Optimal Discharge Speed and Queue Discharge Headway at Signalized Intersections

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ABSTRACT

In academia research regarding the intersection saturation headway, there are various and sometimes seemingly conflicting findings in terms of how the discharge headway or saturation flow rate changes as green time elapses. Some research found the discharge headways remained constant; some found the discharge headways had a compression trend. Others found the discharge headways got longer after a certain point of time as the discharge continued. This paper introduces an optimal discharge speed concept to explain the different trends found in saturation headway research. For a queue of traffic to discharge from an intersection, if the discharge speed quickly reached the maximum discharge speed which was at or below the optimal discharge speed, the discharge headways would remain constant; if the discharge speeds continued to increase but never exceeded the optimal speed in the whole discharge process, the headway would show a compression trend; if the discharge speeds at a certain point exceeded the optimal discharge speed, the headway would show an elongation trend. The queue discharge characteristics at one signalized intersection located in Toledo, Ohio were studied. The discharge headways of through lane traffic demonstrated an elongation trend. The optimal discharge speed that was associated with the lowest average headway was 27 mph.

IMPORTANCE OF SATURATION HEADWAY

Saturation headway decides saturation flow. Saturation flow is the single most important parameter in signal timing optimization and intersection capacity estimation (*1*). Signal retiming is the most cost effective way to improve traffic flow and safety, reduce delay and congestion, and reduce fuel consumption and emissions. Signal cycle length, offset, and splits are three key parameters to be optimized when conducting signal retiming on a coordinated corridor. A small change in saturation flow rate would affect signal cycle length and splits design; this could affect a whole corridor's operational efficiency (*2*). An accurate estimate of saturation headway or saturation flow is crucial for signal timing optimization.

A previous study (*3*) showed that a tiny error in capacity estimates produced a large error in delay time estimates. Wrong delay estimates could lead to misclassifying intersection operational levels of service, resulting in making poor decisions in operation and design. Improving the accuracy of capacity estimates is critical. Therefore, there is a need for a queue discharge characteristics study to be conducted at different places to improve the saturation flow estimation.

LITERATURE REVIEW

In academia research regarding the intersection saturation headway, there are various and sometimes seemingly conflicting findings in terms of how the discharge headway or saturation flow rate changes as green time elapses. Some possible causes were provided by some researchers to explain their observations.

Headway Remain Constant

HCM 2010 (*4*) contains tools to evaluate the performance of highway and street facilities in terms of operational and quality of service measures. HCM 2010 assumes a constant headway after the first few vehicles passed the stop line. In agreement with HCM assumptions, some researchers found that with long green times the headway values remained relatively flat (neither increased nor decreased significantly) after the first few vehicles. Cohen (*5*) examined the queue discharge problem with application of a modified Pitt car-following system, and found the discharge headway remains little changed after the fifth queued vehicle. Karan Khosla (*6*) found the headway neither increased nor significantly decreased with a long green time in studying five intersections in the Dallas-Fort Worth area.

Headway Compression

Some researchers found the headway would keep getting shorter further into green time. Bonneson (*7*) observed a headway compression trend and presented a discharge headway model for through movements. Ali S. (*8*) observed discharge headways at some signalized intersections in Riyadh, the capital of Saudi Arabia, and found a compressed trend for the headways of queuing position 1 to 15; he also found the average headway was lower than that of other countries documented in previous studies. He considered this was due to aggressive drivers in Riyadh, who were driving too closely and tailgating. Lin (*9*, *3*, *10*) conducted some studies in Taiwan and Long Island, New York. He also found some similar trends of gradual compression of headways as the queue discharge continued for both straight through movement and protected left turn movement. Lin commented that the drivers in the back of a long queue tended to press their headways to increase the chance of being able to pass through the intersection before the green time ran out. The queuing vehicles at one of his studied intersections were usually fully discharged some time before the green interval expired; the vehicles at the end of the queue still had shorter headways. He suggested that smaller headway at the end of a long queue may be an inherent nature. A similar trend was observed in Auckland by Chaudhry (*11*). The possible reason provided to explain that trend was similar to Lin's. Drivers located at the back of the queue were aware that they were more likely to not make it through the intersection than those located at the beginning of the queue with the expiring green interval. This awareness possibly influenced drivers queued back to keep smaller headway with their preceding vehicle. PP Dey (*12*) studied the queue discharge characteristics under mixed traffic conditions, and found a clear gradual compression pattern. The highest observed discharge speed at the reference line did not exceed 22 mph in that study. Lee (*13*) also observed headway compression trend as queues got longer for small cities.

Akcelik and Besley (*14*) did not observe headway increase even with very long green intervals of some intersections in Melbourne and Sydney, Australia. Akcelik et al (*15*) developed an exponential function headway model to describe the relationship between the departure headway and the time since the start of green interval. In his model, the minimum queue discharge headway is considered to happen at the end of the queue, where the discharge speed is the highest.

Headway Elongation

On the other hand, some other researchers found the headways would get longer after a certain point of time as the discharge continued. Teply (*16*) conducted a study in Canada, and found that the headway usually rose after about 50 seconds of green interval. He considered that saturation headway depends on site-specific conditions, the duration of green interval and type of community. In another paper, Teply and Jones (*17*) pointed out that different traffic situations, different reference lines, and different points of reference of vehicles used for counting headway might cause varying headways observed in different regions. The Canadian Capacity Guide (*18*) considered that some drivers in the back of a long queue became less attentive, and their headways would be longer. The guide provided some saturation flow adjustment factors based on the duration of the green interval. Li and Prevedourous (*19*) studied one approach of an intersection in downtown Honolulu, Hawaii. They found that the headway of the through movement reached the lowest value between vehicles 9 and 12 and then increased after the 12th vehicle. They stated that the vehicles may exceed 40mph when reaching the stop line, and conservative drivers may increase their spacing or drive at a lower speed for safety. The large gap also increased the chances of motorists' lane changing, which also caused longer headways for through traffic. In their study, the observed left turn headway continued to decrease after 12 vehicles. A possible reason stated in the study was that motorists understood the limited duration of the LT phase and tailgated to avoid missing out on the green interval. Denney (*20*) analyzed one intersection in Virginia, and considered the gaps left by departing turning vehicles in the through lanes as the cause of the increased through headways with long green interval. The intersection studied is located in a very rural area, and there is no business around the intersection. The intersection was later upgraded into an interchange. Day et al. (*21*) analyzed an oversaturated intersection in Indianapolis, by applying the critical lane concept with varying cycle lengths. Their findings implied that the headway increased at some point into green for a long green duration.

OPTIMAL DISCHARGE SPEED

Figure 1 shows a typical freeway bottleneck, the basic relationship between speed and flow for the traffic on the freeway segment after this bottleneck can be illustrated by the curve in Figure 2. This curve was identified by many empirical studies in the past and has been recognized in the transportation engineering field. There is an optimum speed (critical speed) or a range of speeds at which the flow is maximized. The flow rate decreases when the speed is either higher or lower than that optimum speed.

The region B of the curve in Figure 2 represents spot speeds and flow rates under saturated conditions that can be observed at different points downstream of the bottleneck in Figure 1 (*15*). Intuitively, the further downstream from the bottleneck, the higher speeds the discharge traffic will reach, and the higher the flow rates will get. We have V1<V2<V3 and Q1<Q2<Q3, where V represents speed and Q represents flow rate. At a certain distance further downstream from the bottleneck, the flow rate reaches a maximum value Q_m with traffic speed at V_o, the optimum speed (critical speed). Even further downstream, conditions are changed to region A of the curve in Figure 2. The speed continues to increase and the flow rate begins to decrease.

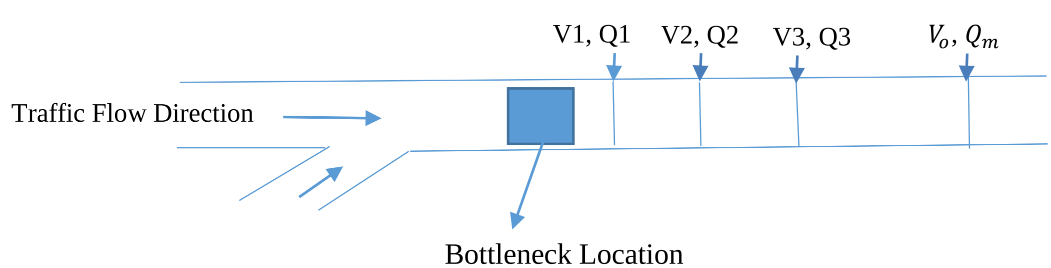

Figure 1 Freeway Bottleneck

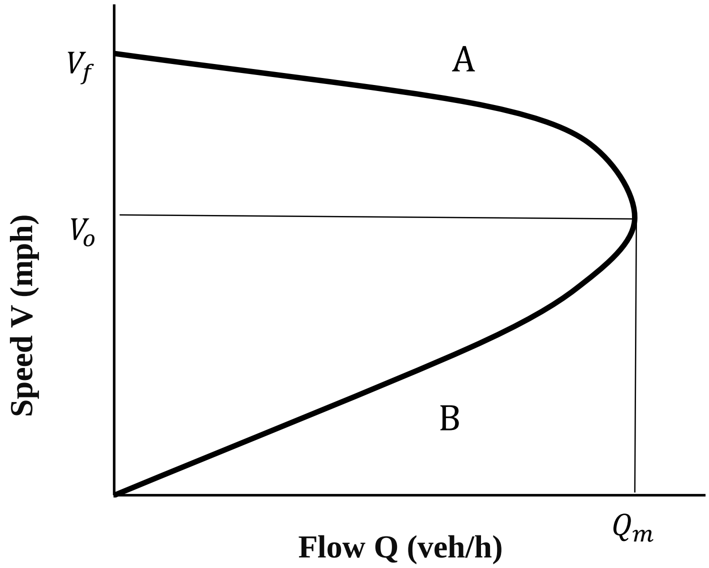

Figure 2 Speed and Flow Curve

The spot speeds and flow rates discussed above are measured at different locations downstream of the bottleneck. The bottleneck location remains unchanged. For a queue of traffic discharge from a stop bar under a traffic signal control, the speeds of the vehicles passing through the stop bar continue to increase as the vehicles motion starting point moves further and further away from the stop bar. Imagine the vehicle motion starting point as the bottleneck, the spot speeds and flow rates measured at the stop bar during a long green signal interval are equivalent to those measured at different locations downstream of the bottleneck discussed above. The flow rates increase as the discharge speeds at the stop bar increase until reaching to an optimal speed value, then the flow rates begin to decrease as the discharge speeds continue to increase.

In light of the above discussion, logically the intersection discharge speed and saturation flow rate may possess a similar relationship and pattern illustrated in Figure 2. The environment around an intersection usually is more complicated than that around the freeway segment. Drivers pay attention to the signal, signs, businesses, etc. around the intersection. These information points (*22*) would effectively lower the optimum speed that produces the low discharge headways. The optimal discharge speed at an intersection should be lower than the optimum speed (critical speed) at a freeway segment in most cases. Other factors that can affect the value of optimal discharge speed at a specific site may include roadway and intersection configurations, pavement surface quality, roadway speed limit, vehicle types and acceleration ability, and characteristics of driver population.

The conflicting findings in the trend of discharge headways discussed in the literature review section can be explained by this optimal discharge speed concept. For a queue of traffic to discharge from an intersection, if the discharge speed quickly reached the maximum discharge speed which was at or below the optimal discharge speed, the discharge headways would remain constant; if the discharge speeds continued to increase but never exceeded the optimal speed in the whole discharge process each cycle, the headway would show a compression trend;

For example, in the PP Dey (*12*) study, the highest observed discharge speed did not exceed 22 mph, a clear gradual compression pattern of discharge headways was observed. In Akcelik et al (*15*) study report, only one out of the 16 studied sites was characterized as located in a central business area. The attached intersection pictures in the report showed that majority of those studied intersections were located in quite rural areas. There were few information points (*22*) around those intersections. The drivers would have a greater chance to concentrate on driving; therefore the optimal discharge speed would be relatively high. The highest average site discharge speed reported in their report was 34.8 mph. So it was very possible that the highest discharge speed achieved in those studied sites never exceeded their optimal discharge speeds, and this relationship decided a steady headway trend after initial headway decrease.

If the discharge speeds at a certain point exceeded the optimal discharge speed, the headways will begin to increase. The headway elongation trend would be observed. For example, in the Li and Prevedourous (*19*) study, the observed vehicle discharge speeds at the back of the queue were over 40 mph.

The ultimate discharge speed achieved at a study site can be affected by various factors such as roadway configurations, pavement surface quality, roadway speed limit, vehicles types and acceleration ability, characteristics of driver population and information points around the intersection. Besides these the factors, queue length, green interval length, downstream interference, and how far away the downstream intersection is could be the deciding factors in determining the maximum discharge speed.

All of previous research (*9, 3, 10, 19*) reviewed indicated a steady increase of saturation flow rate for left turn lanes. This optimal discharge speed concept offers another possible reason: the discharge speed is well controlled. The discharge speed cannot go as high to exceed the optimal speed due to the limited turning radius.

One busy signalized intersection with long traffic queues in Toledo, Ohio was studied to identify its queue discharge characteristics such as the discharge headway trend and optimal discharge speed.

SITE SELECTION

Secor Rd/ Monroe is a busy intersection in Toledo, Ohio. Westbound approach inner through lane movement at this intersection was studied. Westbound has a two-way left turn median and left turn storage is relatively long, so the left turning vehicles in upstream through traffic can exit to left turn lane early without affecting the through traffic discharge headways. There are many retail shops around the intersection such as Walgreens and Shell gas station. The speed limit is 35 miles/hour for this segment of the street.

DATA COLLECTION EQUIPMENT AND METHOD

The data collection for intersection of Monroe/Secor was through videotaping so that the discharge headways for different queue positions and the associated discharge speeds could be accurately estimated through the video clips. Data Collection time periods are focused on PM peak hours (3:00-5:00 PM) under sunny or partly cloudy weather conditions, normal traffic, no incidents, and no construction activities.

IPhone 5 was used for video recording the intersection. The IPhone 5 could be installed into a rubber case which was taped onto a wood pole. The pole was taped to a pedestrian pole at the intersection as shown in Figure 3. This setup can minimize the distraction to drivers and help to get more authentic field data. During each green interval for the studied movement, the observer waves a hand in front of the camera when the last queued vehicle passes the stop line. This provides an indication that the vehicle is the last to be studied for that signal cycle during video clips analysis.

Figure 3 Videotaping Equipment Setup

In the video clips analysis, the researcher notes the frame numbers at the beginning of the green indication, and at the time when each of the vehicles' front axles crosses the stop line until the last queued vehicle each signal cycle.

If the video was recorded at a constant 120 frames per second, 1/120 second elapses each frame. The product of 1/120 second per frame and the total number of frames n between two consecutive discharging vehicles is the time headway between the two vehicles. With a known short distance near the stop bar d and the time t it takes for a discharging vehicle to cover that distance, the discharge speed can be calculated as $v=d/t$. In this study a red dot was painted onto the pavement surface 10 feet after the stop line. The time for the vehicle to cover that 10 feet distance can be calculated from the number of frames elapsed from the vehicle's front axles crossing the stop line to the vehicle's front axles crossing the red dot.

Buses, mid-sized delivery trucks, and large trucks were excluded from the analysis to avoid the random impact of large vehicles on queue discharge. All the vehicles behind a large vehicle were also excluded. Thus, the observations mostly consisted of passenger cars, small vans and pickup trucks.

DATA ANALYSIS

Table 1 summarizes the averages of the observed discharge headways and speeds and their related sample sizes for each queue position.

TABLE 1 Queue Discharge Characteristics at Monroe/Secor

Queue Position	Average Headway (s)	Flow Rate (vph)	Average Discharge Speed (mph)	Sample Size
1	2.85	1263	6.5	250
2	2.78	1295	11.3	250
3	2.49	1448	15.5	250
4	2.30	1565	18.1	250
5	2.03	1773	20.7	248
6	2.04	1765	21.5	245
7	2.01	1791	23.8	237
8	1.96	1837	24.0	226
9	1.94	1854	25.1	208
10	1.80	2000	25.5	192
11	1.75	2057	26.9	171
12	1.72	2093	27.0	158
13	1.85	1946	28.5	144
14	1.96	1837	30.1	130
15	1.99	1813	30.4	111
16	2.07	1739	31.6	98
17	2.11	1709	32.0	75
18	1.88	1915	33.7	54
19	1.76	2045	33.8	14
20				

To provide a better insight into the characteristics of queue discharge at the study site, the headway and speed data in Table 1 are presented graphically in Figure 4 and Figure 5 respectively. Figure 4 shows the average headway by queue position for the westbound inner through movement at the intersection of Monroe/Secor. The headway reached the minimum at queue position 12, then increased afterwards. This headway elongation trend is in agreement with the findings from previous studies (*16, 17, 19, 21)*.

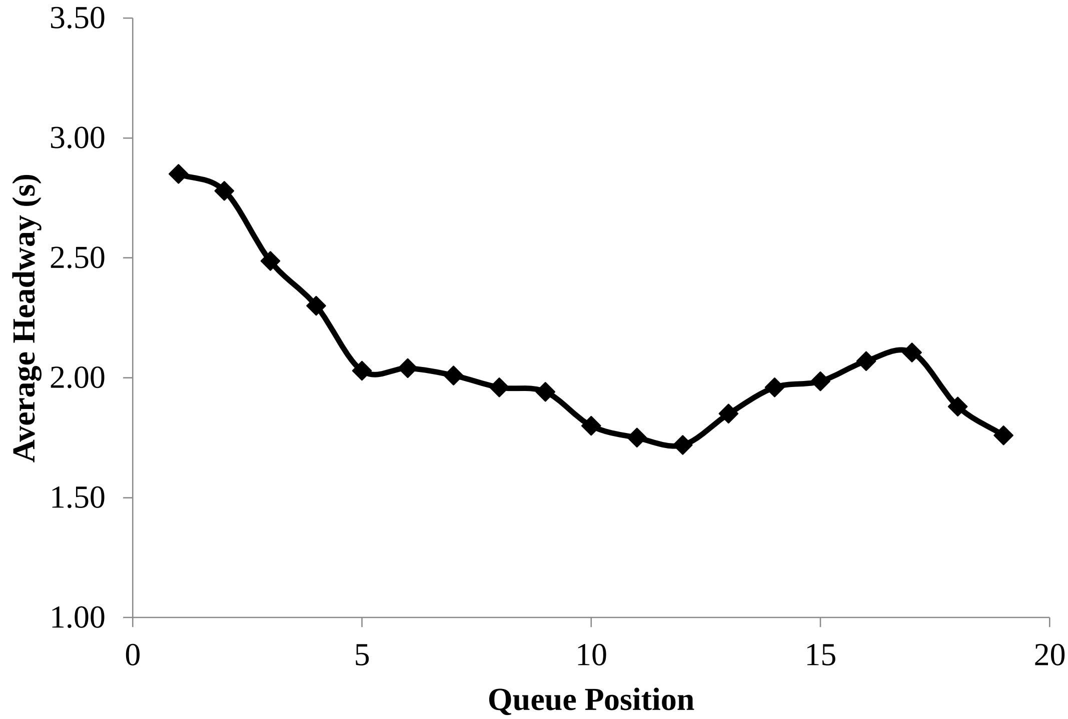

Figure 4 Average Headway by Queue Position at Monroe/Secor

Figure 5 shows the average discharge speed at each queue position. The average discharge speed at queue position 12 was at 27 mph as shown in Figure 5. Since the average discharge headway at queue position 12 is the lowest, 27 mph is the optimal discharge speed. As the speed continued to increase, the headway showed an increasing trend. This can be explained that as the speed increases, the information points (*22*) would have greater impact on some of the motorists who were located at the latter part of the queue. Also, conservative drivers would lengthen their distances with the preceding vehicles as the speed increases. These two factors would contribute to longer headways. At the same time, drivers who were attentive, assertive, and aggressive had the opportunity to press their headways as the speed got higher and spacing between vehicles became relatively long. This factor shortens the headways. But this factor could not overcome the effects of the first two factors when the speed exceeded the 27 mph optimal discharge speed at the study site; therefore an increasing average discharge headway trend was demonstrated after queue position 12. At the last two queue positions 18 and 19, the headway values decreased. This was due to the display of yellow light making most drivers at the end of queue rush through the intersection.

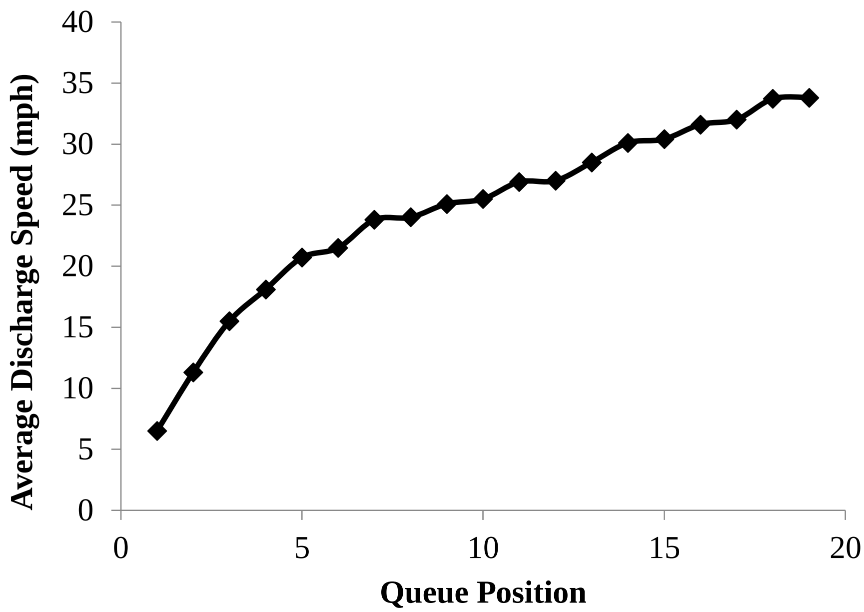

Figure 5 Average Discharge Speed by Queue Position at Monroe/Secor

Figure 6 shows the curve between average discharge speeds and discharge rates. As mentioned earlier, the last queued vehicles typically rushed through the yellow light. In order to see more clearly the general nature of the curve, the data of the last two queue positions was not used in this illustration. The general shape of this curve resembles region B and a portion of region A of the curve in Figure 2. This similarity was expected for the reasons discussed in the optimal discharge speed section. If the maximum discharge speed achieved at this site was higher, we would be able to see more curve that resembles region A of the curve in Figure 2.

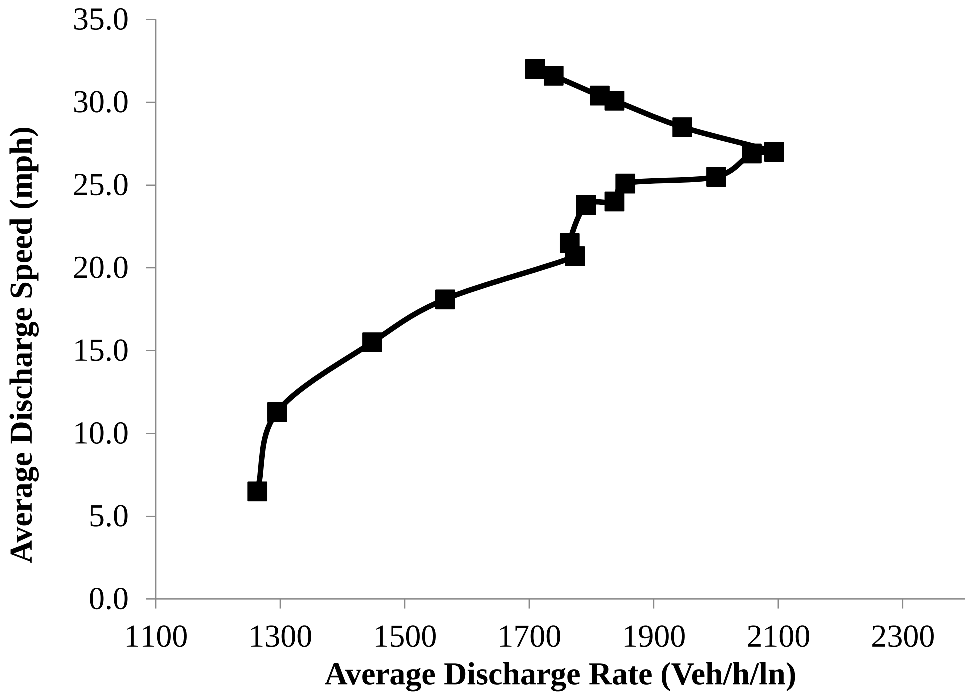

Figure 6 Average Discharge Speed and Discharge Rate at Monroe/Secor

One-way analysis of variance (ANOVA) test was conducted using Minitab to determine the significance of the differences among the average headways of queue position 6, 12 and 16. Table 2 shows the summary. With both the Tukey method and the Fisher method, the average headway of queue position 12 is significantly different from the other two queue positions at 95 percent confidence level, whereas the headways of queue 6 and 16 are not significantly different from each other.

Table 2 ANOVA Test

Queue Position	Sample Size	Mean	Grouping*
6	245	2.04	A
12	158	1.72	B
16	98	2.07	A

* Means that do not share a letter are significantly different.

CONCLUSION AND FURTHER DISCUSSION

The queue discharge characteristics at one signalized intersection located in Toledo Ohio were studied. The discharge headways of through lane traffic demonstrated an elongation trend. The optimal discharge speed that was associated with the lowest average headway was identified as 27 mph. From this study results and previous research findings, this paper presented an optimal discharge speed concept. The relationship between the optimal discharge speed and the maximum discharge speed achieved at a study site determined the trend of discharge headways. The factors that could affect the values of optimal discharge speed and the maximum discharge speed were discussed in this paper. Knowing the optimal discharge speed at a signalized intersection can help to optimize the signal timings to control the traffic queues and increase intersections throughput. Also, the optimal discharge speed provides an important parameter in stretched intersection design (*22*) to reduce startup delay and increase saturation flow.

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