TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Research Article

Transportation Research Record
2023, Vol. 2677(8) 148–157

DOI: 10.1177/03611981231155899
journals.sagepub.com/home/trr
SAGE

Capacity at All-Way Stop Control Intersections: Case Study

Ahmed Al-Kaisy[1] and **Dorukhan Doruk**[1]

Abstract

This paper presents an empirical investigation into the capacity of all-way stop-controlled (AWSC) intersections. Video data was collected over four days at an AWSC intersection site in Bozeman, Montana. The site is characterized by single-lane approaches and high level of vehicular and pedestrian traffic. Using strict protocols, video records were processed at the individual vehicle level and several information metrics were extracted for each vehicle in the data set on all approaches. Study results indicate that the total intersection capacity at the study site varied between 400 and 1,400 vehicles per hour. The study suggests that the wide range of capacity observations is largely associated with the pedestrian crossing activity at the study site. Statistical tests confirmed that both pedestrian crossing activity and the level of conflict have significant effects on intersection capacity at the 95% confidence level. For movement type, the right-turn movement was not found to have a significant effect on intersection capacity while left-turn movement was found to negatively affect the intersection capacity. The results presented in this paper offer valuable information on AWSC intersection capacity, given the limited amount of information in the literature and the dated nature of those empirical observations.

Keywords

operations, highway capacity and quality of service, capacity, Highway Capacity Manual (HCM), interrupted flow, intersections

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

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

The operation of an AWSC intersection is quite complex. The *Highway Capacity Manual* (HCM) defines capacity at AWSC intersections as "the maximum throughput on an approach given the flow rates on the other intersection approaches" (*1*). Consequently, the capacity and delay at any given approach to the intersection is a function of traffic volumes on all other approaches. Vehicles on other approaches, their intended movements, and the subject vehicle's movement (through, right, or left) determine the number of vehicles that are in conflict with the movement of the subject vehicle, and thus the time it takes the subject vehicle to perform the intended maneuver. Figure 1 shows the subject approach to an AWSC intersection and the opposing and conflicting traffic streams. If no turning movement is banned at the location of interest, then vehicles entering the intersection from any of the available approaches may perform one of the three movements: left-turn, through, or right-turn movement.

[1]Department of Civil Engineering, Montana State University, Bozeman, MT

Corresponding Author:
Ahmed Al-Kaisy, alkaisy@montana.edu

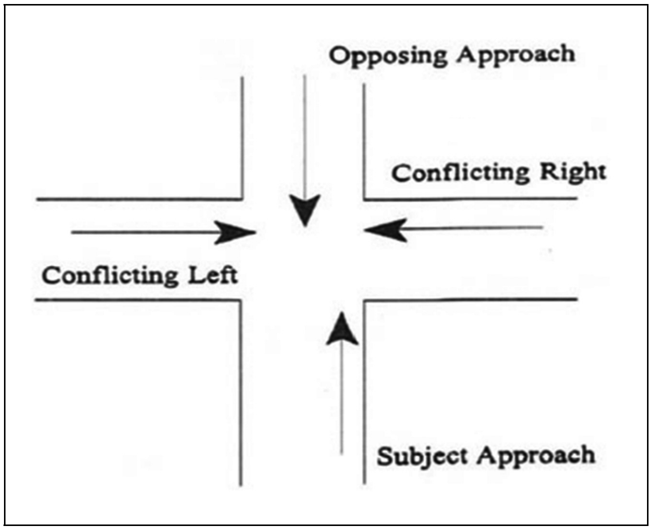

Figure 1. Approaches at four-way stop-controlled intersection (*2*).

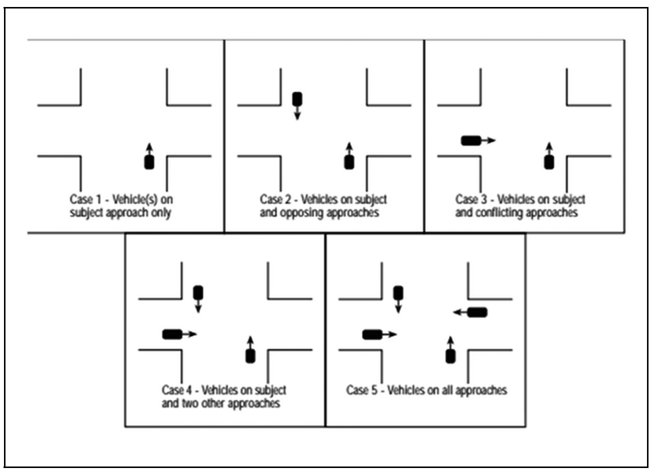

Figure 2. The *Highway Capacity Manual* (HCM) 2000 level of conflict case numbers (*3*).

Historically, vehicles from the conflicting (crossing) or opposing traffic streams have been treated using case classification (case number) to represent the level of conflict on other approaches at the time when the subject vehicle arrives at the stop bar on the subject approach. It is this level of conflict (and the type of movement of the subject vehicle) that determines the time it takes the vehicle to legally enter the intersection and perform the intended maneuver. The HCM 1994 update (*2*) introduced four case numbers for the level of conflict, which was then extended to five case numbers in the HCM 2000 edition (*3*), as shown in Figure 2.

Background

The literature review conducted in the course of this research found few studies on AWSC intersection capacity and they were mostly outdated, that is, most studies were conducted between the 1960s and 1990s.

Hebert (*4*) investigated the capacity at three AWSC intersections with a single lane on each approach in the Chicago metropolitan area. The data were collected using video cameras at the study sites. The study estimated capacity using the average departure headway and investigated the effects of turning movements and the volume split between the two crossing roadways. Total intersection capacity values as high as 1,900 vehicles per hour (vph) were reported by the study. 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 (*5*) 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 had the ability to predict the level of performance at the intersection over a broader range of traffic conditions. They calculated the capacity based on the service time (departure headway) and the time that each vehicle occupies the intersection, which was based on Hebert's work (using Hebert's 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 (*6*) investigated the capacity and delay at single-lane AWSC intersections. They collected data for nearly 25 h of operation from eight different sites in the northwest region. The primary motivation for this research was the need to improve the 1985 HCM 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 represent a limited range of traffic conditions, the developed model may not be applicable 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.

Kyte (*7*) estimated the factors affecting the capacity of AWSC intersections and developed a procedure for estimating the capacity. Kyte used 30 h of data and more than 7,000 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 an increase in the proportion of right-turning vehicles and decreases with an increase in the proportion of left-turning vehicles, pedestrian traffic, and heavy vehicle traffic. In a follow-up study, Kyte et al. (*8*) 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 the opposing and conflicting approaches and 1,100 vph when the subject driver faces no opposing or conflicting vehicles.

Another study by Wu (*9*) 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 was not modeled in sufficient detail in the HCM 2000 procedures. The study compared total capacities from the HCM 2000 procedures with those found using the ACF technique. Further, the study also suggested modifications to the HCM model that would make results more realistic (more consistent with older studies). Both the ACF technique and the modified HCM model yielded capacities that are notably higher than those from the HCM 2000 procedures.

Motivation

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

Study Site

The study site used in this research is located in Bozeman, Montana at the 11th Avenue and West Grant Street intersection. The 11th Avenue runs north–south, connecting downtown Bozeman with the southern part of the town, passing through the Montana State University (MSU) campus, while Grant Street is a minor collector running east–west, providing access to the MSU campus from the east. The speed limit on both streets is 25 mph. At the location of the intersection, both streets have standard lane widths, and bicycle lanes are provided in all directions. The site was selected for its relatively high traffic levels and significant pedestrian activity, and the suitability of the site 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.

Figure 4. Video footage showing the study site.

Data Collection and Processing

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

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. A total of 84 h of video recordings were collected at the study site. The video footage was then analyzed using digital video recording software and a very systematic manual procedure for processing the data. Specifically, to be consistent in extracting the required data from video records, a set of rules (protocol) was developed to extract accurately all the variables of interest for each vehicle entering the intersection from the subject approach. A pilot study was performed in developing these rules before processing the complete data sets. The information that was extracted for each vehicle entering the intersection from any of the intersection approaches involved the following:

- Date
- Arrival time: this is the time when the subject vehicle arrives at the stop bar of the subject approach.
- Departure time: this is the time when the front edge of the subject vehicle crosses the stop bar location and enters the intersection.
- Clearance time: this is the time when the rear edge of the subject vehicle clears the physical area of the intersection.
- Wait time: this is the time during which 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 that are present when the subject vehicle arrives at the stop bar as classified by the HCM procedures. The HCM case number classification is shown in Figure 1.
- 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. These observations were not considered in the analysis to control on their potential effect on intersection capacity (these instances are very few overall). Further, intersection operation at capacity for any duration less than 60 s was not considered in the analysis. The 60 s duration was deemed an appropriate tradeoff between ensuring sustained capacity operations at the intersection and the ability to obtain a reasonable number of capacity observations for analysis purposes.

Methodology

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

Method I: This method identified intervals of time when the subject approach to the intersection was queued for a “tangible” period of time, that is, 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. To account for traffic condition on other approaches, case number was used in this method to account for traffic entering the intersection from other approaches. The numbers of vehicles entering from the subject approach as well as those entering from other approaches are counted over the time interval and the information is used to calculate capacity as an hourly flow rate. This process was repeated for the different intersection approaches.

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 many waiting (mostly queued) vehicles entering the intersection consecutively from any of the intersection approaches. To apply this method, the data from all intersection approaches have to be combined first (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 duration of time were used in calculating 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.

Analysis of Results

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

Method 1 Analysis

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. As shown in Table 1, the mean capacity value using this method is around 892 vph with a standard deviation of around 164 vph. The minimum capacity observed was just 432 vph while the maximum observed capacity was around 1,345 vph. The range of capacity observations is wide, 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.

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 major determinant of intersection capacity. At the study site, where pedestrian crossings are allowed on all approaches, a vehicle may have 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 2 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 are in conflict with the subject vehicle movement.

Table 1. All-Way Stop-Controlled (AWSC) Intersection Capacity Descriptive Statistics—Method 1

AWSC intersection capacity descriptive statistics—Method 1	
Mean	892.02
Median	880.08
Standard deviation	164.26
90th percentile	1,093.82
Minimum	432
Maximum	1,344.58
95% confidence interval	31.94
Sample size	104

Table 2. Number of Conflicts Using the *Highway Capacity Manual* Case Numbers

Case number	Number of vehicles
Case 1	0
Case 2	1
Case 3	1
Case 4	2
Case 5	3

3. Number of vehicles on other approaches: this is the number of vehicles that are already waiting on other 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 2. This variable is expected to affect the AWSC intersection capacity as vehicles entering from different approaches increases the possibility of two vehicles using the intersection simultaneously (for non-conflicting movements).
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*).

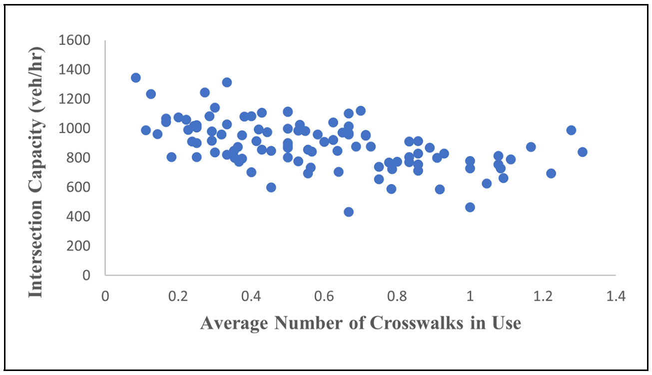

Figure 5. Intersection capacity versus number of crosswalks in use.

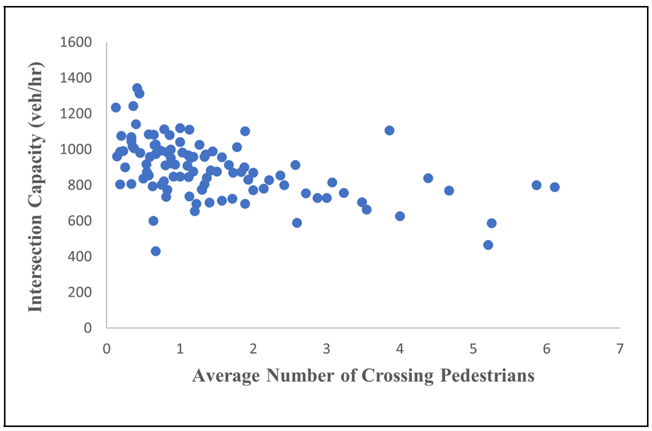

Figure 6. Intersection capacity versus average number of crossing pedestrians.

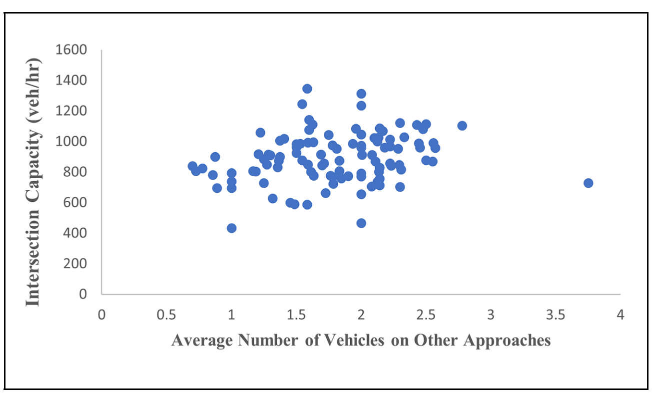

Figure 7. Intersection capacity versus average number of vehicles on other approaches.

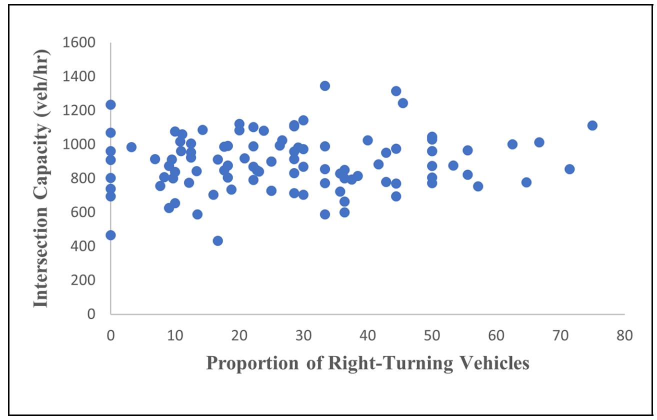

Figure 8. Intersection capacity versus proportion of right-turning vehicles.

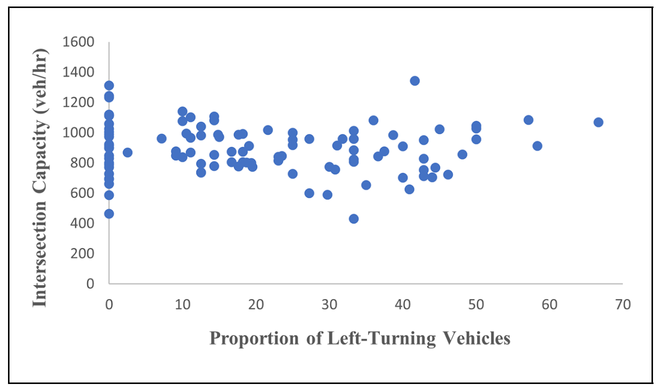

Figure 9. Intersection capacity versus proportion of left-turning vehicles.

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.

The scatterplot in Figure 5 exhibits a declining pattern where intersection capacity decreases with the increase in the number of crosswalks in use. This pattern is expected given the longer time a vehicle would need to cross the intersection when more crosswalks are occupied with pedestrians. A similar declining pattern is shown in Figure 6 where the intersection capacity decreases with the increase in the average number of crossing pedestrians using the conflicting crosswalks. The scatterplot shown in Figure 7 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 (discussed earlier) when vehicles enter the intersection from different approaches. With regard to movement type, no clear patterns can be discerned in Figures 8 and 9 to confirm the effect of the proportion of right-turn and left-turn movements on AWSC intersection capacity.

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

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 App	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

Figure 10. Regression output for estimating capacity—Method I.

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 estimate is around 124 vph and the F value from the ANOVA test indicates that the overall regression model is significant. By examining the t-test results, all independent variables except the proportion of right-turning vehicles were found to have significant effect on intersection capacity.

Method II Analysis

This section presents the results of the intersection capacity analysis using Method II described earlier. We identified 110 intervals and used them to estimate the intersection capacity over the four days of data collection. Descriptive statistics of AWSC intersection capacity are provided in Table 3. The mean capacity value using Method II is around 783 vph. The standard deviation for capacity observations is around 161 vph. The minimum capacity observed was around 420 vph while the maximum observed capacity was around 1,292 vph. Similar to Method I, the range of capacity observations is wide, which can largely be attributed to the variation in pedestrian activities during the periods of interest.

Similar to the previous analysis for Method I, Figures 11 to 15 show scatterplots for the AWSC intersection capacity versus the average number of crosswalks in use, average number of crossing pedestrians, average number of vehicles on other approaches, the proportion of right-turning vehicles, and the proportion of left-turning vehicles respectively. Figures 11 and 12 clearly exhibit 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 very consistent with the patterns shown in Figures 5 and 6 of Method I analysis. The scatterplot shown in Figure 13 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). Similarly, no clear association can be discerned between the AWSC intersection capacity and the proportions of right-turning and left-turning vehicles using the scatterplots shown in Figures 14 and 15 respectively.

Table 3. All-Way Stop-Controlled (AWSC) Intersection Capacity Descriptive Statistics—Method II

AWSC intersection capacity descriptive statistics—Method II	
Mean	782.86
Median	786.2
Standard deviation	161.16
90th percentile	976.27
Minimum	420.23
Maximum	1,292.3
95% confidence interval	10.31
Sample size	111

To have a better understanding of the association between the AWSC capacity and the five variables of interest, the multivariate linear regression was conducted

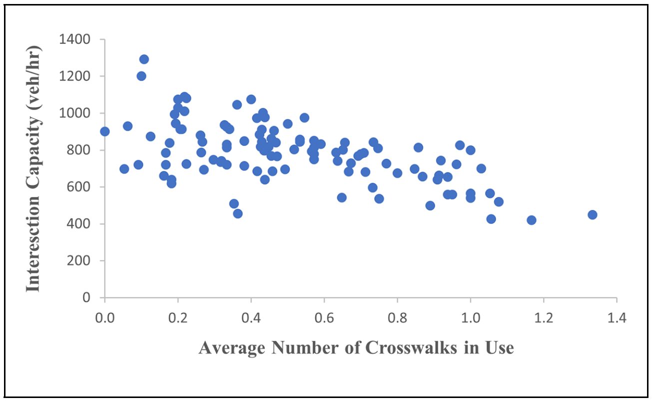

Figure 11. Intersection capacity versus number of crosswalks in use.

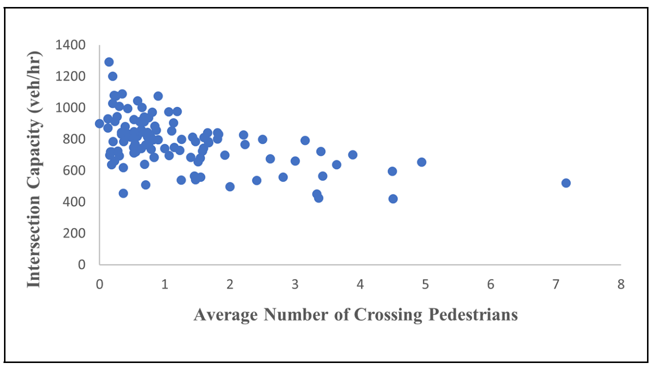

Figure 12. Intersection capacity versus average number of pedestrians.

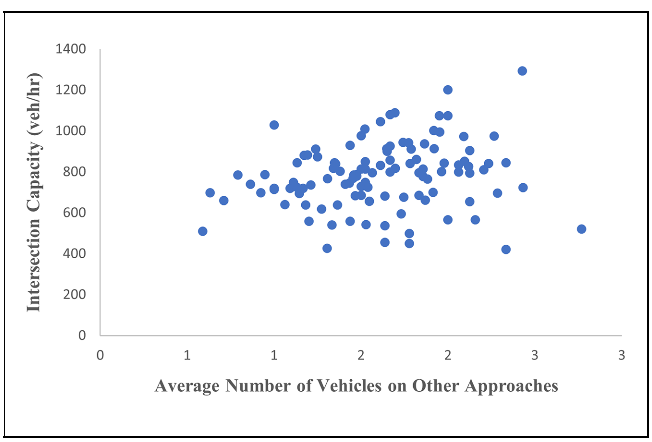

Figure 13. Intersection capacity versus number of vehicles on other approaches.

using the intersection capacity as the dependent variable and the five variables of interest as the independent variables. The regression results are presented in Figure 16. The coefficient of determination value indicates that variables included in the model explain around 56% of the

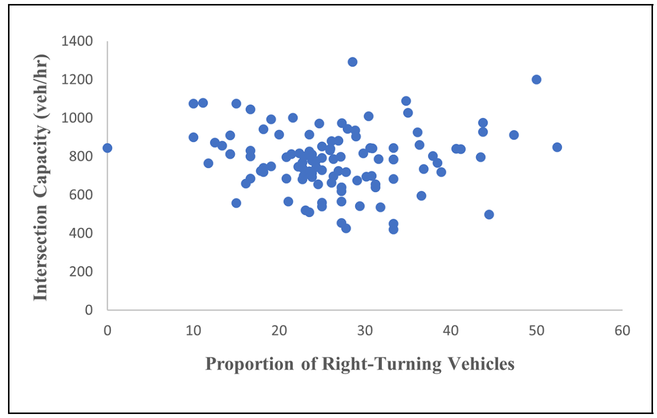

Figure 14. Intersection capacity versus proportion of right-turning vehicles.

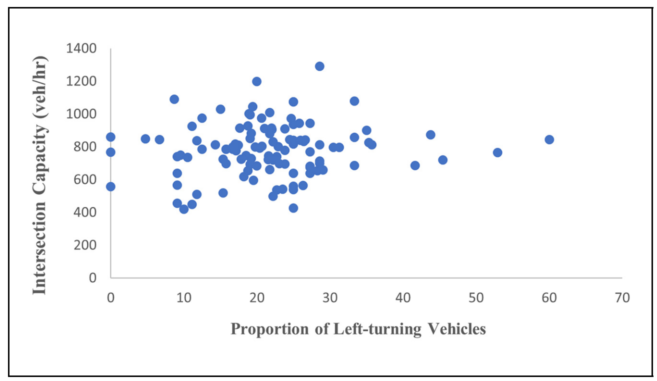

Figure 15. Intersection capacity versus proportion of left-turning vehicles.

variation in the dependent variable, that is, the AWSC intersection capacity. The standard error of estimate is around 110 vph and the F value from the ANOVA test indicates that the overall regression model is significant. The t-test results confirmed that all variables included in the model are statistically significant at the 95% confidence level, with the exception of the proportions of right-turning and left-turning vehicles.

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 vph, which is around 14% higher than the capacity estimated using Method II (783 vph). On careful examination of the data, it was found that the Method I observations are associated with higher percentage of traffic coming from other

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

Figure 16. Regression output for estimating capacity—Method II.

approaches (higher average number 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 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. To the knowledge of the authors, no recent AWSC intersection capacity observations are reported 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 major 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 with some values reported in the literature. Specifically, in this study, capacity operations at the intersection have to be sustained for at least one minute to be included in capacity observations. Shorter intervals, often associated with smaller departure (saturation) headways and higher capacities, were excluded from analysis as they do not represent sustained capacity operations (e.g., very short headways associated with a few vehicle departures only).

Summary of Findings and Recommendations

This paper presents an empirical investigation into AWSC intersection capacity and the effect of some of the variables that are believed to affect intersection capacity. Specifically, field data 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 at the study site. Capacity observations were estimated using two methods and the effect of the following variables were examined: level of conflict (HCM case number), pedestrian crossings at the intersection, and the type of movement for the subject vehicle. The major findings of this study are provided below.

- In general, capacity observations using the two methods ranged roughly between 400 vph and 1,400 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 Method I being more associated with lower percentage of traffic on the subject approach resulting in slightly higher capacity observations.
- Pedestrian activity at the study site was found to have profound effect on saturation headways and consequently on total intersection capacity. Average number of vehicles on other approaches, a surrogate measure for the HCM case number, was also found to have significant effect on total intersection capacity. The proportion of right-turn movement was not found to have significant effect on intersection capacity, which is inconsistent with some of the findings from the older literature. Further, the proportion of left-turning vehicles was found to have significant effect on intersection capacity using Method I analysis only.

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

Acknowledgment

The authors would like to thank Taylor Lonsdale of the Western Transportation Institute (WTI) (currently affiliated with the City of Bozeman) for his help in field data collection.

Author Contributions

The authors confirm contribution to the paper as follows; study conception and design: A. Al-Kaisy; data collection: D. Doruk; analysis and interpretation of results: A. Al-Kaisy, D. Doruk; draft manuscript preparation: A. Al-Kaisy, D. Doruk. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Ahmed Al-Kaisy https://orcid.org/0000-0003-1198-0975

References

1. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis*, 6th ed. Transportation Research Board, Washington, D.C., 2016.
2. *Highway Capacity Manual*, 3rd ed. Transportation Research Board, National Research Council, Washington, D.C., 1994 Update.
3. *Highway Capacity Manual*, 4th ed. Transportation Research Board, National Research Council, Washington, D.C., 2000.
4. Hebert, J. A Study of Four-Way Stop Intersection Capacities. *Highway Research Record*, Vol. 27, 1963, pp. 130–147.
5. Richardson, A. J. Delay Model for Multiway Stop-Sign Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 1987. 1112: 107–114.
6. Kyte, M., and J. Marek. Estimating Capacity and Delay at a Single-Lane Approach, All-Way Stop-Controlled Intersection. *Transportation Research Record: Journal of the Transportation Research Board*, 1989. 1225: 73–82.
7. Kyte, M. Estimating Capacity of an All-Way-Stop-Controlled Intersection. *Transportation Research Record: Journal of the Transportation Research Board*, 1990. 1225: 73–82.
8. Kyte, M., Z. Tian, J. Kuhn, H. Poffenroth, M. Butorac, and B. Robertson. Saturation Headways at Stop-Controlled Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 1994. 1457: 111–117.
9. Wu, N. Total Capacities at All-Way Stop-Controlled Intersections: Validation and Comparison of *Highway Capacity Manual* Procedure and Addition-Conflict-Flow Technique. *Transportation Research Record: Journal of the Transportation Research Board*, 2002. 1802: 54–61.