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Comparing the Saturation Flow Rate on the Exit Lane Between Urban Multilane Roundabouts and Urban Signalized Intersections Through Field Data

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Abstract: Urban multilane roundabouts and signalized intersections are two major roadway devices used for controlling and managing traffic flow. This paper presents a comparative analysis of the saturation flow rate between urban multilane roundabouts and multilane signalized intersections using field data from the Dammam Metropolitan Area (DMA) in Saudi Arabia. The data of this study were collected at four roundabouts and four signalized intersections in Dammam metropolitan area (DMA), Saudi Arabia. A total of 7028 saturation headways at the roundabouts and 2626 saturation headways at the signalized intersections were included. The results indicated that the signalized intersections had a higher saturation flow rate at the exit lane than the roundabouts at about 1046 vehicles per hour. These findings emphasize that signalized intersections outperform roundabouts in terms of the vehicular movement rate during green lights. Moreover, when the light is green, it takes 1.82 s for a car to move through the middle lane of a traffic light intersection. This study draws a unique connection between speed fluctuations in roundabouts with energy consumption, concluding how vehicles consume more energy this way. Thus, single-lane roundabouts are recommended for optimal traffic flow management in all directions.

Keywords: saturation flow rate; exit middle through-lane; signalized intersection; roundabout; field data

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1. Introduction

Roundabouts are a form of road intersection control, where traffic is directed to circulate around a central island, facilitating smoother traffic flow. Intersections are designed to regulate traffic, ensuring both safety and capacity in urban environments [1]. The concept of roundabouts was first introduced in the United States in 1905, and since then, they have been adopted worldwide due to their efficiency, especially in managing the weaving and merging of high-speed vehicles [2].

On the other hand, signalized intersections use traffic lights to control the duration and sequencing of traffic movements. These intersections are usually suitable for areas with huge volumes of traffic, as they manage the allocation of time and space to specific traffic flow. Signalized intersections are known for their effectiveness in reducing 32 conflict points between vehicles and pedestrians [1].

Several studies have focused on evaluating the safety and operational performance of roundabouts [3–8]. These studies have reported that roundabouts can reduce noise and delays, though they may increase gas emissions and air pollution. Moreover, even though an increase in roundabouts has been linked to an increase in overall traffic flow, a reduction in the severity of accidents has also been observed. This is due to the fact that roundabout traffic flow is determined by driver behavior and their decision-making regarding gap acceptance as they turn around the central island. Thus, many accidents at roundabouts are low-impact-angle collisions, without injuries and fatalities. In contrast, the flow at signalized intersections moves perpendicularly during designated green-light periods. As a result, even though accidents at signalized intersections are less frequent, they are often severe and pose a higher risk of injuries and fatalities.

Even though much research has been carried out on roundabouts, most of the studies have focused on their performance, with limited direct comparisons to signalized intersections. This study seeks to address this gap by providing a comprehensive analysis of the saturation flow rate at urban roundabouts and signalized intersections. Using field data from Dammam in Saudi Arabia, an area with limited research on traffic flow patterns and infrastructure, this study is set to provide novel insights into the comparative performance of these two intersection types during peak hours.

2. Literature Review

Roundabouts are effective in reducing conflict points [9,10]. Converting signalized intersections to roundabouts has emerged as a common practice to reduce conflict points, resolve roadway issues, and improve traffic operations [2,11]. Ramadan et al. [12] found roundabouts to be most effective in managing medium traffic for maximizing capacity and minimizing delays, whereas signalized intersections were better for managing heavy traffic and high left-turn volumes. Similarly, Islam et al. [13] found roundabouts to be effective in preventing congestion at peak hours in Chittagong City. Leonardi and Distefano [14] compared multilane and turbo-roundabouts in Italy, finding turbo-roundabouts to be more effective for high traffic volumes. However, this approach requires careful consideration of its implications. Figures 1 and 2 show typical configurations of urban multilane roundabouts and signalized intersections.

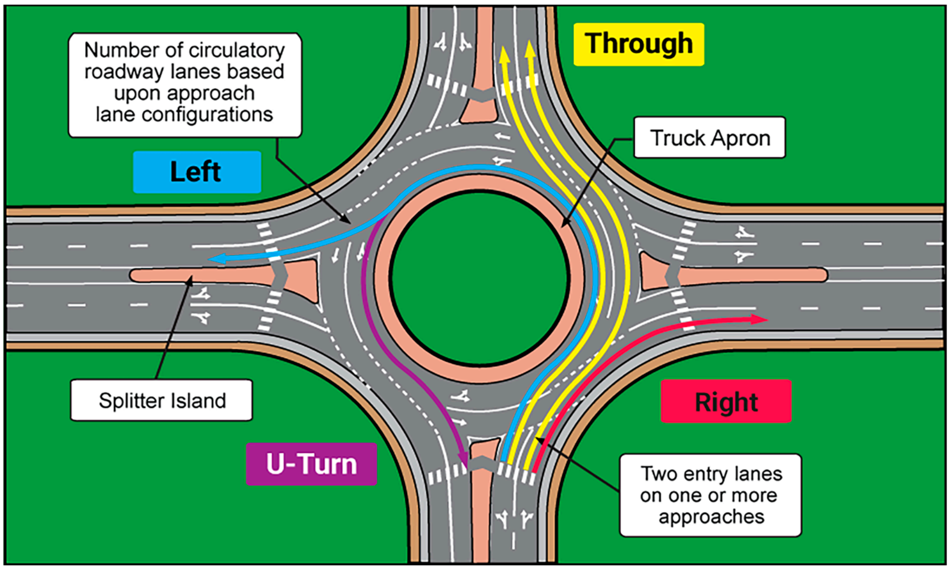

Figure 1. The geometrical design of an urban multilane roundabout.

Recent studies have compared various aspects of traffic operation between signalized intersections and roundabouts, including safety, air emissions, noise pollution, delay, and performance [15–19]. Moreover, roundabouts have been shown to reduce the severity of accidents, particularly in urban areas where perpendicular collisions are more common. Table 1 summarizes the findings and shows that roundabouts offer improvements in accident severity, air pollution, and performance. However, existing research often overlooks factors such as construction costs and the comparison of saturation flow rates at the exit lanes of both intersection types [2–9,11–19].

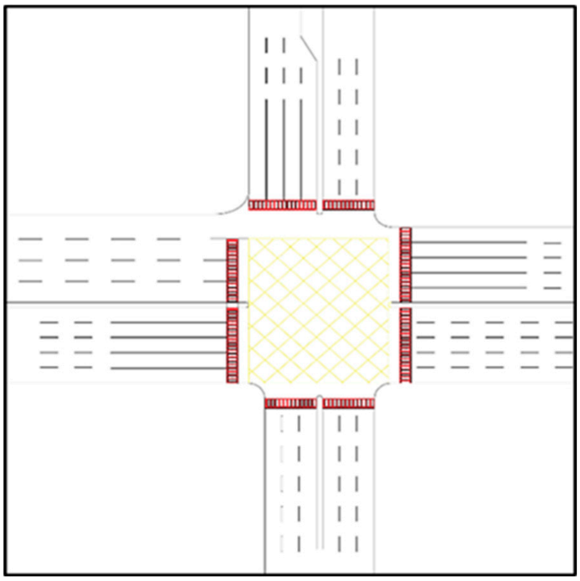

Figure 2. The geometrical design of an urban signalized intersection.

Table 1. A comparison between signalized intersections and urban multilane roundabouts.

Factor Location	Number of Accidents	Severity of Accidents	Air Emissions	Noise Pollution	Average Delay per Vehicle	Performance and LOS	Example Studies
Urban Signalized Intersection		✓		✓	✓		[2,5,6,8,9,18]
Urban Multilane Roundabout	✓		✓			✓	[2,7–9,11,16,17,20]

The mark ✓ indicates a high rate.

A few studies have compared the capacity of roundabouts versus signalized intersections [21,22]. Zhou et al. [19] and others [21,22] used simulation models to evaluate average saturation headways at entrance lanes or roundabout middle lanes. However, such models are limited in representing real-world conditions, as they fail to account for critical factors like driver behavior, reaction time of drivers, acceleration, and gap acceptance [19]. On the other hand, measuring the saturation flow rate at exit lanes provides more reliable data, since drivers tend to maintain a steady speed. This makes the flow rate easier to measure [21].

Studies have reported that the flow rate at roundabouts is higher than signalized intersections, with an average of 1300 vehicles per hour per lane, partly due to a two-second increase in saturation headway at the roundabout lanes. Roundabouts experience a higher saturation headway because vehicles must yield and merge into circulating traffic, causing slight delays between vehicles. Even though simulation models are cost-effective for testing scenarios, they need to be calibrated with real-life situations to represent actual road conditions, as determined by Zhou et al. [19]. According to Curchoe [23], simulation models are useful for presenting macroscopic traffic operations but are ineffective on the mesoscopic and microscopic operation levels.

Several studies have failed to properly estimate the flow rate at roundabouts by collecting data only from the entrance or middle lanes. This does not accurately reflect the lane's productivity at the roundabout [22,24]. The capacity of the lane shows the maximum average flow rate of passenger vehicles during peak hours under saturated conditions, and environmental factors such as weather, number of pedestrians, and buses [25]. Figure 3 shows the concept of departure rates and effective green time at a traffic signal.

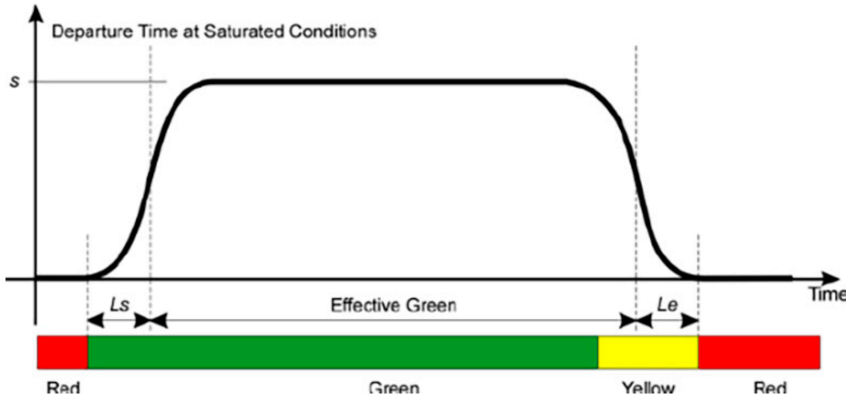

Figure 3. Departure rates and effective green time [26].

This study focuses on comparing the average saturation discharge headway at the exit lanes of urban signalized intersections and multilane roundabouts under saturated conditions using field data. It offers a fresh perspective on comparing the flow rate behavior and productivity between urban signalized intersections and multilane roundabouts.

3. Materials and Methods

3.1. Study Design and Area

This study used a comparative approach to analyze the saturation flow rate between multilane roundabouts and four-leg signalized intersections using field data from four signalized intersections and four roundabouts in the Dammam Metropolitan Area (DMA), Saudi Arabia. The DMA is ranked as the third-largest urban area in the country [27]. The DMA includes Dammam, Khobar, and Dhahran, with a population of 1.166 million in 2018, making it one of the seven metropolises comprising the 33 million people in the country. The area covers 562 km^2, with a population density of approximately 2000 persons/km^2. The area is now divided into four settlements, namely, Dammam, Khobar, Dhahran, and the suburbs of Aziziyah and Half Moon Bay [28].

The DMA is a major link for travelers between Gulf countries. The first oil field, called field seven, was discovered between 1860 and 1900. It offers numerous job opportunities and has 63 residential neighborhoods, 3 urban centers, universities, an airport, and shopping centers. Figures 4 and 5 show the study locations in the DMA. Figure 5 shows the distribution of the cities and several major districts in DMA.

The DMA's roadway network includes 4 highways, 4 arterial roads, 12 major roads, and numerous collectors and local roads, with 108 signalized intersections and 10 roundabouts [29]. This study collected data on the saturation discharge headway at four signalized intersections and four roundabouts on major and arterial roads [4,5,7]. The traffic and environmental conditions at these locations differ from those in previous studies [3–8,17–21,30].

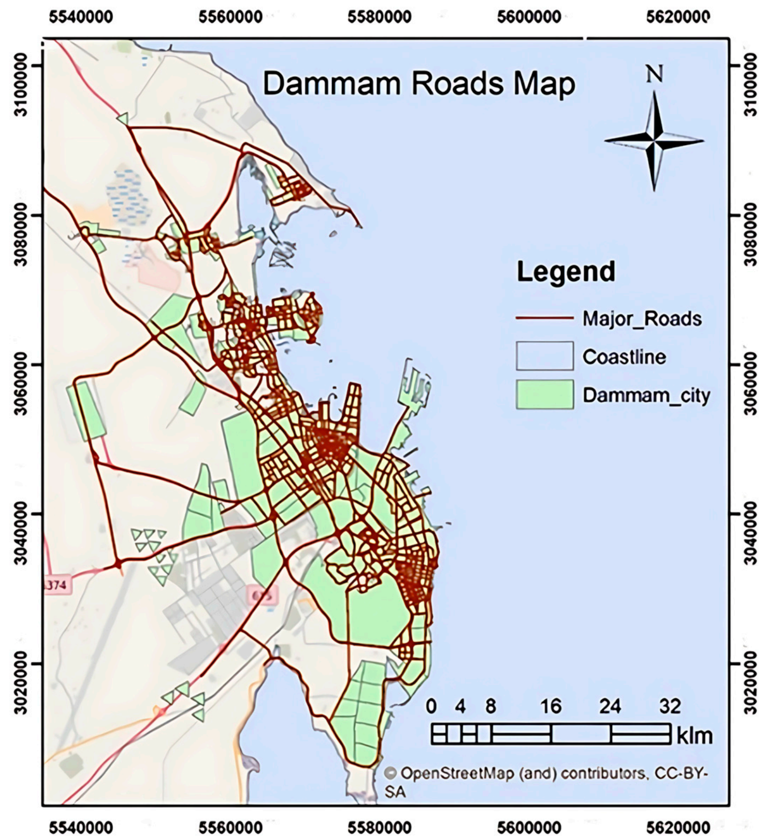

Figure 4. Distribution of major roads in the DMA.

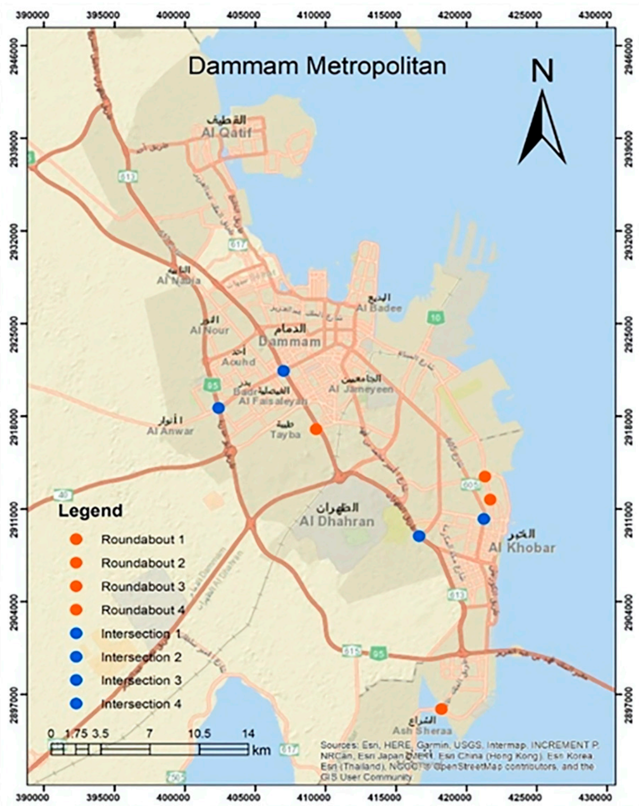

Figure 5. Spatial distribution of the study locations in the DMA.

3.2. Data Collection

Saturation discharge headway data were collected, comprising the time headways between vehicles on exit lanes at signalized intersections and roundabouts in the DMA. Only data from useful cycles at four signalized intersections were included. Useful cycles were defined as signal phases with 10 or more vehicles in the queue on the targeted approach. Forty surveyors, divided into eight groups of five, recorded data during peak traffic hours at four study locations (legs of four roundabouts and signalized intersections). Among the five surveyors per group, four were assigned to record the data, with one supervisor overseeing the process. Data were collected from September to December 2021 during regular weekdays and during peak hours (8:00 a.m. to 6:00 p.m.) under regular traffic, environmental, and weather conditions. Surveyors recorded data for one leg at each location. The method for identifying the study locations and recording data at the legs of these locations included the following:

1. Examining the typical configuration of the roundabout and signalized intersection.
2. Identifying the configuration of the study locations.
3. Figuring out the prevailing environmental and traffic conditions around the location to determine the required adjustment factors on the average saturation discharge headway.
4. Counting the average hourly volume from 8 a.m. to 6 p.m. to identify the saturation peak hour at the location.
5. Enumerating the number of heavy vehicles to identify the percentages of heavy vehicles at the location and calculate the associated adjustment factor for the presence of heavy vehicles.
6. Recording the discharge saturation time headways between successive vehicles on the exit through the through-lane at the approach of the departure legs of the locations.

Data recording points were set 25 m from the stop line at the four signalized intersections and 25 m from the crosswalk at the four roundabouts. To ensure accurate data on normal vehicle acceleration and returning to the desired speed, data for the through-lane were recorded 25 m away. Stopwatches and time-recording apps on smartphones were used for data collection. Data from the left and right turning lanes were excluded to provide a clearer picture of traffic flow, targeting only the through-lane where vehicles went straight through the intersections.

A total of 5627 saturation discharge time headways were recorded at the four signalized intersections, and 7028 headways were recorded at the four roundabouts. The intersections were selected based on criteria representing typical configurations and conditions in the DMA. The list below summarizes the typical configurations and prevailing conditions at the selected study locations:

- Locations on arterials and major roads.
- Locations with four-leg approaches.
- Locations having 10 or more vehicles in line at the signalized intersections during red lights.
- No lanes or bays exclusively
- Headway at the saturated environments during peak hours.
- Lanes that were 11 to 13 feet wide.
- Cycle length of 270 s at the signalized intersections.
- The presence of heavy vehicles.
- Locations with no grade or parking and without buses or pedestrians in a circle of 250 feet.

Based on the above-mentioned conditions, four roundabouts met the requirements for data collection [31]. These roundabouts and the four signalized intersections are shown in Figure 5. The sample size for the average saturation discharge headway at each location was based on vehicles exiting the middle lanes.

3.3. Data Extraction, Reduction, and Analysis

The strategy used for extracting and selecting the data was based on the National Academics of Sciences, 2016. Equation (1) was used to estimate the mean saturation flow rate per lane:

$$s = 3600/hr \quad (1)$$

where s denotes the mean saturation flow rate for an hour/lane, and hr denotes the mean time of the headway between successive vehicles during a saturated normal environment and in prevailing traffic conditions.

Data reduction was performed by focusing on instances where 10 or more vehicles were queued simultaneously at each of the four roads at the signalized intersection. After data reduction, the total number of extracted samples of the average saturation discharge headways consisted of 2626 samples at the signalized intersection locations. The data from the roundabout locations did not require reduction and were continuously recorded during peak hours. As a result, the total data from the four urban multilane roundabout locations included 7028 samples.

The collected data were tested for normality to ensure the validity of the comparison analysis and statistical tests. Because of the large sample size, the data were assumed to be normally distributed [32]. The average time gaps between vehicles at each location were then plotted for analysis. A t-test was conducted after adjusting for the presence of heavy vehicles to compare the means of the saturation discharge headways at both the signalized intersection and multilane roundabout locations. The t-test was chosen due to the absence of a population standard deviation and the assumption of a normal distribution for the data [33].

Calculation of the Adjustment Factors for Heavy Vehicles

The data collected from heavy vehicles were used to extract the adjustment factors for the saturation discharge headways. The method for extracting these adjustment factors followed the methodology outlined by the National Academies of Sciences. The percentage of heavy vehicles was calculated from the collected data using Equation (2):

$$\mathrm{F_{hv}} = 1/1 + \mathrm{Phv}\ (E_{hv} - 1) \quad (2)$$

where Fhv is the adjustment factor to show the existence of heavy vehicles, Phv is the percentage of heavy vehicles, and Ehv is the equivalency of heavy vehicles to passenger vehicles. According to the level of the configuration of the study locations, a value of 1.5 was used as the equivalency of heavy vehicles in Equation (2).

4. Results

The data obtained from all the locations were then processed through Sidra and Synchro for analyzing data. Table 2 shows the data sample, average hourly volume, peak hour, percentages of heavy vehicles, and the associated adjustment factor for the presence of heavy vehicles per study location.

Table 2. Summary of the average saturation discharge headway on the exit lane.

Variable Location	Peak Hour	Hourly Volume (Vehicles/Hour for Multiple Lanes)	Heavy Vehicles (%)	Adjustment Reduction Factor for Heavy Vehicles	Exit Lane Average Saturation Discharge Headway (Seconds)	Exit Lane Average Saturation Discharge Flow Rate (Vehicle/Hour)
Signalized Intersections						
Location 1	5–6 p.m.	2276	0.0%	1	1.04	3462
Location 2	4–5 p.m.	5100	5.0%	0.975	2.42	1488
Location 3	4–5 p.m.	2252	1.5%	0.994	1.97	1827
Location 4	4–5 p.m.	9672	3.0%	0.983	1.86	1935
Average	*	4825	*	*	1.82	1978
Roundabouts						
Location 1	4–5 p.m.	2308	3.5%	0.983	4.43	813
Location 2	4–5 p.m.	5056	3.0%	0.984	4.37	824
Location 3	5–6 p.m.	2400	18%	0.917	3.05	1180
Location 4	11–12 a.m.	5844	21%	0.904	3.58	1006
Average	*	3902	*	*	3.86	932

* represents the calculation of average is not required.

On average, cars at the roundabouts took approximately 2.04 s longer to follow one another compared to those at the signalized intersections. This suggests that more cars can pass through a signalized intersection during a green light as compared to a roundabout in the same amount of time. For example, about 1046 cars could pass through a single lane at the signalized intersections in one hour, which is faster than at the roundabouts. In other words, signalized intersections can accommodate about 1046 more cars per hour than roundabouts, assuming similar traffic conditions. This flow rate was computed based on the observed saturation headways and traffic conditions at the study locations. Overall, the findings emphasize that signalized intersections provide a faster and more efficient flow of traffic, whereas roundabouts require drivers to wait for gaps and experience slower vehicle acceleration.

Figures 6 and 7 present the frequency distribution of the average saturation discharge headways occurring on the exit or departure lane at the four signalized intersections and urban multilane roundabouts. This figure illustrates just how long on average it takes for cars to pass through these lanes. Some of the discharge headways or time gaps were very small, meaning that cars were closely following or tailgating each other, resulting in low values. It is important to note that the low values are significant because if they were removed, the comparison between the two types of traffic control (signalized intersections vs. roundabouts) would become inaccurate due to a lower overall average discharge headway.

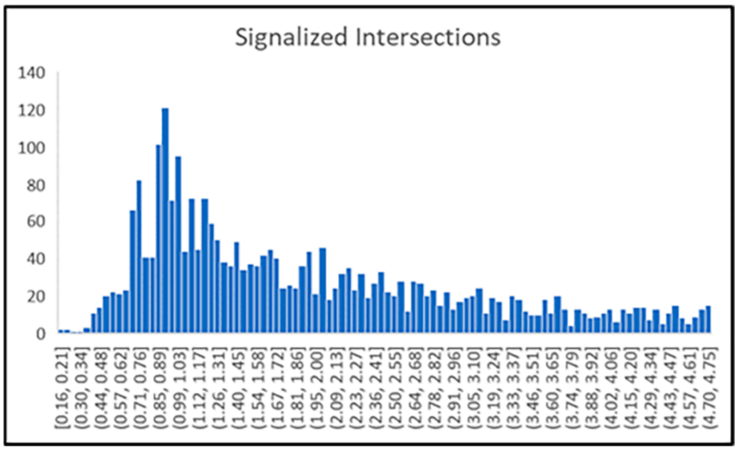

Figure 6. Frequency distribution of the saturation discharge headway and the number of vehicles at the four signalized intersections.

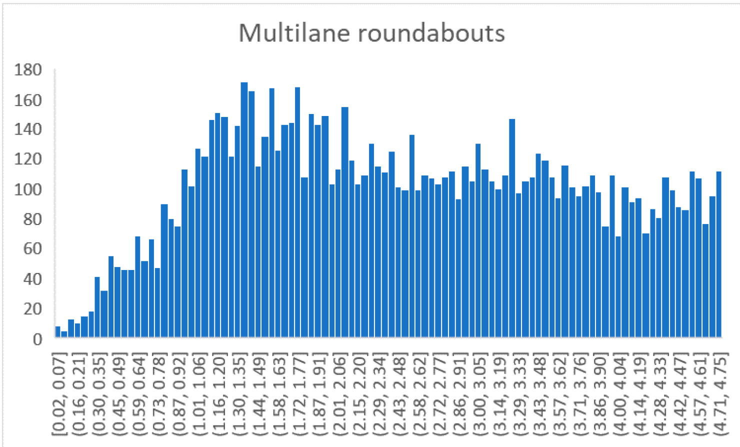

Figure 7. Frequency distribution of the saturation discharge headway and the number of vehicles at the four urban multilane roundabouts.

A statistical analysis of the saturation discharge headways between the four signalized intersections and four roundabouts was conducted, and the results are shown in Table 3. In this table, descriptive statistics such as the mean, standard deviation, and other means of summarizing the data for both the signalized intersections and roundabouts are shown to better demonstrate the typical behavior of traffic flow at both kinds of traffic control. Student's t-test was conducted on the data shown in Table 3, comparing the average saturation discharge between two types of traffic control. The analysis suggests the presence of a significant difference between the two groups. This means that the real difference in the traffic flow at each location is reflected in the observation of the difference in the time gaps between vehicles at the intersections and did not occur due to random chance. The findings highlight the data normality to be skewed towards the left, when ideally the data should be following a normal distribution. Although the data are skewed towards the left, they still show a tendency towards normality. The skewness towards the left indicates a higher number of lower-than-average headway values, especially for the roundabouts. This skewness is related to the large sample size, which led to variations. Additionally, the skewness could have been attributed to the inclusion of a high value at the roundabouts, since there was a continuous flow of vehicles and the presence of gap acceptance behavior among the drivers at the roundabouts.

Table 3. *t*-test analysis of the saturation discharge headway between signalized intersections and multilane roundabouts.

Location	Sample Size	Mean	Median	Mode	ST. D	p-Value
Signalized Intersection	2626	1.82	1.59	0.85	1.10	4.544×10^{-132}
Multilane Roundabout	7028	3.86	2.43	1.60	1.20	

In contrast to the roundabouts, very few data values were recorded at the four signalized intersections that were greater than 2.5 s. This was associated with the car-following behavior that occurred during the green-light phase when cars closely followed each other, resulting in shorter time gaps between vehicles. This close following behavior is mostly promoted due to the kinds of traffic operation and control at signalized intersections, leading to consistent and short headway values as compared to roundabouts. In summation, Table 3 illustrates a clear contrast between signalized intersections and roundabouts. Moreover, the statistical analysis confirms that the differences were not due to random variation; rather, they hold significance.

5. Discussion

This study investigated and compared the saturation flow rate on the exit and middle through-lanes between multilane urban roundabouts and urban signalized intersections during normal environmental and prevailing saturated traffic operation conditions. The findings showed that the saturation flow rate at the exit lanes at the urban signalized intersections was higher than at the urban multilane roundabouts, with about 1046 vehicles per hour. This highlights the difference in the behavior of car-following and gap acceptance at 1046 vehicles per hour per lane. The results of the present study are in contrast with the results of Wu and Zhu [34], who compared the operational outcomes and performance of a signalized intersection (I-Signal), an intersection using the FCFS policy (I-FCFS), a roundabout via the typical major–minor priority pattern (R-MM), and a roundabout adopting the FCFS policy (R-FCFS) through CAVs. By applying queueing theory, the I-Signal method was found to have the largest capacity for separating conflict points but with a higher propensity for delays. The strategy with the least average control delay was R-FCFS, which emerged as optimal for CAV signal-free management.

The results of the present study are also dissimilar to the results of Ramadan et al. [12], who examined signalized intersections, two-way stop control, and roundabouts. They concluded that roundabouts were the most optimized strategy for intersection control, having a maximum capacity and minimum delays in certain conditions of medium traffic. However, signalized intersections were the optimal choice for regulating heavy traffic volumes and when there was a high proportion of left-turning volume. However, the present study's findings are similar to Islam et al. [13], who analyzed the traffic scenario of Bangladesh and inspected several peak hours at the Tiger-Pass intersection in Chittagong City. The study examined the possibility of using a signalized intersection in the form of a geometric design for creating a multilane roundabout. The results showed that roundabouts helped the vehicles in crossing the intersections without causing congestion and frequent halts.

A study by Leonardi and Distefano [14] conducted a cross-analysis of the operational and safety performance between multilane roundabouts and turbo-roundabouts in Italy. Two simulation software packages were used, including AIMSUN Next 20.0.1 for measuring operational performance and SSAM 3.0 aiming to gauge safety performance. The results showed that in scenarios with a low-to-medium flow of traffic, multilane roundabouts were effective and recorded higher operational performance. However, for managing a high volume of traffic flow, turbo-roundabouts were highly effective in terms of safety and operational performance. These results are aligned with the findings of the present study. Taking these results into consideration, the study suggested replacing all the multilane roundabouts by building turbo-roundabouts and introducing new laws related to the design of turbo-roundabouts.

Taglieri et al. [35] investigated the effects of roundabouts implemented at intersections and found that roundabouts had a better performance compared with signalized intersections allowing left turns in a permitted manner in the case of single roundabouts in terms of all operational metrics. However, in the case of roundabouts with two travel lanes, the performance of the signalized intersections prohibiting a left turn network was higher in terms of trip-serving capacities and flow-moving. The reduction in the performance of the roundabouts resonated with the complexity of the situation when an entering vehicle attempted to queue at the inner lane. Since vehicles attempt sporadically to decrease and increase their speed in roundabout networks, vehicles require more energy. Therefore, intersections of roundabouts are optimal when there is a single travel lane networking in all directions.

This study can be useful when examining the performance of these two types of intersections, particularly at the exit lane. Such insights can provide comprehensive insights for traffic management, district management, researchers, and students to compare and contrast the operational capacity and functionality of these approaches.

This study is by no means perfect and is therefore subject to certain limitations, including discrepancies in saturation headways across intersections, suggesting potential issues in the data collection. Moreover, even though this study presents empirical data on saturated flow rates at roundabout exits and signalized intersections, it lacks a model to explain the variability in these rates. This limits its contribution to new scientific knowledge. This study also failed to take into account the unique flow characteristics at roundabouts, such as the distribution of gaps determined by the entry capacity and the share of vehicles turning left around the roundabout island, which can cause increased gaps at the exit. These factors should be considered to provide a more accurate analysis of the saturated flow rate at roundabouts. Furthermore, the present study reported a low average value of 1.04 s for the exit lane saturation time interval at a particular location, which may not be within the more typical range reported in many studies. Several factors, including measurement errors, differences in local traffic, or infrastructure conditions at the location, might have caused this. Therefore, further investigation is needed to validate the accuracy of this value.

6. Conclusions

The findings of this study can help transportation officials in deciding to change the configuration of roadway networks from a signalized intersection to a roundabout and vice versa in order to enhance traffic operation and safety. Also, the findings can assist researchers and academics in comparing and calibrating different models with different driving behaviors, including car-following, gap acceptance, and lane-changing models. Future studies can compare the travel time, the level of service, configuration costs, and speed between urban signalized intersections and urban multilane roundabouts. In this study, the average delay of each vehicle and the service level associated with the operation of the signalized intersections and roundabouts were not recorded. Studies that have investigated the average delay of each vehicle at roundabouts reveal that the mean delay of each vehicle was recorded to be higher at signalized intersections. However, these studies have failed to include a comparative analysis of the exit lane saturation flow rate at locations during saturated, normal environmental, and prevailing traffic operation conditions. This study provides a unique connection of two factors, i.e., sporadic speed fluctuations at roundabouts and higher energy consumption by vehicles; therefore, single-lane roundabouts are suggested for optimal energy-efficient traffic management.

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