



# Capacity at All-Way Stop Control Intersections: Case Study

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1        **Capacity at All-Way Stop Control Intersections: Case Study**

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1 **ABSTRACT**

2 This paper presents an empirical investigation into the capacity of All-Way Stop-Controlled  
3 (AWSC) intersections. Video data was collected over four days at an AWSC intersection site in  
4 Bozeman, Montana. The site is characterized by single-lane approaches and high level of vehicular  
5 and pedestrian traffic. Using strict protocols, video records were processed at the individual vehicle  
6 level and several information metrics were extracted for each vehicle in the data set on all  
7 approaches. Study results indicate that the total intersection capacity at the study site varied  
8 between 400 and 1400 vehicles per hour. The study suggests that the wide range of capacity  
9 observations is largely associated with the pedestrian crossing activity at the study site. Statistical  
10 tests confirmed that both pedestrian crossing activity and the level of conflict have significant  
11 effects on intersection capacity at the 95% confidence level. Regarding movement type, the right-  
12 turn movement was not found to have significant effect on intersection capacity while left-turn  
13 movement was found to negatively affect the intersection capacity. The results presented in this  
14 paper offer valuable information on AWSC intersection capacity, given the limited amount of  
15 information in the literature and the dated nature of those empirical observations.

16  
17 **Keywords:** All-way stop control, intersection, capacity, pedestrians, conflicts

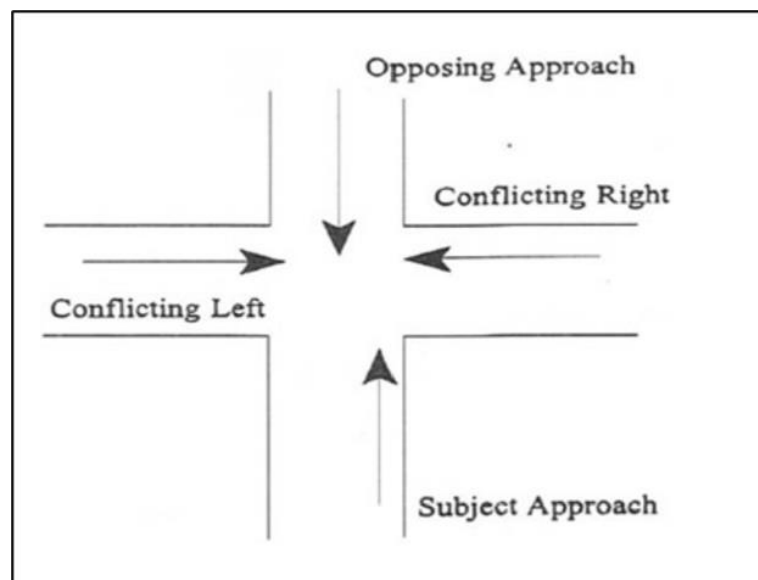
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## 1 INTRODUCTION

2 Intersections are an essential component of the highway network both from operations and  
 3 safety perspectives. Specifically, the capacity of intersections primarily controls the capacity of  
 4 corridors and networks in the highway system due to the many movements (traffic streams) they  
 5 serve. At the same time, intersections are usually associated with a high percentage of crashes,  
 6 especially in urban areas due to conflicting traffic movements and traffic stream interruptions.

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

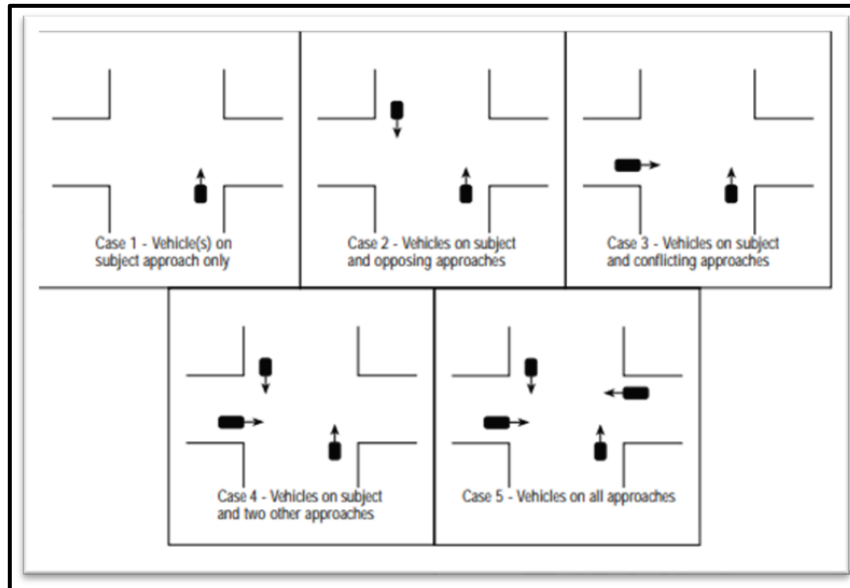
13 The operation of an AWSC intersection is quite complex. The Highway Capacity Manual  
 14 (HCM) defines capacity at AWSC intersections as “the maximum throughput on an approach  
 15 given the flow rates on the other intersection approaches” (1). Consequently, the capacity and  
 16 delay at any given approach to the intersection is a function of traffic volumes on all other  
 17 approaches. Vehicles on other approaches, their intended movements, and the subject vehicle’s  
 18 movement (through, right, or left) determine the number of vehicles that are in conflict with the  
 19 movement of the subject vehicle, and thus the time it takes the subject vehicle to perform the  
 20 intended maneuver. Figure 1 shows the subject approach to an AWSC intersection and the  
 21 opposing and conflicting traffic streams. If no turning movement is banned at the location of  
 22 interest, then vehicles entering the intersection from any of the available approaches may perform  
 23 one of the three movements: left-turn, through, or right-turn movement.  
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25  
 26 **Figure 1. Approaches at 4-way stop-controlled intersection (2)**

27  
 28 Historically, vehicles from the conflicting (crossing) or opposing traffic streams have been  
 29 treated using case classification (case number) to represent the level of conflict on other approaches  
 30 at the time when the subject vehicle arrives at the stop bar on the subject approach. It is this level

1 of conflict (and the type of movement of the subject vehicle) that determines the time it takes the  
 2 vehicle to legally enter the intersection and perform the intended maneuver. The Highway  
 3 Capacity Manual (HCM) 1994 update (2) introduced four case numbers for the level of conflict,  
 4 which was then extended to five case numbers in the HCM-2000 edition (3) as shown in Figure 2  
 5 below.  
 6



7  
 8 **Figure 2. The HCM-2000 Level of Conflict Case Numbers (3)**

9 **BACKGROUND**

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

13 Hebert (4) investigated the capacity at three AWSC intersections with a single lane on each  
 14 approach in the Chicago metropolitan area. The data was collected using video cameras at the  
 15 study sites. The study estimated capacity using the average departure headway and investigated  
 16 the effects of turning movements and the volume split between the two crossing roadways. Total  
 17 intersection capacity values as high as 1900 vehicles per hour were reported by the study. The  
 18 study found that right-turning vehicles are associated with smaller departure headways thus  
 19 increasing intersection capacity. The study also found that a balanced volume split between the  
 20 two crossing roadways contributes to higher capacities.

21 Later in 1987, Richardson (5) drew attention to the issue of the previously published methods  
 22 and the lack of any analytical model for capacity estimation. The author introduced a new model  
 23 that had the ability to predict the level of performance at the intersection over a broader range of  
 24 traffic conditions. He calculated the capacity based on the service time (departure headway) and  
 25 the time that each vehicle occupies the intersection, which was based on Hebert's work (using his  
 26 minimum departure headways). In addition, Richardson used this model to forecast intersection  
 27 capacity and delay under different scenarios of volume split between the crossing roadways.

1 Kyte and Marek (6) investigated the capacity and delay at single-lane all-way stop-controlled  
2 intersections. They collected data for nearly 25 hours of operation from eight different sites in the  
3 northwest region. The primary motivation for this research was the need to improve the 1985  
4 Highway Capacity Manual AWSC intersection procedures. The study presented two methods for  
5 estimating the capacity of an AWSC intersection using the highest flow rate observations and  
6 departure headway data. The study reported that the highest single observed flow rate was 2,016  
7 vph, whereas the maximum observed flow rate for an intersection approach was 732 vph. A  
8 regression model was developed for departure headway that could be used in estimating approach  
9 capacity. Since the data collected represents a limited range of traffic conditions, the developed  
10 model may not be applicable to the wide range of traffic conditions in real-world applications. The  
11 study also reported values for departure headways under capacity operation for different scenarios  
12 of vehicles using other approaches (level of conflict) and the corresponding approach and total  
13 intersection capacity values.

14 In 1990, Michael Kyte estimated the factors affecting the capacity of AWSC intersections and  
15 developed a procedure for estimating the capacity (7). He used 30 hours of data and more than  
16 7000 departure headways from 20 study sites including single-lane and multilane AWSC  
17 intersections. The main variables used in his capacity model are the number of lanes on each  
18 approach, the distribution of traffic among different approaches, and the proportion of turning  
19 movements on each approach. The study found that the AWSC capacity increases with the increase  
20 in the proportion of right-turning vehicles and decreases with the increase in the proportion of left-  
21 turning vehicles, pedestrian traffic, and heavy vehicle traffic. In a follow-up study, Kyte et al. (8)  
22 investigated saturation headway using an AWSC intersection site in Portland, Oregon. The study  
23 examined saturation headway under the effect of vehicle movement from the subject approach,  
24 and the presence of vehicles on the conflicting and opposing approaches. The capacity of an  
25 approach was found to vary between 525 vph when the subject driver faces a continuous queue of  
26 vehicles on both the opposing and conflicting approaches and 1, 100 vph when the subject driver  
27 faces no opposing or conflicting vehicles.

28 Another study by Ning Wu (9) developed a new model for estimating total AWSC intersection  
29 capacities (with single lane approaches) using the so-called Addition-Conflict-Flow (ACF)  
30 technique. The study claimed that the effect of turning streams or movements was not modeled in  
31 sufficient detail in the HCM 2000 procedures. The study compared total capacities from the HCM  
32 2000 procedures and those found using the ACF technique. Further, the study also suggested  
33 modifications to the HCM model that would make results more realistic (more consistent with  
34 older studies). Both the ACF technique and the modified HCM model yielded capacities that are  
35 notably higher than those from the HCM 2000 procedures.

## 36 **MOTIVATION**

37 The limited empirical research on the capacity at all-way stop controlled intersections was the  
38 main drive behind the current research. Further, the few studies that are found in the literature are  
39 generally very old and may not necessarily reflect the current-day vehicle performance, driver  
40 behavior, and geometric standards. Therefore, it was important to update the literature with recent  
41 observations of all-way-stop-controlled intersection capacities and to examine, to the extent  
42 practical, other factors that are known to have an effect on the capacity at this type of intersection.

1 **STUDY SITE**

2 The study site used in this research is located in Bozeman, Montana at the 11th Avenue and  
3 West Grant Street intersection. The 11<sup>th</sup> Avenue runs north-south, connecting downtown Bozeman  
4 with the southern part of town, passing through the MSU campus, while Grant Street is a minor  
5 collector running east-west, providing access to the MSU campus from the east. The speed limit  
6 on both streets is 25 mph. At the location of the intersection, both streets have standard lane widths,  
7 and bicycle lanes are provided in all directions. The site was selected for relatively high traffic  
8 levels, significant pedestrian activity, and the suitability of the site for data collection setup. The  
9 intersection has four single-lane approaches and crosswalks in all directions. A street view of the  
10 study site is shown in Figure 1.

11



12

13 **Figure 3. Street View of the Study Site (Source: Google Maps)**

14

15 **DATA COLLECTION & PROCESSING**

16 The data used in this research was collected using a surveillance camera on a mobile traffic  
17 monitoring trailer set at a height overlooking the study site. Video records of the study site showing  
18 all intersection approaches were acquired on four different workdays in November 2017 (see video  
19 footage in Figure 4).

20



21

22 **Figure 4. Video footage showing the study site**

1 The camera was set up so that all vehicles entering and exiting the intersection could be viewed  
2 simultaneously, including the queue presence on the subject approach. A total of 84 hours of video  
3 recordings were collected at the study site. The video footage was then analyzed using digital video  
4 recording (DVR) software and a very systematic manual procedure for processing the data.  
5 Specifically, in order to be consistent in extracting the required data from video records, a set of  
6 rules (protocol) were developed to accurately extract all variables of interest for each vehicle  
7 entering the intersection from the subject approach. A pilot study was performed in developing  
8 these rules prior to processing the complete data sets. The information that was extracted for each  
9 vehicle entering the intersection from any of the intersection approaches involved the following:

- 10 - Date
- 11 - Arrival time: this is the time when the subject vehicle arrives at the stop bar of the subject  
12 approach.
- 13 - Departure time: this is the time when the front edge of the subject vehicle crosses the stop bar  
14 location and enters the intersection.
- 15 - Clearance time: this is the time when the rear edge of the subject vehicle clears the physical  
16 area of the intersection.
- 17 - Wait time: this is the time during which the subject vehicle was waiting at the stop location  
18 before entering the intersection. It is measured as the time lapse between the arrival and  
19 departure times.
- 20 - Occupancy time: this is the time when the subject vehicle occupies the physical area of the  
21 intersection. It is measured as the time lapse between the departure and clearance times.
- 22 - Departure headway: this is the time between two consecutive departures on the subject  
23 approach, measured as the time lapse between the departure times of the subject vehicle and  
24 the preceding vehicle on the same approach.
- 25 - Movement type (through, right, or left)
- 26 - Case number: the case number indicates the vehicles on all other intersection approaches that  
27 are present when the subject vehicle arrives at the stop bar as classified by the Highway  
28 Capacity Manual (HCM) procedures. The HCM case number classification is shown in  
29 Figure 1.
- 30 - Queue presence on subject approach
- 31 - Pedestrian crossing(s) and type: this field indicates if pedestrian(s) are crossing the  
32 intersection using the near, far, or both crosswalks conflicting with the vehicle movement.
- 33 - Number of pedestrians involved in the crossing maneuvers

34 Data processing was completed for each subject approach independently prior to data analysis.  
35 It should be noted that data processing also marked heavy vehicles, bicyclists crossing the  
36 intersection, and vehicles violating the all-way-stop-control rules. These observations were not  
37 considered in the analysis to control on their potential effect on intersection capacity (these  
38 instances are very few overall). Further, intersection operation at capacity for any duration less  
39 than 60 seconds was not considered in the analysis. The 60 seconds duration was deemed an  
40 appropriate tradeoff between ensuring sustained capacity operations at the intersection and the  
41 ability to obtain a reasonable number of capacity observations for analysis purposes.

## 1 METHODOLOGY

2 The processed video recording data described in the previous section was used in extracting  
3 the intersection capacity observations measured in vehicles per hour. The underlying assumption  
4 is that the intersection operates at capacity when there is at least one vehicle stopped waiting to be  
5 served on any of the intersection approaches. This study utilized total intersection capacity as  
6 opposed to approach capacity used by the AWSC intersection capacity analysis procedures of the  
7 Highway Capacity Manual (HCM). In this study, total intersection capacity refers to the maximum  
8 throughput expressed as an hourly rate for all vehicles entering the intersection from any of the  
9 intersection approaches. Two methods were utilized in extracting total intersection capacity  
10 observations.

11 *Method I:* This method identified intervals of time when the subject approach to the intersection  
12 was queued for a “tangible” period of time, i.e., when a large number of queued vehicles are  
13 discharged consecutively from the subject approach. This approach focuses on the queuing on one  
14 approach regardless of the presence of queue(s) on other approaches. The time interval was  
15 measured as the time lapse between the first vehicle entering the intersection and the last vehicle  
16 in the interval clearing the intersection. To account for traffic condition on other approaches, case  
17 number was used in this method to account for traffic entering the intersection from other  
18 approaches. The number of vehicles entering from the subject approach as well as those entering  
19 from other approaches are counted over the time interval and the information is used to calculate  
20 capacity as an hourly flow rate. This process was repeated for the different intersection approaches.

21 *Method II:* This method identified time intervals where at least one vehicle was waiting to be  
22 served at any of the four intersection approaches. Similar to the previous method, intervals should  
23 be long enough to include a large number of waiting (mostly queued) vehicles entering the  
24 intersection consecutively from any of the intersection approaches. To apply this method, the data  
25 from all intersection approaches have to be combined first (as different approaches were processed  
26 independently) before time intervals for capacity operations are identified and marked. For each  
27 interval, the number of vehicles entering the intersection and the duration of time were used in  
28 calculating capacity observations. The time duration is calculated as the time lapse between the  
29 first vehicle entering the intersection and the last vehicle in the interval clearing the intersection.  
30

## 31 ANALYSIS OF RESULTS

32 This section presents the results of the capacity analysis at the study site using the  
33 methodologies described in the previous section. The analyses using each of the two methods  
34 for estimating the intersection capacity are presented separately.

### 35 Method I Analysis

36 Using the procedure described in the previous section, 104 intervals were identified and  
37 used to estimate the intersection capacity over the four days of data collection for all  
38 intersection approaches. As shown in Table 1, the mean capacity value using this method is  
39 around 892 vehicles per hour with a standard deviation of around 164 vehicles per hour. The  
40 minimum capacity observed was only 432 vehicles per hour while the maximum observed  
41 capacity was around 1345 vehicles per hour. The range of capacity observations is wide which  
42 can largely be attributed to pedestrian activities during the period of interest. Specifically, slow  
43 walking speed for some pedestrians and pedestrians crossing in large numbers are typical

1 situations that could significantly affect the number of vehicles entering the intersection during  
 2 a given interval.

3 **Table 1. AWSC Intersection Capacity Descriptive Statistics – Method I**

<b>AWSC Intersection Capacity Descriptive Statistics - Method I</b>	
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

4

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

- 8 1. Number of crosswalks in use: it is well known that pedestrian crossing activity at an AWSC  
 9 intersection is a major determinant of intersection capacity. At the study site, where  
 10 pedestrian crossings are allowed on all approaches, a vehicle may have conflict with  
 11 pedestrians using the near crosswalk on the incoming approach, pedestrians using the  
 12 crosswalk on the far (outgoing) approach, or both. This variable assumed a value of 1 if  
 13 either crosswalk is in use and 2 if both crosswalks are in use.
- 14 2. Number of crossing pedestrians: this variable accounts for the total number of crossing  
 15 pedestrians at the intersection that are in conflict with the subject vehicle movement.
- 16 3. Number of vehicles on other approaches: this is the number of vehicles that are already  
 17 waiting on other approaches when the subject vehicle arrives at the stop sign. This number  
 18 is a function of the HCM case number described earlier. The number of vehicles  
 19 corresponding to each case number is shown in Table 2. This variable is expected to affect  
 20 the AWSC intersection capacity as vehicles entering from different approaches increases  
 21 the possibility of two vehicles using the intersection simultaneously (for non-conflicting  
 22 movements).

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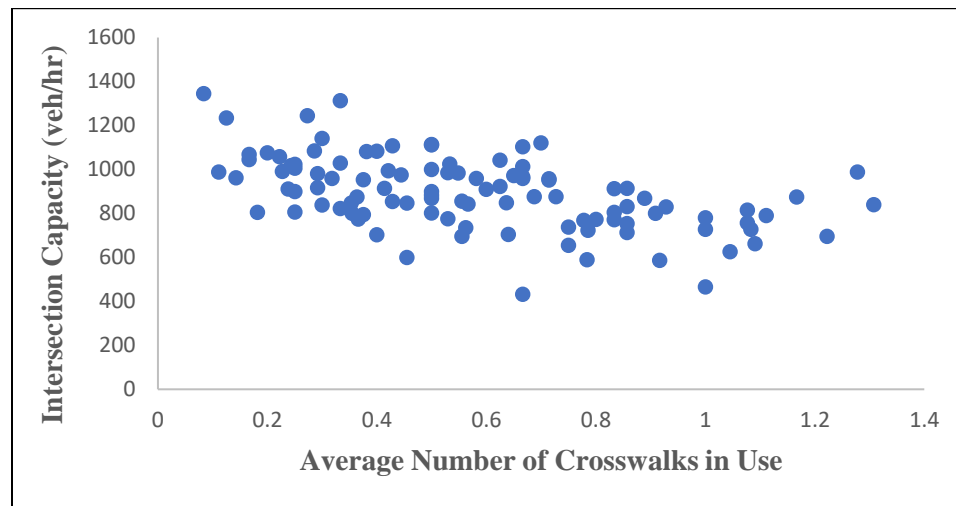
**Table 2. Number of conflicts using the HCM case numbers**

<b>Case Number</b>	<b>Number of Vehicles</b>
Case 1	0
Case 2	1
Case 3	1
Case 4	2
Case 5	3

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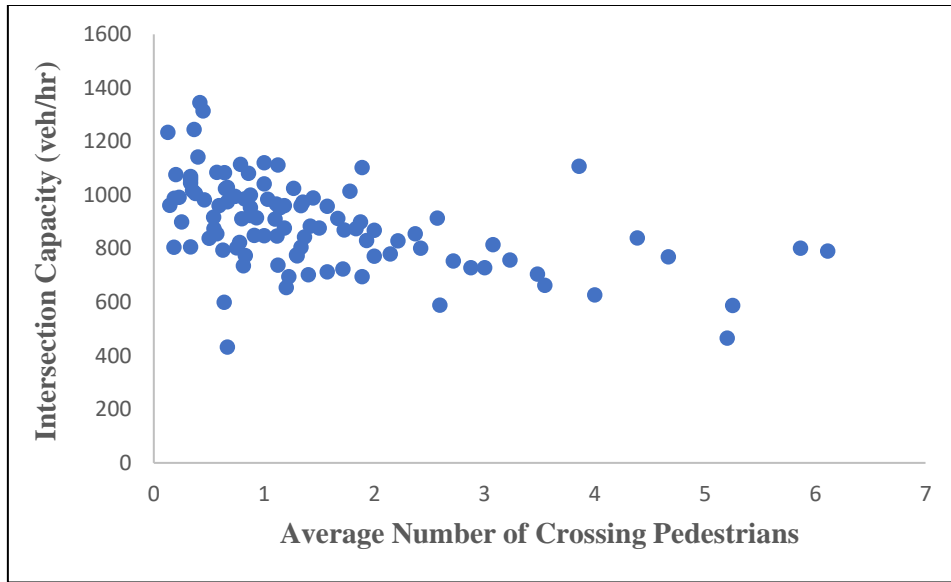
4. Proportion of right-turn movement: this is the proportion of right-turning vehicles during the time interval when the intersection was operating at capacity. As the right-turn maneuver has fewer conflicts with other movements than other maneuvers, it is expected that higher proportion of right-turning vehicles may contribute to higher capacities. Specifically, higher proportion of right-turning vehicles may increase the possibility of two vehicles using the intersection simultaneously. Such an effect is also reported in older studies (4, 7).
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 higher proportion of left-turning vehicles may lead to lower capacities. Such an effect is also reported in the literature (7).

To examine the effect of the above variables on AWSC intersection capacity, scatterplots were established showing the relationships between the AWSC intersection capacity and the five variables described earlier. These scatterplots are shown in Figures 5 to 9.



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**Figure 5. Intersection Capacity versus Number of Crosswalks in Use**

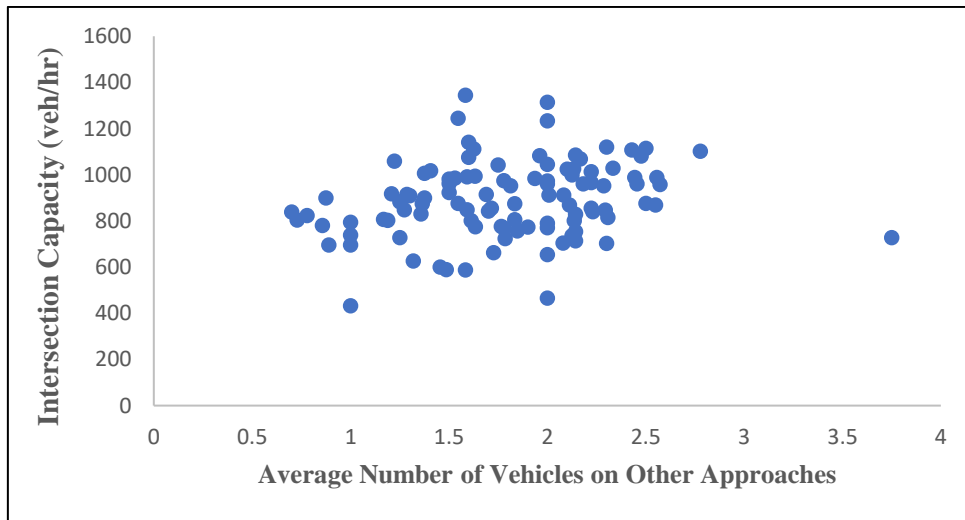


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**Figure 6. Intersection Capacity versus Average Number of Crossing Pedestrians**

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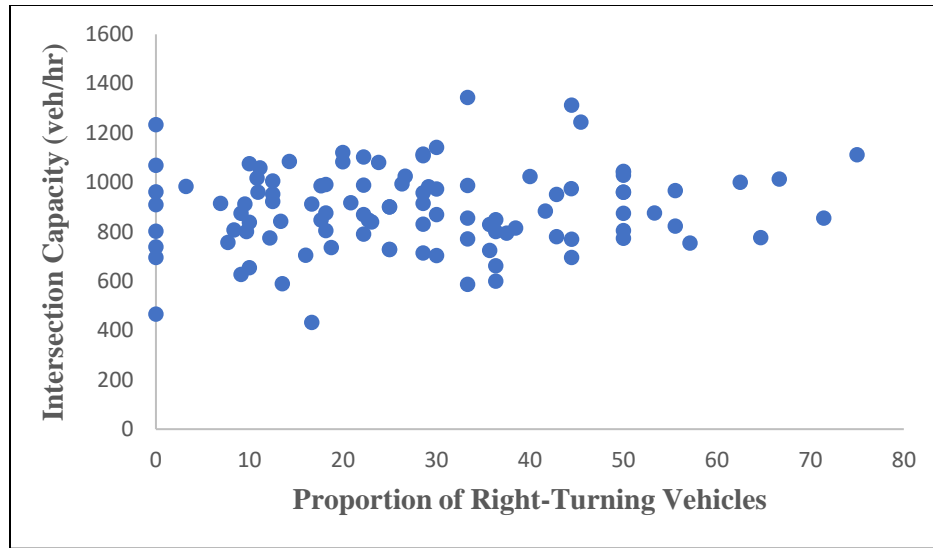
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**Figure 7. Intersection Capacity versus Average Number of Vehicles on Other Approaches**

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**Figure 8. Intersection Capacity versus Proportion of Right-Turning Vehicles**



**Figure 9. Intersection Capacity versus Proportion of Left-Turning Vehicles**

6 The scatterplot in Figure 5 exhibits a declining pattern where intersection capacity decreases  
 7 with the increase in the number of crosswalks in use. This pattern is expected given the longer  
 8 time a vehicle would need to cross the intersection when more crosswalks are occupied with  
 9 pedestrians. A similar declining pattern is shown in Figure 6 where the intersection capacity  
 10 decreases with the increase in the average number of crossing pedestrians using the conflicting  
 11 crosswalks. The scatterplot shown in Figure 7 exhibits a slight rising pattern between the  
 12 intersection capacity and the average number of vehicles on other approaches (when the subject  
 13 vehicle arrives at the stop sign). This is consistent with the expectation of higher capacities  
 14 (discussed earlier) when vehicles enter the intersection from different approaches. Regarding  
 15 movement type, no clear patterns can be discerned in Figures 8 and 9 to confirm the effect of the  
 16 proportion of right-turn and left-turn movements on AWSC intersection capacity.

1 To closely examine the effect of the five variables on intersection capacity, the multivariate  
 2 linear regression was performed, and the results are shown in Figure 10.

SUMMARY OUTPUT						
<i>Regression Statistics</i>						
Multiple R	0.68					
R Square	0.46					
Adjusted R Square	0.43					
Standard Error	123.97					
Observations	104					
<i>ANOVA</i>						
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>	
Regression	5	1273014.51	254602.90	16.57	7.91324E-12	
Residual	98	1506127.32	15368.65			
Total	103	2779141.83				
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>
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

3  
4 **Figure 10. Regression Output for Estimating Capacity – Method I**

5  
6 The coefficient of determination (R-square) value in the regression output indicates that around  
 7 46% of the variability in intersection capacity is explained by the five variables that are part of the  
 8 regression model. The standard error of estimate is around 124 vehicles per hour and the F value  
 9 from the ANOVA test indicates that the overall regression model is significant. By examining the  
 10 t-test results, all independent variables except the proportion of right-turning vehicles were found  
 11 to have significant effect on intersection capacity.

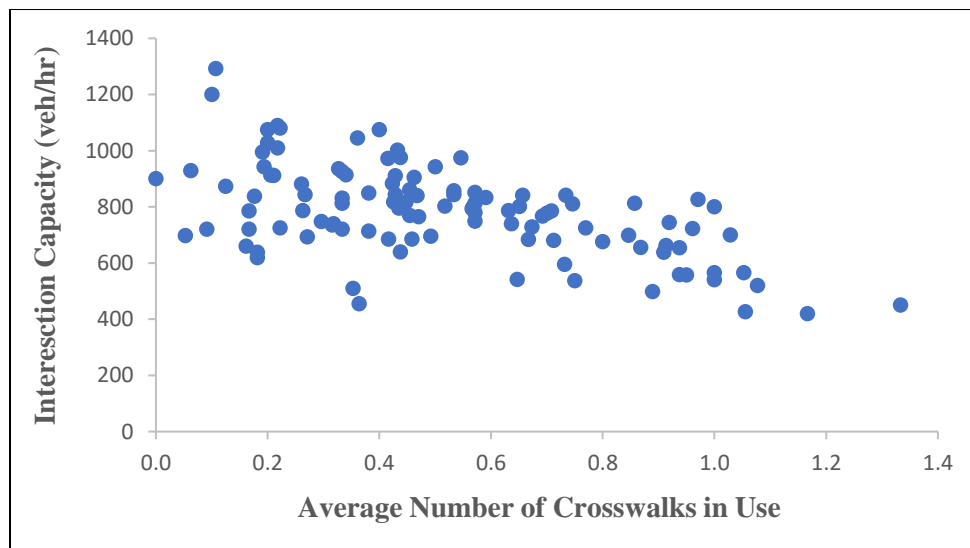
## 12 **Method II Analysis**

13  
14 This section presents the results of the intersection capacity analysis using Method II described  
 15 earlier. One hundred ten intervals were identified and used to estimate the intersection capacity  
 16 over the four days of data collection. The AWSC intersection capacity descriptive statistics are  
 17 provided in Table 3. The mean capacity value using method II is around 783 vehicles per hour.  
 18 The standard deviation for capacity observations is around 161 vehicles per hour. The minimum  
 19 capacity observed was around 420 vehicles per hour while the maximum observed capacity was  
 20 around 1292 vehicles per hour. Similar to method I, the range of capacity observations is wide  
 21 which can largely be attributed to the variation in pedestrian activities during the periods of  
 22 interest.  
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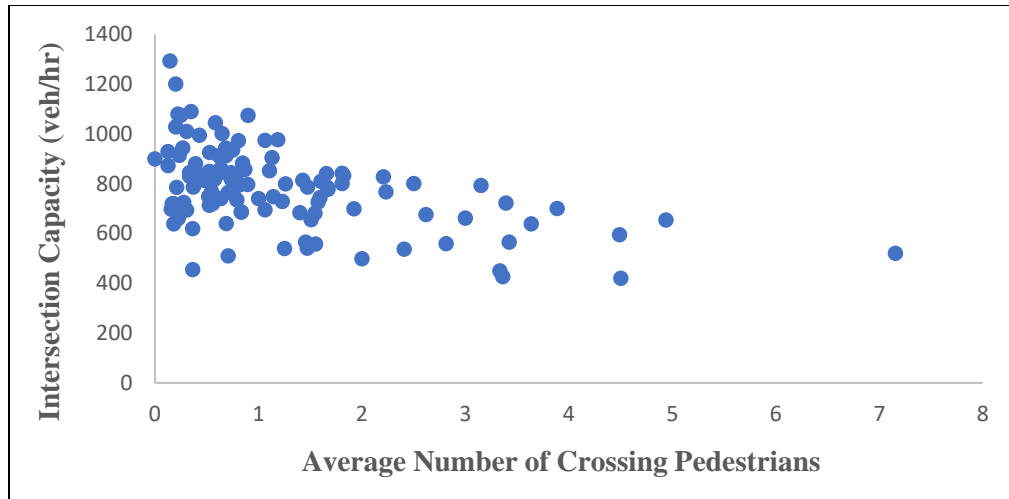
1 **Table 3. AWSC Intersection Capacity Descriptive Statistics – Method II**

AWSC Intersection Capacity Descriptive Statistics - Method II	
Mean	782.86
Median	786.2
Std Deviation	161.16
90th Percentile	976.27
Minimum	420.23
Maximum	1292.3
95% Confidence Interval	10.31
Sample Size	111

2  
 3 Similar to the previous analysis for method I, Figures 11 through 15 show scatterplots for the  
 4 AWSC intersection capacity versus the average number of crosswalks in use, average number of  
 5 crossing pedestrians, average number of vehicles on other approaches, the proportion of right-  
 6 turning vehicles, and the proportion of left-turning vehicles respectively. Figures 11 and 12 clearly  
 7 exhibit a declining pattern where intersection capacity decreases with the increase in the average  
 8 number of crosswalks in use and the average number of crossing pedestrians. This is very  
 9 consistent with the patterns shown in Figures 5 and 6 of Method I analysis. The scatterplot shown  
 10 in Figure 13 reveals no discernable relationship between the AWSC intersection capacity and the  
 11 average number of vehicles present on other approaches when the subject vehicle arrives at the  
 12 stop sign (a surrogate measure for the case number used in the HCM). Similarly, no clear  
 13 association can be discerned between the AWSC intersection capacity and the proportions of right-  
 14 turning and left-turning vehicles using the scatterplots shown in Figures 14 and 15 respectively.

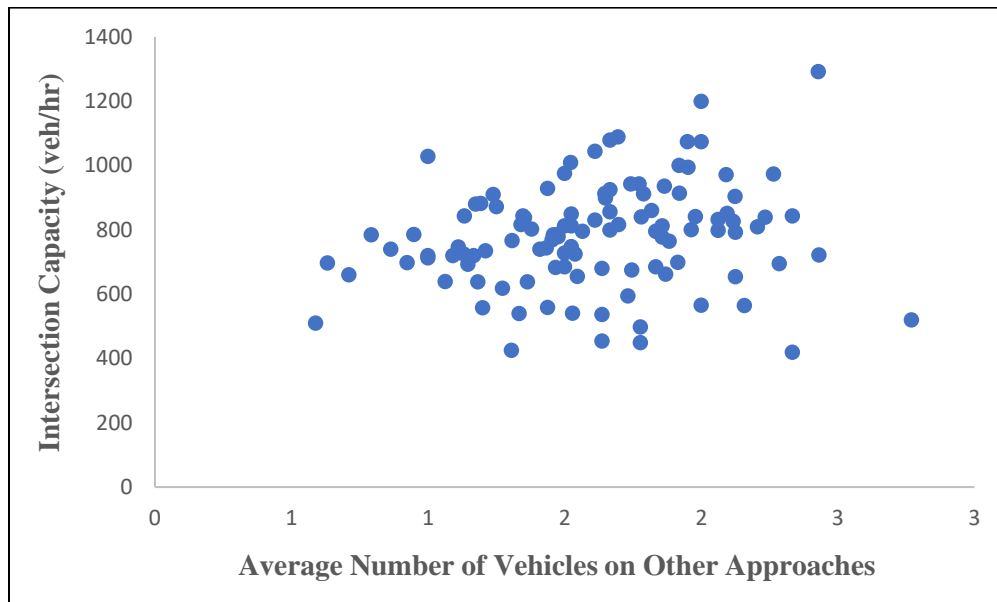


16 **Figure 10. Intersection Capacity versus Number of Crosswalks in Use**



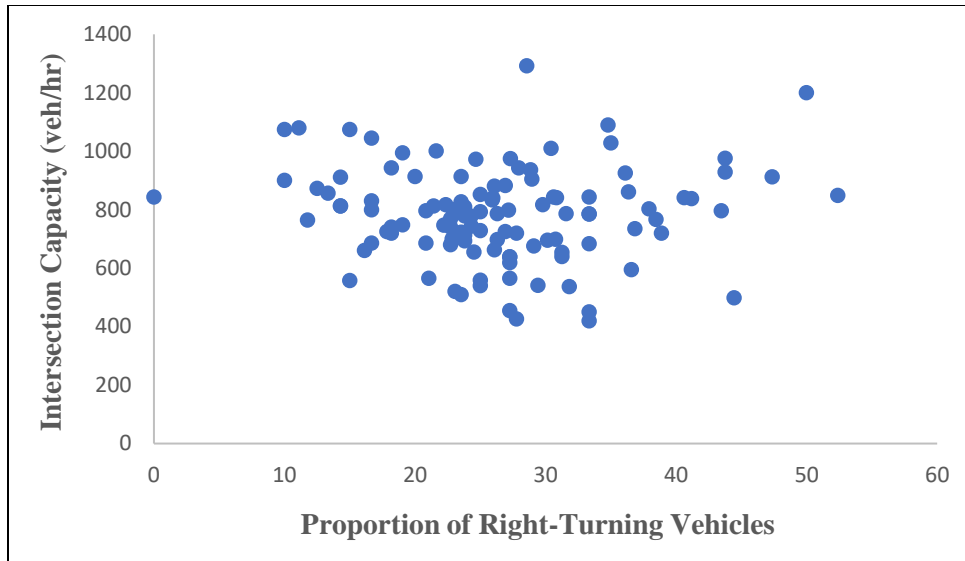
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**Figure 11. Intersection Capacity versus Average Number of Pedestrians**



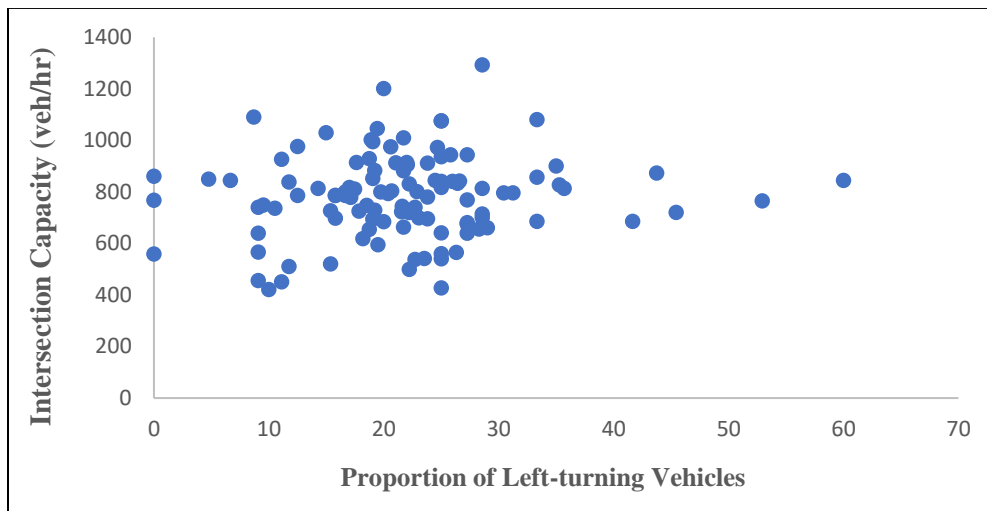
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**Figure 12. Intersection Capacity versus Number of Vehicles on Other Approaches**



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**Figure 14. Intersection Capacity versus Proportion of Right-Turning Vehicles**



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**Figure 135. Intersection Capacity versus Proportion of Left-Turning Vehicles**

6 To have a better understanding of the association between the AWSC capacity and the five  
 7 variables of interest, the multivariate linear regression was conducted using the intersection  
 8 capacity as the dependent variable and the five variables of interest as the independent variables.  
 9 The regression results are presented in Figure 16. The coefficient of determination value indicates  
 10 that variables included in the model explain around 56% of the variation in the dependent variable,  
 11 i.e., the AWSC intersection capacity. The standard error of estimate is around 110 vehicles per  
 12 hour and the F value from the ANOVA test indicates that the overall regression model is  
 13 significant. The t-test results confirmed that all variables included in the model are statistically  
 14 significant at the 95% confidence level, with the exception of the proportions of right-turning and  
 15 left-turning vehicles.

SUMMARY OUTPUT						
<i>Regression Statistics</i>						
Multiple R	0.75					
R Square	0.56					
Adjusted R Square	0.54					
Standard Error	109.85					
Observations	111					
<i>ANOVA</i>						
	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				
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>
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

Figure 16. Regression Output for Estimating Capacity – Method II

## DISCUSSION OF RESULTS

In the previous section, the AWSC intersection capacity was calculated and analyzed using the two methods described earlier in this paper. 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, which is around 14% higher than the capacity estimated using method II (783 vehicles per hour). Upon careful examination of the data, it was found that the Method I observations are associated with 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 compared with Method II which is somewhat expected given the higher mean value. The standard deviation is very close (almost the same) for the two methods. The regression analyses for the two methods yielded results that are 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 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 effect on intersection capacity. However, the proportion of left-turning vehicles was found to have significant effect on intersection capacity according to Method I model, while the effect was not found significant using 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 that are reported in the literature. However, it should be mentioned that those reported capacity observations either come from a couple of older

1 studies and are considered dated (with the most recent study around three decades ago) or  
2 estimated using theoretical models and are not based on field observations. To the knowledge of  
3 the authors, no recent AWSC intersection capacity observations are reported in the literature. The  
4 other aspect that is evident in other studies in the literature is the lack of notable pedestrian traffic  
5 at the study sites (pedestrian traffic was not a major study variable in any of these studies).  
6 Therefore, the effect of pedestrians on AWSC intersection capacity is lacking from all the studies  
7 published on this subject including those discussed in the background section. Finally, the protocol  
8 used in data processing may partly explain the lower capacity estimates observed in this study  
9 compared to some values reported in the literature. Specifically, in this study, capacity operations  
10 at the intersection have to be sustained for at least one minute in order to be included in capacity  
11 observations. Shorter intervals, often associated with smaller departure (saturation) headways and  
12 higher capacities, were excluded from analysis as they don't represent sustained capacity  
13 operations (e.g., very short headways associated with a few vehicle departures only).

#### 14 **SUMMARY OF FINDINGS AND RECOMMENDATIONS**

15 This paper presents an empirical investigation into AWSC intersection capacity and the effect  
16 of some of the variables that are believed to affect intersection capacity. Specifically, field data  
17 from a busy AWSC intersection in Bozeman, Montana was used in this investigation. Four days  
18 of video records were acquired at the study site using a traffic surveillance camera on a mobile  
19 trailer deployed at the study site. Capacity observations were estimated using two methods and the  
20 effect of the following variables were examined: level of conflict (HCM case number), pedestrian  
21 crossings at the intersection, and the type of movement for the subject vehicle. The major findings  
22 of this study are provided below.

- 23 • In general, capacity observations using the two methods ranged roughly between 400 vehicles  
24 per hour and 1400 vehicles per hour. The wide range of capacity observations is primarily  
25 related to the varying conditions at the study site, especially pedestrian traffic. These  
26 observations are generally lower than those reported in some of the older studies in the  
27 literature.
- 28 • Capacity observations using the two methods are somewhat different, but overall comparable.  
29 The difference in the mean capacity values could be related to the fact that method I is more  
30 associated with lower percentage of traffic on the subject approach resulting in slightly higher  
31 capacity observations.
- 32 • Pedestrian activity at the study site was found to have profound effect on saturation headways  
33 and consequently on total intersection capacity. Average number of vehicles on other  
34 approaches, a surrogate measure for the HCM case number, was also found to have significant  
35 effect on total intersection capacity. The proportion of right-turn movement was not found to  
36 have significant effect on intersection capacity, which is inconsistent with some of the findings  
37 from the older literature. Further, the proportion of left-turning vehicles was found to have  
38 significant effect on intersection capacity using method I analysis only.

39 Given the scarcity of empirical studies on AWSC intersection capacity, and the many variables  
40 affecting traffic operations at this type of intersection, the authors recommend further research into  
41 this subject using multiple study sites and diverse traffic and geometric conditions. This is  
42 especially important given the lack of consistency in capacity estimates among the few published  
43 studies as well as the HCM capacity estimates.

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4 **AUTHOR CONTRIBUTIONS**

5 The authors confirm contribution to the paper as follows; study conception and design:  
6 Ahmed Al-Kaisy; data processing: Dorukhan Doruk; data analysis and interpretation of results:  
7 Ahmed Al-Kaisy and Dorukhan Doruk; draft manuscript preparation: Ahmed Al-Kaisy and  
8 Dorukhan Doruk. All authors reviewed the results and approved the final version of the  
9 manuscript.

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