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Title: AN EVALUATION OF GAP ACCEPTANCE BEHAVIOR AT UNSIGNALIZED INTERSECTIONS

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Gap acceptance behavior is critical to the safety and operational performance of unsignalized intersections. The complex nature of the human behavior and its dependence on various socioeconomic and environmental parameters makes it challenging for transportation professionals to assess the performance of such intersections. To investigate the behavioral patterns of drivers at unsignalized intersections, a novel procedure was developed and validated for the accurate observation of naturalistic gap acceptance behavior. Specifically, the authors examined two-way stop-controlled (TWSC) intersections with a two way left turn lane (TWLTL) on the major road. After examining the critical gap and identifying behavioral changes caused by waiting time, time of day, presence of passengers, and presence of queue, the authors further investigated the relationship between waiting time and gap acceptance and analyzed the variations in waiting time for right and left turn maneuvers. The results of this study reinforce the notion that

driver behavior is affected by external factors such as waiting time, time of day, presence of passengers, presence of queue, etc. and should continue to be investigated in localities across the country.

AN EVALUATION OF GAP ACCEPTANCE BEHAVIOR AT UNSIGNALIZED INTERSECTIONS

by

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Sahar Nabaee, Author

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CONTRIBUTION OF AUTHORS

Dr. David Hurwitz contributed to the ideas behind both manuscripts and provided suggestions and feedback through multiple revisions. Derek Moore assisted in the preparation of the first manuscript. Additionally, he and my other colleagues Halston Tuss and Brennan Burbank helped in the data collection for both projects. Cole Fitzpatrick also contributed to digitizing and reducing the video data.

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CHAPTER 1

INTRODUCTION

1.1 Intersection Control

At-grade intersections introduce conflicts between different vehicular and pedestrian movements and as such are complex elements of the surface transportation system. Different levels of control can be implemented at intersections to manage these conflicts and assign the right of way in such a manner to improve safety and provide for the efficient movement of vehicles and pedestrians. The determination of what level of control should be implemented at an intersection depends on a number of factors, the most crucial being the probability of a conflict between any two vehicular and/or pedestrian movements. Intersection control alternatives include the following:

- Type I - Basic rules of the road

  These rules are declared in the states' traffic law, apply at any intersection, and all drivers are expected to know them. For instance, through movement always have the right of way over left turning vehicles, unless obliged differently by traffic control devices. To comply with the basic rules of the road, drivers need adequate sight distance (SD) to detect potential conflicts and to make proper decisions in a reasonable duration of time. Thus, if SD requirements are not met at an intersection, different remedies or other levels of control are needed. It should be noted that even if no SD issues exist, there might be other reasons to implement higher levels of control, such as high traffic demand or intersection complexity (Roess et al., 2011).

- Type II - Yield and stop control

  The conditions for which yield or stop control should be considered for implementation are specified in the Manual on Uniform Traffic Control Devices (MUTCD). However, it is worthy of note that the MUTCD warrants are intended to provide guidance, not necessarily an absolutely decision. As such, engineering judgment is required for the imposition of yield and stop control. According to the MUTCD, whenever a less important road intersects with a major road, a lack of driver compliance with the normal right of way rule is anticipated; thus, yield or stop control is needed. Also, on a designated through highway, to give the through drivers a clear right of way, the entering streets should be yield or stop controlled. Lastly, if an intersection that is located along an arterial where all other intersections are signalized, it should at least be stop or yield controlled, if traffic signals are not warranted (Roess et al., 2011).

- Type III - Traffic control signals

  Traffic signals are the most substantial type of intersection control. By alternately assigning right of way to particular movements, traffic signals can, to a large extent, reduce the number of potential vehicular and pedestrian conflicts. The MUTCD warrants for traffic signals are more specific and detailed as compared to those for yield or stop signs. However, due to the high installation and maintenance costs that traffic signals introduce to the intersection, care should be taken not to overuse them and install them only after less restrictive levels of control have been considered and proven to be inadequate (Roess et al., 2011).

1.2 Two-Way Stop Controlled Intersections

Two-way stop-controlled (TWSC) intersections are the most common form of type II intersection control (Roess et al., 2011) and one of the most common intersection types in the United States (Kittleson and Vandehey, 1991). TWSC intersections involve one or two stop signs, depending on the number of intersection approaches (Roess et al., 2011). This type of control is most commonly applied at intersections where roads of different functional classification intersect (Pollatschek et al., 2002). Specifically, priority is granted to the major approach(s) where no traffic control is present, while minor approach(s) are controlled by stop signs. Thus, drivers on the minor approach should yield the right of way to traffic on the major road and proceed into the intersection only after a full stop is performed (Transportation Research Board, 2000). It is recommended to minimize the number of vehicles affected by stop signs and if a full stop is not necessary at all times, less restrictive measures such as yield signs should be considered prior to stop signs (Federal Highway Administrations, 2009). Table 1.1 describes stop sign applications suggested by the MUTCD.

Table 1.1 Stop sign applications

The use of STOP signs on the minor-street approaches should be considered if engineering judgment indicates that a stop is always required because of one or more of the following conditions:
A. The vehicular traffic volumes on the through street or highway exceed 6,000 vehicles per day; **B.** A restricted view exists that requires road users to stop in order to adequately observe conflicting traffic on the through street or highway; **C.** Crash records indicate that three or more crashes that are susceptible to correction by the installation of a STOP sign have been reported within a 12-month period, or that five or more such crashes have been reported within a 2-year period. Such crashes include right-angle collisions involving road users on the minor-street approach failing to yield the right-of-way to traffic on the through street or highway.

(Source: Federal Highway Administration, *Manual on Uniform Traffic Control Devices,* 2009)

Three-leg intersections or T-intersections are considered to be a standard type of TWSC intersections, if the minor approach or the leg of the intersection is controlled by a stop sign (Transportation Research Board, 2000). Figure 1.1 shows all possible movements and conflict points at a typical T-intersection including crossing, merging (when two traffic streams join into one), and diverging (when one traffic stream divides into two).

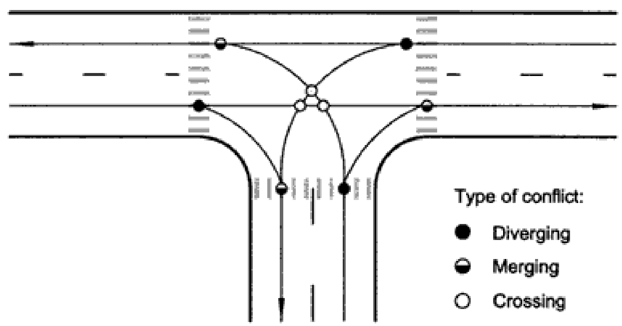

Figure 1.1 Conflict points at T-intersection

(Source: *Rodegerdts et al., Signalized Intersections: Informational Guide*, 2004)

The major street through and right-turning vehicles have priority over all other conflicting traffic. Vehicles turning left from the major street onto the minor have a permitted left turn and must yield to conflicting through and right-turning movements on the major street. Vehicles turning right from the minor street onto the major only conflict with the major through movement in the near lane and have to yield the right of way. The left turning vehicles have the least priority and are required to yield the right of way to all other conflicting movements (Transportation Research Board, 2000).

1.3 Gap Acceptance

The current Highway Capacity Manual (HCM) defines gap as "*the time, in seconds, for the front bumper of the second of two vehicles to reach the starting point of the front bumper of the first*". The drivers arriving at the TWSC intersection from the controlled approach are required to come to a full stop, evaluate the gaps on the major road, and enter the intersection when there is a large enough gap between two successive vehicles on the major stream to safely execute the desired maneuver in such a manner that the traffic stream on the mainline remains unaffected. Therefore, the drivers on the minor road need to decide when a gap allows for a safe entry, while also conforming to the right of way hierarchy. This decision making process is commonly known as gap acceptance and depends on three basic factors:

- Availability of gaps between vehicles on the major road of a particular size and arrival pattern;
- Usefulness of gaps and the extent to which drivers find gaps of a particular size useful to perform their intended maneuver; and
- Relative priority of movements at the intersection which typically promotes the movement of major stream vehicles.

In the presence of a queue on the minor approach, it also takes additional time for the driver to move to the front of the queue (i.e. the stop line). The delay and capacity of the controlled leg are major determinants of the level of service (LOS) at a TWSC intersection. They are highly dependent on the availability and distribution of gaps on the major stream, the driver's gap acceptance behavior, and the queue move-up time for each vehicle (Transportation Research Board, 2000).

The total time elapsed between the arrival of a vehicle on the minor approach and the time it departs from the stop line, including the initial deceleration delay, queue move-up time, stopped delay, and final acceleration delay, is defined as the control delay. Control delay is a primary measure of LOS and performance of TWSC intersections. Table 1.2 shows the LOS criteria based on average control delay that is suggested by the current HCM.

Table 1.2 LOS criteria for TWSC intersections

Level Of Service	Average Control Delay (s/veh)
A	0 - 10
B	> 10 - 15
C	> 15 - 25
D	> 25 - 35
E	> 35 - 50
F	> 50

(Source: Transportation Research Board of the National Academies, *Highway Capacity Manual*, 2000)

Due to the significant role that driver behavior plays in conflicting traffic, the capacity and LOS analysis for TWSC intersections are more complex than that of intersections with higher levels of control (Kittleson and Vandehey, 1991). The critical gap is a parameter typically associated with the safety and operational performance of TWSC intersections. Although, inconsistencies exist in the way that the critical gap has been defined in the literature, the term has almost always been used as a measure of the minimum accepted gap and is usually treated as a single average value (Madanat et al., 1994). Greenshields et al. used the term critical gap for the first time in 1947 and defined it as the size of the gap that is accepted by 50 percent of the drivers. It was later defined as the size of the gap for which half of all traffic will reject larger gaps, while half will accept smaller gaps (Raff and Hart, 1950). In another notable variation, critical gap was defined as the smallest accepted gap by a minor approach driver, assuming that a driver accepts all gaps equal to or greater than the critical gap, while rejecting all the smaller gaps (Miller, 1971). The most recent definition suggested by HCM 2000 is "*the minimum time interval in the major street traffic stream that allows intersection entry for one minor street vehicle*". Critical gap could be estimated based on the largest rejected and smallest accepted gap for a given intersection (Transportation Research Board, 2000).

It cannot be overstated that gap acceptance behavior is highly dependent on individual driver characteristics and preferences. The critical gap for a particular maneuver varies between drivers and even for an individual driver at different times (Mahmassani and Shefi, 1981). Therefore it is not realistic to anticipate homogeneous behavior from all drivers at all times. In fact, drivers on minor approaches have shown a tendency to accept a gap when "the benefit from entry is greater than the associated risk" (Pollatschek et al., 2002). When the waiting time exceeds the drivers' expectation and tolerance limit, they will accept higher levels of risk associated with smaller gaps. After a certain wait time and rejecting a number of gaps, drivers might even accept gaps shorter than gaps that had previously been rejected (Xiaoming et al., 2007). Kittleson and Vandehey (1991) studied minor street left turning gap acceptance behavior at unsignalized intersections. They found that for a group of drivers with an average wait time of 8.9 sec/veh, the critical gap is significantly higher than that of a group with an average wait time of 19.5 sec/veh. The strong relationship between the previous rejection of longer gaps and the length of the critical gap, is because at stop controlled intersections, drivers are able to reduce their delay by accepting shorter gaps, although in doing so drivers are accepting higher levels of risk. Thus, delay should not be the only measure of LOS at stop controlled intersections. Though, overall driver safety and comfort should also be considered in definition of the LOS (Kittleson & Vandehey, 1991).

It has been shown that intersection geometries can greatly influence gap acceptance behavior. The presence of a storage area (i.e. two way left turn lane (TWLTL), raised or striped median) on the major street, that is wide enough to accommodate a number of vehicles, allows for what is known as a two-stage gap acceptance. This describes a process by which drivers first cross the near lane(s) of the major street and wait in the storage area, until they find another adequate gap in the opposite stream (Transportation Research Board, 2000). Therefore, the minor streams do not need coinciding gaps to execute crossing or left turning maneuvers. Due to this effect, two-stage gap acceptance has the potential to increase the capacity for minor movements (Brilun and Wu, 2003), while also improving safety at the intersection (Transportation Research Board, 2003). Figure 1.2 shows the two-stage gap acceptance process at divided intersections.

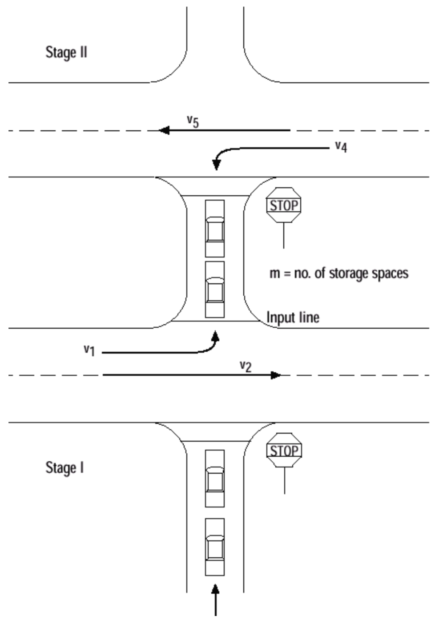

Figure 1.2 Two-stage gap acceptance at a divided intersection

(Source: Transportation Research Board of the National Academies, *Highway Capacity Manual*, 2000)

Alternatively, if we consider a TWLTL instead of a median divided major road, the left turning vehicles from the minor approach may cross the near side of the major road, merge into the TWLTL, and slowly move for a short distance along the TWLTL until they find an acceptable gap in the major stream to complete the maneuver (Rodegerdts et al., 2004). Thus, the whole LT maneuver could be considered as two separate stop controlled maneuvers. Two-stage gap acceptance behavior at intersections with a TWLTL on the major approach, if not limited by the state law, can result in improved safety and capacity, as compared to undivided major approaches (Transportation Research Board, 2000). Hamed et al. (1997) studied left turn maneuvers at stop-controlled T-intersections and found that the presence of a median with an exclusive left turn lane on the major approach resulted in smaller critical gaps. It is difficult to determine with certainty, but it appears that the manuscript describes left turning vehicles both from the minor and the major road.

Researchers have studied the effects of various parameters on gap acceptance behavior. Hamed et al. (1997) also studied gaps at different times of the day and found that during off-peak periods; gaps are larger and more stable, making it easier for the drivers to perform left turning maneuvers, resulting in shorter wait times during off-peak than for peak periods. Dissanayake et al. (2002) studied the driver age differences in daytime and nighttime gap acceptance capabilities and found that for older drivers (>65 years old) accepted gaps are longer during nighttime and poor lighting condition. When comparing male and female drivers, Hamed et al. (1997) found that male drivers showed greater risk of ending their wait time than females. The same result was found by Teply et al. (1997).

Hamed et al. (1997) also included trip purpose in their model and found that daily commuters and those who are travelling to work usually accept shorter gaps, compared to drivers travelling to shop. This might be due to greater time constraints and/or familiarity with the route for the daily commuters. Vehicle acceleration capabilities were studied by Teply et al. (1997) in order to identify potential impacts on drivers' gap acceptance behavior. Although no significant impact was found, the possibility of accepting a given gap increased as acceleration capability went from "low" to "average" to "high".

The effect of passenger presence on gap acceptance behavior has also been examined in the literature. Jackson and Gray (1976) found that male drivers have significantly shorter waiting times when in the presence of male passengers as compared to female passengers or when alone. They also determined that female drivers were not influenced by passengers. Teply et al. (1997) found that those with passengers present in their vehicle accept relatively longer gaps than those without any passengers. The authors attributed this to increased driver caution when in the presence of passengers. Wennel and Cooper (1981) however, were not able to identify a consistent effect of presence of passengers on the median accepted gap. Teply et al. (1997) also studied the behavioral effects of passengers in the form of traffic pressure. They found a linkage between the presence of other vehicles behind the left turning vehicle and the driver's wait time, meaning that the driver might feel some pressure from queued drivers.

1.4 Research Methodology

1.4.1 Introduction to the Existing Data Collections Methods

A variety of different data collection methods and techniques were identified through an extensive review of the existing literature on the gap acceptance behavior and theory. The data acquisition process has tended towards less automated methods, often utilizing some sort of videotaping equipment and manual data reduction, depending on the fidelity necessitated by the specific research question. Videotaping can be done at many types of intersections, freeway ramps, curb cuts, and pedestrian crosswalks (Currin, 2001), unless restricted by the location geometry. The data collection process usually takes place in two separate stages. The first stage involves videotaping the traffic flow and drivers' behavior at the intersection. The second stage involves manually extracting and coding data from the video for analysis. Examples of this approach to data acquisition were found among studies conducted by Madanat et al. (1994), Lall and Lu (1994), Teply et al. (1997), Polus et al. (2003), Kay et al. (2006), etc.

An alternative method was adopted by Hamed et al. (1997), where a tape recorder was used to record arrival and departure times, as well as gap acceptance/rejection. The traffic flow and speed on the major road were also measured, recorded, and aggregated in one minute intervals. All left turning motorists were surveyed about their demographics after they completed their turning maneuver.

Some studies use supplemental equipment in addition to video cameras, to observe the traffic characteristics of the major stream with greater accuracy. One example was a study conducted by Gattis and Low (1999) at atypical stop-controlled intersections, where a traffic classifier was located upstream of the intersection to collect approach speeds and arrival times. In another study conducted by Zohdy et al. (2010), a GPS device was installed at the intersections to acquire accurate, synchronized global time. The time information was used to code the data.

This type of data collection, although providing researchers with significant information about driver behavior, appears challenging, labor intensive, and time consuming. Finding a suitable location for video monitoring is associated with its own challenges as the cameras should be installed such that they do not affect the behavior of the drivers, while allowing for a full view of the study area (Currin, 2001). The associated data reduction and transcription is also labor intensive as the video footage typically needs to be replayed several times, to extract the measures of interest at the required level of accuracy.

Some researchers have attempted to develop more automated data collection methods. Such efforts have resulted in the development of various computer programs that accept keystrokes and automatically record the associated timestamps. For example, a laptop computer was used by Kittleson and Vendehey (1991) to study left turn movements at unsignalized intersections. Arrival and departure times of the minor approach vehicles were recorded as a measure of wait time and gap acceptance/rejection behavior. Arrival and departure times of the major approach vehicles were also recorded to measure the number and lengths of the available gaps.

In another gap acceptance study at TWSC intersection by Dissanayake et al. (2002), a Microsoft Access based software was developed to recode the available gaps on the major approach, as well as accepting/rejecting responses of the minor approach drivers either turning left or going through. Such computer programs are usually only capable of recording time stamps and depending on the type of information required, manually record demographic information may still be required. However, the amount of time and manpower needed is significantly improved from the conventional methods mentioned earlier.

The study of drivers' gap acceptance behavior could also be carried out in simulated or controlled traffic conditions. Yan et al. (2007) used a driving simulator to study the effects of major road vehicle speed and driver age and gender on LT gap acceptance. The driving scenario consisted of TWSC intersection, where the drivers were asked to execute a LT maneuver. Cooper and Zheng (2002) studied the gap acceptance decision using an instrumented approach, where eight vehicles continuously circled round to travel along a test track. A test vehicle was located on the minor approach, with the parking brakes engaged and the transmissions in neutral, but the engine running. Each participant was presented with 100 gaps and was instructed to press down on the acceleration pedal, once they decided a gap was safe for a left turn maneuver. The test vehicle was instrumented to record the pressure on the pedal and maintain a continuous time record during the test.

1.4.2 Data Collection Methodology

The research team was concerned with the acquisition and analysis of naturalistic driver behavior as vehicles performed right or left turning movements from the minor to the major approach at a TWSC intersection. Thus, a software package was developed collaboratively between Oregon State University (OSU) and the University of Massachusetts Amherst (UMass Amherst) to facilitate real-time collection of naturalistic field data and aid in the analysis. The software, "Gap Acceptance Processing System (GAPS)" was developed in Access specifically for collecting gap acceptance information on a laptop in the field. Figure 1.3 shows the graphical user interface (GUI) visible to the researcher when collecting gap data, illustrating a vehicle making a right turn and the corresponding keystroke feedback. The software allows researchers to collect gap availability and acceptance as well as many other driver, intersection and environmental characteristics.

The data collection protocol required pairs of researches in the field to complete the observations with the requisite degree of accuracy. One researcher was responsible for operating the GAPS software on the laptop while the other would capture detailed information about the drivers and vehicles approaching the stop sign on the minor street. This detailed information included gender, approximate age, presence of passengers, queue size at turn and vehicle type, all records were stored in the program database at the completion of each site visit. Once all data had been collected, macros imbedded in the GAPS software reduced the data into a file easily exported and analyzed in Microsoft Excel.

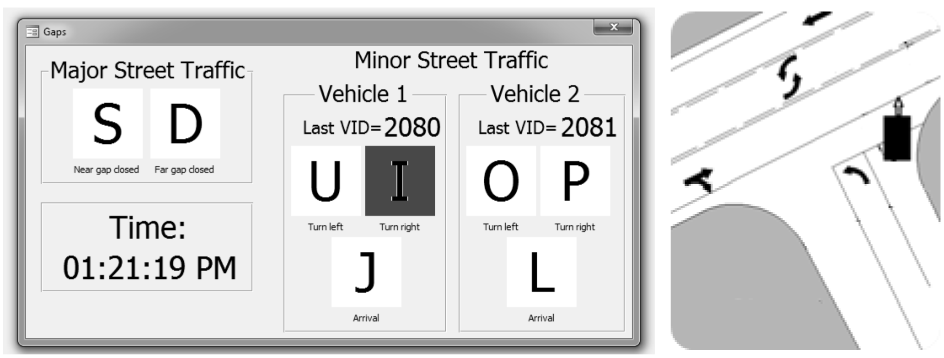

Figure 1.3 Screenshot while collecting data with the GAPS program (left panel) and corresponding vehicle movement (right panel)

1.4.3 Validation of Data Collection Procedure

To ensure the accuracy of the field observations acquired with the GAPS software, the researchers used a high-definition (HD) video camera to simultaneously record one of the stop controlled intersections while manual data collection took place. 50 minor street vehicles were captured in conjunction with the mainline gaps. The video was reduced in the office on HD televisions in slow motion to provide accurate observations of the time (accurate to a hundredth of a second) vehicles arrived at the intersection, initiated a right or left turn, and the length of available gaps in mainstream traffic. The authors then compared the data obtained from manual data collection to the video transcription, which was considered to be the ground truth.

This initial validation was concerned with three measures vital to the analysis of the database. We verified that the number and order of vehicles entering the intersection on the minor approach matched the video. A comparison of wait time, defined here as the time between the vehicle reaching the stop line and initiating the turning movement, proved to be reliable at a threshold of 90% with an average difference of 1.38 seconds. The comparison of the accepted gaps used in analysis revealed that approximately 80% of the accepted gaps observed manually were within one second of the actual accepted gaps acquired from the video.

1.5 Research Approach

The first research effort, “Revisiting driver behavior at unsignalized intersections: time of day implications for two way left turn lanes (TWLTL)” resulted in a full manuscript submission to the 6th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design. The manuscript received an external scientific review by a panel of three researchers and was approved for publication in the proceedings of the conference. The focus of this manuscript was to contribute to the literature dealing with a geometric configuration that has received relatively less attention than some others (T-intersections with a TWLTL on the major approach). The authors studied the effects of the presence of passengers and queue size on the wait time and the gaps selected by drivers as the time of day varied. Additionally, they examined factors such as driver age, gender and type of vehicle to verify the results obtained by the previous work.

The GAPS software provides reasonably accurate measurements of the minor street vehicle's wait time and accepted gaps, providing means for consistent and reliable data collection. This tool gives practicing engineers a mechanism to assess critical gap within a time frame and at a cost that is more realistic than a full video study.

The research team restricted their experimental locations to stop controlled T-intersections in order to eliminate the complexities associated with the additional opposing traffic that exists at typical four-leg intersections. Since relatively little attention has been paid to the factors that affect right turn gap acceptance behavior, the study intersections included exclusive left turn and right turn lanes on the minor approach, to allow for the study of right turns independently. By controlling for the physical characteristics of the intersections, factors such as the distance travelled by a vehicle making a turning movement, posted speed limits, and available sight distance remained relatively consistent between experimental locations. This allowed for the aggregation of data collected at each location thereby increasing the sample size and statistical significance of the results.

The results of the first effort motivated additional research. Specifically, in the second manuscript, “Gap acceptance behavior at unsignalized intersections: implications of waiting time,” the authors studied the behavioral effects of wait times exclusively for right turn and left turn maneuvers. In an attempt to obtain a bigger sample size and greater statistical significance, the researchers surveyed more locations and drivers. The authors also desired to study the effects of the type of lanes assigned to turning movement, if any, on the gap acceptance behavior. Therefore, half of the select intersections had exclusive left turn and right turn lanes on the minor approach, while the other half had a single shared lane for both movements.

This second research effort resulted in a submission to the Transportation Research Record: Journal of the Transportation Research Board (TRR Journal). Specifically, it will be submitted for review by the Traffic Control Devices (TCD) Committee (AHB50). The TCD committee provides between 3 and 5 scientific reviewers per manuscript in addition to a review by the committee chair.

CHAPTER 2

REVISITING DRIVER BEHAVIOR AT UNSIGNALIZED INTERSECTIONS: TIME OF DAY IMPLICATIONS FOR TWO WAY LEFT TURN LANES (TWLTL)

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2.1 Summary

A novel procedure was developed and validated for the accurate observation of naturalistic driver gap acceptance behavior at unsignalized intersections. Specifically, two way stop controlled intersections with a two way left turn lane (TWLTL) on the major road were examined. Three intersections were included as experimental locations. A sample size was collected of approximately 875 minor street vehicles which were exposed to over 2400 individual gaps. Characteristics such as gender, approximate age, vehicle type, presence of a queue behind the lead vehicle, and presence of passengers in the vehicle were collected as a function of the time of day (TOD). This work provides updated measures for the accepted gap as TOD varies, as well as exploring how accepted gaps are related to the wait time of a vehicle at the stop line.

2.2 Introduction

Two way stop controlled (TWSC) intersections are one of the most common intersection types in the United States (Kittleson and Vandehey, 1991). This type of intersection control is most commonly applied where roads of different functional classification intersect (Pollatschek et al., 2002). At TWSC intersections priority is provided to the major approach (es) (no traffic control present), while stop signs control vehicular movements on minor approach (es). Drivers on the minor approach should yield the right of way to traffic on the major road and proceed into the intersection only after a full stop is performed and when there is a large enough gap between two successive vehicles on the major road to safely execute the maneuver of interest, in such manner that the traffic stream on the mainline remains unaffected (Transportation Research Board, 2000).

2.3 Gap Acceptance/Critical Gap

When a driver arrives at the stop line on the minor approach to a TWSC intersection, they need to decide when to execute a maneuver based on right of way hierarchy as well as the availability and distributions of the major road gaps (Transportation Research Board, 2000). Due to the important role that personal driver behavior plays in confronting the conflicting traffic, the capacity and level of service analysis for TWSC intersections are more complex than that of intersections with higher levels of control (Kittleson and Vandehey, 1991).

The critical gap is a principal parameter of the capacity analysis at TWSC intersections. Previous studies defined the critical gap as the size of the gap for which half of all traffic will reject larger gaps while half will accept smaller gaps (Drew, 1968). More recent studies have augmented this general definition by postulating that those gaps large enough to be accepted by almost all drivers (approximately 12s to 15s) provide little meaningful information about drivers' gap acceptance behavior and should not be used in the analysis (Gattis and Low, 1999). The most commonly accepted definition for critical gap is the minimum usable gap accepted by the minor approach drivers (Roess et al., 2004). This definition assumes all the gaps that are equal to or greater than the critical gap will be accepted and all the smaller gaps will be rejected (Transportation Research Board, 2000). It cannot be overstated that gap acceptance behavior is highly dependent on the driver characteristics and preferences. Therefore, homogeneous behavior from the all drivers at all times is not realistic.

In fact, drivers on minor approaches have shown a tendency to accept a gap when "the benefit from entry is greater than the associated risk" (Pollatschek et al., 2002). When the waiting time exceeds the drivers' expectation and tolerance limit, they will accept higher levels of risk associated with smaller gaps. It is somewhat unclear in the literature if drivers accurately perceive the increased risks associated with the acceptance of these smaller gaps. After a certain wait time threshold, drivers might even accept gaps shorter than gaps that had previously been rejected (Xiaoming et al., 2007).

It has also been shown that intersection geometries can greatly influence gap acceptance behavior. Hamed et al. (1997) studied left turn maneuvers at stop-controlled T-intersections and found that the presence of a median with an exclusive left turn lane on the major approach resulted in smaller critical gaps. According to the Highway Capacity Manual (HCM) 2000, the presence of a storage area on the major road that is wide enough to accommodate left turning vehicles, allows for two-stage gap acceptance, resulting in the entire left turn maneuver being considered as two separate stop controlled maneuvers. Thus, Intersections with a TWLTL on the major approach have improved safety and capacity, in comparison with undivided major approaches (Transportation Research Board, 2000). In fact, a continuous TWLTL might result in up to 35% decrease in total crashes, 30% decrease in delay, and 30% increase in capacity (Transportation Research Board, 2003). Hamed et al. (1997) also studied the gaps at different times of the day and found that during off-peak periods, gaps are larger and more stable, making it easier for the drivers to perform a left turning maneuver, resulting in shorter wait times during off-peak periods than for peak periods.

Much of the previous gap acceptance research has concerned itself with the safety implications of selecting smaller gaps. This is likely related to the seriousness of crashes resulting from the selection of inappropriately small gaps. Relatively less attention has been paid to the capacity implications of gap acceptance behavior.

The focus of this study was to contribute to the literature by focusing on a geometric configuration that has received relatively less attention than others (T-intersections with a TWLTL on the major approach) as well as to consider factors that have not previously been considered as influencing gap acceptance behavior.

These factors included: approximate driver age, gender, vehicle type, presence of passengers, and queue size on the waiting time and the gaps selected by drivers as the time of day varied.

2.4 Method

This study was concerned with the acquisition and analysis of naturalistic driver behavior as vehicles performed right or left turning movements at a two way stop controlled intersection from the minor to the major approach. A software package was developed collaboratively between the University of Massachusetts Amherst (UMass Amherst) and Oregon State University (OSU) to collect the naturalistic field data and aid in the analysis.

2.4.1 Locations

Experimental locations were restricted to T-intersections (three approaches intersecting at approximately a 90 degree angle) in Corvallis and Albany, Oregon. This configuration resembles that of many driveways experiencing high volumes of traffic and allowed for efficient evaluation of gap acceptance behavior by eliminating the complexities associated with opposing traffic at regular four-leg intersections. To eliminate the effects of different geometric characteristics, locations with similar configurations were selected. Specifically, study intersections have exclusive left turn and right turn lanes on the minor approach, while the major roadway has a TWLTL separating single lanes of opposing traffic. This configuration is fairly common in Oregon. Compared to other intersection configurations, less effort has been expended determining how this affects gap acceptance behavior (Figure 2.1).

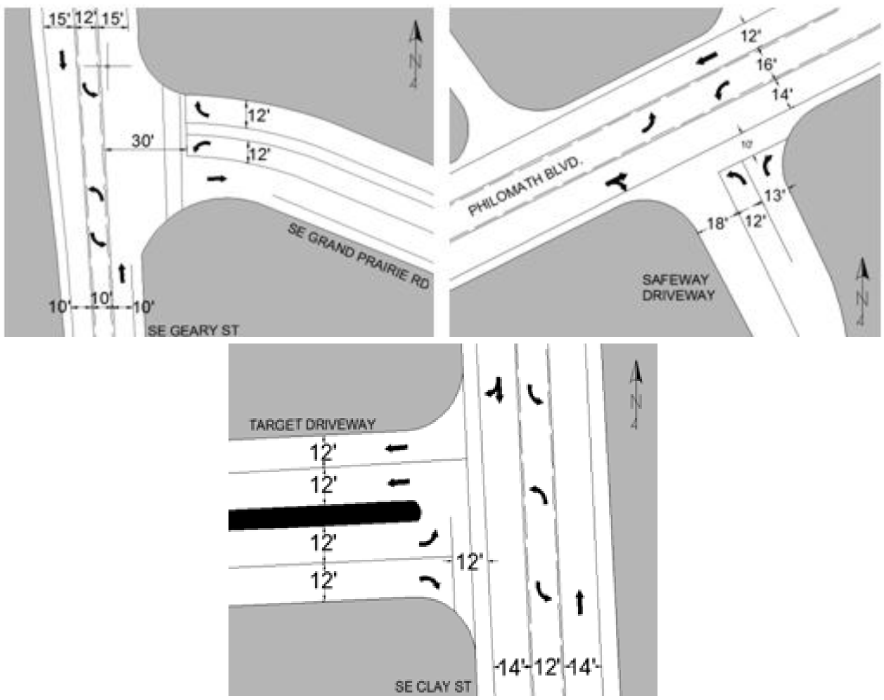

Figure 2.1 Intersections selected for data collection

By controlling for the physical characteristics of the intersections, factors such as the distance travelled by a vehicle making a turning movement, posted speed limits, and available sight distance remained relatively consistent between experimental locations. This allows for the aggregation of data collected at each location increasing the sample size and statistical significance of the results. It was desired to capture gap acceptance behavior throughout the day to determine if the critical gap is influenced by time of day. Data collection intervals were established to break the day into four sections and data was collected at each location during each time interval.

2.4.2 Software Package

The software package, developed as a collaborative effort between the University of Massachusetts Amherst and Oregon State University, is an Access based program developed specifically for collecting gap acceptance information. While running the program on a laptop, the Gap Acceptance Processing System (GAPS) allowed for accurate and efficient data collection in the field. Figure 2.2 shows the graphical user interface (GUI) visible to the researcher when collecting gap data, illustrating a vehicle making a right turn and the corresponding keystroke. The software allows researchers to collect gap availability and acceptance as well as many other driver, intersection and environmental characteristics.

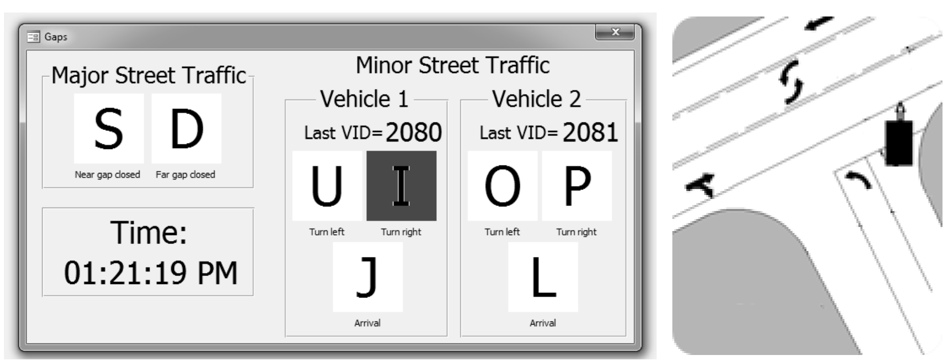

Figure 2.2 Screenshot while collecting data with the GAPS program (left panel) and corresponding vehicle movement (right panel)

2.4.3 Procedure

The data collection protocol required pairs of researches in the field to complete the observations with the requisite degree of accuracy. One researcher was responsible for running the GAPS software on the laptop while the other would capture detailed information about the drivers and vehicles approaching the stop sign on the minor street. This detailed information included gender, approximate age, presence of passengers, queue size and vehicle type, which was input into the program database at the completion of each site visit. Once all data had been collected, macros imbedded in the GAPS software reduced the data into a file easily transferred and analyzed in Microsoft Excel.

2.4.4 Validation of Data Collection Procedure

To ensure the accuracy of the field observations acquired with the use of the GAPS software, a high-definition video camera was used to simultaneously record one of the stop controlled intersections while manual data collection was taking place. 50 minor street vehicles were captured in conjunction with the mainline gaps. The video was reduced in the office on high definition televisions in slow motion to provide accurate information about the exact time (accurate to a hundredth of a second) vehicles arrived at the intersection, initiated a right or left turn, and the length of available gaps in mainstream traffic. Data obtained from manual data collection was compared to the video transcription, which was assumed to be accurate.

This initial validation was concerned with three measures vital to the analysis of the database. It was initially verified that the number and order of vehicles entering the intersection on the minor approach matched the video exactly. A comparison of wait time, defined here as the time between the vehicle reaching the stop line and initiating the turning movement, proved to be reliable at a 90% threshold with an average difference of 1.38 seconds. Additionally, each accepted gap greater than 15 seconds was removed from the analysis. The comparison of the accepted gaps used in analysis revealed that approximately 80% of the accepted gaps observed manually were within one second of the actual accepted gaps acquired from the video.

2.5 Results

To perform analyses based on the characteristics of the drivers and vehicles, it was essential to identify any trends or shifts in these characteristics seen throughout the day. Table 2.1 displays the percentage of each demographic as it varies throughout the day. In some cases approximate age and gender could not be accurately determined, in which case they were identified as “Not Sure.” By visual inspection, there does not appear to be any significant shifts in the population demographics that could potentially affect the analysis.

Table 2.1 Sample Demographics

		7:00am-10:00am	10:00am-1:00pm	1:00pm-4:00pm	4:00pm-7:00pm	Combined
Age Category	Teen	19 (9%)	25 (12%)	42 (19%)	41 (18%)	127 (15%)
	Adult	172 (78%)	158 (73%)	129 (60%)	157 (70%)	616 (70%)
	Elder	27 (12%)	22 (10%)	35 (16%)	19 (9%)	103 (12%)
	Not Sure	3 (1%)	10 (5%)	10 (5%)	7 (3%)	30 (3%)
Gender	Male	106 (48%)	91 (42%)	102 (47%)	114 (51%)	413 (47%)
	Female	115 (52%)	117 (55%)	109 (50%)	106(47%)	447 (51%)
	Not Sure	0 (0%)	7 (3%)	5 (3%)	4 (2%)	16 (2%)

A very important characteristic of gap acceptance behavior is the amount of time spent waiting for an acceptable gap. Figure 2.3 illustrates the relationship between the accepted gap and wait time for approximately 875 cars, which is comparable to relationships seen in previous research (Xiaoming et al., 2007). To gain a better understanding of how this relationship changes based on demographic variables, similar plots were created for individual characteristics, however these plots revealed little information due to the sample size collected. It should be noted that the plot on the left panel displays the entire database, but accepted gaps of greater than 15 seconds have been eliminated from the analysis in the right panel.

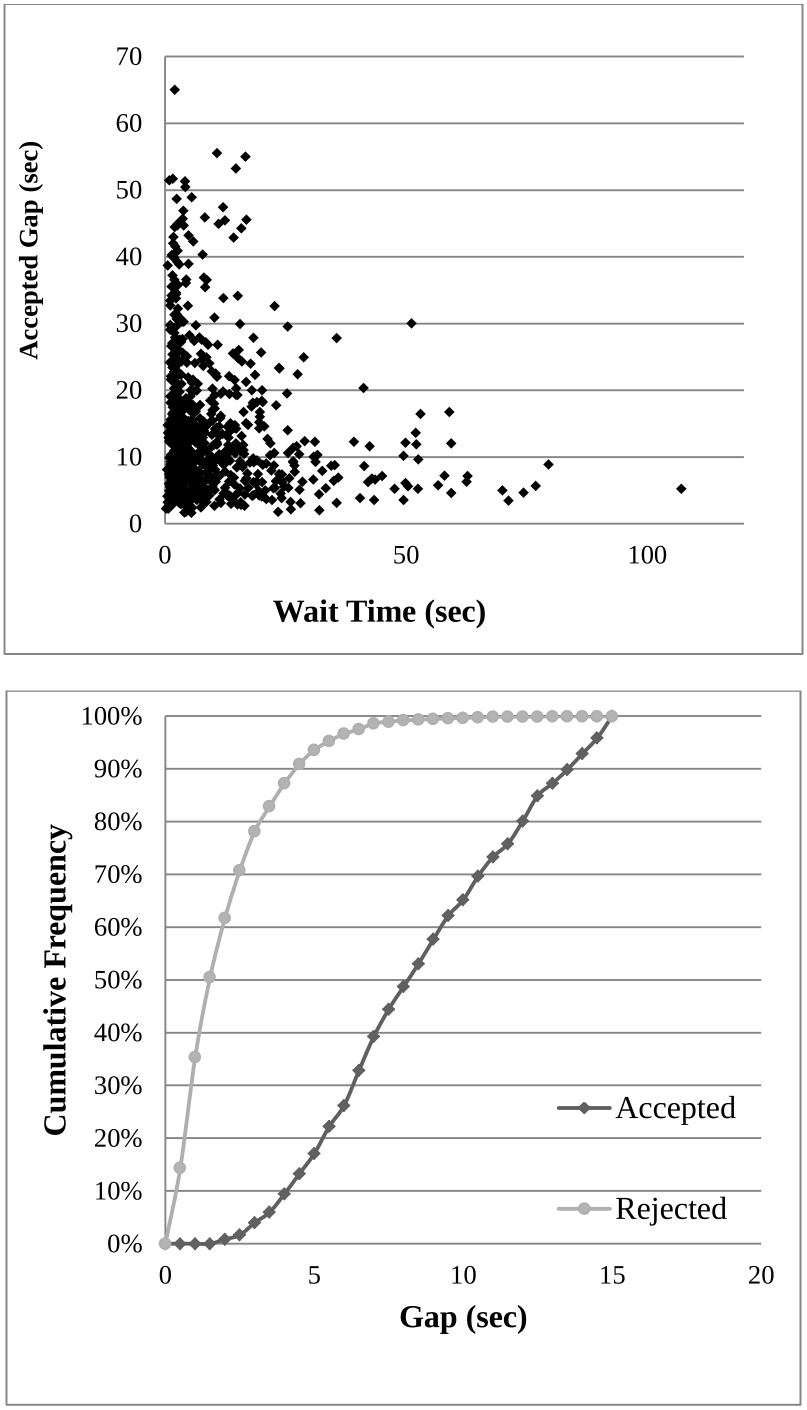

Figure 2.3 Accepted gaps plotted against wait time (top panel) and cumulative frequency of both rejected and accepted gaps (bottom panel)

A visual inspection of the data presented in the left panel of Figure 3 seems to show that the relationship between wait time and accepted gap generally takes the shape of a negative exponential distribution. From the raw data it appears that as the wait time increases, shorter gaps are more commonly accepted than longer ones.

From the total right and left turn data presented in Table 2.2, it appears that later in the day, the average gap accepted by drivers to perform right and left turns decreases by up to 9 and 21 percent, respectively.

Table 2.2 Average Accepted Gaps (seconds)

Left Turn												
	Total		Male		Female		Teen		Adult		Elder	
	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI
7:00am-10:00am	8.45	0.93	8.02	1.33	8.91	1.39	11.18	2.60	7.98	1.02	8.71	4.34
10:00am-1:00pm	8.76	0.72	8.90	1.27	8.75	0.92	7.79	3.24	8.92	0.80	8.96	3.29
1:00pm-4:00pm	7.22	0.72	6.64	0.94	7.72	1.13	7.46	1.92	7.10	0.92	7.21	1.81
4:00pm-7:00pm	7.84	0.74	7.70	1.10	7.76	1.03	6.24	1.08	7.94	0.92	8.50	2.64

Right Turn												
	Total		Male		Female		Teen		Adult		Elder	
	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI	Mean	+/- CI
7:00am-10:00am	9.55	0.81	9.07	1.12	10.01	1.12	8.32	3.28	9.84	0.90	7.64	4.45
10:00am-1:00pm	8.88	0.89	9.57	1.28	8.46	1.31	8.71	4.43	9.34	1.00	6.87	3.06
1:00pm-4:00pm	8.66	0.78	8.74	1.34	8.66	1.00	8.77	1.92	8.47	1.07	9.35	1.79
4:00pm-7:00pm	8.66	0.66	8.57	0.83	8.77	0.98	7.42	1.56	8.72	0.75	10.48	2.52

When considering age categories, teen drivers usually tend to accept shorter gaps than their older counterparts. However, an ANOVA test did not provide evidence of a significant difference for either left or right turn maneuvers among age categories. It is also apparent that there is little shift in left turn gap acceptance behavior among older drivers (no statistical difference at 95%), while teen drivers show a relatively larger shift in their behavior at different times of the day (statistically significant at 95%).

Two-sample t-tests were performed to compare the mean accepted gaps based on the presence of passengers in the car, as well as by presence of a queue behind the turning vehicle. For left turn maneuvers, the results showed a trend toward significantly shorter accepted gaps in the presence of passengers (P-value=0.053). Also, drivers with vehicles waiting behind them accepted significantly shorter gaps than those without (P-value=0.005). Although the same trends for both comparisons were observed for right turns, the differences were not found to be significant.

2.6 Discussion

The findings of this research are generally consistent with previous research on this topic. Research by Xiaoming et al. (2007) identified wait time and the length of queue on the minor approach as factors affecting gap acceptance behavior, with wait time being the most influential. Similarly, Hamed et al. (1997) found that the expected wait time increases as the length of available gaps decreases. They also found that gap acceptance behavior is not uniform throughout the day.

This research effort was intended to develop and test a novel data collection tool for the purposes of quickly and accurately collecting gap acceptance data at TWSC intersections. In doing so, we contributed to the understanding of how and why drivers select gaps at TWSC intersections with a TWLTL on the major road. The following conclusions were reached:

- The GAPS software provides reasonably accurate measurements of minor street vehicle's wait time and accepted gaps, providing means for consistent and reliable data collection.
- Evidence suggests that later in the day, drivers accept shorter mean gaps while performing right and left turns.
- It appears that the development of a queue behind the left turning vehicle decreases the accepted gaps by 1.17 seconds with statistical significance. Also, presence of passengers influences the gap acceptance behavior and decreases the accepted gaps by 0.85 seconds with statistical significance.

These observations are critical in our ability to correctly model both capacity and safety at unsignalized intersections.

2.7 Acknowledgment

The research team would like to recognize Dr. Michael A. Knodler and GRA Steven Tupper at UMass Amherst for their efforts in refining the software

package and the data collection protocols. Additionally, URA Brennan Burbank and GRA Halston Tuss at OSU contributed to data collection and validation. Without the hard work of these individuals this project would not have been a success.

CHAPTER 3

GAP ACCEPTANCE BEHAVIOR AT UNSIGNALIZED INTERSECTIONS: WAITING TIME IMPLICATIONS

Sahar Nabaee and David S. Hurwitz

3.1 Introduction

At-grade intersections are locations where two or more roads join or cross one another. They introduce an increased potential for conflicts between different crossing and turning maneuvers and an increase in the likelihood of certain crash types. In fact, more than 50 percent of all crashes in urban areas and over 30 percent in rural areas are intersection-related and 20 percent of all the fatal crashes occur at intersections (Neuman et al., 2003). Although crash rates are generally higher at signalized intersections, unsignalized intersections are also of concern as they still represent the potential for serious angle crashes (Neuman et al., 2003).

Two-way stop-controlled (TWSC) intersections are one the most common types of unsignalized intersections in the U.S. and elsewhere (Kittleson and Vandehey, 1991). At TWSC intersections, priority is provided to the major approaches, while drivers on the minor approach(es) are required to come to a full stop (typically in relation to a stop line and/or stop sign), and then proceed into the intersection when it is safe to do so. Thus, choosing the appropriate time to enter the intersection relies on drivers' ability to accurately assess the gaps in the major traffic stream. However, drivers usually have difficulties when attempting to judge the size of the gaps (both time and distance) and can occasionally choose to proceed into the intersection when oncoming vehicles are too close or traveling too fast, thus increasing the likelihood of a crash (Neuman et al., 2003). Additionally, high traffic volumes and/or travel speeds on the major approaches may result in relatively few usable gaps for the turning or crossing maneuvers from the minor approach, thus increasing delay and wait times and reducing the intersection capacity (Gluck et al., 1999). Longer wait times may also result in more aggressive driver behavior, complicating the interaction. Therefore, gap acceptance behavior is crucial to both the safety and operational performance of unsignalized intersections.

Although significant research has been done on gap acceptance, there is still a need to further identify and define parameters that contribute to gap acceptance under various conditions. Lack of a reliable data collection mechanism that is not unreasonably labor intensive presents a hindrance to additional research.

The purpose of this study was to contribute to the literature by studying the behavioral effects of waiting time on left and right turning maneuvers at T-intersections with a TWLTL on the major approach, and either a shared lane for left and right or exclusive left and right turn lanes on the minor approach. These geometric configurations have received relatively less attention than others in the literature, despite being fairly common in the U.S.

Furthermore, the data collection tool that the authors adopted for this research provides practicing engineers with a means of collecting reliable and naturalistic behavioral data within a time frame and at a cost that is more realistic than other common approaches such as the manual reduction of videotaped data.

3.2 Background

The critical gap is a principal parameter associated with the safety and operational performance of TWSC intersections. Although, inconsistencies exist in the way that the critical gap has been defined in the literature, the term has almost always been used as a measure of the minimum accepted gap and is usually treated as a single average value (Madanat et al., 1994). Greenshields et al. used the term critical gap for the first time in 1947 and defined it as the size of the gap that is accepted by 50 percent of the drivers. It was later defined as the size of the gap for which half of all traffic will reject larger gaps, while half will accept smaller gaps (Raff and Hart, 1950). In another notable variation, critical gap was defined as the smallest accepted gap by a minor approach driver, assuming that a driver accepts all gaps equal to or greater than the critical gap, while rejecting all the smaller gaps (Miller, 1971). The most recent definition suggested by HCM 2000 is "*the minimum time interval in the major street traffic stream that allows intersection entry for one minor street vehicle*". Critical gap could be estimated based on the largest rejected and smallest accepted gap for a given intersection (Transportation Research Board, 2000). The base critical gaps suggested by the current HCM for TWSC intersections are given in table 3.1.

Table 3.1 Base critical gaps for TWSC intersections

Maneuver	Base Critical Gap, $t_{c,base}$ (sec)	
	Two Lane Major Street	Four/Six Lane Major Street
Left Turn From Minor	7.1	7.5
Right Turn From Minor	6.2	6.9

It should be noted that left turn maneuver from a minor road is considered the most difficult maneuver at TWSC intersections (Transportation Research Board, 2000). It is more complicated than the right turn maneuver as drivers have to find coinciding gaps in the major traffic on both the near and the far side of the road, let alone the longer distance that needs to be traveled. Thus, left turn maneuvers are generally believed to require longer gaps.

The HCM requires the base critical gap to be adjusted for the presence of heavy vehicles, approach grade, T-intersections, and two-stage gap acceptance. The critical gap for each minor movement is calculated from the equation 3.1,

$$t_{c,x} = t_{c,base} + t_{c,HV}\, P_{HV} + t_{c,G}\, G - t_{c,T} - t_{3,LT} \qquad (3.1)$$

Where

$t_{c,x}$ = critical gap for movement x,

$t_{c,base}$ = base critical gap from table X,

$t_{c,HV}$ = adjustment factor heavy vehicles,

P_{HV} = proportion of heavy vehicles for minor movement,

$t_{c,G}$ = adjustment factor for grade,

G = percent grade divided by 100,

$t_{c,T}$ = adjustment factor for two-stage gap acceptance (1.0 for two-stage gap; 0.0 otherwise),

$t_{3,LT}$ = adjustment factor for intersection geometry (0.7 for minor-street left turn movement at T-intersection; 0.0 otherwise).

Recent investigations have shown that gap acceptance behavior is variable and highly dependent on individual driver characteristics and preferences. Thus, the critical gap for a particular maneuver varies between drivers and even for an individual driver during different times (Mahmassani and Shefi, 1981).

In fact, drivers on minor approaches tend to accept gaps when the benefit from entry overweighs the associated risk (Pollatschek et al., 2002). If the wait time exceeds the driver's acceptable threshold, frustration may lead to the acceptance of smaller gaps, which are typically associated with higher levels of risk. It is not atypical to observe a driver accepting a gap shorter than one previously rejected, after a long wait time and the rejection of a number of gaps (Xiaoming et al., 2007). Kittleson and Vandehey (1991) studied minor street left turn gap acceptance behavior at unsignalized intersections. They found that for a group of drivers with an average wait time of 8.9 sec/veh, the critical gap is significantly higher than that of a group with an average wait time of 19.5 sec/veh. The strong relationship between the previous rejection of longer gaps and the length of the critical gap, is because at stop controlled intersections, drivers are able to reduce their delay by accepting shorter gaps, although in doing so, they might be accepting higher levels of collision risk.

Intersection geometry also has the potential to influence gap acceptance behavior. The presence of a storage area (i.e. two way left turn lane (TWLTL), raised or striped median) on the major street, that is wide enough to accommodate one or more vehicles, allows for a two-stage gap acceptance. This describes the process by which a driver first crosses the near lane(s) of the major street and waits in the storage area, until they find another adequate gap in the opposite stream (Transportation Research Board, 2000). Therefore, minor street vehicles do not need coinciding gaps in both major directions to execute crossing or left turning maneuvers (one-stage gap acceptance). Due to this effect, two-stage gap acceptance has the potential to increase the capacity for minor movements (Brilun and Wu, 2003), while also substantially improving safety at the intersection (Transportation Research Board, 2003). Hamed et al. (1997) studied left turn maneuvers at stop-controlled T-intersections and found that the presence of a median with an exclusive left turn lane on the major approach results in smaller critical gaps. It is difficult to determine with certainty, but it appears that it describes left turning vehicles both from the minor and the major road.

The effect of passenger presence in the vehicle on gap acceptance behavior has also been examined in the literature. Jackson and Gray (1976) found that male drivers have significantly shorter waiting times when accompanied by male passengers as compared to female passengers or when alone. They also determined that female drivers are not influenced by passengers. Teply et al. (1997) found that those accompanied by passengers accept relatively longer gaps than those without passengers. The authors attributed this to drivers being more cautious when accompanied by passengers. Wennel and Cooper (1981) however, were not able to identify a consistent effect of passengers on the median accepted gap.

Teply et al. (1997) studied the behavioral effects of a phenomenon known as traffic pressure. They found a linkage between the presence of other vehicles behind a left turning vehicle and wait time. The authors interpreted that a driver might feel pressure from the presence of queued drivers and choose to end their wait time sooner than expected.

3.3 Methodology

For the acquisition of naturalistic driver behavior information, a software package was developed in a collaborative effort between the Oregon State University (OSU) and the University of Massachusetts Amherst (UMass Amherst). The Gap Acceptance Processing System (GAPS) is Microsoft Access based software and records the length and time of occurrence of the gaps in the major stream, as well as the arrival and departure times of the left and right turning vehicles on the minor approach. In addition to the gap acceptance data, the software allows for recording many other driver, intersection and environmental characteristics. At the end of the field data collection process, macros embedded in the GAPS software reduced the data into an Access spreadsheet that was easily transferred and analyzed in Microsoft Excel (Nabaee et al., 2010). Figure 3.1 shows a screenshot of the software during the field data collection on the left panel with the corresponding keystroke to the right turning maneuver illustrated in the right panel.

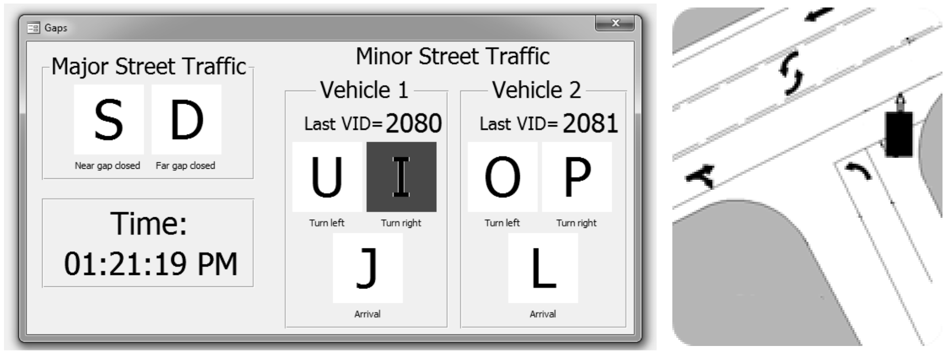

Figure 3.1 Screenshot while collecting data with the GAPS program (left panel) and corresponding vehicle movement (right panel)

To ensure the accuracy of the data collection methodology, a prior video validation was performed by videotaping 50 vehicles and manually reducing the video. The wait time, defined here as the time between the vehicle reaching the stop line and initiating the turning movement, proved to be reliable at a threshold of 90 percent with an average difference of 1.38 seconds. The accepted gaps proved to be reliable at a threshold of 80 percent with an average difference of 1 second from the actual accepted gaps acquired from the video (Nabaee et al., 2010).

For the purpose of this study, the researchers restricted the experimental locations to stop controlled T-intersections to minimize the potential confounding effects of the additional opposing traffic at a typical four-leg intersection. Eight intersections with similar geometric characteristics were selected in Albany, Corvallis, Eugene, and Salem, Oregon. All experimental locations had a three lane cross section on the major approach, with a TWLTL separating single lanes of opposing traffic. General physical characteristics of the intersections such as the distance travelled by minor approach vehicles, posted speed limits, and available sight distance were relatively consistent between all locations. This allowed for the aggregation of data collected at each location, increasing the sample size and statistical significance of the results.

Four visits were made to each location during different times of day to minimize the potential for temporal effects on driver behavior and to avoid overrepresentation of a specific group of drivers. Figure 3.2 depicts the general geometric characteristics of the experimental locations. Also, table 3.2 provides additional characteristics of the select intersections including distance and type of control of the adjacent intersections, posted speed limits, and presence of bike lanes on major road.

As no literature could be identified that examined the influence of lane utilization on gap acceptance, both shared left right, and exclusive left and right turning lanes were considered on the minor approach. Therefore, four of the select intersections had exclusive left turn and right turn lanes on the minor approach, while the other four had a single shared lane for both movements.

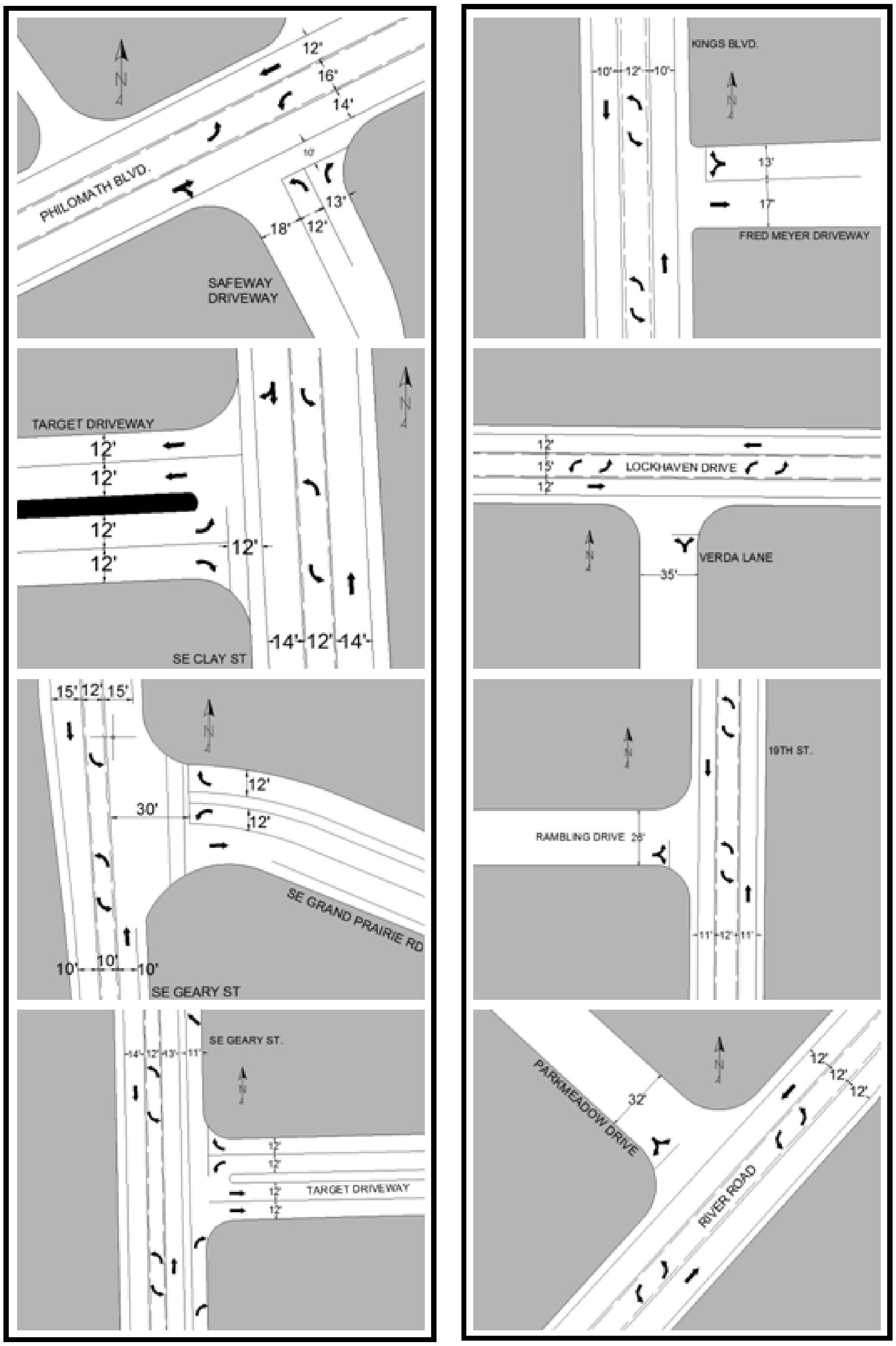

Figure 3.2 Experimental locations: Intersections with exclusive left turn and right turn lanes (left panel) and intersections with a shared lane for left turn and right turn (right panel)

Table 3.2 Experimental locations: additional characteristics

Intersection	City/ State	Upstream Int. Distance (ft)	Upstream Int. TCD	Downstream Int. Distance (ft)	Downstream Int. TCD	Posted Speed Limit (mph)	Major Street Bike Lanes
Fred Meyer at Kings Blvd	Corvallis/ OR	214	Stop Sign	403	Signal	25	Yes
Safeway at Philomath Blvd	Corvallis/ OR	726	Signal	725	Signal	45	No
Old Navy at Geary St	Albany/ OR	426	Signal	304	Stop Sign	35	Yes
Ground Prairie & Geary St	Albany/ OR	751	Stop Sign	405	Signal	35	Yes
Target at & Clay St	Albany/ OR	1022	Signal	480	Signal	35	Yes
Rambling & 19th St	Eugene/ OR	907	Signal	995	Signal	35	Yes
Verda Ln & Lockhaven Dr	Salem/ OR	775	Stop Sign	1510	Signal	35	Yes
Parkmeadow & River Rd	Salem/ OR	1765	Stop Sign	965	Stop Sign	40	Yes

3.4 Results and Analysis

3.4.1 Determination of sample size and characteristics

A total of 1502 minor road vehicles, executing 592 left turn and 910 right turn maneuvers, were observed and various statistical analyses and comparisons were performed to determine additional parameters that affect gap acceptance behavior.

A normalization transformation was performed on the data prior to the analysis and normality and residual plots were obtained in R, to ensure that the assumptions for T-test (analysis of means) and F-test (analysis of variance) were met. The comparison of means and distributions of wait times and accepted gaps showed significant differences between left turn and right turn maneuvers. The effects of all collected parameters on the gap acceptance behavior of right and left turning drivers were analyzed separately. Table 3.3 shows the results of the T-tests and F-tests on wait times and accepted gaps between right turn and left turn movements.

Table 3.3 Comparison of wait times and accepted gaps between right and left

	Maneuver	N	Mean (sec)	T-Test P-Value	SD	F-Test P-Value
Wait Time	Left Turn	592	13.3	< 0.001*	13.71	< 0.001*
	Right Turn	910	6.19		7.10	
Gap	Left Turn	400	7.93	< 0.001*	3.33	0.616
	Right Turn	444	8.95		3.42	

* Indicates statistical significance at 95% confidence level.

The comparisons of means and distributions for wait times and accepted gaps between maneuvers from shared lanes and exclusive lanes revealed no statistically significant effect caused by the lane utilization. Thus, no categorization of data was performed based on type of lane configuration and data from all experimental locations were combined for the analysis.

It should be noted that in the comparison of length of the gaps, the researchers excluded gaps longer than 15 seconds in duration. Thus, the sample size for the analysis of the accepted gaps was reduced to 400 left turning vehicles and 444 right turn vehicles. The decision to exclude longer gaps from the analysis was made based on findings from previous literature, where it was assumed that gaps between 12 seconds to 15 seconds are generally accepted by all drivers and provide no meaningful information about gap acceptance behavior, thus should not be included in the analysis of gaps (Teply et al., 1997; Gattis & Low, 1999; Yan et al., 2007; Xiaoming et al., 2007).

3.4.2 Determination of critical gap

As stipulated in the HCM method, the base critical gap for right turn maneuver is 6.2 seconds and requires no adjustment factors. For the left turn maneuver, adjustments were made for two-stage gap acceptance and the T-intersection, resulting in a critical gap of 5.4 seconds predicted by the HCM method. In comparison, we observed a critical gap of 5 seconds for right turn and 4.25 seconds for left turn at the experimental locations in this study. Both values are approximately 1.2 seconds less than the HCM values. It should be noted that for the experimental data, we used the Currin (2001) method to calculate the critical gaps. Currin suggests 15^{th} percentile accepted gaps as an estimation of the critical gap.

Figure 3.3 shows the plot of the cumulative frequency of accepted gaps for left and right turning maneuvers. The arrows show the critical gaps calculated with the Currin method.

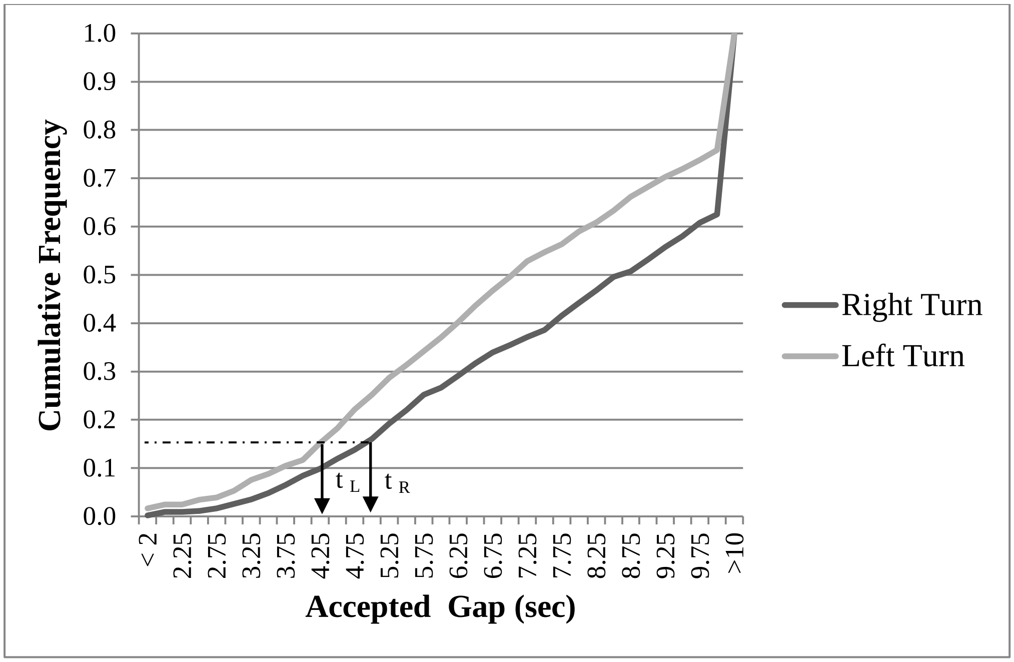

Figure 3.3 Cumulative frequency vs. length of accepted gaps (only gaps ≤ 15 s)

Although the general belief is that left turning drivers seek larger gaps, the critical gap for left turn maneuver from our empirical observation turned out smaller than the right turn maneuver. The T-test suggests a 1.01 seconds difference in the mean critical gap between right turn and left turn movements (p-value < 0.001).

3.4.3 Gap acceptance and waiting time

The differences in wait times for right and left turn maneuvers may contribute to an explanation of the unexpected behavior of left turning drivers. The mean wait time for left and right turning vehicles was 13.3 seconds and 6.19 seconds, respectively. Figure 3.4 shows the plot of percentage of right and left turning drivers in different wait time categories. It can be interpreted from the graph that while all drivers generally tend to have smaller wait times, the drivers turning left tend to have longer wait times than those turning right.

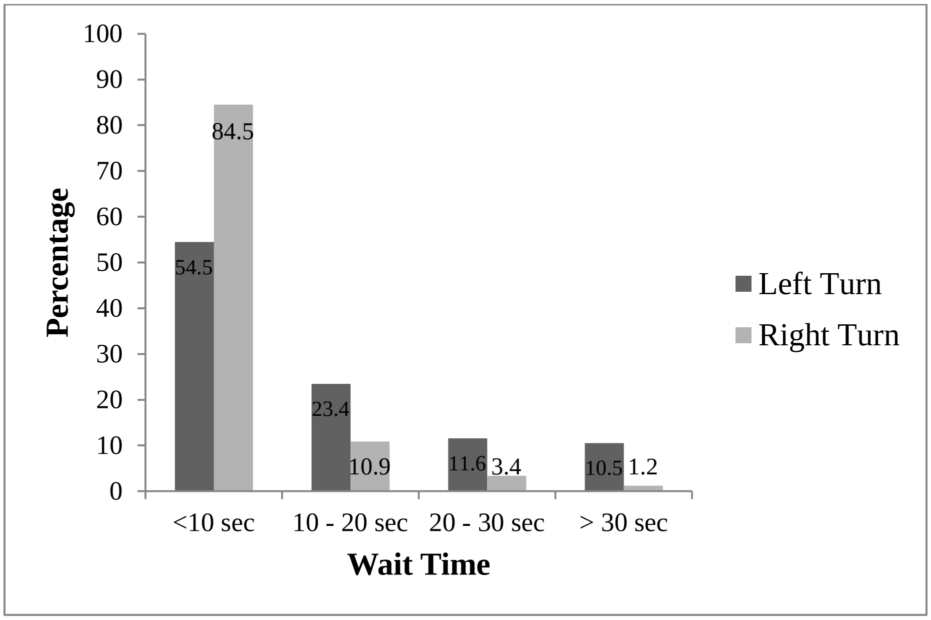

Figure 3.4 Left turn and right turn wait times

When looking at wait time independently from other variables, we found a statistically significant negative correlation between wait time and the length of accepted gap (p-value < 0.001), providing some evidence to support the notion that drivers accept smaller gaps as their wait time increases. Figure 3.5 shows the plot of accepted gaps against wait times for both turning maneuvers. It can be seen that the length of accepted gaps decrease as wait times increase.

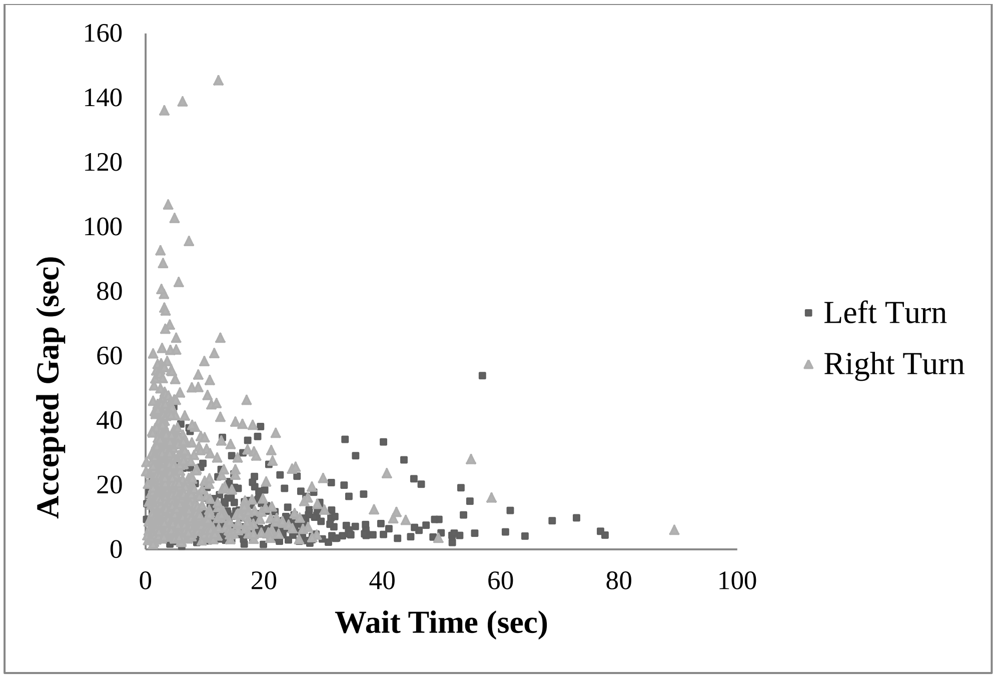

Figure 3.5 Accepted gaps vs. wait times

This could provide one interpretation for why the left turning drivers traversing a TWLTL on a three lane cross section act more aggressively choosing to end their wait times prematurely by accepting relatively shorter gaps. Since the right turning maneuver is relatively less challenging and requires less interaction with the opposing traffic, the wait time typically terminates before drivers are motivated to accept an unreasonably short gap. Left turning drivers, however, typically have to wait for longer durations to find coinciding gaps in both directions of travel. If they do not find an acceptable gap in a reasonable amount of time, it is likely they will reduce their gap acceptance threshold to minimize delay (albeit at higher levels of risk).

3.4.4 Gap acceptance and number of rejected gaps

The number of rejected gaps appears to be highly correlated with wait time and could be used as an alternative factor in the gap acceptance analysis (Teply et al., 1997). Figure 3.6 compares the gap acceptance behavior of drivers with various numbers of rejected gaps. The plot shows that for both right and left turn maneuvers, the critical gap (t_{cr}) decreases as the number of rejected gaps increase. This suggests that the behavior and mentality of the minor road drivers change over time, as they observe more vehicles on the major road passing them by.

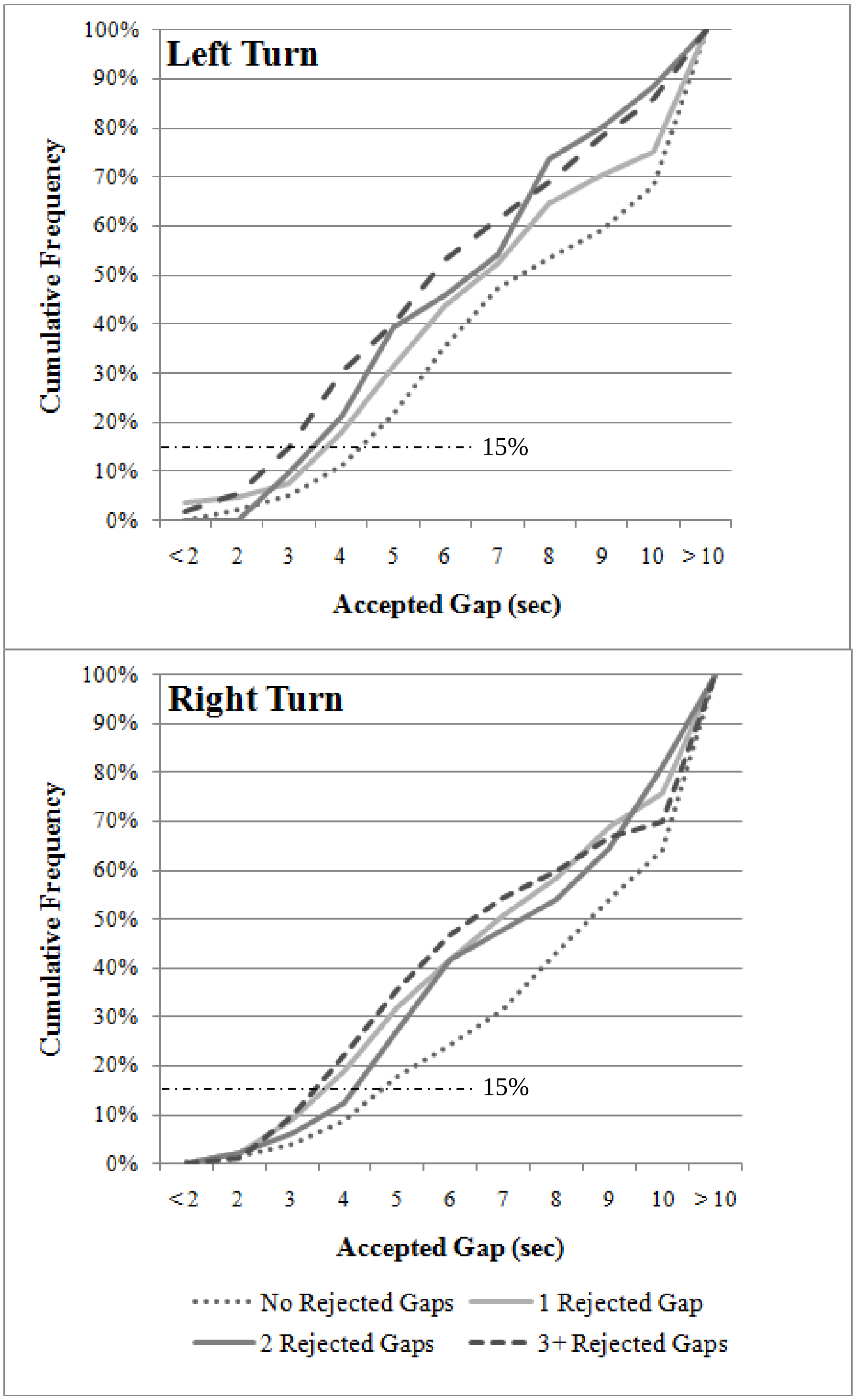

Figure 3.6 Length of left and right turn accepted gaps by number of rejected gaps

Unexpectedly, in spite of the TWLTL at all of the intersections, among all 592 left turning vehicles observed, only 12 drivers (2%) used the TWLTL to execute a two-stage left turning maneuver. It should be noted that the Oregon Driver Manual stipulates that "*you may turn from a side street or driveway into a two-way left turn lane and stop to wait for traffic to clear before merging into the lane to your right*" (ODOT, 2010). The HCM method also assumes a two-stage gap acceptance behavior in the presence of a TWLTL, regardless of the actual utilization of such facility. Our empirical observation however, suggests that the current HCM assumption regarding the two-stage gap acceptance is not necessarily met at all locations.

3.4.5 Variability in waiting times

The authors examined the variations in wait time based on several parameters including driver gender and approximate age (teen, adult, elder), presence of passengers, presence of a queue, and time of day (7 am to 10 am, 10 am to 1 pm, 1 pm to 4 pm, 4 pm to 7 pm). No statistically significant differences in means were observed in wait time distributions between age groups or times of day. However, when comparing female and male drivers, men showed more variations in their waiting times, both for right turn and left turn maneuvers. Table 3.4 shows the results of the T-test and F-test performed on the data.

Table 3.4 Wait time variations by gender for right turn and left turn maneuvers

				T-Test		F-Test
	Maneuver	N	Mean (sec)	P-Value	SD	P-Value
Left Turn	Male	278	14.4	0.116	14.81	0.014*
	Female	314	12.6		12.82	
Right Turn	Male	458	6.8	0.031*	8.59	< 0.001*
	Female	452	5.7		5.86	

* Indicates statistical significance at 95% confidence level.

The authors also considered the effect of queuing on waiting times. Table 3.5 provides a summary of the analysis. Those drivers at the stop line, while additional vehicles are queued behind them, appear to have longer wait times. This can be attributed to the fact that an increased prevalence of queuing can occur during periods of increased congestion on the major road. The F-test results do show significantly greater variation in behavior of drivers who are experiencing the pressure of the queue behind them. Thus, driver behavior is more variable under this condition, making it difficult to predict when a particular driver will end their waiting time.

Table 3.5 Wait time variations by presence of a queue for right turn and left turn maneuvers

				T-Test		F-Test
	Maneuver	N	Mean (sec)	P-Value	SD	P-Value
Left Turn	No Queue	438	11.8	< 0.001*	11.62	< 0.001*
	Queue	154	17.7		17.74	
Right Turn	No Queue	765	5.5	< 0.001*	6.83	< 0.001*
	Queue	145	10.4		10.41	

* Indicates statistical significance at 95% confidence level.

Table 3.6 shows the results of statistical tests to determine the influence of passengers on waiting time. No statistical differences were identified between the mean wait times of vehicles with and without passengers present. However, the authors determined that both left and right turning vehicles without passengers had greater variability in wait times than those with passengers.

Table 3.6 Wait time variations by presence of passengers for right turn and left turn maneuvers

				T-Test		F-Test
	Maneuver	N	Mean (sec)	P-Value	SD	P-Value
Left Turn	No Passengers	425	12.7	0.079	14.07	0.016*
	Passengers	143	14.8		11.86	
Right Turn	No Passengers	603	6.1	0.162	7.64	0.006*
	Passengers	213	6.9		6.51	

* Indicates statistical significance at 95% confidence level.

3.5 Discussion

The findings of this research suggest that there is a strong relationship between gap acceptance behavior and waiting times. The result is generally consistent with previous work conducted in the area of gap acceptance such as Xiaoming et al. (2007), Hamed et al. (1997), Teply et al. (1997), Kittleson and Vandehey (1991), among others. Additionally, the findings regarding the number of rejected gaps are consistent with Teply et al. 1997. This research contributes new knowledge to the literature broadly in the following three areas:

- The behavioral differences between right turning and left turning drivers and the parameters that affect their waiting times and accepted gaps were further examined,
- A novel data collection tool was further developed and tested for the purpose of quickly and accurately collecting gap acceptance data at TWSC intersections. The potential of this tool to inform the work of traffic engineers analyzing potential access points should not be underestimated. As with many parameters related to the safety of transportation systems, the ability to assess in-situ conditions quickly and effectively can contribute to drastically improved designs, and
- This study also contributes to the understanding of gap acceptance behavior at TWSC intersections with a TWLTL on the major road, which

have received relatively less attention as compared to other types of intersections.

The major findings for minor street vehicles attempting to perform a left or right turn at a TWSC T-intersection with a three lane cross section and a TWLTL can be summarized as follows:

- Drivers generally desire shorter wait times and such, as the waiting time or the number of rejected gaps increase (not necessarily mutually exclusive), the critical gap will decrease. This finding is in agreement with what was found by Kittleson and Vandehey (1991).
- Left turning drivers are more likely to experience relatively longer waiting times as compared to right turning drivers as they must interact with two opposing streams of traffic. This could result in more aggressive behavior and the acceptance of critical gaps shorter than those for right turning vehicles. This is likely exacerbated by the performance of a one-stage gap as compared to a two-stage gap.
- It appears that most of the left turning drivers tend to not use the TWLTL to execute a left turning maneuver in two stages. This might be due to reluctance to the multiple accelerations and decelerations required for the two-stage maneuver over a relatively short distance, a lack of comfort

occupying the relatively unprotected space of the TWLTL, or a lack of awareness of the traffic law.

- It appears that the development of a queue behind the left turning vehicle adversely affects gap acceptance behavior by producing more variation in wait time. It also appears that presence of passengers reduces the degree of variation observed in wait time. Gender also appears to influence gap acceptance behavior, resulting in more variable behavior in male drivers.

The results of this study reinforce the notion that driver behavior is variable and should continue to be investigated in localities across the country.

3.6 Acknowledgement

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CHAPTER 4

CONCLUSION

Gap acceptance behavior is very critical to safety and operational performance of unsignalized intersections. The complex nature of the human behavior and its dependence on various socioeconomic and environmental parameters makes it challenging for transportation professionals to assess the performance of such intersections. The manuscripts presented in Chapters 2 and 3 of this thesis contribute to the existing literature on gap acceptance behavior through the investigation of various factors affecting driver gap acceptance behavior when approaching stop-controlled intersections. Several of the factors considered have received little attention in the existing body of knowledge.

The first manuscript, "Revisiting driver behavior at unsignalized intersections: time of day implications for two way left turn lanes (TWLTL)," which will be published in the compendium of the 6th International Driving Assessment conference, examined the effects of various parameters on drivers' critical gap at TWSC intersections. These parameters included time of day, wait time, driver's approximate age and gender, presence of queue, presence of passengers, and type of vehicle. The findings revealed that presence of passengers in the car, development of a queue behind the car, and driving later in the day, may result in a tendency towards accepting shorter gaps. These observations may lead to more accurate and realistic measurements of the critical gap and directly affects our ability to model both capacity and safety at unsignalized intersections.

The research effort also resulted in findings regarding the effects of wait time on critical gap and how drivers change their behavioral patterns, after waiting for a certain amount of time. This observation was central to the motivation for the second manuscript. We also noticed during the initial data collection effort, that the TWLTL's were rarely, if ever, used by left turning drivers, in spite of their potential in lowering wait times and risk of angle crashes. Thus, in the following research effort we focused on the effects of waiting time on gap acceptance behavior. The previously developed and tested data collection software (GAPS), allowed for the collection of a larger sample population of drivers and more experimental locations in a reasonable amount of time and with desirable accuracy.

The findings of the second research effort, “Gap acceptance behavior at unsignalized intersections: implications of waiting time,” which will be submitted to the Transportation Research Record Journal, identified a strong dependence of gap acceptance behavior on wait time and the number of rejected gaps, confirming previous findings in the literature. More specifically, we found that drivers generally desire shorter wait times and thus, as the waiting time or the number of rejected gaps increase, the critical gap will decrease. Also, a comparison of left and right turn maneuvers showed that left turning drivers are prone to relatively longer waiting times, as they must interact with two opposing streams of traffic. Thus, we believe they behave more aggressively due to longer delays and often accept critical gaps shorter than those for right turning vehicles. This is likely exacerbated by the performance of a one-stage rather than a two-stage gap. It appears that most of the left turning drivers do not tend to use the TWLTL to execute a left turning maneuver in two stages. This might be to the result of reluctance to the multiple accelerations and decelerations required for a two-stage maneuver over a relatively short distance, a lack of comfort occupying the relatively unprotected space of the TWLTL, or a lack of awareness of Oregon traffic law. However, the current HCM method for determining capacity and LOS makes the assumption that in the presence of a TWLTL, drivers execute the gap acceptance maneuver in two stages. According to the field observations, this assumption is not necessarily met and may result in underestimation of the risk exposure of the minor approach vehicles, especially those executing a left turn maneuver.

The results of this study reinforce the notion that driver behavior is affected by external environmental and driver characteristics and should continue to be investigated in localities across the country. Engineers should consider the demographics and characteristics of local users and the extent to which they affect driver behavior. Future work towards the development of a recommendation for the one-stage vs. two-stage assumption in the HCM standards and methods is warranted based on the results of this effort.

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