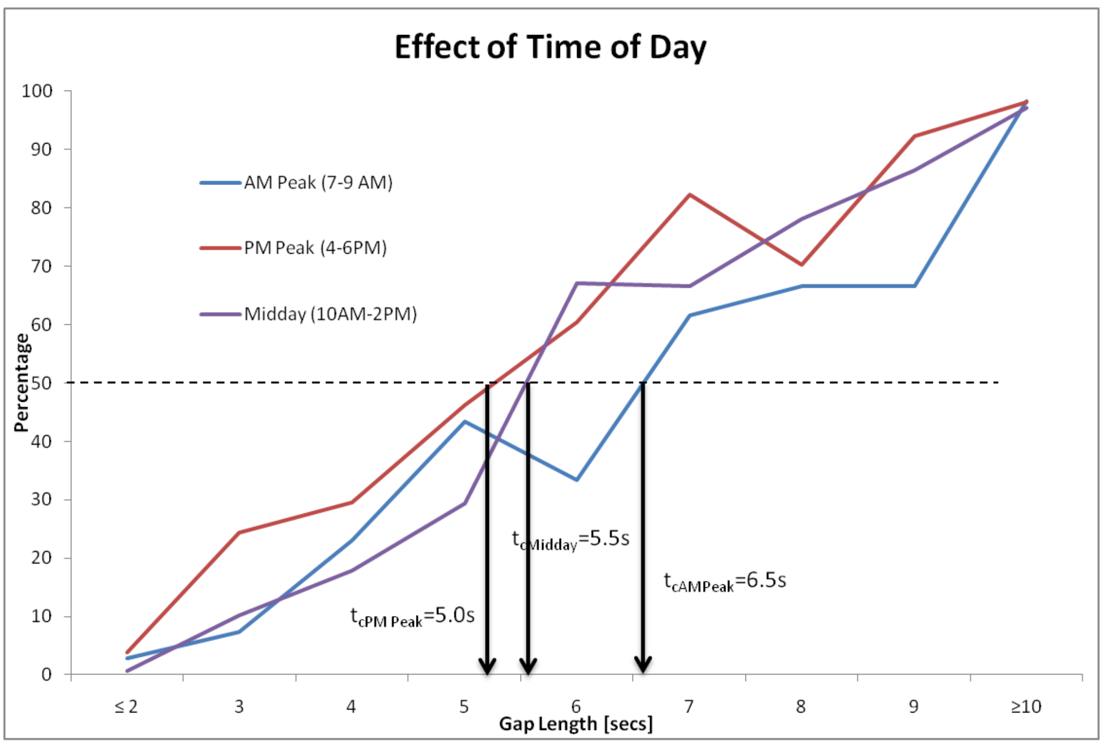


Figure 30. Effect of Time of Day

Day of Week

The comparison by day of week was implemented in the same fashion as the time of day analysis. Since data was only collected on weekdays, the analysis is limited to Monday through Friday. Table 16 presents the results of the comparison by day of week.

Table 16. Effect of Day of Week

Critical Gap Analysis Method	Monday	Tuesday	Wednesday	Thursday	Friday
Raff Method [s]	5.5	6	5	6	5.5
Cumulative Acceptance Method [s]	5.5	4.75	6.25	6.25	7
Fit Maximization Method [s]	5.25	6	5	6.25	6

*includes Oregon data

There are no clear trends by day of week as there is a great deal of variability between analysis methods. Figure 31 presents the gap acceptance curves by day of week. It is possible that more data could uncover trends; however it is also likely that drivers do no change their gap acceptance behavior by the day of the week.

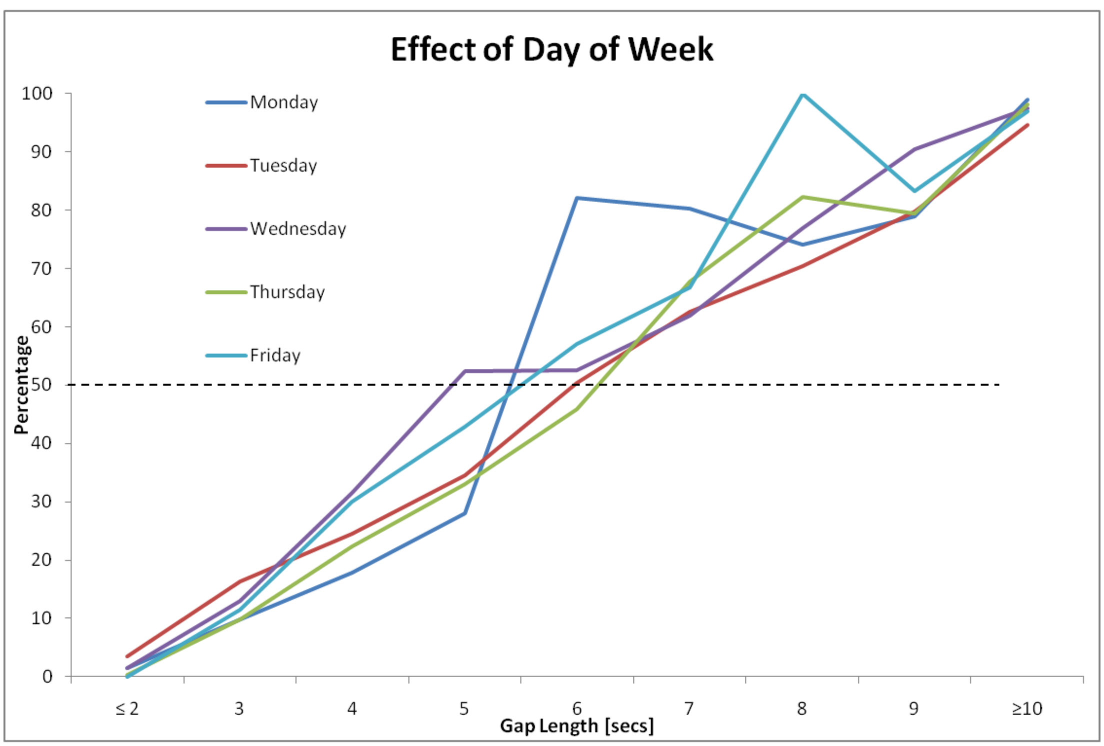


Figure 31. Effect of Day of Week

Queue Presence

One of the more interesting results from this research initiative related to a change in driver behavior when there are vehicles queued up behind the driver. While the gap data was being observed in the field, the second observer took note of how many vehicles were queued up behind the vehicle exiting the minor street when the driver made the turning maneuver. For analysis, the cases where a queue was present and where no queue was present were compared. These results are presented in Table 17.

Table 17. Effect of Queue Presence

Critical Gap Analysis Method	No Queue	Queue Present	Difference
Raff Method [s]	6.0	4.5	1.5
Cumulative Acceptance Method [s]	6.5	5.25	1.25
Fit Maximization Method [s]	6.0	4.5	1.5
Chi-Square Test p-Value	p<<0.05, statistically significant difference		

By all three analysis methods utilized, the estimated critical gap when a queue is present was much shorter than when no queue was present. The gap acceptance distributions of these to conditions were shown to be different at a very high level of statistical significance.

This trend is even more pronounced when examining the gap acceptance curves shown in Figure 32. For all but the smallest and largest gaps a greater percentage of gaps were accepted when a queue was present.

These results prove that drivers who have vehicles queued up behind them will accept shorter gaps. These drivers likely feel pressured by the vehicles behind them and therefore are willing to accept a gap smaller than they normally would.

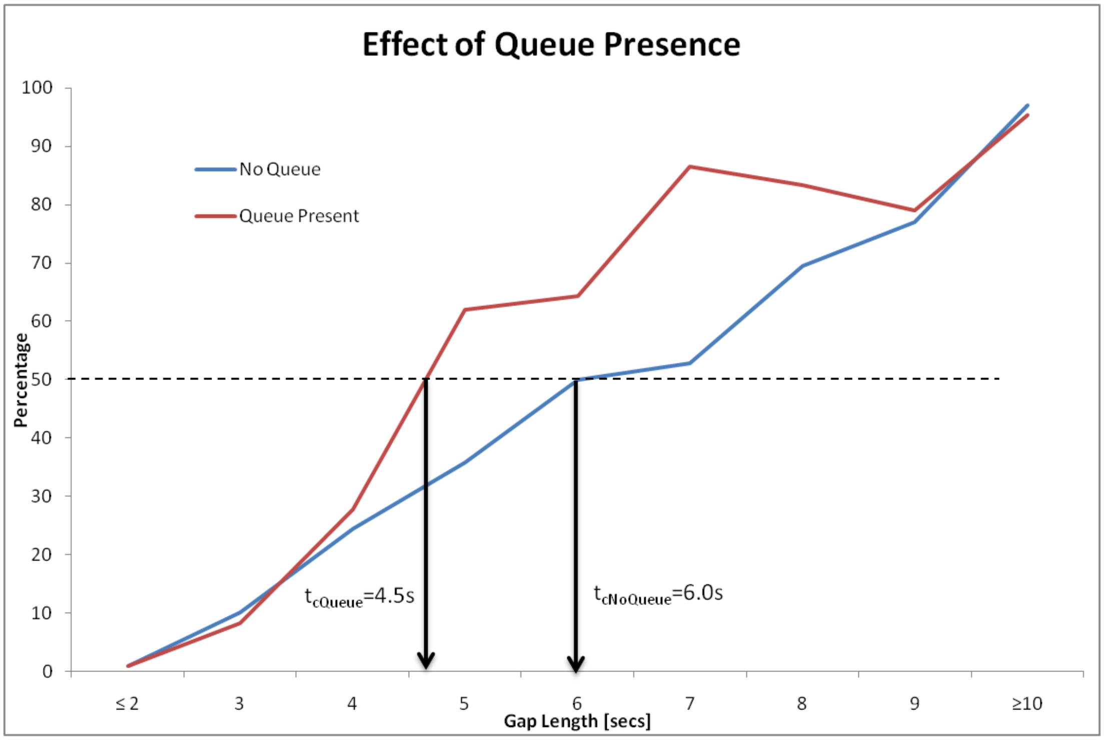


Figure 32. Effect of Queue Presence

Wait Time

As any driver can attest, if you have been waiting a long to time to take a turn you may start thinking about accepting a gap smaller than you normally would. According to the results of this study, drivers not only think about selecting a smaller gap, but do in fact select a smaller gap after waiting for an extended period of time.

Using the time stamped action data from the field study, the amount of time each vehicle waited before turning was calculated. For analysis purposes these wait time were aggregated into four intervals: less than 10 seconds, 10 to 20 seconds, 20 to 30 seconds, and greater than 30 seconds. The Cumulative Acceptance Method was then used to estimate the critical gap for turning maneuvers that feel into each of these four categories. The results of this analysis are presented in Figure 33.

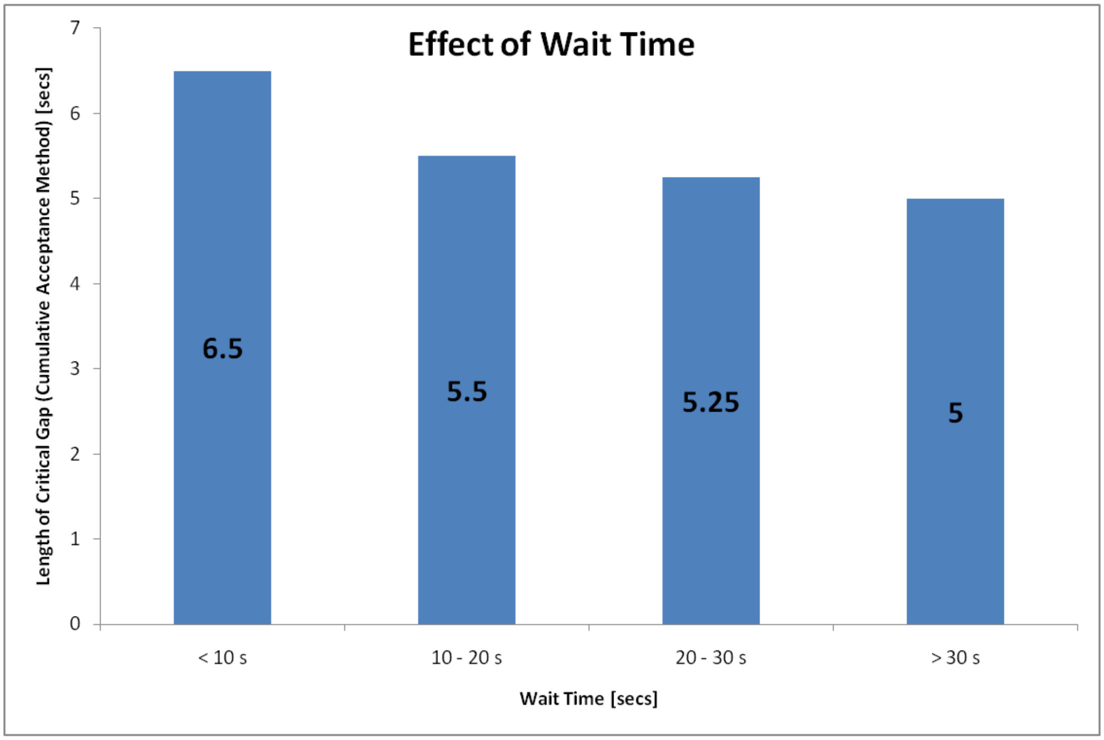


Figure 33. Effect of Wait Time

As the data shows, drivers were willing to accept smaller gaps as the amount of time they had been waiting increased. This falls in line with expectations and suggests that drivers are willing to sacrifice a bit of safety as they become impatient.

Number of Rejected Gaps

Closely related to wait time is the number of gaps the drivers rejects. As the driver waits from an acceptable gap they reject more and more gaps. As the number of gaps that they have rejected increases they are likely to become more impatient and possibly accept a smaller gap

Aggregating the field data by the number of gaps the driver rejected, conclusions could be drawn. As with wait time, the Cumulative Acceptance Method was used to estimate the critical gap for turning maneuvers that feel into each category. Figure 34 presents the results of this analysis.

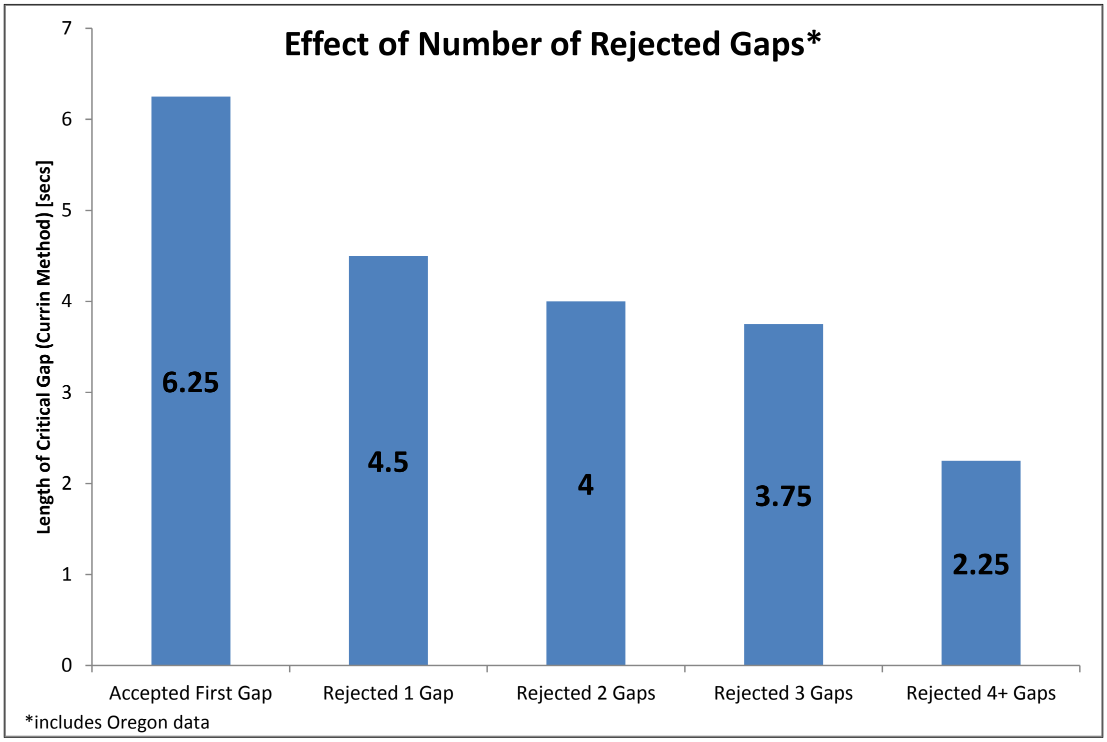


Figure 34. Effect of Number of Rejected Gaps

As the data shows, drivers were willing to accept smaller gaps as the number of gaps they rejected increased. As with the wait time analysis, this falls in line with expectations and suggests that drivers are willing to sacrifice a bit of safety as they become impatient.

Factors for Future Consideration

While the large-scale field test allowed answers to be developed to many questions about the factors that affect gap acceptance decisions, a few remain. The effects of the minor street speed limit, major and minor speed functional class, and excessive speeding were unclear. There was insufficient data tackle the questions of the possible effect of weather, road conditions, type of traffic control device on the major and minor streets, and sightline restrictions. An additional question that arose in the course of the analysis was whether the conflicting vehicle was traveling in the same or opposite direction as the subject drivers desired turn direction effected the driver's gap acceptance decision. The data set gathered in this study has the potential to answer this question as well.

CHAPTER 7

CONNECTING DRIVER BEHAVIOR TO CRASH EXPERIENCE

As described in the methodology section, data from the UMass Safety Data Warehouse was used in this research initiative. The crash, citation, and other relevant data were accessed from various agencies through the UMass Safety Data Warehouse, which was developed as a tool for maximizing the use of highway safety data. Data available from the Warehouse include traditional datasets, such as crash and citation data, as well as less traditional highway safety information, such as health care data and commercial vehicle safety data. The use of assorted, diverse data allows for truly comprehensive analyses of highway safety problem areas. The accompanying schematic shows the variety of data that is available in the UMass Safety Data Warehouse. The data was analyzed to understand the nature of the crash and relative differences between age and gender groups.

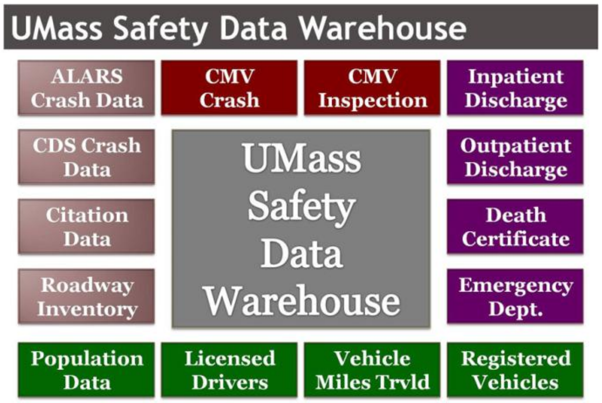


Figure 35. UMass Safety Data Warehouse Schematic

In order to identify crashes within the Data Warehouse related to gap acceptance a process was developed for this research initiative to identify "gap acceptance related crashes." To maintain a manageable sample size crashes occurring in Massachusetts between 2007 and 2009 were analyzed. The crashes considered were those with characteristics that matched the conditions under which the gap acceptance data was collected; occurring at an unsignalized T-intersection where a vehicle was making a left or right hand turn. To ensure that the crashes were related to gap acceptance issues, the crashes were further narrowed by those where a driver was cited for an intersection right of way violation, an indication of inappropriate gap acceptance behavior (9).

The gap acceptance related crash identification process narrowed the data set from a total of 93,253 crashed to 156 crashes related to gap acceptance as shown in Figure 36.

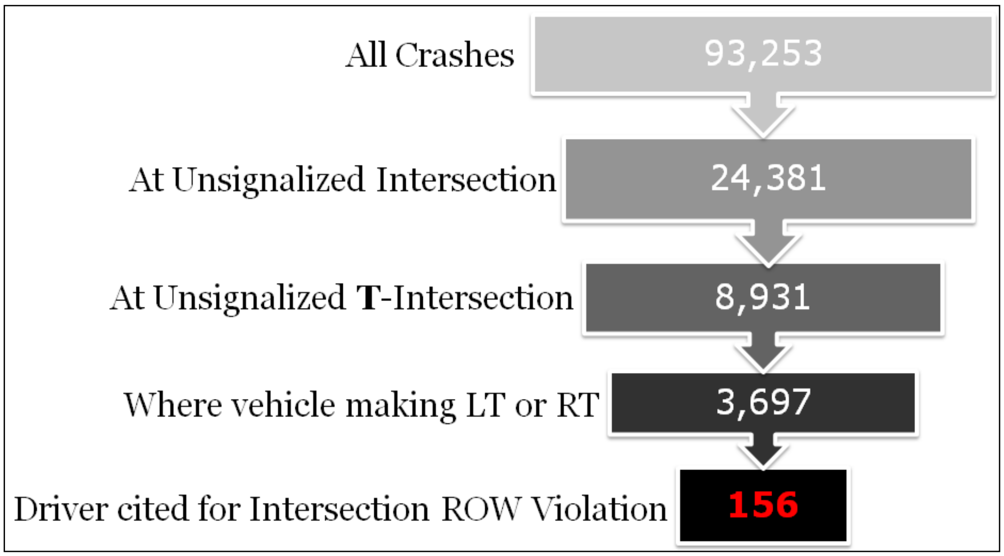


Figure 36. Identifying Gap Acceptance Related Crashes (Massachusetts 2007-09)

To ensure that the 156 remaining crashes were indeed gap acceptance related crashes the crash narratives, as recorded on the crash reports were reviewed. The crash narratives were quite telling as to the circumstances of the crash. One crash narrative reads:

Vehicle 2 was traveling east on Main St. when vehicle 1 pulled out onto Main St. from Harrington ***cutting in front of*** *vehicle 2 causing a collision.*

For whatever reason, the driver of vehicle 1 accepted too small of a gap when executing their turn. Another crash narrative reads:

Vehicle 1 was traveling west on Rt. 44 when he stated that vehicle 2 pulled out from Mill St. and ***cut in front of him****. Vehicle 1 then swerved to the right to avoid hitting oncoming traffic and vehicle 2. Vehicle 1 then ran into a ditch off of Rt. 44, struck a Kahains furniture sign, telephone pole, and street sign. Vehicle 2 operator stated he observed vehicle 1 traveling west on Rt. 44 and* ***estimated that he had enough time to execute a left turn*** *onto Rt. 44 heading east. Two witnesses stated vehicle 2 cut off vehicle 1 and caused the accident. Vehicle 2 operator cited for failure to yield.*

In this case, the operator of vehicle 2 explicitly states that they considered the gap available to them, determined it was large enough, and accepted it. The operator of vehicle 1 and onlookers clearly believed it was an insufficient gap. One other crash narrative reads:

Vehicle 1 was travelling westbound on Washington St., vehicle 2 pulled out of Walker St. without looking, causing vehicle 1 to drive directly into the driver side of vehicle 2. The operator of vehicle 2 stated that ***he could see vehicle 1 in the distance and believes that vehicle 1 speed caused the accident****. Operator 2 was cited for 89/8 fail to yield right of way/intersection.*

This case has an added complication that speed may have been a factor, however, regardless of the speed of vehicle 1, the operator of vehicle 2 made the determination that the gap was sufficiently large, when in fact, it was not. These narratives serve as validation that the crashes identified were in fact gap acceptance related and an intersection right of way violation is an effective parameter to identify such crashes.

The analysis of the crash data was quite simple. The driver involvement and citation rates in these gap acceptance crashes were normalized by the size of the respective driving population. The driver populations that were over or under represented were identified.

The final step in the analysis was to compare the gap acceptance behavior with the relative representation in gap acceptance related crashes.

Comparing the results from the gap acceptance analysis and crash analysis the most interesting findings where drivers where making left turns. This is also the maneuver that presents the greatest challenge and danger.

First looking at the gap acceptance data, there are differences in gap acceptance behavior between male and female drivers, particularly when considering left turns, the maneuver that resulted in a greater number of crashes. Table 18 compares the critical gap as determined by the Raff Method by driver gender for left turns. The data shows that male drivers accept smaller gaps than female drivers. This represents more aggressive gap acceptance behavior by the male drivers.

Table 18. Left Turn Critical Gap by Gender

	Critical Gap
Male Drivers	5.5 s
Female Drivers	7.0 s

Gap acceptance data, again with a focus on left turns, was also compared for teen drivers and adult drivers as shown in Table 19. The results show that teen drivers are willing to accept smaller gaps than adult drivers, a sign of aggressive gap acceptance behavior. Unfortunately, the relatively small sample of elderly drivers yielded inconclusive results, however studies have shown that elderly drivers tend to be more conservative in the gap acceptance behavior waiting for larger gaps before turning (4).

Table 19. Left Turn Critical Gap by Age

	Critical Gap
Teen	5.5 s
Adults	6.5 s

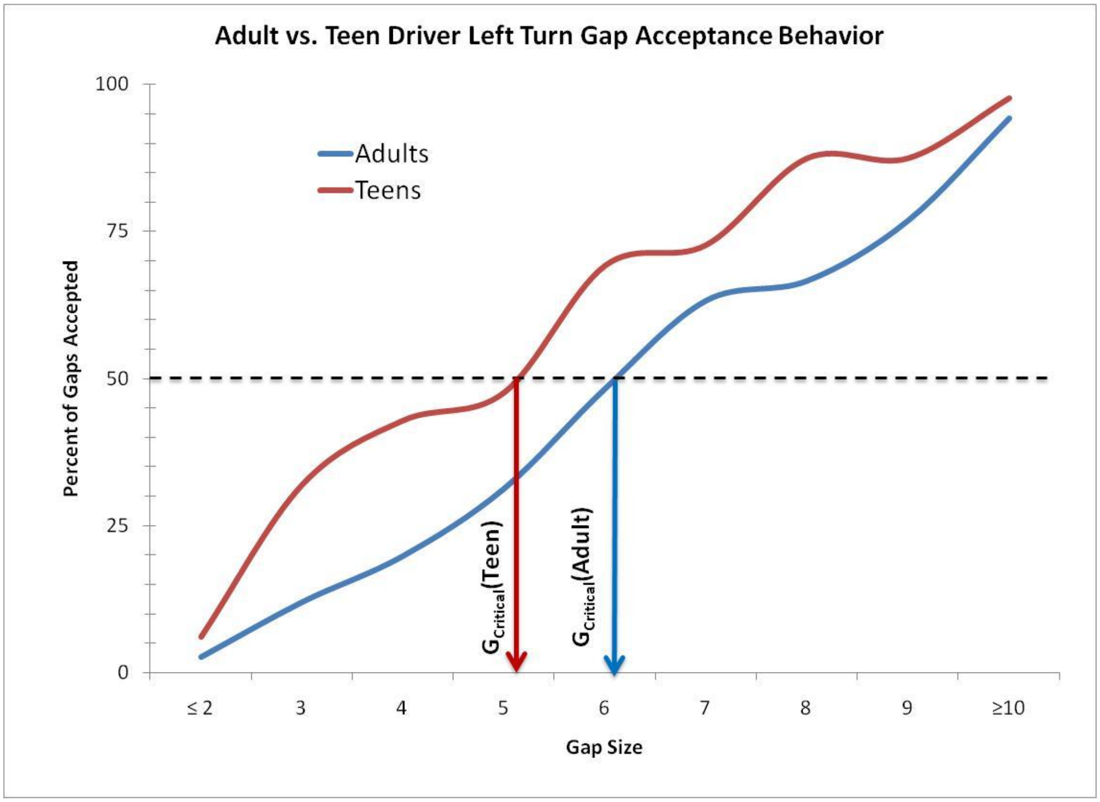


Figure 37. Adult versus Teen Driver Left Turn Gap Acceptance Behavior

Looking closer at the results of findings on driver age, the percent of accepted and rejected gaps are plotted by gap length in Figure 37. This figure shows that for any length gap the teen driver is more likely to accept it than the adult driver. The critical gap, as depicted in the graph, represents the 50/50 decision point where drivers are equally likely to reject or accept the gap. The critical gap is significantly shorter for the teen drivers than the adult drivers. This further reinforces the conclusion that teen drivers are more aggressive in the gap acceptance behavior than adult drivers.

With the apparent differences in gap acceptance behavior between driver groups, the question is whether some of these aggressive behaviors translate into gap acceptance related crashes. To answer that question, the gap acceptance related crashes were analyzed by driver group. The percentage of each driver group's involvement in the crashes was compared to the group's proportion of the driving population. The resulting metric measures whether the group is over or under represented in gap acceptance crashes relative to the number of licensed drivers in the group; numbers greater than 1 correspond to overrepresentation of a group and values less than 1correspond to underrepresentation of the group. Table 20 presents the results of these findings.

Table 20. Relative Involvement in Gap Acceptance Related Crashes by Driver Group

	Relative Involvement*
Female Drivers	0.9
Male Drivers	1.1
Adults Drivers (age 20 - 64)	1.0
Teen Drivers (under 20)	3.4

*% of drivers involvement in gap acceptance related crashes divided by % of driving population

These results show that male drivers are overrepresented and female drivers are underrepresented, suggesting that the male drivers aggressive gap acceptance behavior may be resulting in gap acceptance related crashes. The comparison between teen and adult drivers are even more striking with the adult drivers being appropriately represented given the number of adult drivers and the teen drivers being overrepresented by more than a factor of three. These results by age group would be even more striking if the vehicle miles traveled were considered as teen drivers tend to drive less than adult driver meaning they have less exposure but significantly more crashes.

CHAPTER 8

SUMMARY AND CONCLUSION

This research initiative has shown that it is possible to collect gap acceptance data in the field with the use of computer software, that the results of these studies accurately reflect conditions in the field, that the method of analysis used affects the results, that there are a number different factors that affect gap acceptance decisions, and that differences in gap acceptance behavior between different driver groups can have implications on safety.

The results of each of the four research objectives identified in this research initiative are summarized below.

Research Objective 1 - Develop and Validate Data Collection Tool

Detailed data on driver gap acceptance behavior can be accurately and efficiently collected in the field with the aid of computer software, and the results can be validated using parallel field video recording.

A large-scale field study was completed by over a dozen team members in Massachusetts and Oregon. In total 60 sites, 2,767 drivers, 10,419 driver decisions, and 22,639 gaps in traffic were observed. These observations represent a wide array of site conditions, under various traffic conditions, but many different drivers. To ensure that the results of the field study were accurate, video validation was performed.

As shown by the number of turning maneuvers recorded, the gap availability profiles, and the results of the gap acceptance analysis, the methodology outlined by this research initiative and carried out by trained observers allows for the accurate collection of naturalistic data acceptance data in the field. Across all analysis methods there is little or no difference between the gap acceptance metrics from the video truth data and the observer data. With no practical or statistical differences between the gap acceptance data collected by the observers and the true conditions and captured by the video, it is reasonable to deduce that the observers are collecting data that accurately reflects the field conditions.

Research Objective 2 - Analysis by Method

The method in which gap acceptance data is analyzed can have profound and identifiable effects of the conclusions of the analysis.

Five gap acceptance data analysis methods were identified with two variations of each. All methods except for the Average Accepted Gap Method resulted in estimates of critical gap. The Average Accepted Gap, Cumulative Acceptance, and Raff Methods were the most computationally simple followed closely by the Fit Maximization Method. Of the methods compared, the Equilibrium of Probabilities Method was the most computationally demanding. The Raff, Equilibrium of Probabilities, and Fit Maximization Methods utilized both the accepted and rejected gap data, requiring a smaller sample size. The Average Accepted Gap and Cumulative Acceptance Methods used on accepted gap data requiring a large sample size for meaningful results.

The variation of excluding gaps over 12 seconds seemed to make so of the resulting critical gap values more in line with expectations, but causes loss of some of the sample size. Similarly, the maximum rejected gap variation seems to result in values that more accurately reflect the driver population, but causes loss of some of the sample size.

Methods, such as the Siegloch Method, were excluded because their application did not match the study conditions. Other methods, such as the Troubeck Method, were excluded as they were too computationally intensive for practical applications.

The method used for analysis, at times, resulted in significantly different results. A number of methods gave estimates close to critical values defined by the Highway Capacity Manual.

Research Objective 3 - Analysis by Factor

There exist appreciable and identifiable differences in gap acceptance behavior across drivers under varied conditions.

Factors that appeared to affect drivers' gap acceptance decision including driver characteristics, site characteristics, and other factors related to conditions at time of the turn were analyzed.

The driver characteristics that appear to effect driver's gap acceptance behavior are driver gender, driver age, passenger presence, vehicle type, and driver decision making ability.

In general, site characteristics appeared to have less of an effect on drivers' gap acceptance behavior than other factors studied. The major street speed limit and number of lanes on the major street had some effect on drivers' gap acceptance decisions.

The most compelling results of factors were from factors not directly related to either driver or site characteristics. These factors are related to other conditions present when the driver is making the gap acceptance decision. The time of day and day of week are two such characteristics that showed some effect on drivers' gap acceptance behavior. The presence of a queue behind the driver, wait time, and number of gaps rejected had more profound effects on drivers' gap acceptance behavior.

While the large-scale field test allowed answers to be developed to many questions about the factors that affect gap acceptance decisions, a few remain. The effects of the minor street speed limit, major and minor speed functional class, and excessive speeding were unclear. There was insufficient data tackle the questions of the possible effect of weather, road conditions, type of traffic control device on the major and minor streets, and sightline restrictions. An additional question that arose in the course of the analysis was whether the conflicting vehicle was traveling in the same or opposite direction as the subject drivers desired turn direction effected the driver's gap acceptance decision. The data set gathered in this study has the potential to answer this question as well.

Research Objective 4 - Connecting Driver Behavior to Crash Experience

Differences in gap acceptance behavior across drivers under varied conditions have effects on safety that can be seen in the analysis of gap acceptance related crashes.

Using the process described in this research initiative, "gap acceptance related" crashed can be identified and analyzed. These results of the analysis of gap acceptance related crashes showed strong connections to the results of the gap acceptance analysis. Driver groups displaying more aggressive gap acceptance behavior, male drivers and teen drivers, are overrepresented in gap acceptance related crashes. Understanding these connections could lead to more targeted solution to the gap acceptance related crash problem. Such solutions could involve education of the drivers group displaying dangerous behavior. Further analysis could also highlight other factors associated with aggressive gap acceptance behaviors or gap acceptance related crashes. Solutions targeting dangerous roadway characteristics could lead to an even more targeted solution. If these solutions still fall short in mitigating the gap acceptance related crash problem advancing technologies should be investigated such as those that can alert drivers whether or not a safe gap in traffic exists. (24) The gap acceptance related crash problem is a complex one that requires further investigation and a multi-faceted mitigation approach if significant improvements in safety are to be made.

Conclusions

This research initiative represents a promising step in enhancing the professions understanding of gap acceptance behavior. The data collection tool developed and validated through this research initiative will allow for large-scale collection of naturalistic driver gap acceptance behavior. The large data set collected in this research initiative could be used to update and strength the current understanding of driver gap acceptance behavior. This tool could be used by academics and practitioners across the country to develop a larger data set that could lead to a greater understanding of driver gap acceptance behavior.

This research initiative has identified and quantifies the effects of different driver, site, and environmental factors that affect drivers' gap acceptance behavior with a greater level of certainty than has previously been possible given the large sample set.

Comparisons were made between different analysis methods about their overall applicability, ease of use, and reasonableness of results. Conclusions were be drawn on how closely the numbers the results of these analysis methods compare to those presented in the *Highway Capacity Manual 2000*.

Connections were drawn between gap acceptance behavior and crash experience, developing a better understanding of the driver and environmental factors that significantly contribute to increased crash risk will help guide the way to targeted design solutions.

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