CAPACITY INVESTIGATION OF ALL-WAY STOP-CONTROLLED INTERSECTIONS

by

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DEDICATION

To my parents, family, and beloved friends, who believed in me, and my capabilities. To those who motivated me both physically and mentally. Also, to those who never stop growing and stops learning throughout their lives.

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ABSTRACT

Depending on traffic conditions, highway functional classification, sight distance, area setting, and other considerations, various traffic controls are used at the location of intersections. One of the essential traffic controls used at intersections is All-Way Stop Control (AWSC) which requires all vehicles to stop before entering the intersection. Proper capacity and headway estimations are essential for AWSC intersections to estimate the capacity. On the other hand, estimating the capacity of these types of intersections was always a challenging and essential task for a transportation engineer. Therefore, this research aims to develop a suitable methodology to estimate the capacity and empirically investigate the AWSC intersections. The literature review of this research identified many existing methodologies for estimating the capacity for unsignalized intersections; however, a few existing studies were for AWSC type of intersection, and others were outdated. Four days of intensive field data collection took place to identify the individual vehicle that entered and exited the intersection—the study site was characterized by single-lane approaches and high levels of vehicular and pedestrian traffic. Using strict protocols, collected data were processed at the individual vehicle. Then the collected data was extracted into a series of spreadsheets for analysis purposes. The method used several variables such as level of conflict, pedestrian activity, and type of movement at the intersection. The study resulted that the total intersection capacity varied between 400 and 1400 vehicles per hour. The study suggested that the wide range of capacity observations is primarily associated with the pedestrian crossing activity at the intersection of interest. Regarding movement type, the right-turn movement was not significantly affected intersection capacity. In contrast, the left-turn movement negatively affected the intersection capacity. Pedestrian traffic at the study site profoundly affected the mean saturation headways for saturation headways. The impact of the type of movement was found notable on the mean saturation headways, and the lowest mean was observed in right-turning vehicles.

CHAPTER ONE

INTRODUCTION

Background

Intersections are an essential component of the highway network from operations and safety perspectives. Stop signs are the primary form of traffic control at intersections across the United States. The general form of intersection forms includes yield-controlled intersections, stop-controlled intersections, signalized intersections, and modern roundabouts. Its primary function is to allow the change of route directions. They are nodes in the transportation network, where two roads meet to form an at-grade junction. Being one of the traffic control devices, it governs the rules for how the traffic streams from two specific roads interact.

The intersection, overall, is an area of decision for all drivers; each must select one of the available choices to proceed, which requires an additional effort by the driver that is not necessary for non-intersection areas of a highway section or a roundabout. The flow of traffic on any street or highway is greatly affected by traffic flow through the intersection. Precisely, the capacity of intersections primarily controls the capacity of corridors and networks in the highway system due to the many movements (traffic streams) they serve. From a different perspective, conflicts at an intersection are different for different intersections. When including right-turn, left-turn, through movements, and pedestrian conflicts, a typical four-legged intersection has about 32 types of.

Depending on traffic conditions, highway functional classification, sight distance, area setting, and other considerations, various traffic controls are used at the location of intersections. One of the essential traffic controls used at intersections is All-Way Stop Control (AWSC) which requires all vehicles to stop before entering the intersection. This type of control is usually used when traffic volumes on the crossing roadways are relatively low and when both arteries belong to the same functional classification, typically local or collector roadways.

The operation of an AWSC intersection is quite complex. The capacity and delay at any given approach to the intersection is a function of traffic volumes on all other approaches. Vehicles on different approaches, their intended movements, and the subject vehicle's movement (through, left, or right) determine the number of vehicles that conflict with the direction of the subject vehicle. Thus, the time the subject vehicle takes to perform the intended maneuver. Figure 1 shows the subject's approach to an AWSC intersection and the opposing and conflicting traffic streams.

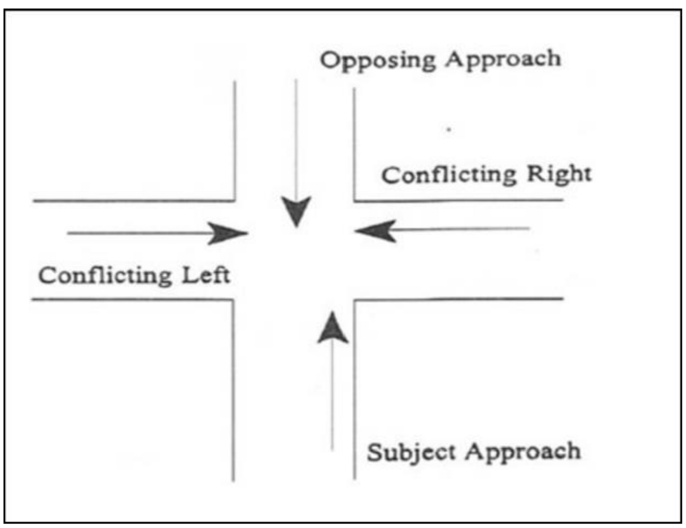


Figure 1. Approaches at the 4-way stop-controlled intersection
(Sussman and National Research Council the USA 1997)

Historically, vehicles from conflicting (crossing) or opposing traffic streams have been treated using case classification (case number) to represent the level of conflict on other approaches when the subject vehicle arrives at the stop bar on the subject approach. The Highway Capacity Manual (HCM) 1994 update (Sussman and National Research Council the USA 1997) introduced four case numbers for the level of conflict, which was then extended to five case numbers in the HCM-2000 edition (Wachs et al. 2000)**,** as shown in Figure 2.

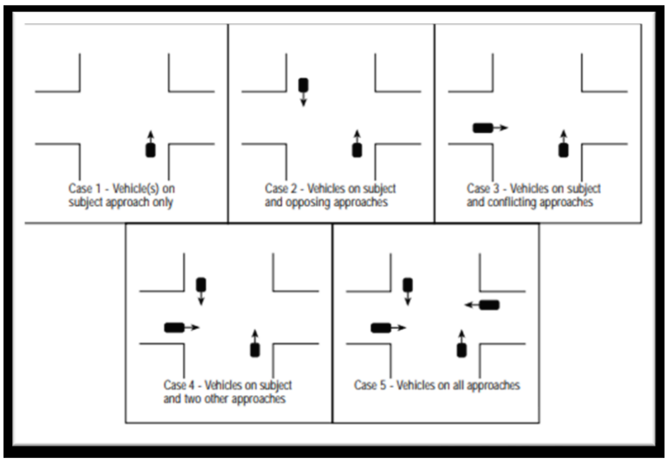


Figure 2. The HCM-2000 Level of Conflict Case Numbers (Wachs et al. 2000)

Capacity and Saturation Headways at All-Way Stop-Controlled Intersections

One of the traffic engineer's essential tasks is estimating the capacity of transportation facilities. The current Highway Capacity Manual (HCM) (National Academies of Sciences AD) contains detailed procedures for determining the capacity of nearly all facilities. These procedures usually include determining a capacity under ideal conditions, and limited procedures are present regarding the all-way stop-controlled intersections. These procedures, however, do not include non-ideal conditions and account for the impact of any other variables that could be found at the intersection during the operations, such as pedestrian activity and directional turning movement type.

An AWSC intersection capacity is essential since they usually act like a bridge between the corridors and arterial roadways. The need for a detailed methodology for calculating the capacity at AWSC is inevitable. Further, there is a need to investigate the relationships between varying variables that affect intersection performance during operations. Unfortunately, the literature review for the capacity analysis at AWSC only found a few mostly dated studies. Even though some studies in the literature analyze the operations at AWSC intersections by simulation, only a few studies have found that use field data validation methods.

On the other hand, estimating the capacity of these types of intersections was always a challenging and essential task for a transportation engineer. The primary parameter to compute the intersection capacity is saturation headway. The 2016 Highway Capacity Manual (HCM) notes that the saturation headway is "the time between departures of successive vehicles on a given approach for a particular case" (Highway Capacity Manual 2016).

Past traffic operations studies prove that the saturation headway for a vehicle at an AWSC intersection is a function of traffic flow characteristics and intersection geometry (Michael; Kyte et al. 1996)**.** HCM-2016 stresses (Highway Capacity Manual 2016) that if traffic is present on the other approaches and the subject approach, the saturation headway on the subject approach will increase somewhat, depending on the degree of conflict that results between the subject approach vehicles and the vehicles on the other approaches. This implies that conflicting approaches cause more significant saturated headway for the subject approach and eventually lead to less capacity or failure of the operations at the intersection. After HCM-2000 was released, the number of conflict situations a subject vehicle may face increased to five for the revised edition, as Figure 2 illustrates.

Objectives

This research aims to empirically investigate the capacity of All-Way Stop-Controlled (AWSC) intersections and the saturation headways. The primary goal is mainly divided into three sub-objectives. The first two identify two different methodologies for determining the capacity of AWSC intersections and the effect of the pedestrian activity, directional turning movement type, and level of conflicts. The third objective is to empirically assess the saturation headways at the intersection of interest and investigate the impact of pedestrian activity, directional turning movement type, and level of conflict with field data. These analyses would identify the effects of the described variables on the saturation headways and the capacity.

Outline

This thesis has six chapters. The first chapter is the introduction, which presents the research's background objectives and the thesis's outline. The second chapter is the literature review chapter which presents existing studies about AWSC intersection capacity and operations identified from a comprehensive literature search. The third chapter describes the study site in this research and further discusses the data collection procedures and processing rules. The fourth chapter assesses the identified analyses and their corresponding results for the capacity analysis.

The fifth chapter discusses the analysis results for the saturation headway analysis. The sixth chapter discusses the potential differences, benefits, and challenges of using the methodologies described in previous chapters. Finally, the last chapter summarizes the results, presents the significant findings, and summarizes this research.

CHAPTER TWO

LITERATURE REVIEW

The primary purpose of empirically investigating an intersection's capacity and saturation headways is to correctly identify the need for the intersection and find the spots that need improvement. Over time, the need for an empirical study of AWSC intersections emerged since studies mostly dated way back and did not cover the essentials. The literature review of this thesis can be separated into two sections: capacity at AWSC intersections and saturation headway analysis at AWSC intersections.

Capacity at All-Way Stop-Controlled Intersections

The literature review conducted during this research only found a few studies on AWSC intersection capacity that are mostly dated, i.e., most studies were conducted between the sixties and nighties of the past century.

Hebert (Hebert 1963) investigated the capacity at three AWSC intersections with a single lane on each approach in the Chicago metropolitan area. The data was collected using video cameras at the 12 study sites. The study estimated capacity using the average departure headway and investigated 13 the effects of turning movements and the volume split between the two crossing roadways. The study reported total intersection capacity values as high as 1900 vehicles per hour. The study found that right-turning vehicles are associated with smaller departure headways, thus increasing intersection capacity. The study also found that a balanced volume split between the two crossing roadways contributes to higher capacities.

Later in 1987, Richardson (Richardson 1987) drew attention to the issue of the previously published methods and the lack of any analytical model for capacity estimation. The author introduced a new model that could predict the level of performance at the intersection over a broader range of traffic conditions. He calculated the capacity based on the service time (departure headway) and the time each vehicle occupies the intersection based on Hebert's work (using his minimum departure headways). In addition, Richardson used this model to forecast intersection capacity and delay under different scenarios of volume split between the crossing roadways.

Kyte and Marek (Michael Kyte and Marek 1989) investigated the capacity and delay at single-lane all-way stop-controlled intersections. They collected data for nearly 25 hours of operation from eight sites in the northwest region. The primary motivation for this research was the need to improve the 1985 Highway Capacity Manual AWSC intersection procedures. The study presented two methods for estimating the capacity of an AWSC intersection using the highest flow rate observations and departure headway data. The study reported that the highest single observed flow rate was 2,016 vph, whereas the maximum observed flow rate for an intersection approach was 732 vph. A regression model was developed for departure headway that could be used in estimating approach capacity. Since the data collected represents a limited range of traffic conditions, the developed model may not apply to the wide range of traffic conditions in real-world applications. The study also reported values for departure headways under capacity operation for different scenarios of vehicles using other approaches (level of conflict) and the corresponding approach and total intersection capacity values.

In 1990, Michael Kyte estimated the factors affecting the capacity of AWSC intersections and developed a procedure for estimating the capacity (Michael Kyte 1990). He used 30 hours of data and more than 7000 departure headways from 20 study sites, including single-lane and multilane AWSC intersections. The main variables used in his capacity model are the number of lanes on each approach, the distribution of traffic among different approaches, and the proportion of turning movements on each approach. The study found that the AWSC capacity increases with the increase in the proportion of right-turning vehicles and decreases with the increase in the proportion of left-turning vehicles, pedestrian traffic, and heavy vehicle traffic. In a follow-up study, Kyte et al. (Kyte et al. 1994) investigated saturation headway using an AWSC intersection site in Portland, Oregon. The study examined saturation headway under the effect of vehicle movement from the subject approach and the presence of vehicles on the conflicting and opposing approaches. The capacity of an approach was found to vary between 525 vph when the subject driver faces a continuous queue of vehicles on both opposing and conflicting approaches and 100 vph when the subject driver faces no opposing or conflicting vehicles.

Colyar et al. published a study in 1997 focused on the field measurements of capacity and delay at unsignalized intersections (Zongzhong, Kyte, and Colyar 1997). The published study focused on improving the HCM methods and models based on some assumptions. The primary purpose of this study was to introduce a practical method for measuring capacity and delay at unsignalized intersections. The proposed model is based on average queue length and queueing theory. The motivation behind this study was that the HCM model provides an average total delay based on the LOS. To calculate the average total delay, the traffic volume of the minor street needs to be known. The method includes; queue length with the measurements of the number of vehicles departing from the stop line; then, the average queue length and the hourly flow rate over the measurement period can be calculated. The researchers compared the field measurements for capacity and the proposed model estimations with the methods used in HCM-1994 using 15-minute time intervals of data collection at an AWSC intersection. They found 549 veh/hr, 482 veh/hr, and 621 veh/hr for the proposed method, in field measurements, and for HCM-1994, respectively. The results show that data collected from the field showed good correlations between the average delay and queue length; consequently, the proposed calculation method is easier to apply for capacity estimation and yields more accurate results than HCM-1994 procedures. While the proposed method in this paper gives some reliable information and results, it still does not account for a pedestrian activity or turning movement; instead, it accounts for the total delay and the approach's movement capacity.

A study derived capacities at unsignalized intersections using the conflict technique (Brilon and Wu 2001). This study focused on developing a new theoretical approach for determining capacities at unsignalized intersections based on the method of additive conflict streams. The study claims that this new procedure can deal with shared lanes, short lanes, flared entries, and cases of limited priority. They mainly focus on the TWSC intersections and their conflict groups. The new model provided significant advantages over some older methodologies by considering pedestrian movements as an additional element. For derivation purposes, the researchers ranked each movement by their conflicts with traffic streams and included the pedestrians. With this newly developed model, the study claims that it is possible to map the complicated regulations regarding pedestrian priority. Moreover, this model can simulate and consider real-life road user behavior. However, the study does not consider any directional vehicular movement by the nature of the article and primarily focuses on two-way stop-controlled intersections.

Another study by Wu (2002) developed a new model for estimating total AWSC intersection capacities (with single-lane approaches) using the so-called Addition-Conflict-Flow (ACF) technique. The study claimed that the effect of turning streams or movements needed to be modeled in more detail in the HCM 2000 procedures. The study compared total capacities from the HCM 2000 procedures and those found using the ACF technique. Further, the study suggested modifications to the HCM model to make results more realistic (more consistent with older studies). The ACF technique and the modified HCM model yielded notably higher capacities than those from the HCM 2000 procedures.

Another study was conducted an empirical field study to determine the capacity at two-way stop-controlled urban intersections (Li and Deng 2007). As discussed, two-way stop-controlled intersections have been a focus for many years for capacity investigations. The study claims that the capacity analysis of TWSC somewhat depends on understanding drivers' interaction at the intersection. The study mainly aimed to develop an appropriate model which includes the traffic interactions in the gap acceptance process, platoon dispersion, and signalized control systems. Based on the field investigation and observations, the study could compare the gap features of major traffic streams at the TWSC intersection of interest. Afterward, the researchers presented a methodology for determining the capacities at TWSC intersections under one-way and two-way gap conditions, and a program/software was developed and computed. In contrast to HCM-2000, the methodology proposed in this article was more effective the HCM-2000 model. Even though this study was not an AWSC, it still does show the effects of the traffic stream interactions and comparison with HCM-2000 overall. The results of the developed program showed a maximum relative error of 17% while HCM-2000 had 30%; thus, the empirical study then compared the HCM-2000 methodology for estimating capacities at TWSC and proved the effectiveness compared to HCM-2000. The time headway for a median vehicle type was 3 seconds, while for a heavy vehicle, 4 seconds. The critical gap for the heavy and median vehicles was 7.5 and 6 seconds, respectively. While this new methodology provides a quite valuable reference for determining the capacities at TWSC urban intersections, the study did not consider any effect of pedestrian activity, turning movement, or level of conflict at the intersection.

Another study by Li et al. focused on the capacities of unsignalized intersections under mixed vehicular traffic conditions (2009). The study used a conflict technique method to develop capacity models for three different types of unsignalized intersections, two-way stop-controlled, all-way stop-controlled, and uncontrolled intersections. The study used field data collected from several intersections, and the model parameters were calibrated and modified by comparison of actual traffic conditions in China. The field data used in this study included intersections with different configurations and relatively heavy traffic of all kinds of road users. Similarly to this thesis study, the data were gathered by a video-image system and were analyzed by a program package, SPSS. The capacities obtained by the model are well-matched with the observed capacities. The researchers looked at the effect of vehicular movements in contrast to other studies published in this study area and pedestrian movements. To examine the impact of the pedestrian movements, the researchers grouped the volume and occupation time after observing and estimating the group size of pedestrians waiting to cross the intersection. Several equations and variables were used to investigate this impact, such as the flow rate of pedestrian movement, the average time of crossing, the total width of the lanes, and the average walking speed. As a result, the study found that the right-turning vehicular movement had the highest capacity for various methods used in the project, such as gap acceptance theory and motorcade analysis. Additionally, the study's results indicate that the influence of pedestrian and bicycle movements on the capacities of vehicular movements cannot be ignored.

Ahmad and Prasetijo focused on developing a new model to assess the performance of unsignalized intersections (2012). The primary purpose of this study was to overcome the shortcomings of the gap-acceptance method used in the analysis of an intersection, such as the non-compliance to the right-of-way and the heterogeneous traffic conditions. The study used surveillance equipment to obtain the required data, such as traffic volume and occupation time. The researchers followed the HCM-2000 procedures to evaluate the control delay and level of service and used the vehicle's occupation time to calculate the vehicular movement capacity. Afterward, the study compared the results between the method used in the paper and the method used in HCM-2000, yielding a relationship between occupation time and critical gap. The study focused on two different T-intersections in China which both the intersections had similar atypical layouts with a combination of the shared lane and flared approaches. To measure the occupation time correctly, they used a software called VDET that accounted for the driver's behavior. They used the same technique that Brilon and Wu (2002) used, including the conflicted groups. The results showed that the south-left turning vehicles had the lowest occupation time, and the travel distance between the south and west approaches was the shortest. This indicated the high travel speed of the west right-turning vehicles when entering the south approach. Since the vehicles had to pass through two conflict areas, the highest occupation time occurred in the south right-turning movement. The capacity values were expected to be lower than the significant stream interaction capacities due to impeding vehicular movements. The maximum capacity occurred at the east left-turn movement with 2190 veh/hr for the first intersection and 1429 veh/hr for the second intersection for the south left-turn. Capacity comparisons between HCM-2000 and the method developed by researchers yielded similarly and differed only 10 to 20 veh/hr by each turning movement. After the data analysis, researchers concluded that; the occupation time is inversely proportional to the capacity of the vehicular movement. Long-duration occupation times are often related to slow-moving vehicles and large intersection areas and increase the delay of vehicular movement, thus degrading the LOS. Additionally, the results showed that the exclusive lane for turning movement could reduce the delay of the vehicular stream.

Guler and Menendez conducted a study for estimating capacity and delay at unsignalized multimodal intersections (2016). This study aimed to develop a methodology to evaluate the average delays at multi-modal uncontrolled intersections. Additionally, this methodology considered the demand of different traffic streams along with each stream to determine capacity availability. Five locations in Zurich were used to test this methodology, and the results yielded that the methodology could predict the average delay within 4 s/veh. The methodology first determined the saturation flow rate of different modes and their related priorities. Then it used these values to calculate the inputs for the effective capacity equation using HCM procedures after computing the final effective capacity for each stream, then calculated the average delays. Overall, this study focused more on the average delays at the uncontrolled intersections rather than the capacities; however, it still found some interesting capacity estimates. Adapting to the changing conditions at any intersection makes this methodology robust for different traffic streams and multi-modal analysis. Several inputs to use this methodology includes; stream priorities, directions, and saturation flows which can all be observed easily.

Saturation Headways at All-Way Stop-Controlled Intersections

While conducting a literature review for this research revealed a few studies on saturation headways at all-way stop-controlled intersections. While many studies were for mostly signalized intersections, for AWSC intersections, there was limited research in the literature.

Kyte (1994) investigated the saturation headways at all-way stop-controlled intersections. They investigated a study site on the suburban side of Portland, Oregon, with four legs with a single lane on each approach. The researchers used one video camera to record traffic flow through the intersection. The primary motivation for this research was to investigate the effect of turning movements on saturation headways and to improve the cases considered in addition to the standard four cases. The study presented a method that followed the current HCM procedures then the data was analyzed based on the mean saturation headways and turning movement type. The study examined the mean saturation headway in the four available cases and found that the highest headway occurred in Case 4 while the lowest was in Case 1. Similarly, the highest mean headway was found for the vehicles that turned left compared to the other movement types. The study found that the effect of turning movement direction on the saturation headway was significant and pointed out that this must be considered for future studies; however, as opposed to the turning movement effect, this study did not examine the results of the pedestrian activity.

Another study by Kyte et al. (1996) analyzed the traffic operations at AWSC intersections by simulation in 1996. The developed model was tested against the field data collected during NCHRP Project 3-46. The developed model was later used to predict vehicle delay, queue length, and saturation headways. The researchers had several variables: move-up time, hesitation time, and minimum headway. The study used the subset of Case numbers developed by Kyte et al.

(1994), meaning eight case numbers were used. The simulation values of the compared simulation saturation headway resulted in slightly lower than the field data; however, Case 3 had the same mean saturation headway as the field data measurements. Results showed that saturation headway forecasts by simulation had a good correlation with the field measurements. The study noted that the measures were based on normal traffic conditions and did not investigate the impact of turning movement.

CHAPTER THREE

DATA COLLECTION & PROCESSING

As described in the previous chapter, the literature review presented a handful of publications that focus on all-way stop-controlled intersections. Only a few of these articles used field data to conduct their studies. In this chapter, the collection process and its related study site description are presented as well as data processing.

Description of Study Site

One intersection was exclusively selected for this study containing the all-way stop-controlled right-of-way rule. This intersection qualifies as a significant intersection since having a high traffic flow volume for the morning and afternoon peaks and a relatively lower volume during the daytime hours. The study site used in this thesis research is Bozeman, Montana, at the 11^{th} Avenue and West Grant Street intersection. The 11^{th} Avenue runs north-south, connecting downtown Bozeman with the southern part of town, passing through Montana State University's campus. At the same time, Grant Street is a minor collector running east-west, providing access to the MSU campus from the east. The two intersecting roadways cross each other at a ninety-degree angle, and the speed limit on both streets is 25 mph. Both roads have standard lane widths at the intersection location, and bicycle lanes are provided in all directions. This study site was selected for relatively high traffic levels, significant pedestrian activity, and suitability for data collection setup. The intersection has four single-lane approaches and crosswalks in all directions. A street view of the study site is shown in Figure 3**.**

Figure 3. Street view of the Study Site (Source: Google Maps)

Field Data Collection

The data collection for this study consisted of two main parts. Firstly, a fixed mobile trailer was set at a height overlooking the study site. The researchers used a surveillance camera on a mobile traffic monitoring trailer set at a height overlooking the study site. Video recordings of the study site showing all intersection approaches were acquired on four different workdays in November 2017. Using surveillance on a mobile trailer was convenient and practical for this study. Overlooking the study site was essential to the researchers since it was necessary to be aware of all the queues at the intersection. By the Western Transportation Institute, WTI, an affiliation with MSU, the mobile traffic trailer was put in the parking lot near the intersection site, which was convenient for the researchers so that the trailer would not disrupt any traffic during the operations of the intersection, including pedestrian activity. At the same time, it allowed researchers to have a clear view of the intersection by not diverging attention from either drivers or pedestrians. A report published by WTI (Hayden and Washington 2007) explains the configurations and deployment process in more detail in this publication. Figure 4 below illustrates the mobile trailer used in this field of data collection.

Figure 4. Mobile Trailer for data collection (Hayden and Washington 2007)

Figure 5**.** Video footage showing the study site

The camera was set up so that all vehicles entering and exiting the intersection could be viewed simultaneously, including the queue presence on the subject approach. Eighty-four hours of video recordings were collected at the study site. Figure 5 exhibits the video footage data collected during the data collection process.

Data Processing

This part of the data collection is focused on managing the video data footage data and storing it in the database. Storing the data included manually extracting the information from the video data and entering it into the spreadsheet. This procedure was intensive in that researchers manually watched all the video data, sometimes doubling the speed, and joined each vehicle's information and related variables, which are explained later in this section. Extracting such variables manually from video footage data required a high time dedication.

The second part focused on the collected data being organized and imported to a computer so researchers could analyze and analyze the collected data. Each of the four approaches, north, south, east, and west, was examined in different spreadsheets to be more consistent with the data analyzing procedure. After four days, video data were extracted, and the spreadsheets were organized in such a manner that to be viewed easily by anyone who was not a part of this research. When analyzing the direction of the west approach, the video data revealed that the west approach had a small population of sample size compared to other approaches; thus, this study did not focus on the West approach precisely due to this reason and removed it from the analyzing steps not to have an impact on the actual collected data.

The video footage was analyzed using digital video recording (DVR) software and a systematic manual procedure for processing the data. Specifically, to be consistent in extracting the required data from video records, a set of rules and protocols were developed to accurately remove all variables of interest for each vehicle entering the intersection from the subject approach.

These rules followed the same rules that any AWSC intersection had, such as right-of-way traffic, violation of the stop sign, violation of the intersection rules, such as doing a U-turn at the intersection site, and violation of pedestrian safety. The researchers would still record and store this information in the spreadsheet with a comment when and when they see any vehicle violating one of the rules described above.

A pilot study established these rules before processing the complete data sets. This pilot study used the rules and procedures described above; however, not all four approaches were processed to observe the data's difficulties. To properly process the data and then analyze it, this pilot study was necessary since the spreadsheet has been shaped around this pilot study. The information and the variables that were extracted for each vehicle entering the intersection from any of the intersection approaches involved the following:

- Date
- Arrival time:
- Departure time is when the front edge of the subject vehicle crosses the stop bar location and enters the intersection.
- Clearance time: this is when the read edge of the subject vehicle clears the physical area of the intersection.
- Wait time: this was when the subject vehicle was waiting at the stop location before entering the intersection. It is measured as the time lapse between the arrival and departure times.

- Occupancy time: this is the time when the subject vehicle occupies the physical area of the intersection. It is measured as the time lapse between the departure and clearance times.
- Departure headway: this is the time between two consecutive departures on the subject approach, measured as the time lapse between the departure times of the subject vehicle and the preceding vehicle on the same approach.
- Movement type (through, right, or left)
- Case number: the case number indicates the vehicles on all other intersection approaches present when the subject vehicle arrives at the stop bar as classified by the Highway 21 Capacity Manual (HCM) procedures. The HCM case number classification is shown in Figure 2.
- Queue presence on subject approach
- Pedestrian crossing(s) and type: this field indicates if pedestrian(s) are crossing the intersection using the near, far, or both crosswalks conflicting with the vehicle movement.
- Number of pedestrians involved in the crossing maneuvers

Data processing was completed for each subject approach independently before data analysis. It should be noted that data processing also marked heavy vehicles, bicyclists crossing the intersection, and vehicles violating the all-way-stop-control rules. The study did not consider these observations to control their potential effect on the saturation headway and, eventually, the intersection capacity. These instances were very few overall compared to the sample size of the data. A detailed spreadsheet table for the data set is provided in appendix A at the end of the report.

CHAPTER FOUR

ANALYSIS OF RESULTS: SATURATION HEADWAYS AT AWSC INTERSECTIONS

The processed video recording data described in the previous sections was used in extracting the intersection saturation headway observations measured in seconds. The underlying assumption is that each subject approach had a queue presence when at least one vehicle stopped waiting to be served on any of the approaches. This study utilized three variables describing the impacts on the mean saturation headways while satisfying this assumption. This section presents the results of the saturation headway analysis at the study site using the methodologies described in previous sections. The calculations using the methods for estimating the effects of each variable are presented separately in this section.

1. *Impact of Level of Conflict:* This variable identifies the level of conflict that the subject approach has in the presence of queueing during the operations of the all-way stop-controlled intersection. This variable focuses on the Case Number procedure described in the previous sections and the HCM-2000. The number of conflict situations a subject vehicle may face was increased to five in the revised edition of HCM-2000 (Wachs et al., 2000).
2. *Impact of Pedestrian Activity:* This variable identified the effect of pedestrian activity in the presence of the queue during the operations of the intersection. To examine this variable more in detail, two sub-variables were identified. Using these two sub-variables, the effects of pedestrian activity with no pedestrian crossing were analyzed and presented in the results section.

A. Number of crosswalks in use: at the study site, where pedestrian crossings are allowed on all approaches, a vehicle may conflict with pedestrians using the near crosswalk on the incoming approach, pedestrians using the crosswalk on the far (outgoing) approach or both. This sub-variable assumed a value of 0 if no pedestrian was present, one if either crosswalk was in use, and two if both crosswalks were in use.

B. Number of crossing pedestrians: this variable accounts for the total number of crossing pedestrians at the intersection that conflicts with the subject approach.

3. *Impact of Turning Movement:* It is well known that turning movements are an essential factor in the resulting saturation headway during the operations of all-way stop-controlled intersections. Collected data was divided into three different movement types to examine the effects of turning movements more in detail, and the mean saturation headways were measured. This variable identifies the subject vehicle's movement and direction at the intersection.

After carefully examining the above-mentioned variables, the researchers analyzed each variable concerning their data extracted from the same video footage data. Below, the result from the analyzed data is presented for each variable.

Level of Conflict

Saturation headways are influenced by the level of conflict at the intersection's instant queue presence. In the report of HCM-1994 (Sussman and National Research Council the USA 1997), the level of conflict concept was introduced along with four different case situations mentioned in the previous section. In this section, the impact of the level of conflict was investigated and presented. Below, Table 1 gives a broad descriptive summary of the saturation headways.

Table 1. Saturation Headway Descriptive Statistics

Saturation Headway Descriptive Statistics	
Mean	9.87
Standard Errror	0.07
Median	9
Mode	6
Std Deviation	4.54
Sample Variance	20.64
Minimum	2
Maximum	28
95% Confidence Interval	0.14
Sample Size	3800

As a starting point, the descriptive statistics for saturation headways for all combined data set was established. Table 6 presents the range of saturation headways developed at the intersection of interest. The overall mean for all three approaches was 9.87 seconds which spanned 3800 observations throughout the data collection process. The maximum headway achieved was 28, while the minimum was 2 seconds, with a median of 9 seconds. In these results, the standard deviation was 4.54, suggesting that the average amount of variability is more spread out than a normal distribution. The range of headway values is wide, 26, which can largely be attributed to either driver behavior or pedestrian activity, which will be discussed in later sections.

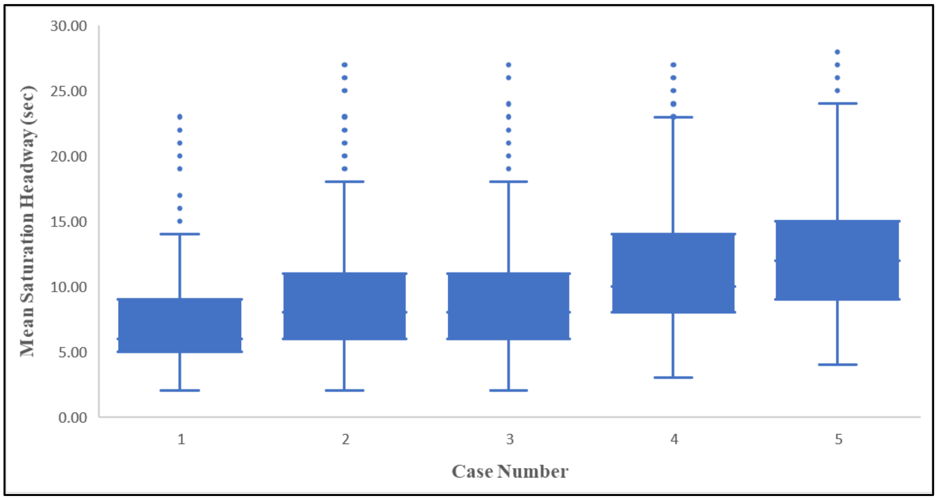


Figure 6. Mean Saturation Headway with Case Numbers

As known, a boxplot uses boxes and lines to depict the distributions of one or sometimes more groups of numerical data. Box limits indicate the range of the central 50% of the data, with a marking at a central line for the median value. The extension of lines from each box represents a capture of the range of the remaining data in the dataset, with dots placed to indicate the outliers. A boxplot is usually used when comparing different groups in an overall dataset.

The boxplot, Figure 6, exhibits an increasing pattern where the mean saturation headway, in seconds, increases with the level of conflict that the vehicle in interest had at the intersection during the data collection process. This level of conflict refers to the “Case Number,” described in previous chapters and based upon the Highway Capacity Manual, HCM, published in the year 2000. More information for case numbers can be found in the first chapters of this thesis study. Having all the intersection conflicts, Case 5, as seen from the figure, had the highest mean saturation headway overall in seconds, which can be expected somehow since the vehicle in the subject approach would spend more time at the approach waiting to be queued dispersed on the other approaches following the right-of-way rule of the AWSC intersection. Case 1, however, has no conflicts; thus, having the smallest mean saturation headway amongst the other cases would be expected.

Additionally, in its simple form, a boxplot can present other statistics to use in our analysis, such as the lower quartile, the upper quartile, the median, and the maximum. The length of a boxplot also corresponds to the interquartile range of the sample values. In this case, even though we see similar median values for Cases 2 and 3, Case 3 has a higher median value, as seen from a visual display. The similarity, however, could be a reason for having the same level of conflict between Case 2 and Case 3 since each case has one conflict corresponding to their cases. For Cases 4 and 5, the interquartile ranges for both cases are higher than other case numbers. This suggests that the spread of the middle half of our data sample for those cases is higher and most of the variability values lie in this range. The maximum values can be read from the whiskers and correspond to the maximum mean saturation headways for associated case numbers in seconds. Those are close, 15, 17, 16, 23, and 25 seconds for cases 1 through 5, respectively.

This pattern is expected given the longer time a vehicle would need to clear the conflicting situation, refers as case number in this study. It also can be seen that the mean saturation headways for Case 2 and Case 3 are close since the study includes a somehow high sample size; the distribution, as expected, is not normal but somewhat scattered. It was expected that both Case 2 and Case 3 would have closer mean headway values. Since both the case numbers have only one conflicted vehicle at the intersection, with Case 2 having opposing conflict and Case 3 conflicted with the passing traffic either right or left. Having an outlier in such a high sample size is also anticipated. When removing the outliers, the IQR rule, known as Interquartile Range Method, was used.

Pedestrian Activity

Saturation headway is affected by many factors during the AWSC intersection operations. Pedestrian activity/crossing is one of the factors influencing vehicle flow, saturation headway, and overall capacity. By analyzing the imagery data collected by video cameras installed at the intersection of interest, the researchers could obtain some characteristics of pedestrian activity at the intersection and, eventually, the impact on the mean saturation headway. To examine the effect of pedestrian activity on saturation headway at AWSC intersection operations, scatterplots showed the relationships between the mean saturation headway. Before forming the scatterplots, two variables were specified:

1. The average number of pedestrian crossings; is the average number of pedestrian crossings that occupy the intersection by each case number. To establish these average values, the total pedestrian count was divided into the number of observations for each level of conflict.

2. The average number of crosswalks in use; is the conflicted crosswalks that were used during the operations at the intersection and averaged by the case number by dividing into the total number of observation and their related parameters, 0, 1, and 2, no crossing, near/far, and both, respectively.

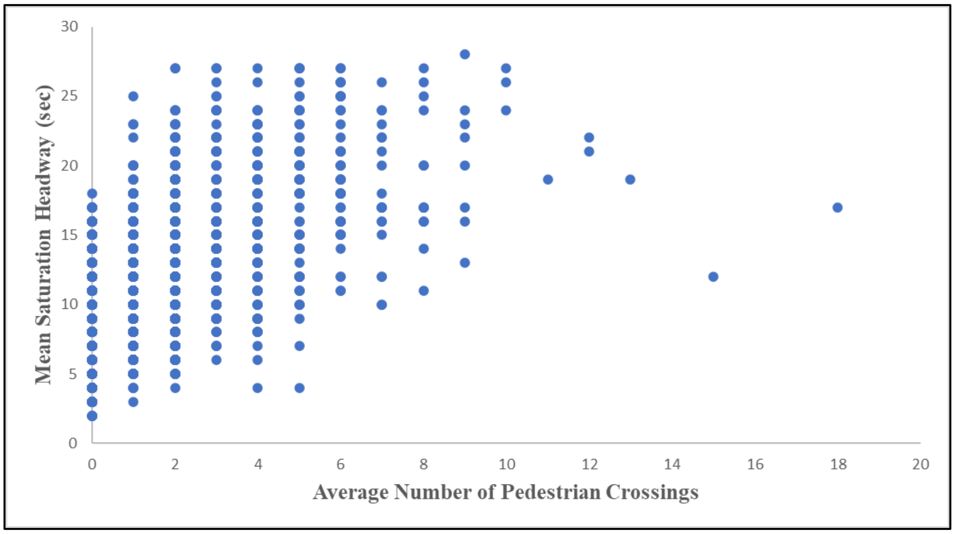


Figure 7. Mean Saturation Headway versus Average Number of Pedestrian Crossings

The scatterplot in Figure 7 above shows the saturation headways and the total number of pedestrian crossings at the intersection of interest. Each data point represents related headway (seconds); each horizontal data point represents the total number of pedestrian crossings at any crosswalk. The plot shows a generally positive correlation between saturation headway and the number of pedestrian crossings. This correlation refers to an increasing pattern where the saturation headway increases with the total number of pedestrian crossings at the intersection of interest. This pattern is somehow expected given the longer time a vehicle would wait in the queue when more pedestrians are simultaneously at the intersection. We may see some of the saturation headway data points for zero crossing are high compared to having pedestrians at the intersection, such as 15 or more seconds; however, this can be explained due to various situations at the intersection, such as driver behavior, not following the AWSC right-of-way rules or anything else. We can see that increasing the number of pedestrian crossings increases the minimum saturation headway.

On the other hand, we can detect that some data points have been scattered around; more specifically, after twelve pedestrian crossings, we see a slight decline in the headway and somehow no relationship between the two variables. However, this discrepancy may be caused by removing the outliers of the dataset. As known, an outlier is a data point that lies outside the overall pattern in a distribution. As discussed in the previous section, for a better understanding of the data analysis purposes, researchers removed some of the outliers using the IQR rule, and the scatterplot could show the rest of the data points after removing outliers.

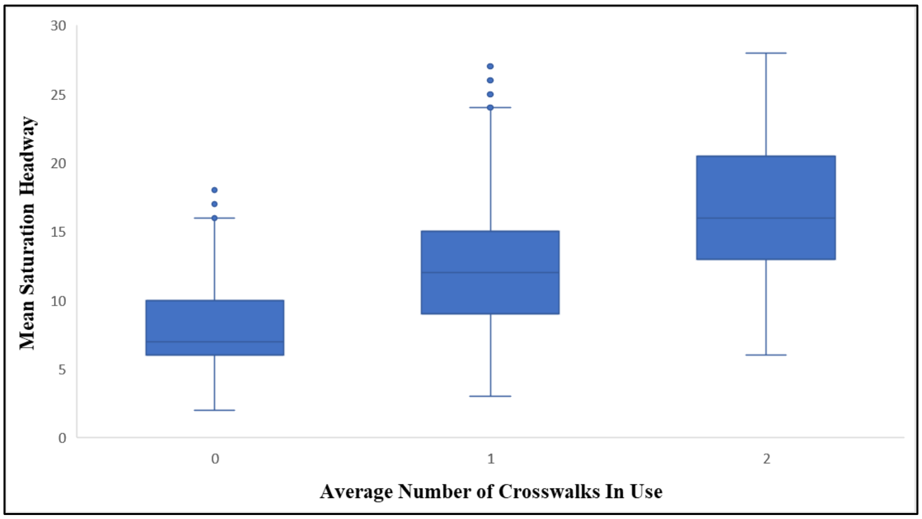


Figure 8. Mean Saturation Headway versus Average Number of Crosswalks in Use

As mentioned in the previous section, a general boxplot is used when comparing different groups in the dataset. In this instance, we used to compare our mean saturation headway values, in seconds, with the number of crosswalks used by pedestrians. This variable, described in the previous section, is defined by three different parameters: the conflicted crosswalks used during the operations at the intersection where 0 represents no crossings occur, 1 represents either of the crosswalks in use, such as near or far. Two represents having at least one pedestrian crossing on both sides of the crosswalks.

Figure 8 exhibits a boxplot to understand the impact of pedestrian activity more in-depth. The figure shows a rising pattern on the mean saturation headways when comparing the usage of different crosswalks at the intersection. The mean saturation headway increases with different crosswalks, which is discussed earlier as a variable. As expected, having no pedestrians at the intersection refers to zero in this variable and is associated with having the smallest overall mean saturation headway. Having at least one or more pedestrians using either the near or far crosswalk at the intersection is associated with higher overall saturation headways. Lastly, having at least one or more pedestrians on both sides of the crosswalks refers to parameter two in this variable. It is associated with the highest overall mean saturation headway at the intersection of interest.

Additionally, we can easily detect the maximum and minimum values with a closer look at the box plot. We can see that when no pedestrian crossings occur at the intersection, we had minimum saturation headway of fewer than five seconds and a maximum of almost 20 seconds, with is an outlier for our range. When we had at least one pedestrian crossing at the intersection, we detected five and nearly 30 seconds for minimum and maximum values, respectively. Notably, when two crosswalks were used simultaneously, we had the highest range and minimum and maximum values for overall saturation headway.

This is consistent with the expectation that the higher the conflicting pedestrian activity, the higher the overall mean saturation headway. This suggests that the higher usage of a crosswalk, including near, far, and both, yields higher mean saturation headway in seconds. Thus, when pedestrians occupy more crosswalks, the time spent in the queue for a vehicle increases.

Table 2. Mean Saturation Headway values with and without Pedestrians

With Pedestrians								
Case Number	**North Approach**		**South Approach**		**East Approach**		**Total**	
	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations
1	10.9	70	9.86	29	11.44	16	10.73	115
2	12.57	100	12.41	75	13	3	12.66	178
3	13.15	74	12.87	55	12.86	83	12.96	212
4	13.73	233	13.37	211	14.95	172	14.02	616
5	14.98	57	15.61	64	15.57	51	15.39	172
Without Pedestrians								
Case Number	**North Approach**		**South Approach**		**East Approach**		**Total**	
	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations
1	6.37	259	6.61	207	6.37	83	6.45	549
2	7.61	206	7.56	215	7.08	12	7.42	433
3	8.03	180	7.87	134	7.8	196	7.90	510
4	8.55	287	8.33	303	9.91	256	8.93	846
5	9.02	53	10.32	63	10.42	53	9.92	169

To understand the effect of pedestrian activity at the Case Number level, Table 2 was developed, discussed, and presented. The mean saturation headway values for the AWSC intersection of interest are presented above for both with and without pedestrians. It was important for the researchers to investigate the impact of the case number variable along with the pedestrian activity, by investigating it through different approaches allowed researchers to understand different aspects of the impacts on the directional level.

The results show a pattern as expected for both pedestrians and without pedestrians. Even though on the East approach, the researchers had a comparably low sample size for Case 2 for pedestrians and without pedestrians, 3 and 12, respectively, the table still shows a good number of observations in total and in any other Case numbers for different approaches, a total of 3800. The mean saturation headway, as expected, is lower without pedestrians even though it had a higher sample size than pedestrians, 1293 and 2507 for with and without pedestrians, respectively. As expected, the highest mean saturation headway found in Case 5, for both with and without pedestrians, is 15.39 seconds and 9.92 seconds, respectively. The highest number of observations was established for both variables in Case 4, which was not expected; however, it is imaginable since Case 4 has three distinct conflicts from all other two approaches at the intersections. Notably, the North approach was the busiest, with the most sample size. This is expected since the North approach acts as the primary collector at the intersection of interest and runs towards the City of Bozeman. Having almost 15 seconds as a mean saturation headway for Case 5 on the North Approach was higher than any study researchers came across in the literature. Notably, the difference between the mean saturation headway values of Case 5 for pedestrians and without pedestrians was higher than expected at 5.5 seconds. It is realized how much pedestrian activity can affect the saturation headway and, consequently, the capacity of an intersection.

Turning Movement

The five headway cases given in the Tables in previous sections do not directly consider the effects of directional movement of the traffic. The five cases provide a very simplified classification of the conditions faced by the subject approach driver at the intersection. To examine the detailed impacts of turning movements on the mean saturation headway, the data set was divided into sections for each turning movement, left, right, and through. This section exhibits the findings and discussions the descriptive and analytical findings. For each subject approach vehicle that was a part of a queue, the saturation headway was measured, and the conditions faced by the driver were identified. Afterward, the turning movement directions for all vehicles were recorded and presented here.

Table 3. Turning Movement Descriptive Statistics

Descriptive Statistics Variables	Left-Turn Movement	Through Movement	Right-Turn Movement
Mean	10.62	9.82	9.36
Standard Error	0.17	0.10	0.15
Median	10.00	9.00	8.00
Mode	7.00	7.00	6.00
Standard Deviation	4.65	4.38	4.71
Sample Variance	21.63	19.24	22.23
Minimum	2.00	2.00	2.00
Maximum	27.00	27.00	28.00
95% Confidence Interval	0.33	0.19	0.30
Sample Size	771	2077	951

After developing descriptive statistics for combined data, the descriptive statistics for each turning movement were established to examine the impact of turning direction more in-depth. Table 3 presents the overlook of descriptive statistics for each turning movement. Having 10.62 seconds of mean saturation headway, the left-turn movement had the highest mean among the turning movements, which can be expected logically since left-turn movements are usually more restrictive and have more conflicted vehicle points present during the operations. Both through and right-turn movements had a closer mean headway with 9.82 and 9.36, respectively. The right-turn movement had the smallest mean headway with 9.36 seconds which was expected since the right-turn movement has the lowest conflicted points and travel distance compared to the other directional movements.

Additionally, the range of mean headway values is wide for each movement. It is 25 seconds for left and through movement and 26 seconds for a right turn, which may be caused by a pedestrian or any other outside effect during the operations. Comparing the standard deviations, each movement had a comparably lower standard deviation for their related sample sizes, which means that the data points are clustered around the mean mostly. From these results, it can be concluded that the subject vehicle's directional movement somehow affects the saturation headway. Overall, it was observed that right-turning vehicles have significantly lower headways compared to left-turning and through-movement vehicles.

Another way of presenting the impact of turning movement is to determine the mean saturation headway for each level of conflict. Table 4 below exhibits these findings qualitatively. This table summarizes the findings for each case number, described in previous sections, by each directional movement type discussed above, along with their number of observations.

Table 4. Mean Saturation Headway values by Pedestrian Activity and Turning Movement

With Pedestrians								
Case Number	**Left**		**Through**		**Right**		**Total**	
	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations
1	12.05	20	10.35	71	10.67	24	11.02	115
2	13.41	29	12.06	124	13.72	25	13.06	178
3	12.72	50	13.22	101	12.74	61	12.89	212
4	15.22	122	13.49	351	13.99	143	14.23	616
5	15.36	42	15.39	87	15.42	43	15.39	172
Without Pedestrians								
Case Number	**Left**		**Through**		**Right**		**Total**	
	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations	Mean Headway (sec)	Number of Observations
1	6.29	95	6.66	327	6.07	126	6.34	548
2	8.16	56	7.68	273	6.96	104	7.60	433
3	8.22	131	8.13	244	7.18	135	7.84	510
4	10.03	179	8.8	425	8.17	242	9.00	846
5	10.53	47	10.19	74	8.98	48	9.9	169

To investigate the turning movement by pedestrian activity, Table 4 was developed and presented. We can see immediately that when we do not have any pedestrian activity at the intersection or any other disruptions encountered with the movement, the right-turn movement has almost always the lowest mean saturation headway in seconds. Even though on the most conflicted points which in this case is Case-5, right-turning vehicles had 8.98 seconds of mean saturation headway without the pedestrian activity. For Case-1 with pedestrians, we can see a slight difference between through movement and right-turning vehicles in terms of the mean saturation headway, comparing between 10.35 and 10.67 seconds. The smaller sample size might cause those right-turning vehicles had with 24 observations compared to 71 observations for through movement. For Case-5, right-turning vehicles had the highest mean saturation headway with 15.42 seconds with 43 observation points. This can be explained again by the smaller sample size and having the most conflicts at the intersections. The almost double size of the observations for no pedestrian activity compared to at least one pedestrian at the intersection, 1293 versus 2506, having no pedestrian activity occurred more at the study intersection. This observation difference could give us more reliable analysis results regarding turning movement at the intersection. Additionally, in almost any case, through movement had the highest observations. In this case, the difference between having and not having pedestrians is significant for any turning movement. Comparing any case for this table results in having a higher mean saturation headway for pedestrians at the intersection.

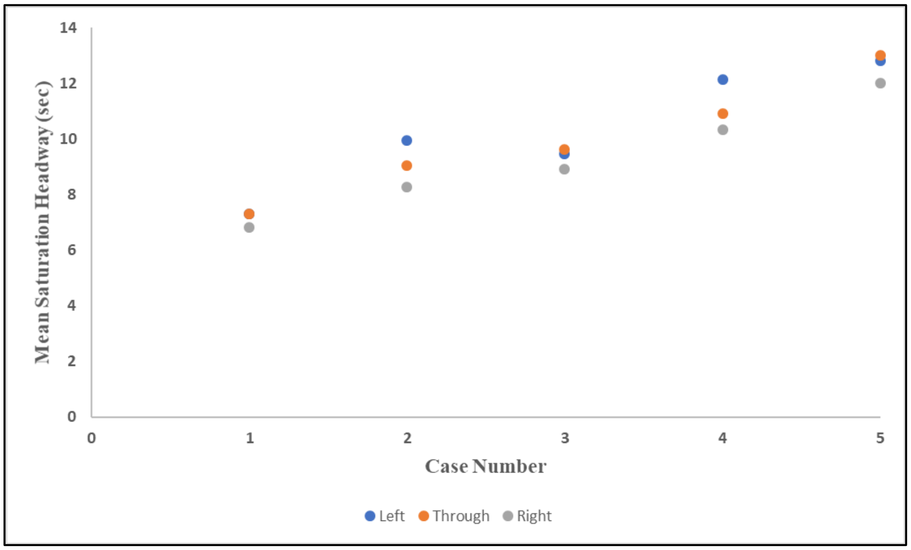


Figure 9. Mean Saturation Headway versus Turning Movement

To investigate the impact of turning movement more in-depth and qualitatively, Figure 9 was developed. The figure presents all three directional movements by case numbers and the related mean saturation headways. Firstly, Case 1 has similar mean saturation headway values for both left-turn and through movements. This is expected since Case 1 has no conflicts; thus, the only vehicle at the intersection during the operations is the subject vehicle. Even though both left and right had similar saturation headways, the right turn had slightly less mean headway. This may be caused by right-turn movement requiring much less distance to be traveled than left and through movement. Similarly, Case 2 resulted in expected mean saturation headways since the left-turn movement is more restrictive than any other movements, and the right-turn is the least restrictive.

For Case 3, since the pedestrian activity was not a controlling factor in this analysis, someone can expect that the through and left-turn movements share similar mean saturation headways, as shown in the scatterplot above. Left-turn and through movements have the same level of conflict for Case 3; thus, having very close mean saturation headways is expected compared to right-turn movement. As to Case 4, having one conflicting vehicle and one opposing it resulted in the expected range of mean headways among the movement types. The left-turn movement had the highest mean saturation headway with 12 seconds; similarly to other cases, the right-turn movement had the lowest mean with 10.3 seconds. Even though through campaign had a slightly larger mean for Case 5, this discrepancy can be explained by the effect of pedestrians or the difference in the number of observations among the Case numbers and the movement types. Since the impact of pedestrians is not controlled as a factor in this section, this minimal difference among the movement types for Case 5 can be neglected

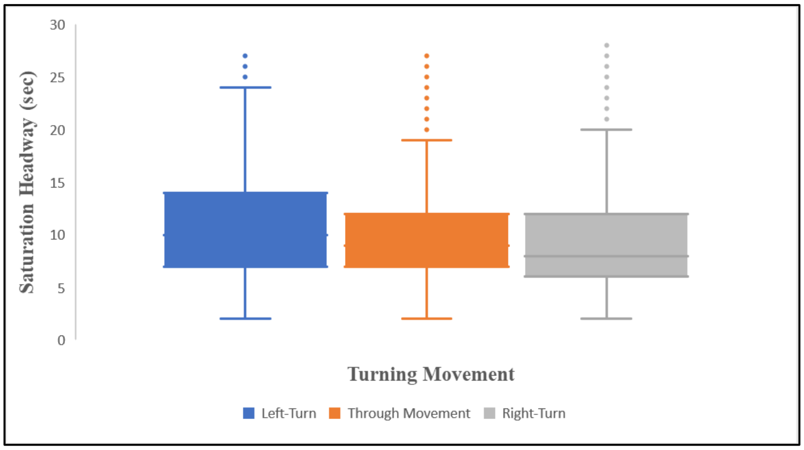


Figure 10. Saturation Headway versus Turning Movement with Pedestrians

To have a better understanding of the impact of the turning movement, Figure 10, boxplot, was developed. Above, a boxplot exhibits this effect in a manner that how a turning movement would affect the saturation headways. The figure shows a declining pattern on the saturation headways, being a left-turn movement as the highest headway. As expected, the right-turn movement had the lowest headway with a mean of below 10 seconds, and the through movement was in the middle of each directional type of movement with a mean of above 10 seconds. The maximum saturation headway occurred with the left-turning vehicles for almost 25 seconds, much higher than any study reviewed in the literature. The highest saturation headway observed was 20 seconds and 21 seconds for through-movement and right-turning vehicles, respectively. Having almost the same number of conflicting points on both movements can explain closer maximum and minimum saturation headway values for both through and right-turning movements. However, we can still detect outlying data points with as much as 25 seconds on the through movement and the right-turning vehicles, which can be explained by either the driver's behavior or the right-of-way violations during the operations at the intersection in addition to having pedestrian activity. Almost all turning movement types had the lowest value of two seconds. This result was consistent with the expectation since left-turning vehicles had the highest conflicted points at the intersection compared to either through movement or right-turning movement. This suggests that a higher volume of left-turning vehicles would yield higher saturation headways and lower capacity estimations at the intersection of interest. To have a more in-depth understanding of the effect of the turning movement in the saturation headways and eliminate the noise of the pedestrian activity at the intersection, researchers plotted a box plot of the saturation headways versus the directional turning movement type excluding the pedestrians.

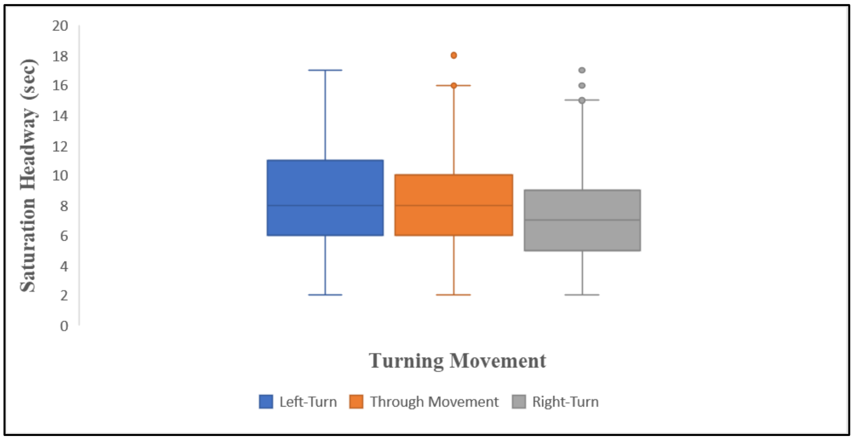


Figure 11. Saturation Headway versus Turning Movement without Pedestrians

Figure 11 illustrates a box plot for saturation headway versus turning movement, excluding pedestrian activity at the intersection. By observing the saturation headway values, we can detect the more considerable difference between having pedestrian activity at the intersection and not having pedestrian activity. Again, the maximum saturation headway occurred during the left-turn movements; however, significantly lower than the previous box plot, Figure 10, with 18 seconds. Similarly, through movement had a lower saturation headway value than left-turning vehicles and higher than right-turning vehicles. The maximum saturation headway for through-movement vehicles was 16 seconds and 14 seconds for the right-turning vehicles. Right-turning vehicles had the lowest saturation headway values even though excluding the pedestrians from the analysis. Having the lowest saturation headways can be explained, for right-turning vehicles, by traveling the least distance when turning right versus either turning left or crossing the intersection directly. Only a few outliers for through movement for 16 seconds can be explained by the right-of-way allocation or violation of the intersection rules. These results show that the right-turning vehicles had the lowest saturation headways independently for pedestrians, and similarly, left-turning vehicles had the highest saturation headways independently for pedestrian activity.

The next step for this chapter of the study was to compute multivariate linear regression to closely and more in-depth examine the four variables' effect on saturation headway. The results are shown in Table 5.

Table 5. Regression output for estimating Saturation Headway

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.69
R Square	0.48
Adjusted R Square	0.48
Standard Error	3.29
Observations	3800

ANOVA

	df	SS	MS	F	Significance F
Regression	4	37393	9348	865	0
Residual	3795	41025	11		
Total	3799	78418			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	6.91	0.22	32.02	< 0.0001	6.49	7.33
Level of Conflict (Case #)	0.79	0.04	18.37	< 0.0001	0.71	0.88
Type of Turning Movement	-0.57	0.08	-7.15	< 0.0001	-0.72	-0.41
Number of Crossing Pedestrians	0.99	0.06	17.55	< 0.0001	0.88	1.10
Number of Crosswalks in use by Pedestrians	2.05	0.15	13.93	< 0.0001	1.76	2.34

This regression computation included categorical variables for turning movement and level of conflict by having the case numbers 1 through 5. Type of movement is coded as; 1 for left-turning vehicles, 2 for through-movement vehicles, and 3 for right-turning vehicles. Similarly, number of crosswalks include 0, 1, and 2 which refers to no pedestrian present at the intersection, either near or far crosswalk is in use, and both crosswalks are in use, respectively. With a coefficient of almost one, 0.99, number of pedestrians affected the saturation headway almost directly with in correlation with regarding number of people.

The coefficient of determination (R-square) value in the regression output indicates that around 48% of the variability in intersection capacity is explained by the three variables that are part of the regression model. The standard error of the estimate is around 3.3 seconds, and the F-value from the ANOVA test indicates that the overall regression model is significant. Closely looking at the p-value results, we can conclude that all variables were found significant and affect the overall saturation headway with a small p-value of less than 0.0001.

These results were somehow expected since the pedestrian crossings would yield higher delays at the intersection and eventually having higher saturation headways and consequently lower capacity values. Additionally, a positive coefficient indicates that as the independent variables' value increases, the dependent variable's mean also tends to increase.

Discussion of Results

The AWSC intersection means saturation headways were analyzed and presented using the three variables described earlier. The overall mean for all three approaches, north, south, and east, was 9.87 seconds which spanned 3800 observations across four days of data collection.

The saturation headway of a subject vehicle depends on the degree of conflict faced by the subject driver as measured by the presence of cars on opposing and conflicting approaches. As expected, the impact of the conflict level was found to be significant on the saturation headway.

During the analysis, Case 1 resulted in the lowest mean saturation headway, and Case 5 yielded in highest mean saturation headway. This was expected since the more conflicts the subject vehicle has, the more time it would need to clear the intersection and yield higher headway times. To have a 95% confidence of interval of 0.14 throughout the sample shows that most of the saturation headway observations fall into the sample population values and are distributed normally.

Similarly, the impact of the pedestrian activity is not negligible during the operations of AWSC intersections. The results yielded as expected, and the highest mean saturation headway was found in Case 5 for both with and without the pedestrian analyses. Using the processed data and the two variables described in previous sections, the impact of pedestrian activity was significant for the mean saturation headway at AWSC intersections. The effect of pedestrian presence on saturation headway was critical. Similarly, the other notable difference between the mean saturation headways was the average number of crosswalks in use; it was expected to see higher yielding mean headways when there is a pedestrian conflict compared to the 'Far' crosswalk. Having pedestrians or not was an essential criterion for measuring the saturation headways since the difference between the mean saturation headways between the case numbers was significant. The most affected approach was the East approach for having pedestrians and not which was expected since it carries most of the student pedestrian traffic to the gym area and toward the campus. Both the North and South approaches had a difference in the mean of saturation headways of 3.2 seconds between pedestrians and not, which was also expected since both approaches have similar flow rates across the campus and the intersection.

Upon further examination of the analyzed data, it was found that the turning movement significantly affects the mean saturation headway. With almost one thousand sample sizes for each turning direction, the analysis was meaningful, including having similar modes for each observation, with 7, 7, and 6 for left, through, and right turning movement, respectively. While the left-turn movement had the highest mean saturation headway with 10.62 seconds, the right-turn movement was associated with lower mean saturation headways than any other directional movement type with 9.36 seconds. The decrease in travel distance causes this during the turning direction and the less restrictive turning movement. The median for all turning movements was similar, with the right turn being the lowest at 8 seconds and the left-turn movement highest at 10 seconds. By examining closely for Case numbers, the turning movement mean saturation headways have resulted in an expected range of values across different directional movements. Left and through movements shared similar mean saturation headway values for Case-1. In contrast, the right-turn movement had a lower mean value for having no conflict at the intersection, which can be explained by simply traveling less distance than other directional movements described above. Different case situations had a logical sense of mean saturation headway values, which Case-3 has the highest through movement, which can be explained by the pedestrian activity or simply having a smaller sample size for that specific case situation. While the right-turn movement had the lowest mean saturation headway values across all case numbers, it still had a rising pattern throughout the observations, with the highest being 12.02 seconds. Since the right-turn movement had the lowest level of conflict compared to other turning movements, this was expected and explained by the field-data calculations.

CHAPTER FIVE

ANALYSIS OF RESULTS: CAPACITY AT AWSC INTERSECTIONS

Different capacity analysis methods for all-way stop-controlled intersections were identified in the literature. Various techniques used different approaches for analysis and different data sets, field data and simulation, and resources. This chapter presents the capacity analysis results for the two methods developed during the study.

A set of rules and methodologies were selected for measuring the capacity at the intersection of interest. The processed video recording data described in the previous chapter was used in extracting the intersection capacity observations measured in vehicles per hour. The underlying assumption is that the intersection operates at capacity when at least one vehicle stops waiting to be served on any intersection approach. Several different variables were identified and discussed in the following subsections. This study utilized two methods in extracting capacity observations while satisfying this assumption.

Method I

This method identified intervals when the subject approach to the intersection was queued for a "tangible" period, i.e., when many queued vehicles are discharged consecutively from the subject approach. This approach focuses on the queuing on one approach regardless of the presence of queue(s) on other approaches. The time interval was measured as the time lapse between the first vehicle entering the intersection and the last vehicle in the interval clearing the intersection. A case number was used for traffic entering the intersection from different approaches to account for traffic conditions on other approaches. The number of vehicles entering from the subject and other approaches is counted over time. The information is used to calculate capacity as an hourly flow rate. This process was repeated for the different intersection approaches.

Using the procedure described in the previous section, 104 intervals were identified and used to estimate the intersection capacity over the four days of data collection for all intersection approaches. Table 6 shows that this method's mean capacity value is around 892 vehicles per hour, with a standard deviation of about 164 vehicles per hour. The minimum capacity observed was only 432 vehicles per hour, while the maximum observed 30 capacity was around 1345 vehicles per hour. The range of capacity observations is vast, which can largely be attributed to pedestrian activities during the period of interest. Specifically, slow walking speed for some pedestrians and pedestrians crossing in large numbers are typical situations that could significantly affect the number of vehicles entering the intersection during a given interval.

Table 6. AWSC Intersection Capacity Descriptive Statistics – Method I

AWSC Intersection Capacity Descriptive Statistics - Method I	
Mean	892.02
Median	880.08
Std Deviation	164.26
90th Percentile	1093.82
Minimum	432
Maximum	1344.58
95% Confidence Interval	31.94
Sample Size	104

It was of interest to examine the effect of some of the variables that are thought to affect the capacity at AWSC intersections. The variables that were investigated in this study are discussed below.

1. Number of crosswalks in use: it is well known that pedestrian crossing activity at an AWSC intersection is a significant determinant of intersection capacity. At the study site, where pedestrian crossings are allowed on all approaches, a vehicle may conflict with pedestrians using the near crosswalk on the incoming approach, pedestrians using the crosswalk on the far (outgoing) approach, or both. This variable assumed a value of 1 if either crosswalk is in use and two if both crosswalks are in use.

2. Number of crossing pedestrians: this variable accounts for the total number of crossing pedestrians at the intersection that conflicts with the subject vehicle's movement.

3. Number of vehicles on other approaches: this is the number of vehicles already waiting on different approaches when the subject vehicle arrives at the stop sign. This number is a function of the HCM case number described earlier. The number of vehicles corresponding to each case number is shown in Table 7. This variable is expected to affect the AWSC intersection capacity as vehicles entering from different approaches increase the possibility of two vehicles using the intersection simultaneously (for non-conflicting movements).

Table 7. Number of Conflicts using the HCM case numbers

Case Number	Number of Vehicles
Case 1	0
Case 2	1
Case 3	1
Case 4	2
Case 5	3

4. Proportion of right-turn movement: this is the proportion of right-turning vehicles during the time interval when the intersection was operating at capacity. As the right-turn maneuver has fewer conflicts with other movements than other maneuvers, it is expected that a higher proportion of right-turning vehicles may contribute to higher capacities. Specifically, a higher proportion of right-turning vehicles may increase the possibility of two vehicles using the intersection simultaneously. Some older studies also reported this effect and discussed it in the literature review section of this thesis study (Hebert 1963; Michael Kyte 1990).

5. Proportion of left-turn movement: this is the proportion of left-turning vehicles during the time interval when the intersection was operating at capacity. As the left-turn maneuver has more potential conflicts with other movements, it is expected that a higher proportion of left-turning vehicles may lead to lower capacities. The literature also reported such an effect (Michael Kyte 1990).

After setting the variables of interest for analysis purposes, scatterplots were established to examine the effect of these variables on AWSC intersection capacity, showing the relationships between the AWSC intersection capacity and the five variables described in the earlier section in Figures 5 to 9.

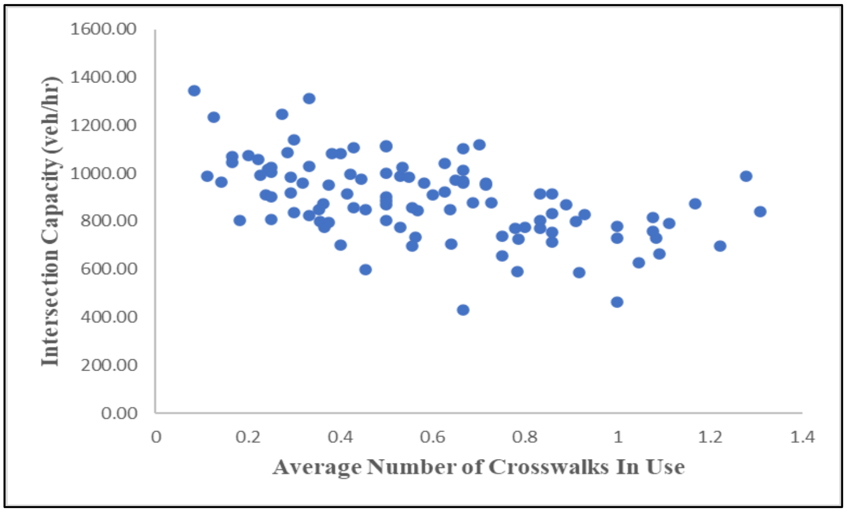


Figure 12. Intersection Capacity versus Number of Crosswalks in Use

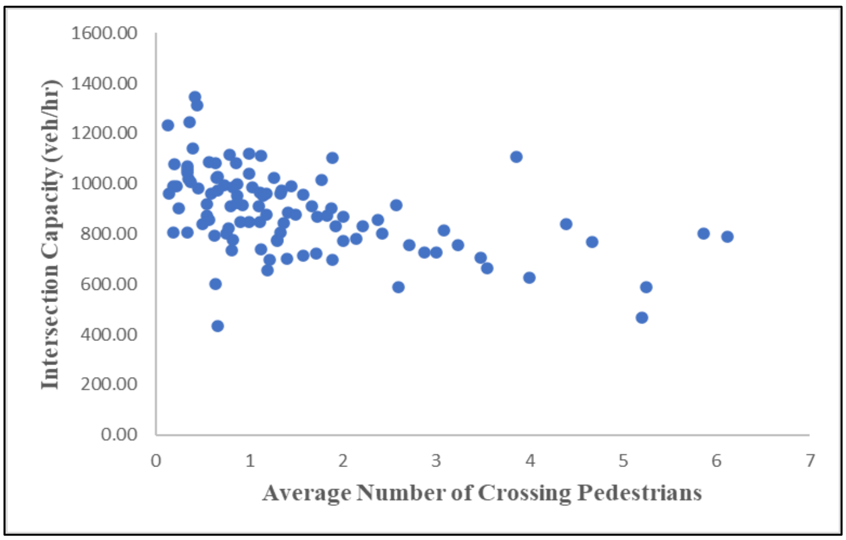


Figure 13. Intersection Capacity versus Average Number of Crossing Pedestrians

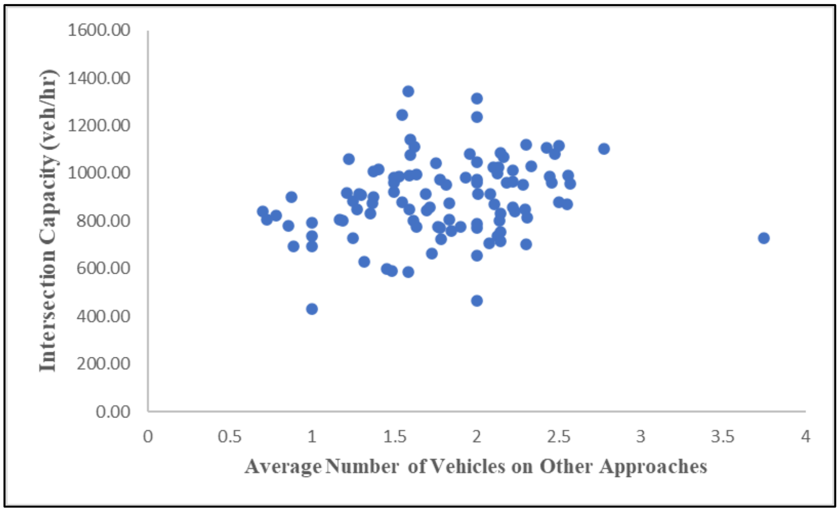


Figure 14. Intersection Capacity versus Average Number of Vehicles on Other Approaches

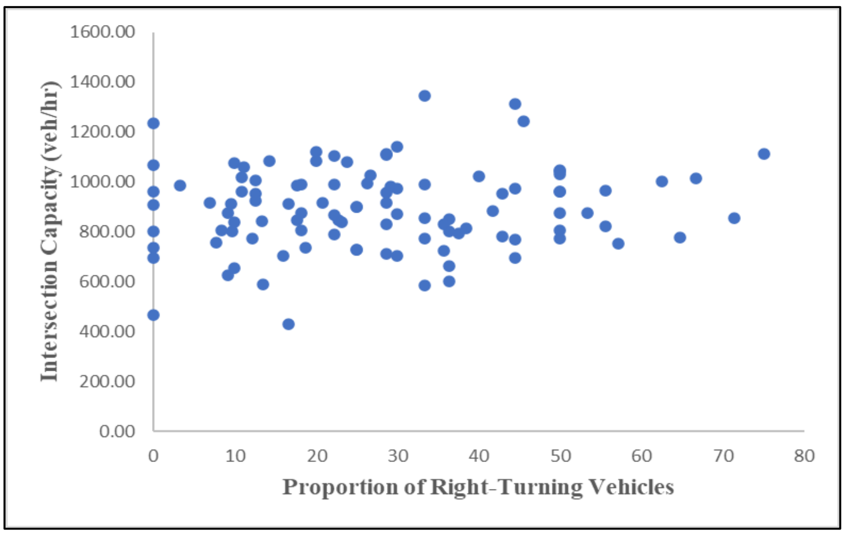


Figure 15. Intersection Capacity versus Proportion of Right-Turning Vehicles

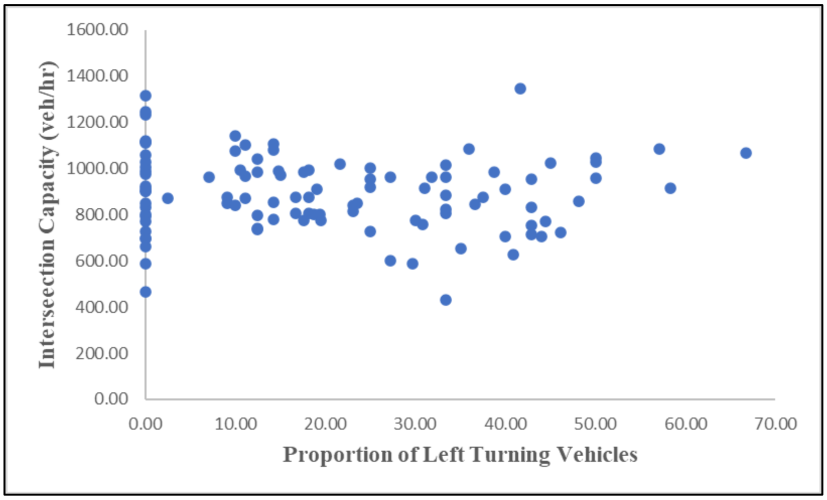


Figure 16. Intersection Capacity versus Proportion of Left-Turning Vehicles

The scatterplot in Figure 12 exhibits a declining pattern where intersection capacity decreases with the increase in the number of crosswalks in use. As mentioned above, a number of crosswalks in use refer to a crosswalk where pedestrian crossings happen and when a vehicle may have a conflict with pedestrians using the crosswalk or not. This pattern is expected given the longer time a vehicle would need to cross the intersection when pedestrians occupy more crosswalks. A similar declining pattern is shown in Figure 13, where the intersection capacity decreases with the increase in the average number of crossing pedestrians using the conflicting crosswalks. This pattern is also expected since the higher number of pedestrians crossing the crosswalk at the intersection would restrict the subject vehicle movement and wait to cross the intersections. Eventually, more increased headways yield lower capacity observations. The scatterplot shown in Figure 14 exhibits a slight rising pattern between the intersection capacity and the average number of vehicles on other approaches (when the subject vehicle arrives at the stop sign). This is consistent with the expectation of higher capacities when vehicles enter the intersection from different approaches. Having other vehicles entering the intersection from other approaches increases the traffic operations volume at the intersection of interest and eventually increases the capacity observations.

Regarding movement type, no clear patterns can be discerned in Figures 15 and 16 to confirm the effect of the proportion of right-turn and left-turn movements on AWSC intersection capacity. Even though we could see some discrepancies between the capacity observations regarding the turning movements, there seems to be a vague pattern in the scatterplots. The next step for this study was to compute multivariate linear regression to closely and more in-depth examine the five variables' effect on intersection capacity. The results are shown in Table 8.

Table 8. Regression Output for Estimating Capacity – Method I

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.68**
R Square	**0.46**
Adjusted R Square	**0.43**
Standard Error	**123.97**
Observations	**104**

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	**5**	**1273014.51**	**254602.90**	**16.57**	**7.91324E-12**
Residual	**98**	**1506127.32**	**15368.65**		
Total	**103**	**2779141.83**			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	**878.07**	**50.27**	**17.47**	**7.4161E-32**	**778.31**	**977.84**
Average Number of Crosswalks In Use	**-236.22**	**60.22**	**-3.92**	**0.000**	**-355.73**	**-116.71**
Average Number of Vehicles on Other Appr	**119.02**	**25.18**	**4.73**	**7.6483E-06**	**69.05**	**168.99**
Average Number of Crossing Pedestrians	**-34.39**	**13.82**	**-2.49**	**0.014**	**-61.81**	**-6.97**
Proportion of Right Turning Vehicles	**0.89**	**0.70**	**1.27**	**0.20758372**	**-0.50**	**2.29**
Proportion of Left Turning Vehicles	**-1.76**	**0.73**	**-2.43**	**0.01712875**	**-3.21**	**-0.32**

The coefficient of determination (R-square) value in the regression output indicates that around 46% of the variability in intersection capacity is explained by the five variables that are part of the regression model. The standard error of the estimate is around 124 veh/hr, and the F value from the ANOVA test indicates that the overall regression model is significant. The standard error of method I show that the average distance that the observed capacity values fall from the regression line of 124 veh/hr. Closely looking at the p-value results, we can conclude that all variables except the proportion of right-turning vehicles were found significant and affect the intersection capacity. With a small p-value of 7.6e-06, the average number of vehicles on other approaches affected the intersection capacity even higher than other variables.

Similarly, having a 0.014, the p-value for the average number of crossing pedestrians showed a significant effect on the capacity as well, which was expected since the pedestrian crossings would yield higher mean headways and consequently lower capacity values. The variable was still significant, with a slightly higher p-value for the proportion of left-turning vehicles of 0.01. Additionally, a positive coefficient indicates that as the independent variables' value increases, the dependent variable's mean also tends to increase.

Method II

This method identified time intervals where at least one vehicle was waiting to be served at any of the four intersection approaches. Similar to the previous method, intervals should be long enough to include a large number of waiting (mostly queued) vehicles entering the intersection consecutively from any of the intersection approaches. To apply this method, the data from all intersection approaches must first be combined (as different approaches were processed independently) before time intervals for capacity operations are identified and marked. For each interval, the number of vehicles entering the intersection and the time duration were used to calculate capacity observations. The time duration is calculated as the time lapse between the first vehicle entering the intersection and the last vehicle in the interval clearing the intersection.

This section presents the results of the intersection capacity analysis using Method II, described earlier. One hundred and ten intervals were identified and used to estimate the intersection capacity over the four days of data collection. The AWSC intersection capacity descriptive statistics are provided in Table 9. The mean capacity value using method II is around 782 vehicles per hour which are 100 veh/hr less than the method I. This difference can be explained by using the methodologies between method I and method II and the sample size difference between the two methods' intervals.

The standard deviation for capacity observations is around 163 vehicles per hour. The minimum capacity observed was about 360 vehicles per hour, while the maximum observed capacity was about 1292 vehicles per hour. Similar to the method I, the range of capacity observations is vast, which can largely be attributed to the variation in pedestrian activities during the periods of interest.

Table 9. AWSC Intersection Capacity Descriptive Statistics – Method II

AWSC Intersection Capacity Descriptive Statistics - Method II	
Mean	782.11
Median	786.2
Std Deviation	163.36
90th Percentile	978.11
Minimum	359.79
Maximum	1292.3
95% Confidence Interval	30.53
Sample Size	110

Similarly, in the previous analysis for method I, Figures 17 through 21 show scatterplots for the AWSC intersection capacity versus the average number of crosswalks in use, the average number of crossing pedestrians, the average number of vehicles on other approaches, the proportion of right-turning vehicles, and the proportion of left-turning vehicles respectively. Figures 17 and 18 exhibits a declining pattern where intersection capacity decreases with the increase in the average number of crosswalks in use and the average number of crossing pedestrians. This is consistent with the patterns in Figures 12 and 13 of Method I analysis as well as expected with the logic behind the capacity analysis. The scatterplot shown in Figure 19 reveals no discernable relationship between the AWSC intersection capacity and the average number of vehicles present on other approaches when the subject vehicle arrives at the stop sign, a surrogate measure for the case number used in the HCM. Even though the scatterplot shows some relationship between the left-turning vehicles and capacity, there is no clear pattern for both right and left-turning vehicle proportions on the intersection capacity observations.

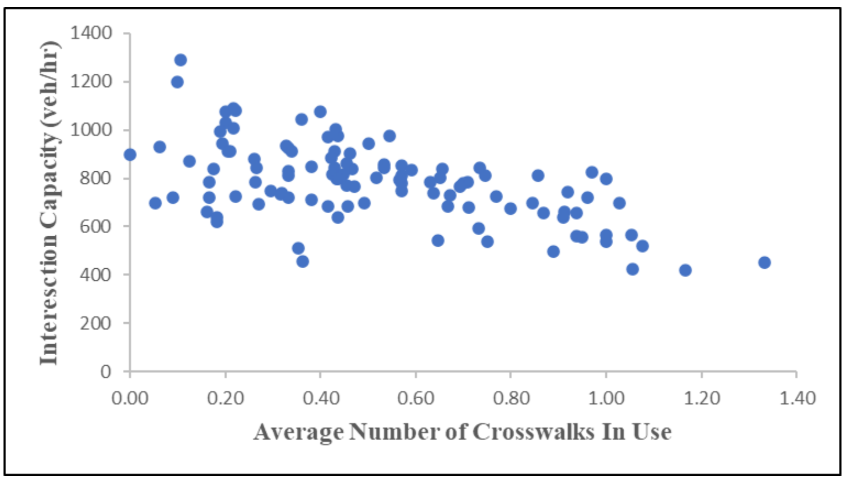


Figure 17. Intersection Capacity versus Number of Crosswalks in Use

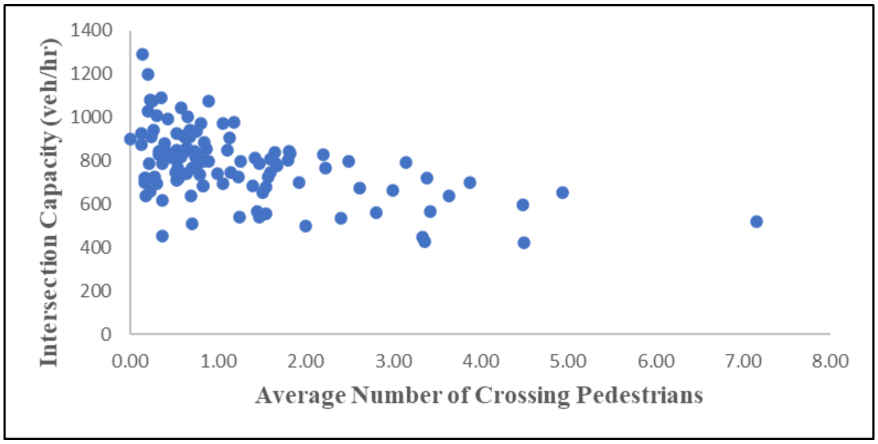


Figure 18. Intersection Capacity versus Average Number of Pedestrians

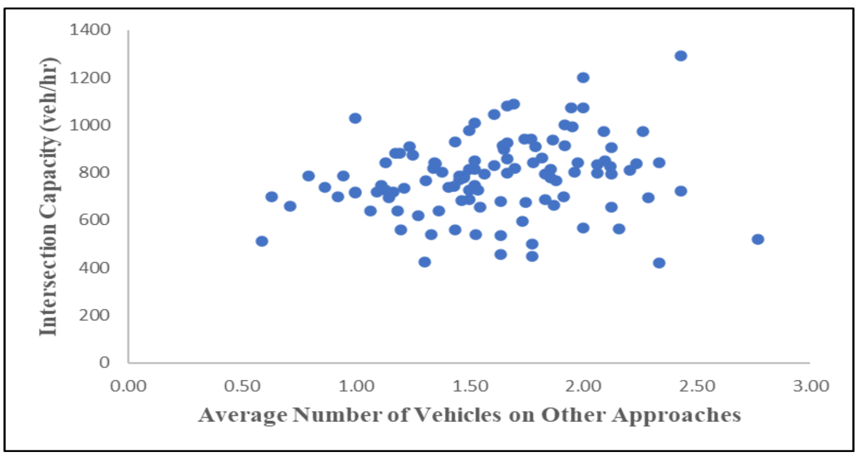


Figure 19. Intersection Capacity versus Number of Vehicles on Other Approaches

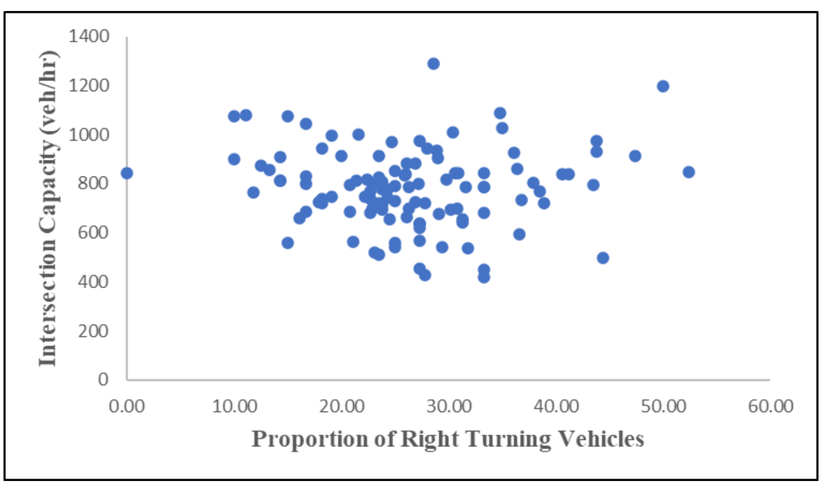


Figure 20. Intersection Capacity versus Proportion of Right-Turning Vehicles

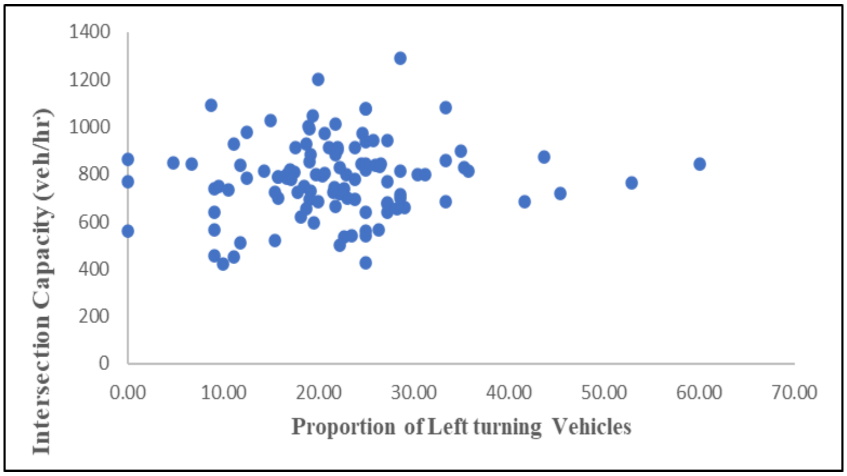


Figure 21. Intersection Capacity versus Proportion of Left-Turning Vehicles

To better understand the association between the AWSC capacity and the five variables of interest, the multivariate linear regression was conducted using the intersection capacity as the dependent variable and the five variables of interest as the independent variables. The regression results are presented and can be found in Table 10. The coefficient of determination value indicates that variables included in the model explain around 56% of the variation in the dependent variable, i.e., the AWSC intersection capacity, which was 10% more than the method I regression's interpretation. The standard error of the estimate is about 110 vehicles per hour, and the F value from the ANOVA test indicates that the overall regression model is significant. The standard error of the method II regression shows that the average distance that the observed capacity values fall from the regression line of 110 veh/hr. The t-test results confirmed that all variables included in the model are statistically significant at the 95% confidence level, except the proportions of right-turning and left-turning vehicles. Compared to method I regression output, the proportion of left-turning vehicles in this method was insignificant, with a p-value of 0.399.

Table 10. Regression Output for Estimating Capacity – Method II

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.75**
R Square	**0.56**
Adjusted R Square	**0.54**
Standard Error	**109.85**
Observations	**111**

ANOVA

	df	SS	MS	F	Significance F
Regression	**5.00**	**1590174.58**	**318034.92**	**26.36**	**0.00**
Residual	**105.00**	**1267049.18**	**12067.14**		
Total	**110.00**	**2857223.76**			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	**663.98**	**70.54**	**9.41**	**< 0.0001**	**524.11**	**803.84**
Average Number of Crosswalks In Use	**-256.81**	**63.15**	**-4.07**	**< 0.0001**	**-382.03**	**-131.59**
Average Number of Vehicles on Other Approaches	**201.08**	**28.42**	**7.07**	**< 0.0001**	**144.72**	**257.44**
Average Number of Crossing Pedestrians	**-49.73**	**15.90**	**-3.13**	**0.0023**	**-81.25**	**-18.20**
Proportion of Right Turning Vehicles	**0.56**	**1.36**	**0.41**	**0.6846**	**-2.15**	**3.26**
Proportion of Left Turning Vehicles	**-1.11**	**1.31**	**-0.85**	**0.3999**	**-3.72**	**1.50**

Discussion of Results

The AWSC intersection capacity was calculated and analyzed in the previous section using the two methods described earlier in this thesis study. One notable difference is the relatively higher intersection capacity estimated using the first method. Specifically, the AWSC intersection capacity using Method I was 892 vehicles per hour, around 14% higher than the capacity calculated using method II (782 vehicles per hour). Upon careful examination of the data, it was found that the Method I observations are associated with a higher percentage of traffic coming from other approaches (higher average # of vehicles on other approaches), which may partly explain the higher capacity observations for method I. Specifically, the higher the percentage of traffic on the subject approach, the lower the likelihood of multiple vehicles using the intersection simultaneously, and the lower the intersection capacity, and vice versa.

The minimum and maximum capacity values are generally higher for Method I than for Method II, which is somewhat expected given the higher mean value. The two methods' standard deviation is close (almost the same). The regression analyses for the two methods yielded results that were slightly different. Specifically, the two models found the number of crosswalks in use, the number of crossing pedestrians, and the number of vehicles on other approaches to have a statistically significant effect on intersection capacity at the 95% confidence level. Further, the two analyses found the proportion of right-turning vehicles to have no significant impact on intersection capacity. However, according to the Method I model, the proportion of left-turning vehicles affected intersection capacity significantly. In contrast, the effect was not found significant using the Method II model. It is also important to mention that Method II yielded a model with a higher coefficient of determination and, thus, a better fit for capacity observations.

In general, the total intersection capacity observations in this study using either method are notably different from the capacity observations reported in the literature. However, it should be mentioned that those reported capacity observations either come from a couple of older studies and are considered dated (with the most recent study around three decades ago) or estimated using theoretical models and are not based on field observations. The authors reported no recent AWSC intersection capacity observations in the literature. The other aspect that is evident in other studies in the literature is the lack of notable pedestrian traffic at the study sites (pedestrian traffic was not a significant study variable in any of these studies). Therefore, the effect of pedestrians on AWSC intersection capacity is lacking from all the studies published on this subject, including those discussed in the background section.

Finally, the protocol used in data processing may partly explain the lower capacity estimates observed in this study compared to some values reported in the literature. Specifically, in this study, capacity operations at the intersection must be sustained for at least one minute to be included in capacity observations. Shorter intervals, often associated with minor departure (saturation) headways and higher capacities, were excluded from analysis as they don't represent sustained capacity operations (e.g., very short headways associated with a few vehicle departures only). Two methods investigated the AWSC intersection capacity and the effect of some of the variables believed to affect the intersection capacity. The significant findings of this analysis are presented above sections.

CHAPTER SIX

CONCLUSION

The primary focus of this thesis study was the all-way stop-controlled intersections. The study focused on saturation headway characteristics and, consequently, the capacity estimations at AWSC intersections. For this study, one particular intersection was chosen and studied specifically; field data measurements were taken from a busy AWSC intersection in Bozeman, Montana was used in this investigation. Four days of video records were acquired at the study site using a traffic surveillance camera on a mobile trailer deployed. Saturation headway observations were made, and capacity estimations were calculated using two methods. The effect of the variables was examined, such as the level of conflict, pedestrian crossing activity at the intersection, and the type of movement for the subject vehicle.

The literature review chapter for this study presented different capacity estimation calculation methods, some using similar methodologies and others using very distinct and different methodologies. Methods are primarily based on gap-acceptance and queueing theory and mostly use either simulation or field data measurements—most of the studies lack in-depth analysis of all-way stop-controlled intersections. In addition, most of the studies reviewed in the literature use a simple approach to estimate either saturation headways or the capacities at the intersection of interest. These approaches do not include the variables described and measured in this study, such as turning movement and pedestrian crossing activity.

Saturation Headways at All-Way Stop-Controlled Intersections

As discussed, for AWSC intersections, the saturation headway is the time headway between two vehicles departing from the same lane under such conditions as continuous queueing. The concept of saturation headway is used in HCM-1985 and HCM-1994 to compute capacity estimations. One of the basic parameters to compute intersection capacity is saturation headway which is an essential parameter since the capacity of an intersection determines the level of service, queueing, and many other conditions that tie together.

Some of the significant findings from the saturation headway studies that presented below in this chapter. The variables of interest include pedestrian activity, turning movement, and level of conflict at the intersection.

- In general, saturation headway observations using case numbers described in HCM ranged roughly between 7.2 and 12.7 seconds. The wide range of headway observations is mainly related to the varying conditions at the study site, specifically pedestrian activity and differences in directional movement type.
- Saturation headway observation estimations using three variables were somewhat different but expected. The difference in the mean saturation headways could be related mainly to pedestrian activity, conflict level, and turning movement. This is associated with a lower level of conflict on the subject vehicle resulting in lower mean saturation headway comparing Case 1 and Case 5. Similarly, right-turn movements yielded lower mean saturation headways, in seconds, compared to any other directional movement type, with left-turn having the highest yield.

- Pedestrian traffic at the study site was found to have a profound effect on the mean saturation headways. The mean saturation headway with pedestrian traffic was 13.15 seconds compared to 8.12 seconds without pedestrian traffic. The number of vehicles on other approaches, described in HCM as case number, also significantly affected the mean saturation headway observations. The turning movement type's impact was also notable in the saturation headway observations. The lowest mean was found on the right-turn movement with 9.36 seconds, and the 10.6 seconds left-turn movement type had the highest mean headway.

Capacity at All-Way Stop-Controlled Intersections: Case Study

The capacity of an intersection is essential in terms of other collector roadways around the intersection and the level of service. This parameter is a significant determinant for evaluating intersection operations. One of the most critical tasks of the traffic engineer is to estimate the capacity of the road control devices such as intersections; it gets complex from time to time. Even though Highway Capacity Manual, HCM, provides an enhanced procedure for estimating the capacity, some factors are not included and include only the base conditions for intersections. Additionally, some HCM procedures do not account for the type of movement and pedestrian activity. Instead, it only accounts for the level of conflict defined by HCM, case numbers.

An empirical framework of approach for capacity estimation procedure was introduced in this thesis study; the factors of interest were established, such as turning movement, pedestrian activity, and level of conflict. The capacity of a particular AWSC intersection was identified and validated with field data collection. Two methods were used to estimate and compare the capacity observations at the intersection. The first method identified intervals of time when the subject approach to the intersection was queued for a period of time. This method focused on the queueing on one approach regardless of the presence of queues on other approaches. The second method identified time intervals where at least one vehicle was waiting to be served at any of the four intersection approaches.

Some of the findings of this study are presented below.

- In general, capacity observations using the two methods ranged roughly between 400 vph and 1400 vph. The wide range of capacity observations is primarily related to the varying conditions at the study site, especially pedestrian traffic. These observations are generally lower than those reported in some of the older studies in the literature.
- Capacity observations using the two methods are somewhat different but overall comparable. The difference in the mean capacity values could be related to the fact that method I is more associated with a lower percentage of traffic on the subject approach resulting in slightly higher capacity observations.
- Pedestrian activity at the study site profoundly affected saturation headways and total intersection capacity. An average number of vehicles on other approaches, a surrogate measure for the HCM case number, also significantly affected total intersection capacity. The proportion of right-turn movement was not found to have a significant effect on intersection capacity, which is inconsistent with some of the findings from the older literature. Further, the proportion of left-turning vehicles significantly affected intersection capacity using the method I analyzed.

Recommendations for Future Research

The investigation revealed that the variables described in previous sections were significantly affecting the saturation headway and consequently the capacity of an intersection of interest, specifically, AWSC intersection as saturation headway is an indicative of approach capacity and intersection approach is the cumulative capacity of each approach used in the intersection. Literature review for this topic shown that there is not adequate published research in the field. This study focused on the capacity and the operation of AWSC intersection; however, some variables were not investigated by the researchers. On this basis, future research should examine some variables that could affect the intersection operations such as; cyclists and heavy vehicles, trucks and buses. The intersection of interest was on at-grade and to expand more in the future research grade separated circumstances could be researched as well as intersections with different geometries.

Future research could further examine different variables that affect the capacity of an intersection. Further, the studies might be conducted in more than one intersection study site in future studies to have more consistency and to examine the effects of the variables more in-depth. The study site includes one-lane approach configuration with no turning lanes, researches recommend that for future work can be done for multilane approach intersection as well as with turning lanes.

REFERENCES CITED

REFERENCES CITED

Brilon, Werner, and Ning Wu. 2001. "Capacity at Unsignalized Intersections Derived by Conflict Technique." *Transportation Research Record* 1776(1): 82–90.

Guler, S. Ilgin, and Monica Menendez. 2016. "Methodology for Estimating Capacity and Vehicle Delays at Unsignalized Multimodal Intersections." *International Journal of Transportation Science and Technology* 5(4): 257–67.

Hayden, Larry, and DC Washington. 2007. "Traffic Monitor Trailers, Configuration and Deployment Final Report."

Hebert, Jacques. 1963. "A Study of Four-Way Stop Intersection Capacities."

Highway Capacity Manual. 2016. https://www.trb.org/Main/Blurbs/175169.aspx (July 5, 2022).

Kyte, Michael. 1990. "Estimating Capacity of an All-Way-Stop-Controlled Intersection." *Transportation Research Board* 1225: 73–82.

Kyte, Michael; et al. 1994. "Saturation Headways at Stop-Controlled Intersections." *Transportation Research Board* 1457.

Kyte, Michael et al. 1996. "Analysis of Traffic Operations at All-Way Stop-Controlled Intersections by Simulation." *https://doi.org/10.1177/0361198196155500109* (1555): 65–73. https://journals.sagepub.com/doi/10.1177/0361198196155500109 (September 17, 2022).

Kyte, Michael; et al. 1996. "Capacity and Level of Service at Unsignalized Intersections." *NCHRP* Project 3-46.

Kyte, Michael, and Joseph Marek. 1989. "Estimating Capacity and Delay at a Single-Lane Approach, All-Way Stop-Controlled Intersection." *Transportation Research Record* 1225.

Li, Haiyuan, and Wei Deng. 2007. *Determination of Capacity at Two-Way Stop-Controlled Urban Intersections*.

Li, Haiyuan, Wei Deng, Zong Tian, and Peifeng Hu. 2009. "Capacities of Unsignalized Intersections under Mixed Vehicular and Nonmotorized Traffic Conditions." *Transportation Research Record* (2130): 129–37.

National Academies of Sciences, Engineering, and Medicine. 1AD. "Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis." *Highway Capacity Manual 7th Edition*.

Prasetijo, Joewono, and Halimshah Ahmad. 2012. “Capacity Analysis of Unsignalized Intersection Under Mixed Traffic Conditions.” *Procedia - Social and Behavioral Sciences* 43: 135–47.

Richardson, Anthony J. 1987. “A Delay Model for Multiway Stop-Sign Intersections.”

Sussman, Joseph M., and National Research Council the USA. 1997. Transportation Research Board *Highway Capacity Manual*. Washington, DC: Transportation Research Board.

Wachs, Martin; et al. 2000. *Highway Capacity Manual*.

Wu, Ning. 2002. “Total Capacities at All-Way Stop-Controlled Intersections: Validation and Comparison of Highway Capacity Manual Procedure and Addition-Conflict-Flow Technique:” *https://doi.org/10.3141/1802-07* (1802): 54–61. https://journals.sagepub.com/doi/10.3141/1802-07 (July 10, 2022).

Zongzhong, Tian, Michael Kyte, and James Colyar. 1997. 67 Journal *Field Measurements of Capacity and Delay at Unsignalized Intersections*.

APPENDICES

APPENDIX A

DATA COLLECTION & METHDOLOGY SPREADSHEETS

This spreadsheet aims to understand and develop a data collection procedure for this thesis study. The needed information for this study was extracted from the video footage data described in previous sections of this thesis. The spreadsheet was constructed to be consistent with the data collection process, and the needed protocols and rules were developed.

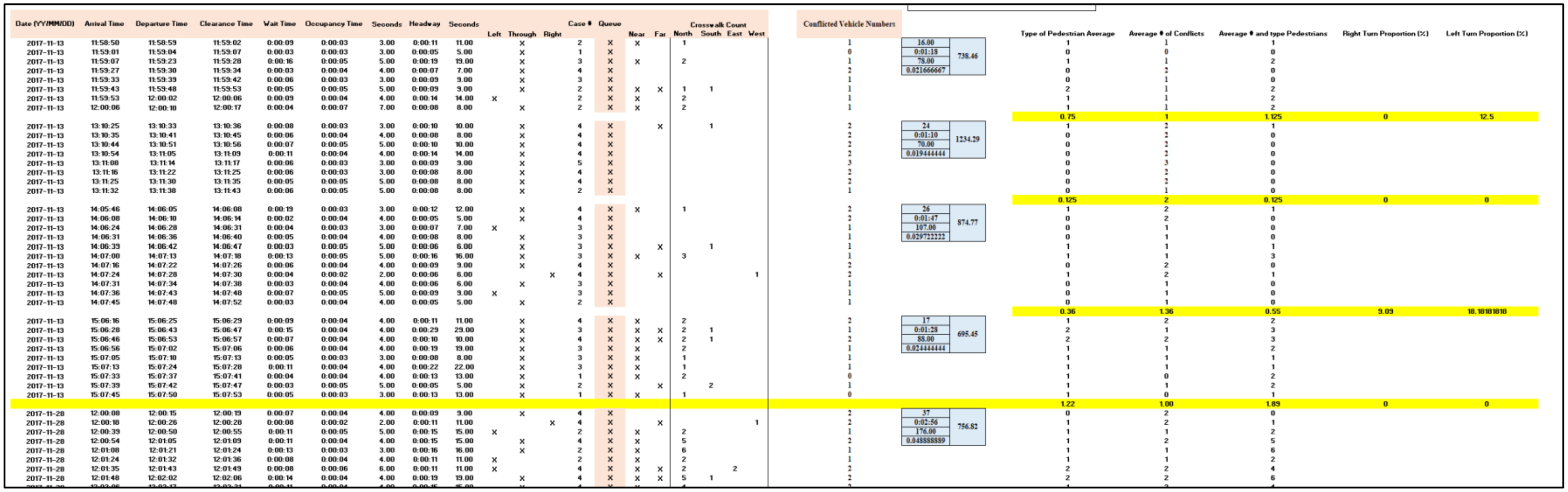
The spreadsheet is divided into 25 columns, including date, arrival time, departure time, clearance time, wait time, occupancy time, headway, directional movements, case numbers, approach type, pedestrian activity, bicycle activity, and any other related comments. Later, since bicycle activity was redundant enough, the study neglected this information.

Additionally, the spreadsheet used for the Method I & II is attached to this appendix to understand better how the data was extracted for analysis purposes.

Corresponding figures and sample data collection spreadsheets can be found below.

Date (YY/MM/DD)	Arrival Time	Departure Time	Clearance Time	Wait Time	Occupancy Time	Seconds	Headway	Seconds	Left	Through	Right	Case #	Queue	Near	Far	Crosswalk Count				TOTAL
																North	South	East	West	
2017-11-13	11:21:09	11:21:16	11:21:21	0:00:07	0:00:05	5.00	0:00:09	9.00		X		1			X		1			1
2017-11-13	11:26:55	11:27:04	11:27:07	0:00:09	0:00:03	3.00	0:00:12	12.00		X		2		X		1				1
2017-11-13	11:28:38	11:28:48	11:28:51	0:00:10	0:00:03	3.00	0:00:12	12.00		X		1		X		3				3
2017-11-13	11:32:35	11:32:43	11:32:46	0:00:08	0:00:03	3.00	0:00:15	15.00			X	1	X	X		1				1
2017-11-13	11:35:37	11:35:49	11:35:53	0:00:12	0:00:04	4.00	0:00:17	17.00		X		1	X	X		2				2
2017-11-13	11:36:55	11:36:59	11:37:03	0:00:04	0:00:04	4.00	0:00:09	9.00		X		2	X	X		1				1
2017-11-13	11:37:04	11:37:11	11:37:15	0:00:07	0:00:04	4.00	0:00:12	12.00	X			1		X		1				1
2017-11-13	11:41:07	11:41:14	11:41:18	0:00:07	0:00:04	4.00	0:00:10	10.00		X		5	X	X		2				2
2017-11-13	11:54:59	11:55:08	11:55:16	0:00:09	0:00:08	8.00	0:00:08	8.00		X		4	X	X	X	1	1			2
2017-11-13	11:55:12	11:55:29	11:55:33	0:00:17	0:00:04	4.00	0:00:21	21.00		X		2	X	X	X	3	2			5
2017-11-13	11:55:34	11:55:39	11:55:50	0:00:05	0:00:11	11.00	0:00:10	10.00		X		2	X	X	X	3	2			5
2017-11-13	11:56:22	11:56:30	11:56:35	0:00:08	0:00:05	5.00	0:00:11	11.00	X			1	X	X	X	2		1		3
2017-11-13	11:56:34	11:56:40	11:56:42	0:00:06	0:00:02	2.00	0:00:10	10.00			X	1		X		3				3
2017-11-13	11:57:45	11:57:49	11:57:52	0:00:04	0:00:03	3.00	0:00:08	8.00		X		4	X	X		1				1
2017-11-13	11:57:58	11:58:09	11:58:13	0:00:11	0:00:04	4.00	0:00:14	14.00		X		3	X	X	X	1	1			2
2017-11-13	11:58:19	11:58:39	11:58:43	0:00:20	0:00:04	4.00	0:00:23	23.00		X		4		X		4				4
2017-11-13	11:58:50	11:58:59	11:59:02	0:00:09	0:00:03	3.00	0:00:11	11.00		X		2	X	X		1				1
2017-11-13	11:59:07	11:59:23	11:59:28	0:00:16	0:00:05	5.00	0:00:19	19.00		X		3	X	X		2				2
2017-11-13	11:59:43	11:59:48	11:59:53	0:00:05	0:00:05	5.00	0:00:09	9.00		X		2	X	X	X	1	1			2
2017-11-13	11:59:53	12:00:02	12:00:06	0:00:09	0:00:04	4.00	0:00:14	14.00	X			2	X	X		2				2
2017-11-13	12:00:06	12:00:10	12:00:17	0:00:04	0:00:07	7.00	0:00:08	8.00		X		2	X	X		2				2

Figure 22. Sample Data Collection Spreadsheet



Date (YY/MM/DD)	Arrival Time	Departure Time	Clearance Time	Wait Time	Occupancy Time	Seconds	Headway	Seconds	Left	Through	Right	Case #	Queue	Near	Far	Crosswalk Count				Conflicted Vehicle Numbers			Type of Pedestrian Average	Average # of Conflicts	Average # and type Pedestrians	Right Turn Proportion (%)	Left Turn Proportion (%)
																North	South	East	West								
2017-11-13	11:58:50	11:58:59	11:59:02	0:00:09	0:00:03	3.00	0:00:11	11.00		X		2	X	X		1				1	16.00	738.46	1	1	1		
2017-11-13	11:59:01	11:59:04	11:59:07	0:00:03	0:00:03	3.00	0:00:05	5.00		X		1	X							0	0:01:18		0	0	0		
2017-11-13	11:59:07	11:59:23	11:59:28	0:00:16	0:00:05	5.00	0:00:19	19.00		X		3	X	X		2				1	78.00		1	1	2		
2017-11-13	11:59:27	11:59:30	11:59:34	0:00:03	0:00:04	4.00	0:00:07	7.00		X		4	X							2	0.021666667		0	2	0		
2017-11-13	11:59:33	11:59:39	11:59:42	0:00:06	0:00:03	3.00	0:00:09	9.00		X		3	X							1			0	1	0		
2017-11-13	11:59:43	11:59:48	11:59:53	0:00:05	0:00:05	5.00	0:00:09	9.00		X		2	X	X	X	1	1			1			2	1	2		
2017-11-13	11:59:53	12:00:02	12:00:06	0:00:09	0:00:04	4.00	0:00:14	14.00	X			2	X	X		2				1			1	1	2		
2017-11-13	12:00:06	12:00:10	12:00:17	0:00:04	0:00:07	7.00	0:00:08	8.00		X		2	X	X		2				1			1	1	2		
																							0.75	1	1.125	0	12.5
2017-11-13	13:10:25	13:10:33	13:10:36	0:00:08	0:00:03	3.00	0:00:10	10.00		X		4	X		X		1			2	24	1234.29	1	2	1		
2017-11-13	13:10:35	13:10:41	13:10:45	0:00:06	0:00:04	4.00	0:00:08	8.00		X		4	X							2	0:01:10		0	2	0		
2017-11-13	13:10:44	13:10:51	13:10:56	0:00:07	0:00:05	5.00	0:00:10	10.00		X		4	X							2	70.00		0	2	0		
2017-11-13	13:10:54	13:11:05	13:11:09	0:00:11	0:00:04	4.00	0:00:14	14.00		X		4	X							2	0.019444444		0	2	0		
2017-11-13	13:11:08	13:11:14	13:11:17	0:00:06	0:00:03	3.00	0:00:09	9.00		X		5	X							3			0	3	0		
2017-11-13	13:11:16	13:11:22	13:11:25	0:00:06	0:00:03	3.00	0:00:08	8.00		X		4	X							2			0	2	0		
2017-11-13	13:11:25	13:11:30	13:11:35	0:00:05	0:00:05	5.00	0:00:08	8.00		X		4	X							2			0	2	0		
2017-11-13	13:11:32	13:11:38	13:11:43	0:00:06	0:00:05	5.00	0:00:08	8.00		X		2	X							1			0	1	0		
																							0.125	2	0.125	0	0
2017-11-13	14:05:46	14:06:05	14:06:08	0:00:19	0:00:03	3.00	0:00:12	12.00		X		4	X	X		1				2	26	874.77	1	2	1		
2017-11-13	14:06:08	14:06:10	14:06:14	0:00:02	0:00:04	4.00	0:00:05	5.00		X		4	X							2	0:01:47		0	2	0		
2017-11-13	14:06:24	14:06:28	14:06:31	0:00:04	0:00:03	3.00	0:00:07	7.00	X			3	X							1	107.00		0	1	0		
2017-11-13	14:06:31	14:06:36	14:06:40	0:00:05	0:00:04	4.00	0:00:08	8.00		X		3	X							1	0.029722222		0	1	0		
2017-11-13	14:06:39	14:06:42	14:06:47	0:00:03	0:00:05	5.00	0:00:06	6.00		X		3	X		X		1			1			1	1	1		
2017-11-13	14:07:00	14:07:13	14:07:18	0:00:13	0:00:05	5.00	0:00:16	16.00		X		3	X	X		3				1			1	1	3		
2017-11-13	14:07:16	14:07:22	14:07:26	0:00:06	0:00:04	4.00	0:00:09	9.00		X		4	X							2			0	2	0		
2017-11-13	14:07:24	14:07:28	14:07:30	0:00:04	0:00:02	2.00	0:00:06	6.00			X	4	X		X				1	2			1	2	1		
2017-11-13	14:07:31	14:07:34	14:07:38	0:00:03	0:00:04	4.00	0:00:06	6.00		X		3	X							1			0	1	0		
2017-11-13	14:07:36	14:07:43	14:07:48	0:00:07	0:00:05	5.00	0:00:09	9.00	X			3	X							1			0	1	0		
2017-11-13	14:07:45	14:07:48	14:07:52	0:00:03	0:00:04	4.00	0:00:05	5.00		X		2	X							1			0	1	0		
																							0.36	1.36	0.55	9.09	18.18181818
2017-11-13	15:06:16	15:06:25	15:06:29	0:00:09	0:00:04	4.00	0:00:11	11.00		X		4	X	X		2				2	17	695.45	1	2	2		
2017-11-13	15:06:28	15:06:43	15:06:47	0:00:15	0:00:04	4.00	0:00:29	29.00		X		3	X	X	X	2	1			1	0:01:28		2	1	3		
2017-11-13	15:06:46	15:06:53	15:06:57	0:00:07	0:00:04	4.00	0:00:10	10.00		X		4	X	X	X	2	1			2	88.00		2	2	3		
2017-11-13	15:06:56	15:07:02	15:07:06	0:00:06	0:00:04	4.00	0:00:19	19.00		X		3	X	X		2				1	0.024444444		1	1	2		
2017-11-13	15:07:05	15:07:10	15:07:13	0:00:05	0:00:03	3.00	0:00:08	8.00		X		3	X	X		1				1			1	1	1		
2017-11-13	15:07:13	15:07:24	15:07:28	0:00:11	0:00:04	4.00	0:00:22	22.00		X		3	X	X		1				1			1	1	1		
2017-11-13	15:07:33	15:07:37	15:07:41	0:00:04	0:00:04	4.00	0:00:13	13.00		X		1	X	X		2				0			1	0	2		
2017-11-13	15:07:39	15:07:42	15:07:47	0:00:03	0:00:05	5.00	0:00:05	5.00		X		2	X		X		2			1			1	1	2		
2017-11-13	15:07:45	15:07:50	15:07:53	0:00:05	0:00:03	3.00	0:00:13	13.00		X		1	X	X		1				0			1	0	1		
																							1.22	1.00	1.89	0	0
2017-11-28	12:00:08	12:00:15	12:00:19	0:00:07	0:00:04	4.00	0:00:09	9.00		X		4	X							2	37	756.82	0	2	0		
2017-11-28	12:00:18	12:00:26	12:00:28	0:00:08	0:00:02	2.00	0:00:11	11.00			X	4	X		X				1	2	0:02:56		1	2	1		
2017-11-28	12:00:39	12:00:50	12:00:55	0:00:11	0:00:05	5.00	0:00:15	15.00	X			2	X	X		2				1	176.00		1	1	2		
2017-11-28	12:00:54	12:01:05	12:01:09	0:00:11	0:00:04	4.00	0:00:15	15.00		X		4	X	X		5				2	0.048888889		1	2	5		
2017-11-28	12:01:08	12:01:21	12:01:24	0:00:13	0:00:03	3.00	0:00:16	16.00		X		2	X	X		6				1			1	1	6		
2017-11-28	12:01:24	12:01:32	12:01:36	0:00:08	0:00:04	4.00	0:00:11	11.00	X			2	X	X		2				1			1	1	2		
2017-11-28	12:01:35	12:01:43	12:01:49	0:00:08	0:00:06	6.00	0:00:11	11.00	X			4	X	X	X	2		2		2			2	2	4		
2017-11-28	12:01:48	12:02:02	12:02:06	0:00:14	0:00:04	4.00	0:00:19	19.00		X		4	X	X	X	5	1			2			2	2	6		

Figure 23. Sample data analysis sheet for Method I

COMBINED							
Block #	Interval (sec)	# of type peds	# of Conflicts	# of ped crossings	RT proportion	LT Proportion	Capacity (veh/hr)
1	78.00	0.75	1	1.125	0	12.50	738.46
2	70.00	0.125	2	0.125	0	0.00	1234.29
3	107.00	0.36	1.36	0.55	9.09	18.18	874.77
4	88.00	1.22	1.00	1.89	0	0.00	695.45
5	176.00	1.08	1.85	3.23	7.69	30.77	756.82
6	73.00	0.3	0.7	0.5	10.00	10.00	838.36
7	293.00	1.05	1.32	4.00	9.09	40.91	626.62
8	346.00	0.57	1.7	1.37	13.33	36.67	842.77
9	91.00	0.6	1.3	1.1	0	40.00	909.89
10	116.00	0.25	1.17	0.33	8.33	33.33	806.90
11	330.00	0.75	2	1.2	10	35.00	654.55
12	157.00	0.53	1.53	0.82	17.65	17.65	985.99
13	364.00	0.35	1.61	2.42	9.68	19.35	801.10
14	87.00	0.2	1.6	0.2	10	10.00	1075.86
15	170.00	0.38	1.81	0.88	12.5	25.00	952.94
16	307.00	0.41	1.69	0.93	6.90	31.03	914.66
17	208.00	0.29	1.21	0.54	20.83	25.00	917.31
18	181.00	0.42	1.63	0.74	26.32	10.53	994.48
19	502.00	0.37	1.63	0.83	12.20	19.51	774.50
20	131.00	0.14	1.50	0.14	0	7.14	961.83
21	562.00	0.78	1.49	2.59	13.51	29.73	589.32
22	180.00	1.31	2.23	4.38	23.08	23.08	840.00
23	238.00	0.35	2.29	1.12	17.65	23.53	847.06
24	229.00	0.24	2.01	0.80	9.52	19.05	911.79
25	242.00	0.45	1.59	1.00	22.73	9.09	847.93
26	660.00	0.58	2.18	1.18	10.91	27.27	960.00
27	85.00	0.18	0.73	0.18	18.18	18.18	804.71
28	143.00	0.86	1.36	1.93	28.57	0.00	830.77
29	157.00	0.5	1.19	0.75	0	18.75	802.55
30	246.00	0.4	1.96	0.64	20	36.00	1082.93
31	190.00	0.92	1.58	5.25	33.3	0.00	587.37
32	333.00	0.55	1.94	1.03	3.23	38.71	983.78
33	207.00	0.23	1.59	0.23	18.18	18.18	991.30
34	315.00	0.24	1.41	0.35	10.81	21.62	1017.14

Figure 24. Sample combined data analysis sheet for Method I

Queue	Pedestrians Crosswalk Yielding		Crosswalk Count						Conflicted Vehicle Numbers	Type of Pedestrian Average	Average # of Conflicts	Average # Pedestrians	Right Turn Proportion (%)	Left Turn Proportion (%)
	Near	Far	North	South	East	West								
X							35	700.00	2	0	2	0		
	X					2	0:03:00		2	1	2	2		
X		X				1	180.00		2	1	2	1		
		X		1			0.05		2	1	2	1		
									2	0	2	0		
X									1	0	1	0		
X		X	2						2	1	2	2		
	X				1				2	1	2	1		
X	X		2						1	1	1	2		
X		X			1				1	1	1	1		
X	X		5						2	1	2	5		
X		X	7						2	1	2	7		
									2	0	2	0		
X	X		6						1	1	1	6		
X		X			3				1	1	1	3		
X	X		2						1	1	1	2		
X	X	X	4	1					2	2	2	5		
X	X	X	2		2				2	2	2	4		
	X	X		1	2				2	2	2	3		
X	X	X	5	2					2	2	2	7		
X	X	X	5	1					2	2	2	6		
X									2	2	2	0		
X	X		4						2	0	2	4		
X		X	5						2	1	2	5		
X	X	X	4		32				2	1	2	36		
	X				2				3	2	3	2		
X		X	4						2	1	2	4		
X	X		3						3	1	3	3		
X	X				4				3	1	3	4		
X		X	3						3	1	3	3		
X	X		3						3	1	3	3		
	X					8			2	1	2	8		
	X				4				2	1	2	4		
X									1	0	1	0		
X		X			2				1	1	1	2		
										1.028571429	1.914285714	3.885714286	22.85714286	28.57142857
X							23	662.40	2	0	2	0		
							0:02:05		1	0	1	0		
X	X		6				125.00		2	1	2	6		
	X				3		0.0347222		2	1	2	3		
X									2	0	2	0		
X	X				4				2	1	2	4		
		X	11						2	1	2	11		
X	X		7						2	1	2	7		
									2	1	2	0		
X									2	0	2	0		
	X		3						3	0	3	3		
	X	X			2	1			1	1	1	3		
									2	2	2	0		
	X	X	1		2				2	0	2	3		
X									1	2	1	0		
X		X	2						3	0	3	2		
	X	X	2	2					2	1	2	4		
	X	X	2	2					2	2	2	4		
		X	5						2	2	2	5		
X	X	X	5			2			1	1	1	7		
	X	X	4		3				2	2	2	7		
									1	2	1	0		
X									2	0	2	0		

Figure 25. Sample data analysis sheet for Method II