sustainability

MDPI

Article

Modeling of Queue Detector Location at Signalized Roundabouts via VISSIM Micro-Simulation Software in Amman City, Jordan

Amani Abdallah Assolie [1,*], Nur Sabahiah Abdul Sukor [1,*], Ibrahim Khliefat [2] and Teh Sabariah Binti Abd Manan [1]

[1] School of Civil Engineering, Universiti Sains Malaysia, Nibong Tebal 14300, Malaysia
[2] Department of Civil Engineering, Faculty of Engineering, AL-Balqa Applied University, Salt 19117, Jordan; khliefat@bau.edu.jo
* Correspondence: amaniassolie@student.usm.my (A.A.A.); cesabahiah@usm.my (N.S.A.S.)

Abstract: The growing number of vehicles in Jordan has contributed to traffic congestion, particularly at roundabouts. Roundabouts deflect high volumes of traffic flow. To improve the performance of roundabouts, it is necessary to consider the impact of all components on traffic conditions, especially delay, queue length, and level of service (LOS), to reduce congestion and enhance efficiency and sustainability, etc. This study aims to (a) identify the optimal queue detector locations on all approaches at two selected roundabouts in Amman, Jordan, using micro-simulation (VISSIM) supported by programming (Python) software, and (b) validate the simulated models with the best LOS. Traffic and geometric data of roundabouts (Prince Faisal Bin al-Hussein, fifth; and Prince Rashid Bin Hassan, sixth roundabouts) were used for simulation purposes. The queue detector (across 15 distinct scenarios at various distances) and standard (base scenario, 50 m from the stop line) locations were assessed for optimal placement. The model validation was made based on all scenarios including signalized and non-signalized roundabouts. The best-case scenario for queue detector location was determined based on the highway capacity manual (HCM) criteria for measurement of effectiveness (MOE) at roundabouts. The optimal location was measured based on the duration of traffic delay (seconds), average queue length (m), and LOS. The optimal queue detector's location was observed to be 97 m from the roundabout stop line. It can reduce the traffic delay (or speed up the traffic flow) by 85.25%. The average queue length can be reduced up to 76.76%. The LOS F status on the selected roundabouts can be improved to LOS D. Overall, the application of adaptive signal and queue detectors in appropriate locations at all roundabout approaches is crucial to improve imbalanced traffic flow while reducing delays.

Keywords: signalized roundabout; detector location; VISSIM; level of service; measurement of effectiveness; highway capacity manual

check for updates

Citation: Assolie, A.A.; Sukor, N.S.A.; Khliefat, I.; Abd Manan, T.S.B. Modeling of Queue Detector Location at Signalized Roundabouts via VISSIM Micro-Simulation Software in Amman City, Jordan. *Sustainability* **2023**, *15*, 8451. https://doi.org/10.3390/su15118451

Academic Editors: Giovanni Leonardi, Katarzyna Turoń and Feng Chen

Received: 15 March 2023
Revised: 2 May 2023
Accepted: 16 May 2023
Published: 23 May 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Various delayed traffic conditions (e.g., traffic jams, accidents, road works, and slow moving traffic) are common in urban areas, and their negative effects on daily life and environmental sustainability are becoming increasingly apparent. Traffic congestion, in particular, has emerged as a significant issue in urban areas, leading to wasted time, decreased productivity, and compromised air quality. The economic impact of congestion is also significant, with billions of dollars lost each year in terms of wasted fuel, lost productivity, and increased healthcare costs associated with air pollution, which can have an impact on environmental sustainability [1–7]. As a result, governments, policymakers, and transportation experts worldwide are dedicating more resources and efforts to finding innovative solutions to mitigate the negative effects of traffic congestion and improve traffic conditions, as well as traffic sustainability, in urban areas [1–6].

The city of Amman is a major metropolitan area in Jordan (4.642 million people in 2021) accounting for about 42% of the country's total population. This concentration of population in Amman has resulted in a significant increase in the number of vehicles on the roads, leading to a surge in traffic congestion on network roads [8–10]. This study focuses on the analysis of traffic conditions at two major roundabouts in Amman, namely, Prince Faisal Bin al-Hussein (fifth roundabout) and Prince Rashid Bin Hassan (sixth roundabout). The implementation of different signalization options at all types of intersections in Jordan may offer a potential solution to address traffic congestion with imbalanced traffic flows. Several studies, including [9,11–14], have demonstrated that signals can modify the roundabout's inherent priority rule, resulting in more evenly spaced delays. In transportation system modeling, simulation is commonly used to test the effectiveness of proposed solutions for roundabouts.

VISSIM is a highly detailed microscopic software that accurately depicts traffic dynamics. It is capable of simulating multimodal traffic flow with features such as speed zones, conflict zones, and 3D modeling, making it more complex than other software (e.g., SIDRA and AIMSUN) [3,13–19]. Python is used as an interface in VISSIM to program signal control with queue detectors, which provides greater accuracy compared with other macro languages (e.g., Visual C++, JavaScript, or Visual Basic). Python is a versatile and efficient programming language that enables easy integration and quick implementation [20,21].

This study aims to (a) identify the optimal queue detector's location on all approaches at the selected roundabouts in Amman, Jordan, using micro-simulation (VISSIM) supported by programming (Python) software, and (b) to validate the simulated models with the best level of service (LOS). These insights can assist transportation planners and decision makers in Jordan and other countries that face similar challenges. Therefore, policymakers can develop efficient signalization strategies to improve traffic flow, reduce congestion, and enhance overall road safety and sustainable mobility.

2. Literature Review

In transportation engineering, imbalanced flow refers to situations where traffic flow is less than the capacity of the road, resulting in smooth traffic movement. However, when the flow rate reaches or exceeds capacity, significant delays, queues, and congestion can occur. Various studies have investigated the impact of unbalanced flows on roundabouts, a popular type of road intersection. While roundabouts are generally effective with balanced flows, operational difficulties can arise with increased flows. Roundabouts perform well when the flows from all approaches are balanced, with platoons present in the circulating flow, and vehicles from each approach can enter the roundabout. This is because the yield rule limits the approach flows to depend on the circulating flow, and the overall roundabout performance depends on both the circulating flow and the approach flows [13–15,18,22–29].

The use of detector technology has been established, with early versions capable of detecting the presence of vehicles as they passed over the detectors at the junctions. Traffic signal systems have become more prevalent in recent times [30–33]. Adaptive strategies, which are a modified version of actuated control, use available data to predict the cycle length required for current traffic conditions. Detectors are placed on stop lines, right-turn sensors, slip lane sensors, and advanced detection sensors, on every road in a signalized network [16,19,28,30]. Traditional traffic light systems rely on hard-programmed delays, with no consideration for real-time traffic flow, leading to congestion [34,35]. Previous research has shown that fixed-time signal control or multi-period fixed-time control is only suitable for intersections with steady traffic, while actuated signal control is more appropriate for multi-leg roundabouts with unstable traffic [31]. However, the use of actuated signal control has not been successful in handling traffic flow in roundabouts, leading researchers to focus on studying roundabout capacity and adaptive signal control [18,26,32,36,37]. Moreover, the adaptive signal control system, specifically designed for roundabouts, was developed to improve their efficiency [28,38]. Signalized roundabouts are equipped with advanced loop detectors and traffic signals to minimize vehicle queuing

lengths, especially on the dominant approach, when unbalanced traffic flow conditions occur. In partially signalized roundabouts, the signal phase times are determined by the location of detectors and changeable queuing lengths, which affect queuing length on each approach [38]. Advanced detection detectors are installed upstream of the stop line to measure headways or gap time, while also dismissing the traffic signal phase in advance, under free-flow settings. These detectors activate when the approach speed is high or when heavy vehicles dominate the traffic [29,39].

For signalized roundabouts, the queue detectors must be installed at the most appropriate location because this can affect the duration of queues at each entry point. An adaptive traffic signal is used and activated when the queue on the controlling approach meets the detector to determine the signal's green/red time [25,26,38]. The standard queue detector location is determined by the *Manual of Traffic Roads and Use Management* [40] which suggests installing these detectors at certain stopping distances for the 85th percentile approach speed, at 35 m (for a 50 km/h speed limit) to 40 m (for a 60 km/h speed limit) upstream of the stop line.

In addition, the literature on queue detectors from international countries includes research from the United States [18,37], Australia [25,28,38], Ghana [15], Portugal [24], Albania [36], Spain [41], and Egypt [16]. Meanwhile, one study in Jordan is related to roundabout metering with queue detectors [13]. Some of these studies analyzed the performance of signalized roundabouts using the standard value of the queue detector [18,37,41]. For example, the author of [37] and Ma, Yi [18] found that an adaptive signal with an advanced detector was more effective than a traditional roundabout, especially for roundabouts with unpredictable flows, and recommended installing the queue detector at 175 feet as a standard value from the yield line or entry point. In addition, Martin-Gasulla, Garcia [41] investigated the use of the optimal model by placing a queue detector at 50 m as a standard value in the metering roundabouts and found that it improved the capacity of the roundabouts up to 80% and reduced delay (22–56%), with the most effective approach being the controlling approach and shorter amber or blank times of 40 s to quickly improve queue conditions. Moreover, few studies have focused on the optimal local queue detectors at congested roundabouts [25,26]. An, Yue [26] found that using a 380 m detector for the controlling approach and a 320 m detector for the metering approach could reduce queuing length on both approaches. Moreover, An, Liu [25] showed that installing a detector at 210 m from the roundabout stop line in an adaptive traffic signal system with advanced detectors could reduce the overall queuing length from 689 m to 499 m.

However, some studies failed to analyze how the optimal queue detector affects the performance of roundabouts [36,42]. For example, Afezolli and Shehu [36] investigated the effectiveness of adaptive signals equipped with advanced detectors at roundabouts and concluded that the length of queues and duration of delays on the controlling approach can be reduced by 20 to 40% at the standard location of a queue detector 50 to 120 m away from the roundabout. Furthermore, Martin [42] compared the capacity of a metering system with a queue detector at 50 m and unmetered roundabouts and discovered that using a metering system could result in a group of vehicles approaching the roundabout with a longer acceptable gap between them. On the other hand, some studies [13,19,23,38,43–46] limited the optimal location of queue detectors in their studies.

Therefore, the novelty of this research is that it investigates the optimal location of queue detectors at congested roundabouts. To improve the efficiency of roundabouts, it is crucial to determine the optimal position for detectors, particularly those that measure queues. Although there are currently no established guidelines, investigating the impact of optimal detector placement at all approaches to roundabout performance could yield valuable insights. Furthermore, addressing congestion at the most heavily congested roundabouts in Amman, specifically, the Prince Rashid bin Hassan and Prince Faisal bin al-Hussein Square roundabouts, is crucial for urban planners.

As a case study, Amman, Jordan's capital city, is a hub of business activities. Zahran Street is a significant street that connects major business districts in the city, resulting in high

traffic volumes and severe congestion, particularly during the morning rush hour. This street comprises eight roundabouts, which are among the most congested roundabouts in Amman. The sixth roundabout, Prince Rashid Bin Hassan, and the fifth roundabout, Prince Faisal Bin al-Hussein Square, are the most congested. The Greater Amman Municipality (GAM) has estimated that the traffic volume growth rate at these roundabouts is 3% per year, based on historical data. Therefore, this study offers a viable solution to improve the overall performance of roundabouts and mitigate traffic congestion, particularly in the two most heavily congested roundabouts in Amman. These roundabouts are located in a bustling commercial district, replete with numerous restaurants, cafes, and entertainment venues, as well as banks, insurance companies, and hotels. Additionally, the surrounding area is renowned as one of the most affluent neighborhoods in Amman city. Despite their location, both roundabouts suffer from long queues and high delays on all approaches, particularly during peak periods. These issues are a result of unbalanced traffic flow and high demand, leading to traffic jams, accidents, and decreased entry capacities of the roundabout approaches as more vehicles enter the circulating lane, creating a bottleneck at the roundabout entrance.

This study has an important contribution to the field of traffic congestion at signalized roundabouts, which is currently among the most concerning research topics in traffic engineering. This study can provide valuable insights into traffic management strategies that can reduce queuing and improve traffic flow, leading to sustainability benefits such as reduced fuel consumption and emissions, and encouraging more sustainable transportation options. Additionally, optimizing queue detector placement can enhance the efficiency of transportation systems, leading to significant economic benefits. The primary objective of this research is to investigate the utilization of VISSIM, a traffic simulation software, to determine the optimal placement of queue detectors on all approaches at signalized roundabouts. Calibrated parameters such as travel time and validated parameters such as queue length were used in the simulated model outputs. The outputs include delay, queue length, and LOS, which were evaluated in this study. This approach ensures the accuracy and validity of the findings, which can inform traffic management strategies to reduce congestion, improve traffic flow, and promote sustainable mobility. Table 1 summarizes the literature on queue detectors at roundabouts from international countries, including Jordan, compared with the current study.

Table 1. The literature on queue detectors at roundabouts from international countries, including Jordan, compared with the current study.

No.	Country (Ref.)	Outcomes Measure	Interventions	Traffic Simulation Software	Programming Software	Traffic Signal Control	Location of Queue Detector	Findings
1.	Jordan [13]	Improving the capacity and LOS at the roundabout	Placing adaptive signals on the roundabout, which connects traffic signals with ground detectors placed at a certain distances.	VISSIM	C++	Adaptive	N.A.	A 90 s cycle length giving a D value of the LOS.

Table 1. *Cont.*

No.	Country (Ref.)	Outcomes Measure	Interventions	Traffic Simulation Software	Programming Software	Traffic Signal Control	Location of Queue Detector	Findings
2.	Australia [25]	• Optimal distance of the queue detector from the stop line • The queuing lengths on the controlling and metered approaches • The total queue length at the intersection	Distance of queue detectors from the stop line of the roundabout	AIMUSN	N.A.	Adaptive	Different scenarios	The total queue length (controlling + metered) is minimized from 689 to 499 m when the detector is relocated to 210 m from the roundabout stop line.
3.	United States [18]	• Delays • Queues	An adaptive metering system for circular intersections	VISSIM	C ++	Adaptive	175 ft	Signal metering can significantly reduce delays and queues at a traffic circle.
4.	Australia [38]	Queuing length	An adaptive neuro-fuzzy inference system model for predicting queuing length at metering roundabouts	MATLAB	N.A.	Adaptive	(50–120) m	An adaptive neuro-fuzzy inference system model was developed to predict queuing length at metering roundabouts. The model is expected to help practitioners in determining optimal detector locations.
5.	Egypt [16]	Capacity LOS	-	VISSIM and SYNCHRO	N.A.	Actuated	N.A.	The roundabout is not able to handle the increasing number of vehicles. The LOS at the roundabout is inadequate.
6.	Ghana [15]	• Capacity • Delay • Queue length	A simulation of various configurations of signalized roundabouts	VISSIM	N.A	Adaptive	N.A	Increases the capacity by as much as 50% in some cases.
7.	Portugal [24]	• Traffic performance • Energy • Environmental • Exposure impacts	A partial metering system	VISSIM	N.A.	Fixed	N.A.	Reduces traffic-related costs in a corridor by up to 13%. The efficiency of the proposed system increases as entering traffic at the metered approaches increases.
8.	Australia [28]	• Total entry delay • Metering signal thresholds • Operational performance • Delay reduction	A metering signal-based strategy	VISSIM	N.A.	Actuated	N.A.	Reduces the total entry delay by up to 25.7%.

Table 1. *Cont.*

No.	Country (Ref.)	Outcomes Measure	Interventions	Traffic Simulation Software	Programming Software	Traffic Signal Control	Location of Queue Detector	Findings
9.	United States [37]	• Delays • Queues	An adaptive metering system	VISSIM	C ++	Adaptive	175 ft	Adaptive metering represents a significant advancement compared with roundabout metering and is suitable for roundabouts that experience unpredictable traffic patterns.
10.	Albania [36]	• Capacity • Performance	Use of metering signals at roundabouts	SIDRA	N.A	N.A.	(50–120) m	Metering signals are used to alleviate excessive delays and queues at roundabouts during peak demand flow periods.
11.	Australia [26]	Queuing lengths on the controlling and metered approaches	Location of detectors at the metering roundabout	AIMUSN	N.A.	Adaptive	Different scenarios	The numerical model predicted queuing of the locations of 380 m (for C) and 320 m (for M) and reduced the queuing length on both approaches.
12.	Spain [41]	• Average delay • Capacity	Metering signals and queue detector	VISSIM	N.A.	Adaptive	50 m	The optimal model presented the lowest average delay (22–56%) and a capacity improvement of up to 80 %.
13.	Jordan (Current Study)	Delay queue length LOS Optimal location of queue detector	Location of queue detector at the signalized roundabout	VISSIM	Python	Adaptive	97 m	Reduces the delay by 85.25%, reduces the avg. queue length by 76.76%, and improves LOS from F to D when placing the queue detector at 97 m from the stop line.

N.A: Not available.

3. Methodology

The methodology employed in this study analyzed various characteristics and data related to roundabouts by utilizing both primary and secondary sources. Primary sources included data collected in 2018 comprising queue length and travel time during rush hour while secondary sources included traffic volume and geometric data obtained from the Greater Amman Municipality in the AM peak traffic hour (7:30–8:30). This study employed modeling and simulation techniques using VISSIM, microscopic software that offers a detailed representation of traffic dynamics.

VISSIM is more complex than other modeling software and includes a range of features such as reduced speed zones, conflict zones, and 3D modeling. This study evaluated the outputs of the simulated model, including delay, queue length, and LOS. It is necessary to calibrate the model by adjusting its parameters and then validate it by comparing the results with real-world data obtained from sensors or cameras to address traffic congestion [3,13,15,16].

The travel time was used as the calibrated parameter, and the model was developed to reflect real-world conditions at the site. The validation of the VISSIM model was carried out using the queue length as the validated parameter to assess its ability to accurately represent a real-life scenario. Furthermore, model validation is directly related to the model calibration process, as calibration adjustments are necessary to enhance the model's ability to replicate traffic dynamics observed in the field. In addition, model validation is crucial for selecting and identifying critical calibration parameters and determining acceptable variations for each parameter throughout the microscopic simulation model. Calibration aims to ensure that the simulation model accurately represents the local traffic conditions. Therefore, system performance was conducted using the *GEH* value to evaluate the performance of the simulation model. The *GEH* statistic was used to validate the queue length, which is a formula commonly used in traffic engineering [15–17,28,47]. The formula is also useful for modeling and forecasting traffic, as well as comparing sets of traffic queues. The observed value was compared with the simulated value at the node of the VISSIM model. The model was run 15 times to validate its accuracy.

The Geoffrey E. Havers (*GEH*) method was used as in the following equation:

$$GEH = \sqrt{\frac{2x(Y_{sim} - Y_{observed})^2}{(Y_{sim} + Y_{observed})}} \quad (1)$$

where:

Y_{sim} is the simulation VALUE.
$Y_{observed}$ is the observed VALUE.

In VISSIM, connectors are used extensively when modeling intersections and roundabouts. They function much like links, but they are defined in the model by the lane change distance and emergency stop distance values. The speed parameter of a connector is based on an empirical curve that can be customized by the user to match field data or studies. The posted speed limit can also be utilized, and each vehicle oscillates around its desired speed until speed zones or roadway geometry necessitate a change in speed. This results in behavior that mimics reality, allowing users to force vehicles to slow down before turning or move slower in areas where the speed limit is lower in reality [3,13–16,19,48–50]. Moreover, VISSIM's newer approach to conflict zones is simpler to define in the model by using gap acceptance, including rear and front gaps, to create more intelligent vehicle behavior. In addition, coding priority rules in VISSIM provide high flexibility and enable traffic to be simulated more closely to real-world conditions. Priority rules comprise a stop line and one or more conflict markers associated with the stop line, which must be defined in the model by minimum headway distance and minimum gap time. These features have been discussed in studies by [3,13–16,19,48–50].

The VISSIM model, interfaced with Python, was utilized to simulate both un-signalized and signalized cases with different signalized scenarios (15 scenarios). The objective was to identify the optimal delay, queue length, and LOS. The validation of the VISSIM model was conducted on the fifth roundabout, and the best-case scenario was used to evaluate the appropriate location of the queue detector for various roundabouts. To validate the study, the sensitivity of the model was evaluated by selecting the best scenario from all possibilities at the sixth roundabout and applying the simulation model to the fifth roundabout in Amman. The validation model was simulated by using VISSIM in two cases to assess the optimal values of delay, queue length, and LOS of the fifth roundabout. In the first case, three detectors were placed at the detector's location in scenario 1, which presented the standard values of the detectors without any replacement. In the second case, the detector locations were placed in the best scenario. The differences in outcomes between the two cases were compared to determine the effectiveness of the model in improving the LOS of the roundabout. This step is crucial to validate the results of the study area by assessing the roundabout's performance based on delay, queue length, and LOS. Figure 1 depicts

a summary of the methodology employed in this study including (a) modeling of queue detector location at a signalized roundabout via VISSIM micro-simulation software and (b) the Python flow chart for stages 1 and 2.

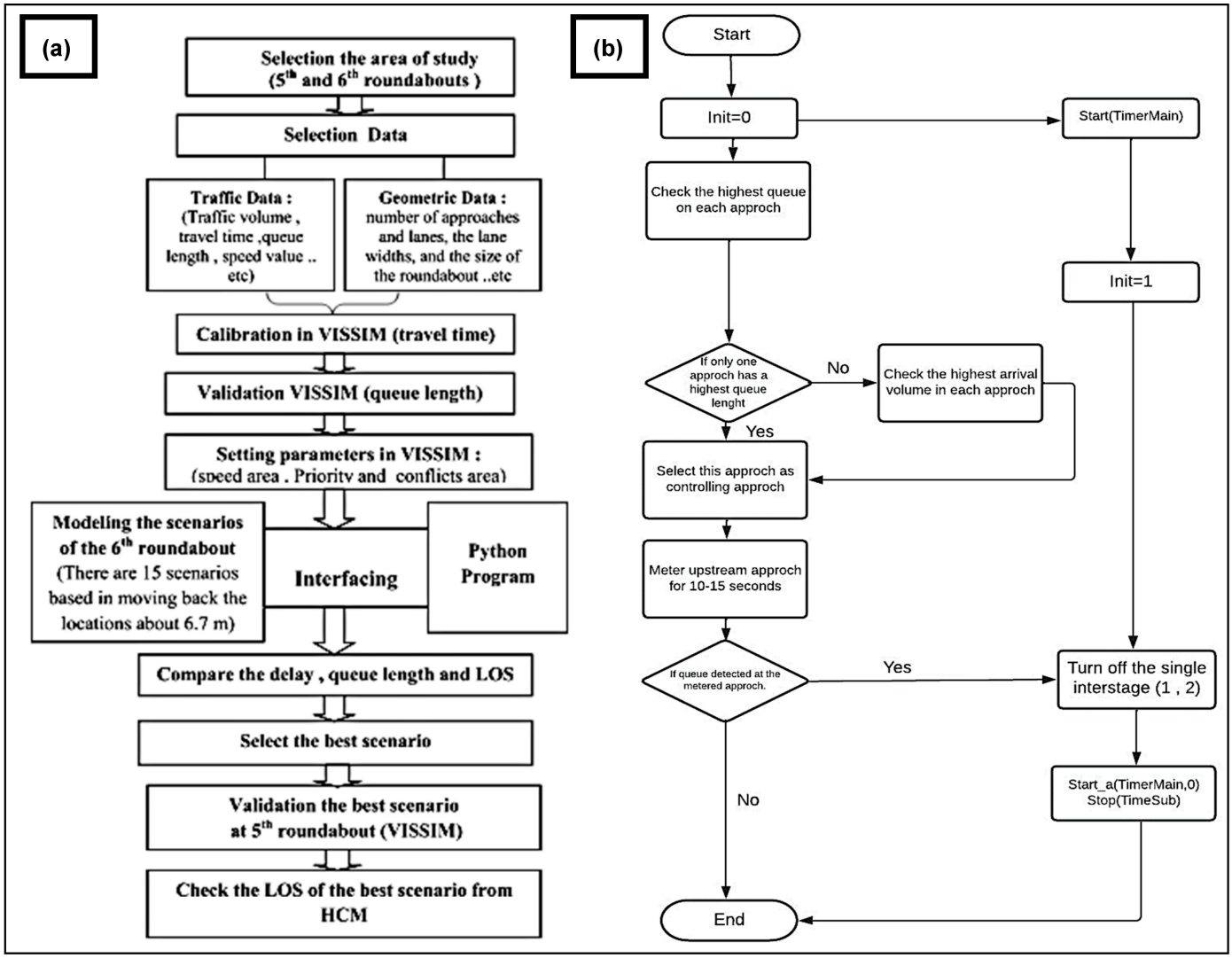


Figure 1. Research methodology (**a**) modeling of queue detector location and (**b**) the Python flow chart for stages 1–2.

3.1. Research Location

The city of Amman, like many modern urban areas, has experienced rapid growth in both size and population. This growth has negatively impacted the city's transportation system, particularly on Zahran Street which connects major business districts. During the morning rush hour, high traffic volumes create significant congestion at the two selected roundabouts. According to historical statistics from the Greater Amman Municipality, the traffic volume growth at these roundabouts is estimated to be approximately 3% per year as shown in Figure 2. Figure 2 presents the average annual daily traffic (AADT, 1000 vehicles/day) for the selected roundabouts between 2015–2018. The sixth roundabout, Prince Rashid bin Hassan roundabout (N 35°51′40.997″, E 50°56′31.001″), was selected as the main site because it is known for being one of the most congested in Amman due to its location in a commercial area with numerous restaurants, cafes, and entertainment venues. The fifth roundabout, Prince Faisal bin al-Hussein Roundabout (N 35°52′49.001″, E 47°57′30.999″), was chosen as a secondary site because it is similarly congested and has

a similar geometric design to the sixth roundabout. This roundabout serves a busy hotel district with six major hotels within a 1 km^2 area. Figure 3 shows the aerial photography of Amman city with the selected roundabouts along Zahran Street.

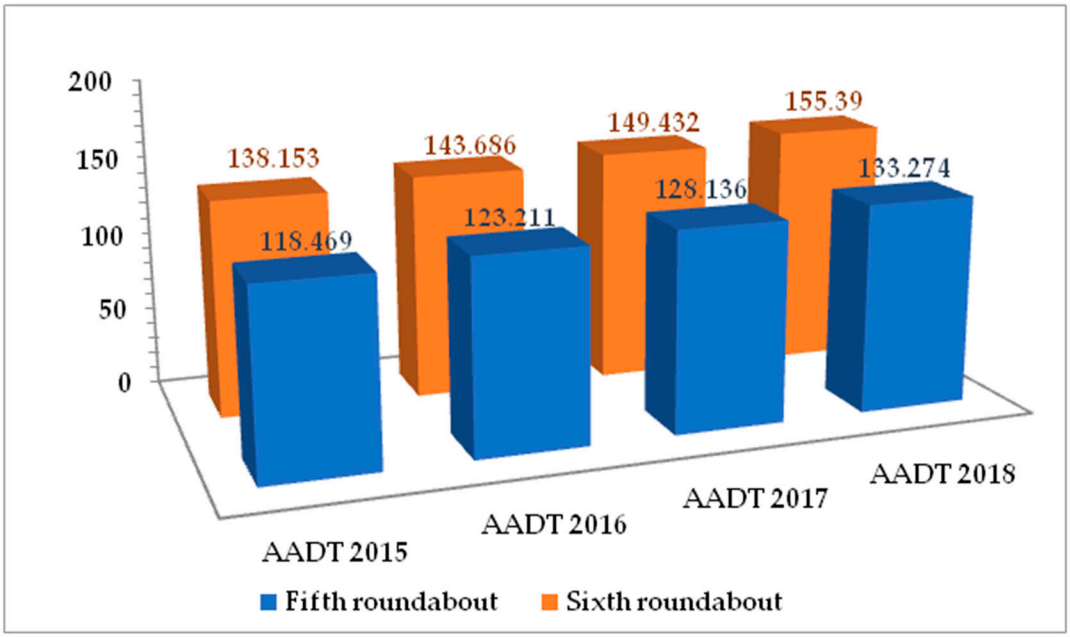


Figure 2. The average annual daily traffic (1000 vehicles/day) for the selected roundabouts between 2015–2018 (GAM, 2018).

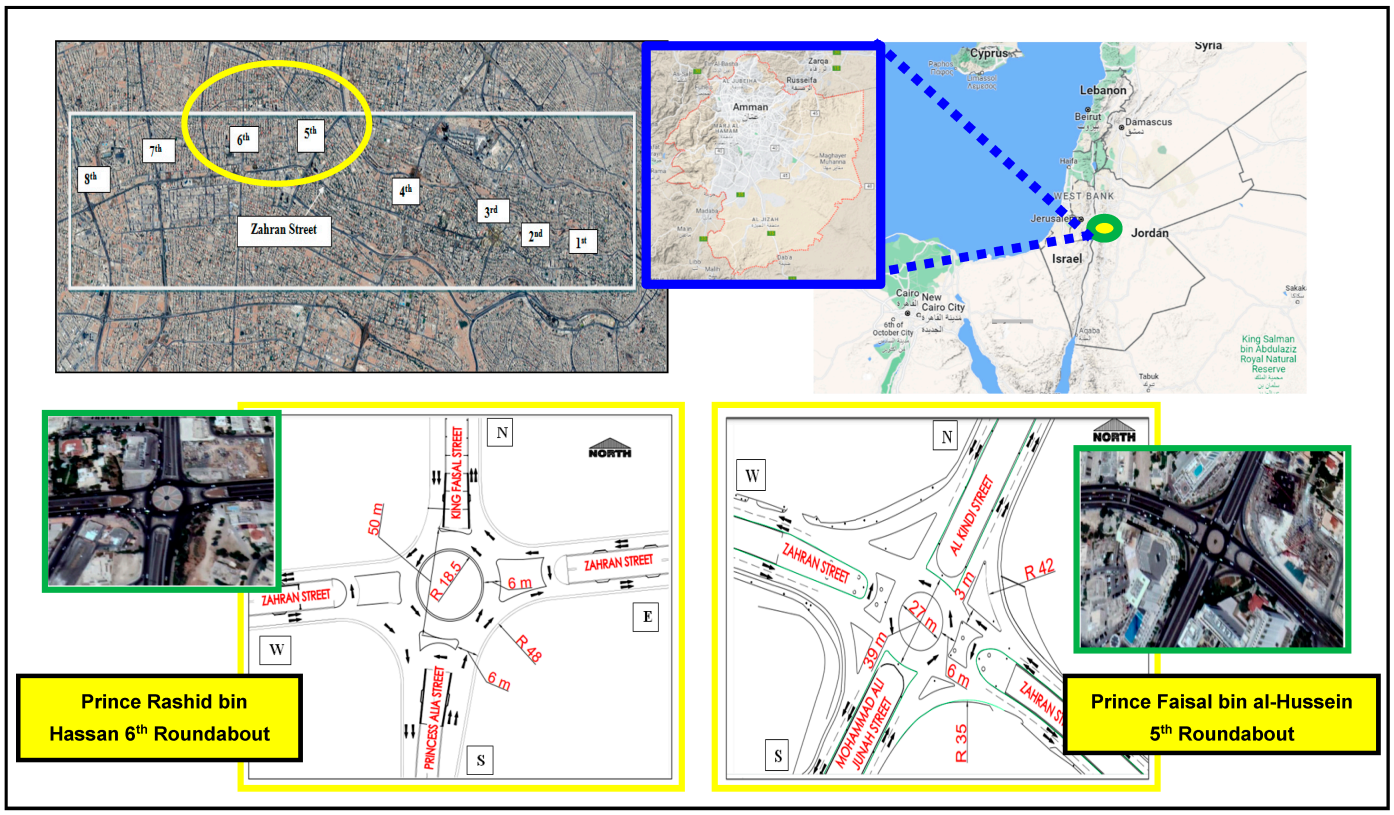


Figure 3. An aerial photograph of Amman city and AutoCAD drawings of the fifth and sixth roundabouts (GAM, 2018).

3.2. Geometric Data

According to the Greater Amman Municipality (GAM) in 2018, geometric data include important information about the design of junctions, such as the number of approaches, number of lanes, lane widths, and size of roundabouts. The sixth roundabout, also known as the Prince Rashid bin Hassan roundabout, has four legs that cross a one-lane circulating roadway. It has a central island diameter of 37 m and an inscribed circle diameter of 50 m. The circulating width is 6 m, and the entry width is 6 m with one lane entry. The path radius is 48 m, and the splitter radius is 54 m. It has a 32-degree entry angle, and there are no pedestrian crossings or police patrols. In addition, the fifth roundabout, also known as the Prince Faisal bin al-Hussein Roundabout, has four legs that cross a one-lane circulating roadway. It has a central island diameter of 27 m and an inscribed circle diameter of 39 m. The circulating width is 6 m, and the entry width is 3 m with one lane entry. The path radius is 35 m, and the splitter radius is 42 m. It has a 36-degree entry angle, and there are no pedestrian crossings or police patrols. Figure 3 and Appendix A show the geometric design of the roundabouts and the direction of traffic flow.

3.3. Traffic Data Collection

The traffic data include information about the characteristics of the traffic flow, such as the volume of traffic. The traffic volume refers to the number of vehicles passing through each stop line within a certain period. To determine the traffic volume during the peak traffic hour in the study area, traffic count data from the Greater Amman Municipality and data records from ground sensors at the sixth and fifth roundabouts provided by the central traffic department were collected. The data were recorded during the morning rush hour in 2018 between 7:30–8:30 a.m. The aim of conducting a site visit was to gather an inventory of the site and to observe driver behavior, conflicts, and queue lengths that typically occur. During congested periods, the travel time of vehicles making left turns from the site was recorded on the congested routes and subsequently checked from video footage. Queue values were determined from the site and video footage at the north approach of the sixth roundabout and the south approach of the fifth roundabout in 2018. To record the travel time values, a vehicle passing the endpoint of the study segment was tested, and the travel time was measured using a stopwatch for a specified distance. The distances between fixed starting points and the fixed end point of the total route were obtained from the vehicle's odometer. This process was repeated until the required number of sample runs (six in total) was obtained, and the average travel time was computed to determine the average travel time for that study segment. The average queue length values were determined from the field in the selected direction, every five minutes during the AM peak traffic hour. This measure was used to compare with the output of the VISSIM model and assess its effectiveness. Observers at a selected approach counted the number of vehicles in the stopping or slowly moving queue and measured the distance between the entry points to the end of the vehicle queue. One observer recorded the queue length values while another checked them from video footage to ensure accuracy during the peak traffic hour (see Appendix B).

3.4. Model Development

To select appropriate software for a traffic model, it is important to understand the two main categories of traffic flow models: macroscopic and microscopic. A microscopic model simulates individual vehicles and their dynamic variables such as position and velocity, while a macroscopic model links traffic flow characteristics such as flow, density, and mean speed through mathematical models. A study examined simulation results from several software packages for an unbalanced single-lane roundabout and found that SIDRA and VISSIM performed well in addressing the roundabout approach volume imbalance base on previous studies. SIDRA is a micro-analytical traffic evaluation tool that estimates intersection capacity and performance characteristics with lane-by-lane and vehicle drive-cycle models [41,51–55]. Meanwhile, VISSIM is more intricate software that simulates

multimodal traffic flow at a small scale and allows for the modification of driver behavior and signal control through its built-in API. VISSIM can mimic various highway classes and construct multimodal infrastructures, and its design provides maximum adaptability and resolution [3,13–19].

In this study, it is recommended to run the model 15 times to produce accurate results. To develop the model network, the study area is imported and properly scaled, and then links and connectors are drawn over the map. The characteristics of the road change at specific spots. Hence, a connector is used to connect two links and continue the network development of the study area. The sixth roundabout is constructed and the connectors are drawn to join the opposite legs for the turning movement and connect them back to the main throughflow. Figure 4a depicts the connector used for the links at intersections. The peak traffic hour volumes were entered into the model. According to the traffic department in Jordan (2018), 98% of the vehicle volume is made up of passenger vehicles, with 2% being buses and trucks. After the vehicle volume at the selected roundabout is entered, the next modeling stage is to define the vehicle routes via static routing decisions at the sixth roundabout. Then, the percentages of vehicles flowing in different directions of the roundabout are assigned using the attribute of relative flow in static routes. Using this network in assigning the traffic volume generates more reliable calibration results for several vehicles moving in each direction near actual field traffic conditions (see Figure 4b).

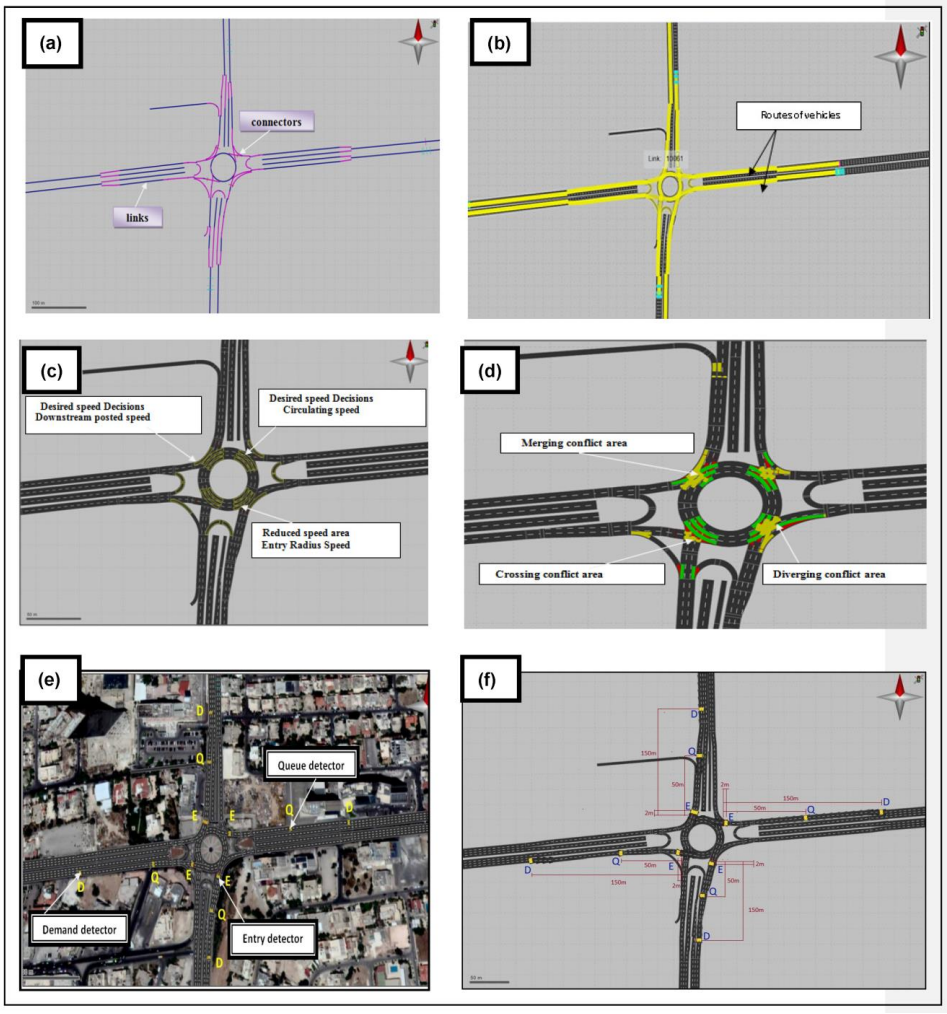


Figure 4. Simulated model in VISSIM at the sixth roundabout: (**a**) links and connectors; (**b**) routes of the initial model; (**c**) the types of speed in the model; (**d**) the types of conflict areas; (**e**) the types of detectors in the model; and (**f**) Scenario 1 at the sixth roundabout.

However, the model will not be appropriately calibrated if an additional routing decision is defined before the end of the previous route. In the study area, circulating vehicles have the right of way over entering vehicles, and the vehicle speeds inside the circulatory roadway of the roundabout as observed from videos were less than the speeds on approach depending upon the design. The selected roundabout does not include crosswalks for pedestrians and this roundabout is controlled by a give-way sign and a give-way road marking in front of each roundabout entrance to force drivers to slow down before traversing the roundabout. Hence, before the entry point of each approach at the sixth roundabout, a reduced speed zone was also set up where the speeds were seen to be approximately 25 km per hour. The circulating speed was determined as between 25 and 30 km per hour, and the value limit of 50 km/h per hour was used as the speed limit for vehicles traveling on the approach (Greater Amman Municipality, 2018). Figure 4c shows the speed area for circulating speed, entry speed, and posted speed, presented in yellow color. VISSIM identifies conflict areas in the network where two links or connectors overlap. These areas can occur at various locations, such as the entry point of a roundabout, depending on the roundabout's design. The user decides which areas to prioritize, and in the case of roundabouts, circulating traffic is given priority. Vehicles entering the roundabout look downstream as they approach the conflict area and if a circulating vehicle is nearing or in the conflict area, the entering vehicle will slow down or stop to allow space for the circulating vehicle to move once the entering vehicle meets the required gap conditions, such as the front gap, rear gap, safety distance, and other parameters. Figure 4d illustrates an example of a conflict area at the entry point of a roundabout.

Adaptive Traffic Signal Control

In this VISSIM model, three detectors were utilized to calculate the entry flow, queue length, and arrival flow rate, as shown in Figure 4e. The details are as follows:

1. Entry flow detector (E): this detector computes the number of vehicles coming into the circulating route or the roundabout;
2. The queue detector (Q): this detector computes the queue length of vehicles at a selected roundabout;
3. Arrival flow or demand detector (D): this detector computes the arrival flow rate at the roundabout.

The simulation was categorized into different cases based on the replacement of the position of detectors at about 6.7 m in each scenario (according to the length of the standard vehicle) and the simulated models were controlled by a queue detector, as described below:

- Standard scenario (base): scenario with standard queue detector (S1) as shown in Figure 4f;
- Different scenarios: all scenarios have a difference value of 6.7 m between the scenario and the following scenario as in Table 2 (see Appendix C).

Table 2. Description of different scenarios (15 scenarios) at the sixth roundabout.

Number of Scenarios	Description
S1 (Standard scenario)	Entry detector at 2 m, queue detector at 50 m, and demand detector at 150 m from the stop line
S2	Entry detector at 8.7 m, queue detector at 56.7 m, and demand detector at 156.7 m from the stop line
S3	Entry detector at 15.4 m, queue detector at 63.4 m, and demand detector at 163.4 m from the stop line
S4	Entry detector at 22.1 m, queue detector at 70.1 m, and demand detector at 170.1 m from the stop line
S5	Entry detector at 28.8 m, queue detector at 76.8 m, and demand detector at 176.8 m from the stop line
S6	Entry detector at 35.5 m, queue detector at 83.5 m, and demand detector at 183.5 m from the stop line
S7	Entry detector at 42.2 m, queue detector at 90.2 m, and demand detector at 190.2 m from the stop line
S8	Entry detector at 48.9 m, queue detector at 96.9 m, and demand detector at 196.9 m from the stop line
S9	Entry detector at 55.6 m, queue detector at 103.6 m, and demand detector at 203.6 m from the stop line
S10	Entry detector at 62.3 m, queue detector at 110.3 m, and demand detector at 210.3 m from the stop line
S11	Entry detector at 69 m, queue detector at 117 m, and demand detector at 217 m from the stop line
S12	Entry detector at 75.7 m, queue detector at 123.6 m, and demand detector at 223.7 m from the stop line

Table 2. *Cont.*

Number of Scenarios	Description
S13	Entry detector at 82.4 m, queue detector at 130.4 m, and demand detector at 230.4 m from the stop line
S14	Entry detector at 89.1 m, queue detector at 137.1 m, and demand detector at 237.1 m from the stop line
S15	Entry detector at 95.8 m, queue detector at 143.8 m, and demand detector at 243.8 m from the stop line

The purpose of the adaptive control strategy signal is to improve the performance of the roundabout metered approach. It was designed to manage all approaches using real-time data to simulate the model and balance queues, particularly in scenarios with large flows or lengthy queues. Unlike traditional traffic controllers, adaptive traffic signal controls were created to minimize traffic congestion and respond to vehicles in real-time at the roundabouts.

The signal was programmed using Python and implemented in the VISSIM microscopic simulation model with a high level of accuracy compared with other programming languages such as Visual C++, JavaScript, and Visual Basic. Python's quick implementation and easy integration make it a preferred language [20,21]. The signal was positioned at the sixth roundabout, and its operation was controlled using a control approach without a fixed cycle time. The yellow timing was fixed at 3 s, and all red timing was fixed at 2 s, following the traffic department's recommendations in Jordan (2018). The priority rule is determined based on the detection of traffic queues at each approach. First, queues on each approach are checked. If there is only one approach, it is automatically selected as the controlling approach. If there are multiple approaches with queues, the approach with the highest arrival rate is chosen as the controlling approach, and the green light is activated for this approach. Then, the upstream approach is selected as the metered approach, and the signal is metered or turned red when the queue is detected on the metered approach. The signal flashes yellow for 3 s as a warning before turning red for 10–15 s to prevent vehicles from approaching. However, if the queue appears on the metered approach, a new controlling approach is selected and this procedure completes all stages at the selected roundabout. In the final stage of the simulation modeling process, the VISSIM simulation was applied for every scenario with different values of detectors at the 6th roundabout to compare the outputs of the simulation model in all 15 scenarios in different locations. This study investigates the appropriate location of queue detectors to minimize congestion at roundabouts. The location of the queue detector is essential in detecting excessive delays and long queues. When there is a high volume of traffic or lengthy queues on one or more approaches to a roundabout, the queue detector sends a message to balance all queues by adjusting the phase time, thereby enhancing the performance of the roundabout. Real-time response of a fully adaptive traffic signal at the appropriate location of the queue detector helps minimize traffic congestion, unlike most traffic controllers that respond slower to vehicles moving in roundabouts.

4. Results

This study analyzed the results of the simulation model, as well as the performance and LOS under un-signalized and signalized conditions, such as delays and queue lengths, with 15 scenarios. Furthermore, the study validated the proposed model to identify the optimal scenario for queue detectors at different roundabouts based on the fifth roundabout.

Calibration aims to ensure that the simulation model accurately represents the local traffic conditions. The parameters used depend on the calibration model of travel time; system performance calibration was conducted using the simulated and observed values of travel time at selected roundabouts. The observed vehicular demand is likely to be unevenly distributed due to varying vehicle entry into the network. The analysis showed poor performance of the roundabout due to congestion. The travel time was used as calibrated parameter and the results of the model's travel time were compared with the actual travel time of the site, with the travel times on congested approaches for left-turning

movements measured from fixed starting and end points, and the simulated travel time reflected the travel time from the site at selected roundabouts (see Appendix D). The average speeds were analyzed based on three types of speeds: limited speed of 50 km/h, 25–30 km/h for circulating speed, and 25 km/h for entry speed based on the Greater Amman Municipality. The parameters of vehicle acceleration and deceleration were disregarded since the same vehicle types, classes, and models are used in both the site and the VISSIM model. The safety distance factor was taken from other studies [3,13–16,19,48–50], while the other parameters, including emergency stopping distance, lane change distance, standstill distance, minimum headway, and waiting time before diffusion, were based on studies on the selected roundabouts [13,14]. The VISSIM model's conflict area parameters were adjusted to reflect the traffic conditions at the site, including visibility, the front gap, the rear gap, and the safety distance factor (see Table 3b).

Table 3. The (**a**) criteria of the GEH method, (**b**) value of parameters in the VISSIM, (**c**) HCM control delay and LOS criteria for un-signalized intersections, and (**d**) MOE values for the un-signalized roundabout.

(a) Criteria of the GEH Method	**GEH Statistic**
A good match	<5
An investigation may be required	From 5 to 10
Possible model error or bad data	>10

(b) The Parameters in VISSIM	**The Parameter Values**
Emergency stopping distance	5 m
Lane change distance	150 m
Standstill distance	5 m
Headway distance	3 m
Front gap	0.5 s
Rear gap	0.5 s
Safety distance factor	1
Visibility distance	100 m
Posted limit speed	50 km/h
Entry speed	25 km /h
Circulating speed	(25–20) km/h

(c) HCM Control Delay for Vehicles (Seconds)	**LOS**	**General Description**
0–10	A	Free flow
>10–15	B	Stable flow (slight delays)
>15–25	C	Stable flow (acceptable delays)
>25–35	D	Approaching unstable flow
>35–50	E	Unstable flow
>50	F	Forced flow

(d) MOE Values for Un-Signalized Roundabout

Name of Route	**Average Queue Length (m)**	**Max. of Queue Length (m)**	**Vehicle Delay (sec)**	**Stopped Delay (sec)**
From east of Zahran Street to K. Faisal ben Abdul Aziz Street	148.62	365.77	142.30	122.80
From east of Zahran Street to west of Zahran Street	133.10	327.59	216.46	186.79
From east of Zahran Street to Prs. Alia Street	201.90	496.90	221.83	191.43
From K. Faisal Ben Abdul Aziz Street to the west of Zahran Street	178.54	439.42	182.39	157.39
From K. Faisal Ben Abdul Aziz Street to Prs. Alia Street	306.46	754.25	615.51	531.16
From K. Faisal Ben Abdul Aziz Street to East of Zahran Street	418.63	1030.33	397.74	343.23
From west of Zahran Street to Prs. Alia Street	121.35	298.66	69.74	60.18
From west of Zahran Street to east of Zahran Street	155.15	381.84	256.79	221.59
From west of Zahran Street to K. Faisal ben Abdul Aziz Street	258.40	635.97	170.73	147.33

Table 3. *Cont.*

(d) MOE Values for Un-Signalized Roundabout				
Name of Route	**Average Queue Length (m)**	**Max. of Queue Length (m)**	**Vehicle Delay (sec)**	**Stopped Delay (sec)**
From west of Zahran Street to west of Zahran Street	131.34	323.26	113.42	97.88
From Prs. Alia Street to East of Zahran Street	274.41	675.36	289.42	249.75
From Prs. Alia Street to K. Faisal Ben Abdul Aziz Street	274.18	674.80	336.42	290.31
From Prs. Alia Street to west of Zahran Street	260.52	641.18	350.90	302.81
All	**207.34**	**510.30**	**247.75**	**211.68**
LOS		**F**		

Results are presented in mean and standard deviation equals 0.5.

In this study, a validation method was employed to evaluate the accuracy of real and simulated models of queue length at a specific roundabout. The visual validation method utilized a graphical representation of the data from the model to visually compare and contrast their differences. The statistical validation method, on the other hand, used goodness of fit measures, confidence intervals, and statistical tests to determine the degree of similarity between the real and simulated models. To validate the base model in this study, the statistical method utilized the GEH method and the queue length as the validation parameter. The model was run 15 times during the AM peak traffic hour simulation duration to ensure comprehensive validation. The resulting GEH values of 1.74 for the sixth roundabout and 2.04 for the fifth roundabout, as presented in Appendix E, indicate a good match between the simulated and observed values. Based on the GEH criteria, the validation model is deemed acceptable for evaluating the outputs of the selected roundabouts (see Table 3).

4.1. Performance and LOS at Un-Signalized Roundabout

This study analyzed and evaluated the performance and LOS at an un-signalized roundabout using the current traffic volume data. The methodology for conducting the LOS analysis procedure was previously explained, which involves selecting the link and roundabout capacity evaluation criteria based on the HCM procedure. The objective of the analysis was to obtain an acceptable LOS, which is a qualitative measure of various factors such as speed, travel time, traffic interruptions, driver comfort, safety, convenience, freedom of maneuvering, and costs incurred for operating a vehicle. For roadway LOS analyses, the HCM provides six LOS levels ranging from free flow to forced flow, denoted by the letters A through F. In contrast, for un-signalized roundabouts, the LOS criteria are based on the average vehicle delay on the stop-controlled approach, with varied threshold values reflecting drivers' expectations of different highway facilities. The six LOS levels for un-signalized roundabouts are denoted by the letters A through F, with increasing average vehicle delays ranging from 10 s or less to more than 50 s as shown in Table 3b. The LOS analyses for the roadways and intersections were performed using appropriate software such as VISSIM (PTV) to ensure accurate and reliable results.

By determining the LOS, this study provides valuable insights into the performance of the un-signalized roundabout, which can assist in making informed decisions for improving the traffic flow and safety at the intersection. Based on the findings in Table 3d, the sixth roundabout's priority control system has a LOS of F, indicating poor performance. The average delay was recorded at 247.75 s, with a stopped delay of 211.68 s, an average queue length of 207.34 m, and a maximum queue length of 510.30 m. The poor performance is attributable to the roundabout's location in a neighborhood area near prominent hotels and high-rise buildings that attract a significant number of trips, leading to high traffic volumes at all entries of the roundabout. Furthermore, all entries appeared to be fully utilized, as evidenced by the high values of average delay and maximum queue length. For

instance, the highest average delay recorded was 418.63 s, with a maximum queue length of 1030.33 m and a LOS of F from north to east, while the lowest average delay was 121.35 s, with a maximum queue length of 298.66 m and a LOS of F from west to south. These values are considerably higher than the HCM-recommended thresholds.

4.2. The Performance and LOS of a Signalized Roundabout with 15 Scenarios

The LOS of a signalized roundabout was evaluated based on the average delay per vehicle. The HCM has established six levels of service, ranging from a LOS of A to a LOS of F, each representing a different average vehicle delay as shown in Table 4a. Four performance measurement effectiveness characteristics were used to evaluate the roundabout operation: vehicle delay, stopped delay, queue length, and maximum queue length. The output data from the table were compared to determine the optimal scenario that yields the best results. The results indicate that the base circumstances operating (scenario 1) at a LOS of E are extremely crowded, resulting in delays and lengthy queues experienced by all approaches. However, when the distance of the queue detector is changed from scenario 2 to scenario 15, a LOS of E becomes a LOS of D (see Table 4b).

Table 4. The (**a**) HCM delay LOS criteria for signalized intersections based on control delay; (**b**) the four measure parameters (MOE) for all scenarios (15 scenarios); and (**c**) the measure of effectiveness (MOE) of the best scenario at the signalized roundabout (scenario 8).

(a) HCM Control Delay for the Vehicle (Seconds)	LOS	General Description
0–10	A	Free flow
>10–20	B	Stable flow (slight delays)
>20–35	C	Stable flow (acceptable delays)
>35–55	D	Approaching unstable Flow
>55–80	E	Unstable flow
>80	F	Forced flow

(b) MOE for All Scenarios (15 Scenarios)

Num. of Scenario	Queue Length (m)	Max. Queue Length (m)	Vehicle Delay (s)	Stopped Delay(s)	LOS
1	76.23	510.21	55.64	40.60	**E**
2	73.90	510.15	52.41	38.12	**D**
3	70.90	510.10	49.27	35.11	**D**
4	62.84	510.02	43.55	30.08	**D**
5	54.87	509.51	40.24	28.47	**D**
6	50.63	509.25	38.89	26.14	**D**
7	48.76	509.19	37.36	25.30	**D**
8	48.17	509.14	36.45	25.21	**D**
9	48.14	509.12	36.42	25.19	**D**
10	48.12	509.11	36.41	25.18	**D**
11	48.12	509.11	36.41	25.18	**D**
12	48.12	509.11	36.41	25.18	**D**
13	48.12	509.11	36.41	25.18	**D**
14	48.12	509.11	36.41	25.18	**D**
15	48.12	509.11	36.41	25.18	**D**

(c) MOE of the Best Scenario at the Signalized Roundabout (Scenario 8)

Name of Route	Avg. of Queue Length (m)	Max. of Queue Length (m)	Vehicle Delay (sec)	Stopped Delay (sec)
From east of Zahran Street to K. Faisal Ben Abdul Aziz Street	**33.3**	**351.94**	**19.02**	**13.15**
From east of Zahran Street to west of Zahran Street	29.82	315.21	34.45	23.83
From east of Zahran Street to Prs. Alia Street	45.23	478.12	32.95	22.79
From K. Faisal Ben Abdul Aziz Street to the west of Zahran Street	40.00	422.81	27.49	19.02
From K. Faisal Ben Abdul Aziz Street to Prs. Alia Street	68.66	725.74	95.19	65.83

Table 4. *Cont.*

(c) MOE of the Best Scenario at the Signalized Roundabout (Scenario 8)				
Name of Route	**Avg. of Queue Length (m)**	**Max. of Queue Length (m)**	**Vehicle Delay (sec)**	**Stopped Delay (sec)**
From K. Faisal Ben Abdul Aziz Street to East of Zahran Street	93.80	991.38	63.11	43.65
From west of Zahran Street to Prs. Alia Street	27.19	287.37	9.98	6.90
From west of Zahran Street to East of Zahran Street	34.76	367.41	39.93	27.62
From west of Zahran Street to K. Faisal Ben Abdul Aziz Street	57.90	611.93	26.75	18.50
From west of Zahran Street to west of Zahran Street	29.43	311.04	16.51	11.42
From Prs. Alia Street to east of Zahran Street	61.48	649.83	46.24	31.98
From Prs. Alia Street to K. Faisal Ben Abdul Aziz Street	61.43	649.29	51.51	35.63
From Prs. Alia Street to west of Zahran Street	58.37	616.95	51.63	35.71
All	**48.17**	**509.14**	**36.45**	**25.21**
LOS	**D**			

Results are presented in mean and standard deviation equals 0.5.

4.2.1. Comparison of Simulated Outputs for All Scenarios (15 Scenarios)

To evaluate the LOS of the roundabout, the average total vehicle delay was utilized as a metric. The LOS criteria include the typical delay for each vehicle during specific periods, such as peak traffic hours. Vehicle delay is a complex measure that depends on a variety of factors, including signal phasing, traffic volume, and the flow of vehicles through the intersection, all of which relate to the intersection's capacity. The data analysis indicated that increasing the distance of the queue detector resulted in a reduction in the average delay of vehicles. Figure 5 illustrates the correlation between the queue detector distance and the delay value. The base/standard scenario (scenario 1) revealed a delay of 55.4 s, which indicates a LOS of E. However, by placing the queue detector at 6.7 m in the second scenario, the delay decreased to 52.41 s, indicating a LOS of D. Further scenarios were tested to improve the delay reduction and LOS, but it was observed that the ideal queue detector distance for controlling delay was 96.9 m, as no significant reduction in delay was observed beyond this distance. An increase in the queue detector will result in a decrease in stop delay (Figure 5). Scenario 1 (standard scenario) exhibited a stopped delay of 55.64 s, which falls under a LOS of E where a LOS of E must be equal to or greater than 60 s. Following HCM, a LOS of D in stopped delay should be less than 44 s, which was achieved by placing the queue detector at 83.5 m in the scenario 6, resulting in a stopped delay of 38.89 s. Additional scenarios were tested to further improve delay reduction and LOS, but it was observed that the optimum queue detector distance for controlling stopped delay was 96.9 m, beyond which no significant reduction in delay was observed. The most efficient location for the detector is where the queuing time is minimized when control methods are implemented. The average queue length of the approaches was 73.90 m at 56.7 m of detector distance (scenario 2). It showed that the 56.7 m detector site was the least favorable distance. However, the combined average queue length was 54.87 m when the detector was placed at a distance of 76.8 m (scenario 5). Moreover, in scenario 8, during peak traffic hours at 96.9 m, the queue length could be shortened by approximately 48.17 m, while the maximum queue length was reduced from 510.21 to 509.14 m, as demonstrated in Figure 5 and Table 4b.

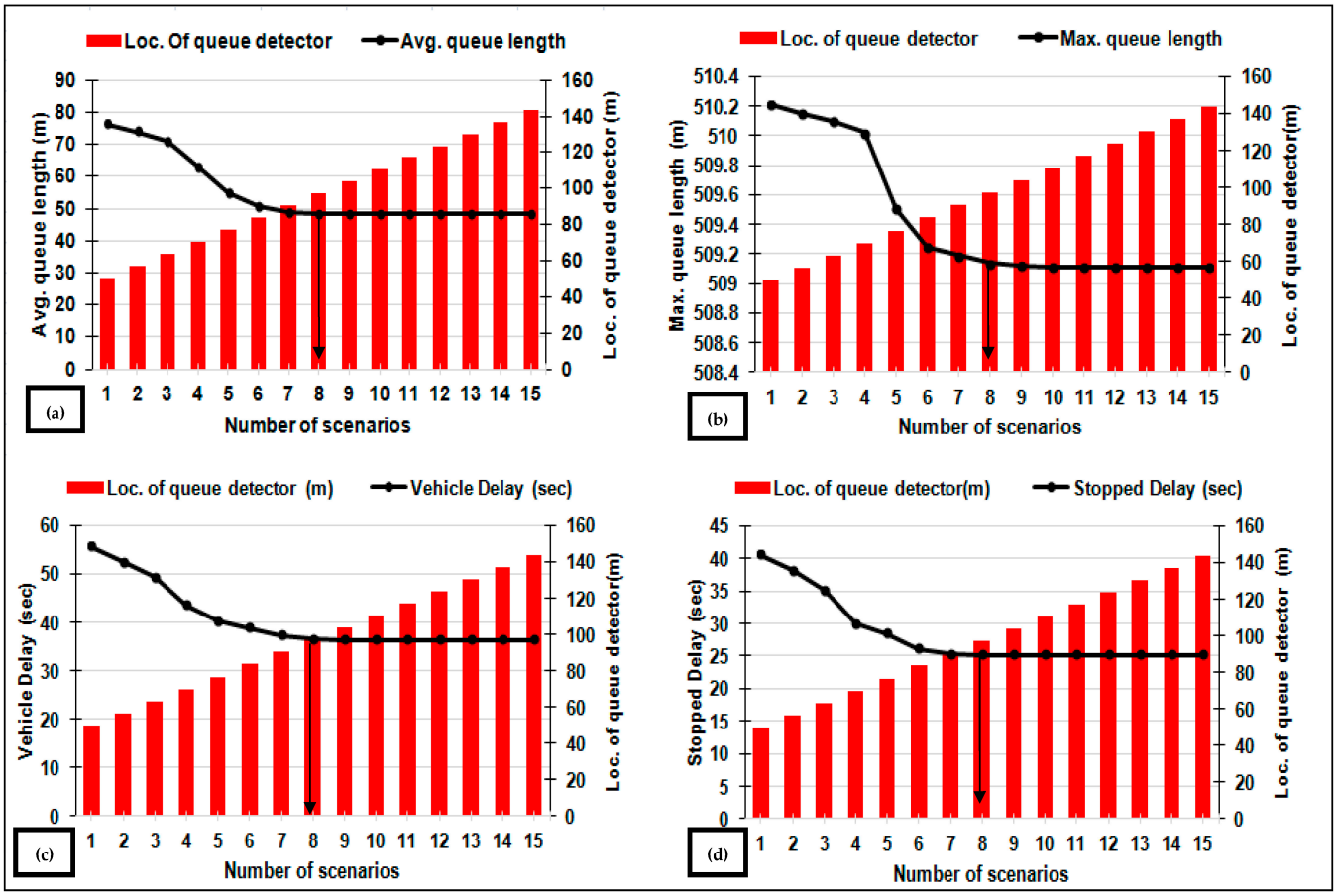


Figure 5. MOE for 15 scenarios at the 6th roundabout: (**a**) queue length (m); (**b**) max. queue length (m); (**c**) vehicle delay (sec); and (**d**) stopped delay (sec).

Therefore, the optimal position for the queue detector was determined by evaluating all possible scenarios, and a VISSIM model was utilized to accurately assess the adaptive metering method with four parameters: the length and maximum length of the queue, as well as the delay per car and the stopped delay. The experiment was run for 15 scenarios, and the results showed significant improvements in vehicle delay, stopped delay, and queue length. Between scenario 2 and scenario 5, the controlled approach experienced a reduction of 12.17 s in vehicle delay (from 52.41 to 40.24 s), a decrease of 5.65 s in stopped delay (from 38.12 to 28.47 s), and a decrease of 19.03 m in queue length (from 73.90 to 54.87 m). From scenario 5 to the scenario 8, the control delay was reduced by 6.19 s (from 40.24 s to 36.45 s), the stopped delay decreased by 3.35 s (from 28.47 to 25.12 s), and the queue length was reduced by 6.70 m (from 54.87 to 48.17 m). The optimization of the queue detector for all scenarios was determined to be 96.9 m in scenario 8, as shown in Figure 5. No further changes were observed after scenario 8, as the values of vehicle delay, stopped delay, and queue length remained consistent. Overall, the signalized sixth roundabout performed better than the conventional roundabout, with a LOS of D, an average delay of 36.45 s, and a maximum queue exceeding 509.14 m. As demonstrated in Figure 4, there were significant improvements in LOS, average delay, and maximum queue length, and the details of simulated outputs of scenario 8 are shown in Table 4c. Figure 6 presents the best scenario from the simulation video in VISSIM: (a) indicates long queues at the north, west, and east directions and the green light activated in the longest queue at the north direction; (b) indicates long queues at the west and east directions and the green light activated in the longest queue in the west direction; and (c) indicates long queues at the west, east, and north directions and the green light activated in the longest queue in the east direction.

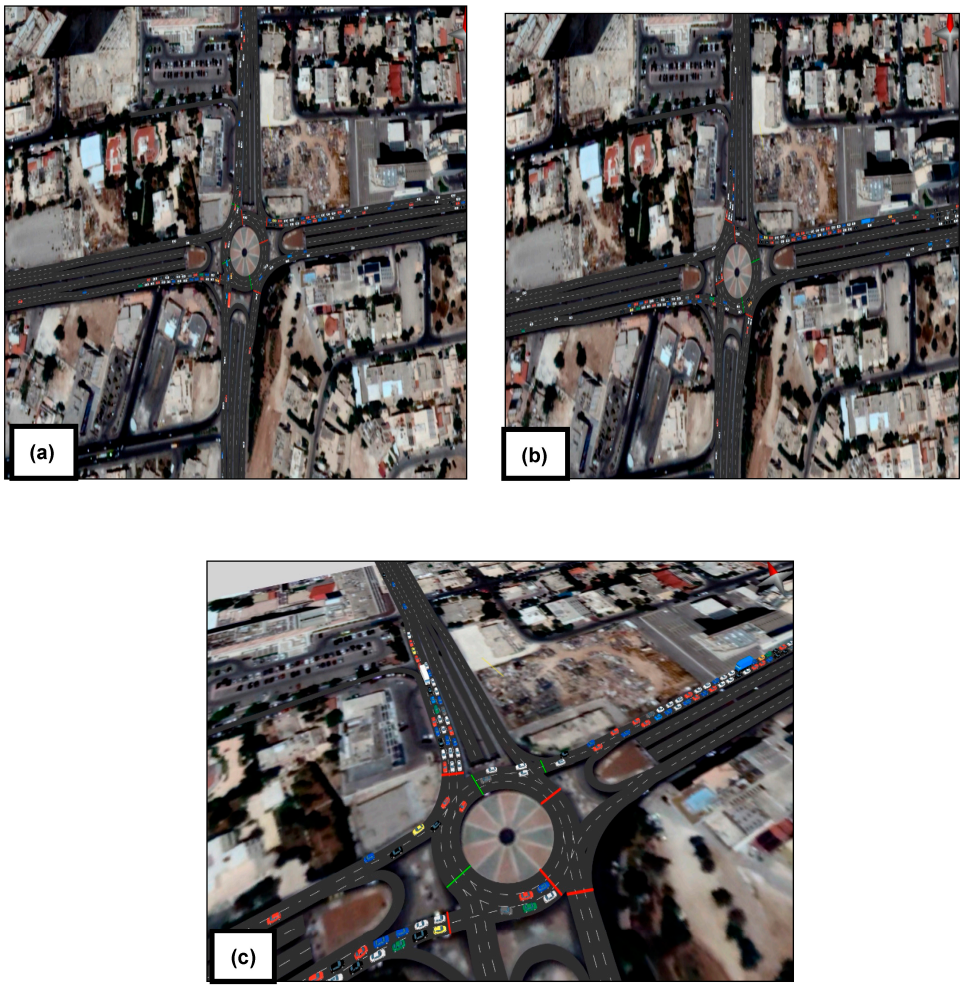


Figure 6. Screenshot from simulation video in VISSIM of the best scenario of the signalized sixth roundabout based on the highest queue length on the different approaches: (**a**) at the north approach; (**b**) the west approach; and (**c**) the east approach. Note: red light—stopping time; green light—moving time.

4.2.2. Comparisons between Scenario 1 (Base/Standard Scenario) and Scenario 8 (Best Scenario)

A simulation of the best detector under various traffic scenarios was conducted using VISSIM software at a selected roundabout. The best scenario (scenario 8) was compared with the base condition at the standard value of queue detectors (scenario 1) using four parameters (MOE), two based on the delay of the entire intersection and two based on queue length. The new model was compared with both the base scenario and the best scenario, and the percent change is shown in Table 5a. The model demonstrated good improvement over the base scenario (at 50 m), with the best improvement shown in scenario 8, which was located 96.9 m from the stop. All four measures of effectiveness demonstrated improvement, with the maximum queue length showing the best change from 76.23 m to 48.71 m, denoting a 28% change. However, the maximum queue length did not show significant improvement from 510.21 m to 509.14 m, representing a 1.07% change. The average delay per vehicle and the stopped delay time at the roundabout showed significant improvement, with a 19.19% improvement in vehicle delay from 55.64 s to 36.45 s and a 15.485% improvement in stopped delay from 40.60 s to 25.12 s (see Figure 7). These improvements demonstrate the effectiveness of the adaptive signal strategy and highlight the importance of selecting an optimal queue detector location based on all relevant parameters.

Table 5. The (**a**) percentage change base condition and best scenario at the sixth roundabout and (**b**) the comparison between the un-signalized case and the signalized case (best scenario) at the sixth roundabout.

(a) Percentage Change Base Condition and Best Scenario at the Sixth Roundabout.			
	Scenario 1 (Standard Values)	**Scenario 8 (Best Scenario)**	**Change %**
Vehicle delay (s)	55.64	36.45	19.19
Stopped delay (s)	40.60	25.21	15.48
Avg. queue length (m)	76.23	48.17	28.06
Max queue length (m)	510.21	509.14	1.07
LOS	**E**	**D**	**One level**
(b) Comparison between Un-Signalized Case and Signalized Case (Best Scenario) at the Sixth Roundabout.			
	Un-Signalized Case	**Signalized Case (Best Scenario)**	**Improvement %**
Vehicle delay (s)	247.75	36.45	85.28%
Stopped delay (s)	211.68	25.21	88.09%
Avg. queue length (m)	207.34	48.17	76.76%
Max queue length (m)	510.30	509.14	0.23%
LOS	**F**	**D**	**Two level**

Results are presented in mean and standard deviation equals 0.5.

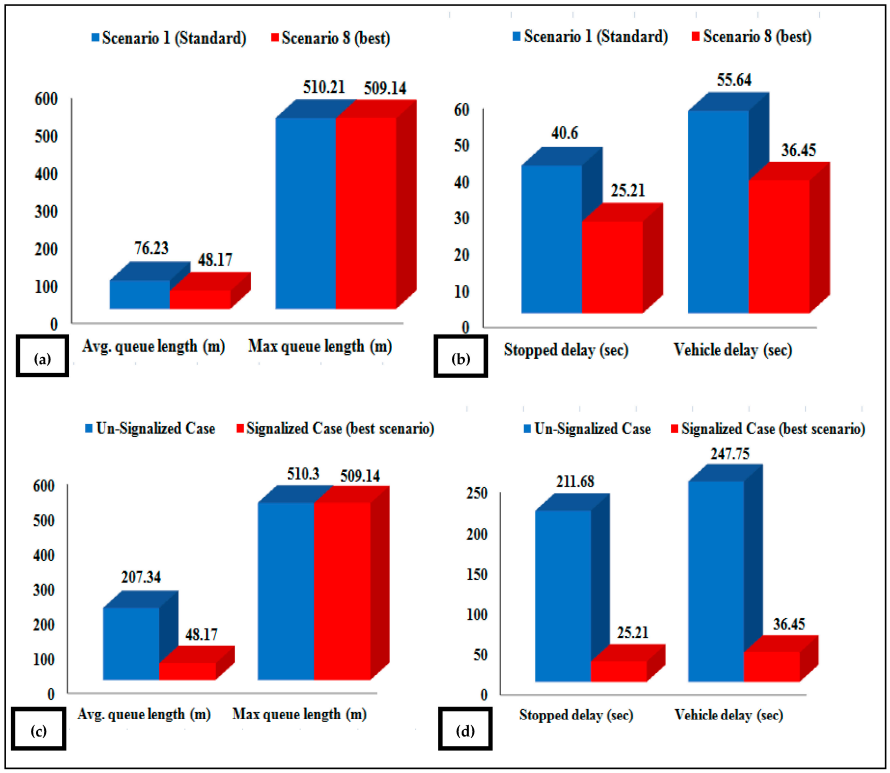


Figure 7. Comparison between the standard scenario (scenario 1) and the best scenario (scenario 8) at the signalized sixth roundabout: (**a**) queue length (m) and (**b**) delay (sec). Comparison between the signalized case with the best scenario and the un-signalized case at the sixth roundabout: (**c**) queue length (m) and (**d**) delay (sec). Results are presented with an error bar equal to 0.5.

4.3. A Comparison of LOS at Signalized and Un-Signalized Roundabouts

The study simulated models for un-signalized and signalized conditions and compared them with the best scenario, showing good improvement over un-signalized conditions. The best improvement was seen when the roundabout was converted to a signalized

condition with a queue detector in the optimal location, resulting in the highest LOS. All four measures of effectiveness (MOE) showed significant improvement. Queue length showed a positive change of 76.76%, from 207.34 to 48.17 m, while the average delay per vehicle at the roundabout improved by 85.28%, from 247.75 to 36.45 s, and it was improved by 88.09%, from 211.68 s to 25.21 s. The results indicate that converting un-signalized roundabouts to signalized ones by installing a queue detector at the best location can significantly improve traffic conditions and reduce congestion as shown in Table 5b and Figure 7.

4.4. Model Validation at Fifth Roundabout

To validate the model, the study assessed the sensitivity of the model by selecting the best scenario from all possibilities at the sixth roundabout and applying the simulation to the fifth roundabout in Amman, which operates at a LOS of F [14]. The VISSIM model was used to simulate the queue detector at a distance of 96.9 m from the signal line to evaluate the effectiveness of the detector using four measures. The comparison between the base scenario (1) and the best scenario (8) is shown in Table 6, revealing that the model exhibits a significant improvement over the base scenario. Scenario 8 showed the highest improvement at the distance of 96.9 m from the stop line, where all four measures of effectiveness exhibited substantial improvement. The maximum queue length showed the most significant positive change of 25.66%, which was reduced from 71.55 m to 45.89 m compared with all scenarios. However, the maximum queue length did not exhibit as much improvement, with only a 0.47% reduction from 510.21 m to 509.8 m, as illustrated in Figure 8. The average delay per vehicle and stop delay time at the roundabout also improved significantly. The percentage of improvement was 16.52% in vehicle delay, reducing from 51.68 s to 35.16 s, and 13.83% in stop delay, reducing from 38.64 s to 24.81 s, as shown in Figure 8. The results showed that the LOS improved from a LOS of E to a LOS of D based on the HCM.

Table 6. Validation of the best scenarios at the fifth roundabout by comparing the MOE between the base scenario (scenario 1) and best scenario (scenario 8).

Scenario	Queue Length (m)	Max. Queue Length (m)	Vehicle Delay (sec)	Stopped Delay (s)	LOS
Base scenario	71.55	510.21	51.78	38.64	E
Best scenario	45.89	509.08	35.16	24.81	D

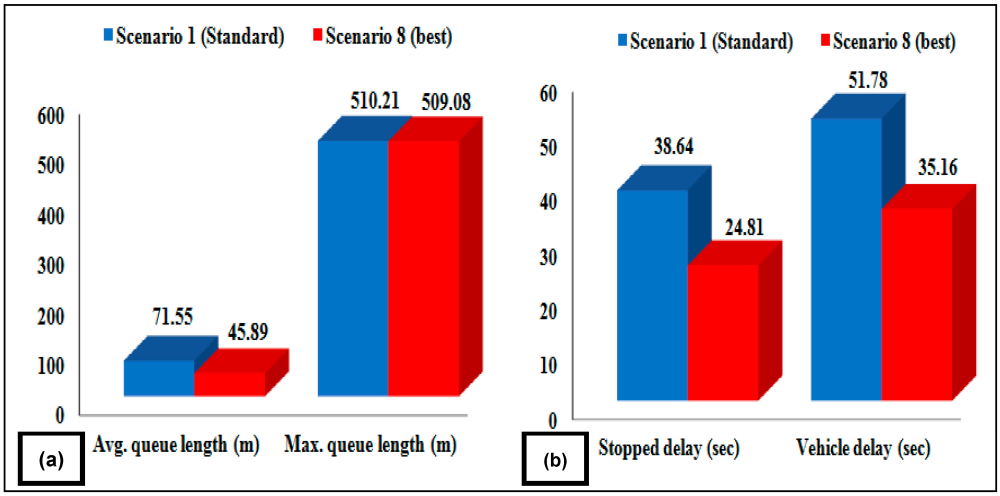


Figure 8. Validation of the best scenario at the fifth roundabout by comparing the MOE between the base scenario (scenario 1) and the best scenario (scenario 8): (**a**) queue length (m) and (**b**) delay (sec). Results are presented with an error bar equal to 0.5.

5. Research Limitations

This section presents an explanation of the limitations of the study, as well as the significance of the study

5.1. Limitations of the Study

This study has a few limitations that need to be considered when interpreting the findings. Firstly, the study focuses only on a four-legged roundabout and does not take into account pedestrians or bicycles based on the data from the traffic department in Jordan. This is due to the roundabout being designed without pedestrian facilities, and pedestrian traffic was not included in the study. Additionally, the simulation did not factor in bicycles because the majority of vehicles in Jordan are passenger cars and heavy vehicles. This could potentially affect the results, as pedestrian traffic and bicycles can impact a roundabout's performance.

Secondly, the study used heavy vehicles which represent only 2% of the total traffic volume, according to the traffic department in Jordan. While this may be an accurate representation of the traffic flow in Jordan, it is important to note that heavy vehicles have different operating characteristics than passenger cars, which could impact the roundabout's performance.

Finally, the study primarily focuses on effectiveness measures such as queue length, delay, and level of service, while emissions and fuel consumption are not considered in the discussion of simulation results. The results may not provide a comprehensive understanding of the roundabout's impact on the environment and sustainability. Therefore, it is important to consider the limitations of the study when interpreting the findings.

5.2. Significance of the Study

This study focused on improving the performance of roundabouts in terms of traffic conditions, specifically delays and queue lengths. The sixth roundabout (main site) was found to have serious congestion problems and the finding was consistent with previous studies conducted on the same roundabout without a traffic signal [13,14]. To evaluate this roundabout, queue length, average control delay, and LOS were measured. Under un-signalized conditions, the roundabout became very crowded, with high delays and long queues. However, when the roundabout was converted to a signalized roundabout, the performance improved. Maximum throughput was significantly higher, and queue lengths and approach delays were reduced, corroborating the findings of many prior studies [13–15,17,44,56]. On the other hand, the previous studies indicated that a queue detector has a significant effect on the performance of signalized roundabouts without focusing on the optimal locations from the stop line [18,37]. Meanwhile, the optimal location of the queue detector improved the performance of signalized roundabouts [25,26,41]. This finding is less highlighted in previous studies because most of the studies focus on the improvement of the performance of roundabouts by selecting the best scenario of the roundabout construction, the optimization of cycle length, the optimization of capacity, and choosing the optimization of different geometric elements at signalized roundabouts, and limited studies focus on the optimal location of queue detectors [13,19,23,43–46,57–60].

In this study, the method (modeling the optimal location of a queue detector at a roundabout by using VISSIM and Python) was based on analyzing both the geometric and traffic characteristics of the roundabout. The geometric characteristics of the roundabout (e.g., central island diameter, inscribed diameter, number of entry and exit points, number of lanes, number of approaches, and curvature) are significant parameters that affect the performance of the queue detector. Traffic volume, congestion patterns, and vehicle types also need to be considered in this analysis. Therefore, this study evaluated the optimal placement of queue detectors across 15 different scenarios at varying distances, as well as the standard base scenario of 50 m from the stop line. The best location for the queue detector was determined based on the highway capacity manual (HCM) criteria for measurement of effectiveness (MOE) at roundabouts. The optimal location was assessed based on traffic delay duration, average queue length, and level of service (LOS).

The modeling method described in this study can be applied to traffic systems worldwide, as long as the geometric designs of the roundabouts are suitable and similar characteristics exist. For example, the Old Belair Road roundabout in Australia has similar geometric characteristics that can be applied using the same approach (parameters: number of legs, lanes, circulating lanes, and circulating lane width). However, traffic volume and other conditions may differ and require adjustments to the model. Specific traffic data can be gathered to modify the model parameters. In this study, the maximum observed queue length during the peak traffic hour on the congested approach was 941 m, which is similar to the 910 m queue length observed in the Old Belair Road roundabout [25,26]. This study suggests that the optimal location of the queue detector (when installing a queue detector on two approaches at a distance of 380 m for the controlling approach and 320 m for metered approach) can slightly reduce the queue length [26]. Another study of the Old Belair Road roundabout found that the optimal location of a queue detector (when installing a queue detector on only one approach at a distance of 210 m) can reduce the queue length by about 25% on the roundabout [25]. Meanwhile, in this study, the optimal location of queue detectors when installing queue detectors on all approaches and using adaptive traffic signals based on the highest queue length at the roundabout reduced the queue length by 76.76%.

On the other side, in the United States and Spain, queue detectors have been used to reduce delays and queue lengths on congested roundabouts. To simulate the performance of the queue detectors, both the geometric and traffic characteristics of the roundabout were analyzed using VISSIM modeling. In the U.S., queue detectors were placed at a standard distance of 175 ft (53 m) on all approaches of congested roundabouts, resulting in a reduction in delays of 27% [37] and over 30% [18], and an average queue length reduction of 36% [37] and over 40% [18] during the highest PM peak hour traffic volume when queue detectors were installed on all approaches and adaptive traffic signals were used. In Spain, queue detectors were placed at a standard distance of 50 m, and the optimal model presented the lowest average delay (22–56%) when applying the queue detector on one approach and using semi-actuated signals in VISSIM [41]. However, this study evaluated the optimal placement of queue detectors in 15 different scenarios with varying distances, including the standard placement of 50 m from the stop line. The optimal location of the queue detector reduced the delay time by 85.25% when queue detectors were installed at 97 m on all approaches and adaptive traffic signals were used based on the highest queue length at the roundabout.

The results of this study can be used as a guide for implementing queue detectors on all approaches and using adaptive traffic signals based on the highest queue length at roundabouts. This study provides best practices for designing and operating signalized roundabouts and can be applied to different regions with varying traffic characteristics, technology and infrastructure availability, and compliance with local regulations. The effectiveness of the modeling method was validated by testing it on another roundabout, and improvements were made based on the performance of the queue detector including the maximum queue length, average queue length, average delay per vehicle, and stop delay time. The findings confirm the sensitivity of the model, indicating that it can be effectively applied to other roundabouts. In conclusion, the described modeling method can be a useful tool for optimizing the location of queue detectors at roundabouts in different cities, as long as the specific traffic and geometric conditions of each roundabout are taken into account.

6. Conclusions and Future Research

This study presents an innovative approach to improve traffic flow at circular junctions. An adaptive, fully signalized system was developed and implemented at a real-world traffic roundabout that experienced uneven flows, using three detectors to monitor queue, demand, and entry. In the absence of queue detection, huge queues were observed on multiple approaches during rush hour in the un-signalized roundabout. In addition, the

installation of traffic signals with one detector at selected intersections was not effective in reducing the congestion; the problem persisted, and the LOS remained at F. The main points of the findings of this study are presented below:

- The selected roundabouts face numerous challenges due to high traffic volumes, which result in unbalanced flow, high capacity, traffic congestion, and unrelenting traffic. The simulation results demonstrated that the sixth roundabout's priority control system has a LOS of F, indicating poor performance. The average delay was recorded at 247.75 s, with a stopped delay of 211.68 s, an average queue length of 207.34 m, and a maximum queue length of 510.30 m.
- Installing a traffic signal at the roundabout and placing a queue detector at the stop line negatively affected its performance, resulting in a crowded situation with a LOS of E, based on the HCM. During peak traffic hours, standard values showed that vehicle delay was 55.64 s, stopped delay was 40.60 s, and queue length was 76.23 m.
- This research employed 15 scenarios using the VISSIM model, with 4 adaptive signalized system parameters: queue length, maximum queue length, vehicle delay per car, and stopped delay. The findings showed that optimal results were achieved when placing the queue detector at 97 m from the stop line.
- The study measured the effectiveness of converting un-signalized roundabouts to signalized ones by installing a queue detector. Four different measures of effectiveness were used, and all of them showed significant improvement. The queue length decreased by 76.76%, from 207.34 m to 48.17 m. The average delay per vehicle at the roundabout decreased by 85.28%, from 247.75 s to 36.45 s, and the maximum delay decreased by 88.09%, from 211.68 s to 25.21 s. These results suggest that the conversion of un-signalized roundabouts to signalized ones with queue detectors can greatly enhance traffic conditions and decrease congestion.
- The validation model for Amman's fifth roundabout was compared with the base (standard) condition and the best-case scenario, with the percentage change displayed. Scenario 8 at 97 m showed the most significant improvement, with a 25.66% decrease in queue length from 71.55 to 45.89 m, a 16.52% decrease in vehicle delay from 51.68 to 35.16 s, and a 13.83% decrease in stopped delay from 38.64 to 24.81 s. The only effectiveness indicator that did not improve was maximum queue length, with a less-than-ideal 0.47% change from 510.21 to 509.8 m. Overall, the new model improved the LOS from LOS E to LOS D, according to the HCM.
- The results of this research could inform the development of new guidelines and best practices for signalized roundabout design and operation which could be useful for improving traffic flow in other regions. The findings confirm the sensitivity of the model, indicating that it can be effectively applied to other roundabouts.
- Future research, as a continuation of this paper, should be focused on developing a simulation model for determining the optimal location of queue detectors at roundabouts and measuring emissions parameters and their impact on traffic sustainability. The research could lead to the creation of new, innovative approaches for multi-criteria decision making in traffic management. By gaining a deeper understanding of how emissions impact traffic sustainability, researchers may be able to devise effective strategies for reducing emissions and improving environmental health. The simulation model will be an indispensable tool for precisely measuring the effects of these strategies and making informed decisions regarding traffic management in the future.

Author Contributions: Conceptualization, methodology, A.A.A.; data curation, writing—original draft preparation, A.A.A.; visualization, investigation, A.A.A.; supervision, N.S.A.S. and I.K.; software, validation, A.A.A.; writing—reviewing and editing, N.S.A.S., I.K. and T.S.B.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Edgewater for Design and Engineering Consulting and Environment, Amman, Jordan.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article. The data presented in this study are as shown in the article.

Acknowledgments: The authors would like to thank TP2 (Train to publish for the second batch under USM) for providing the reviewing and editing of this article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CTD	Central Traffic Department
GAM	Greater Amman Municipality
GEH	Geoffrey E. Havers
FHWA	Federal Highway Administration
HCM	Highway capacity manual
LOS	Level of service
MOE	Measure of effectiveness
API	Application programming interface
ASCT	Adaptive signal control technologies

Appendix A

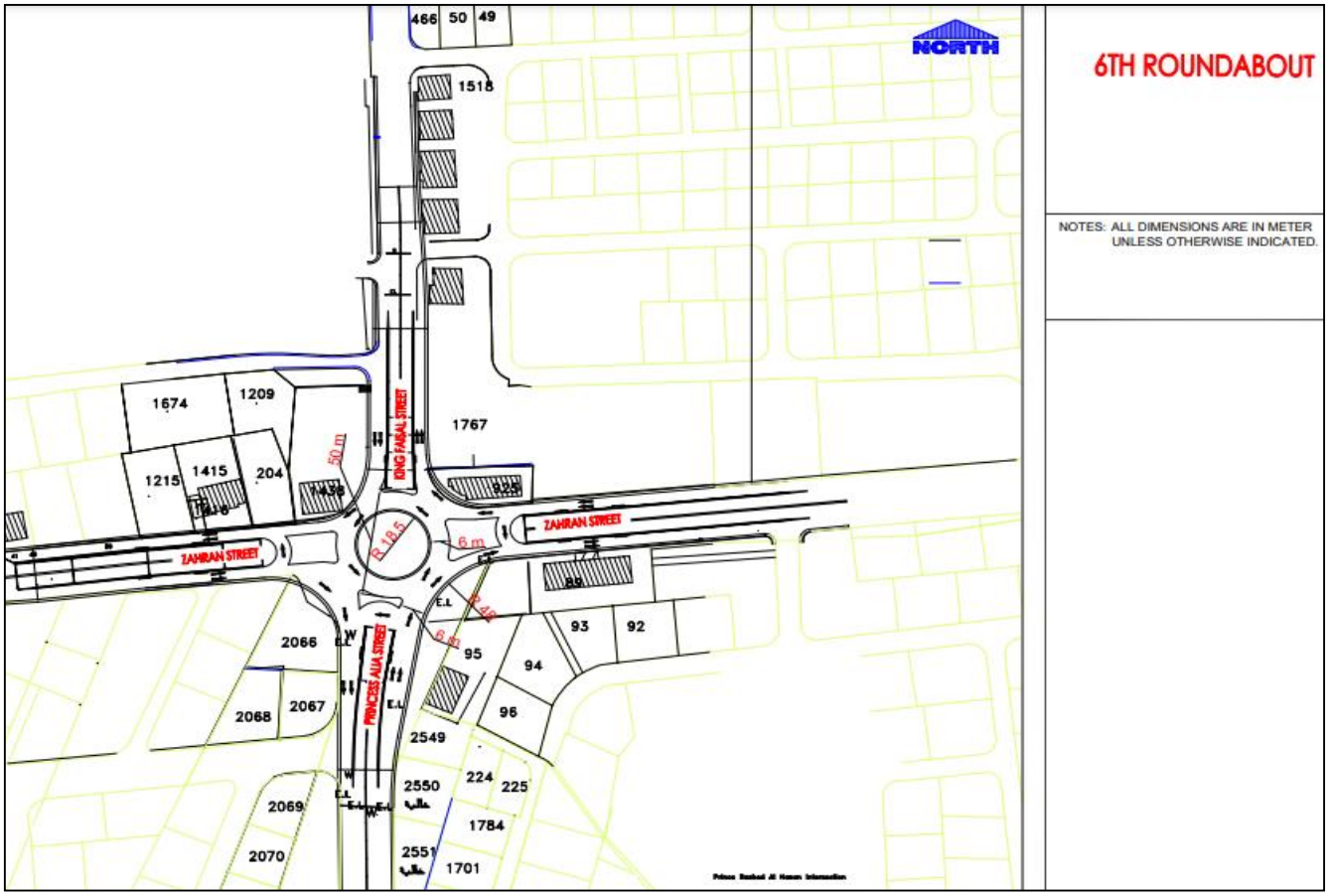


Figure A1. AutoCAD file of the sixth roundabout.

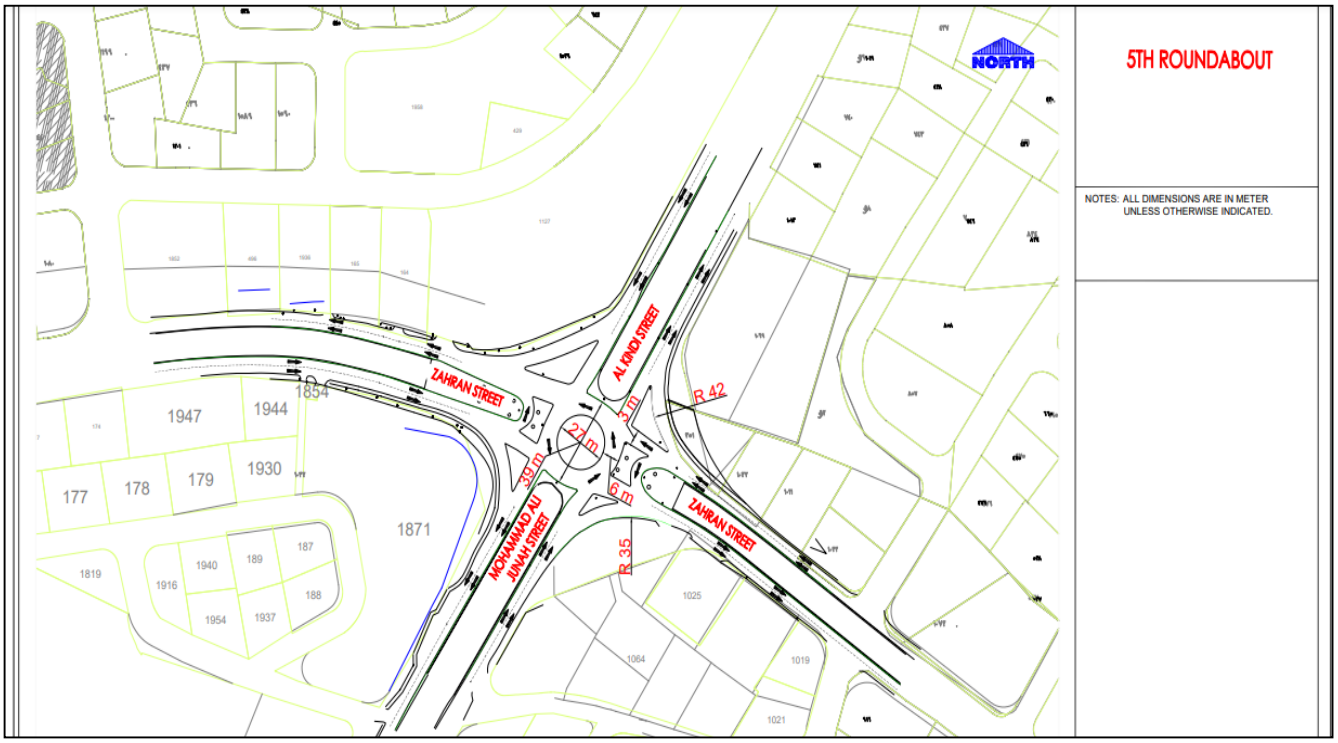


Figure A2. AutoCAD file of the fifth roundabout.

Appendix B

Table A1. Traffic Data for the sixth and fifth roundabouts during the peak traffic hour (7:30–8:30): (**A**) traffic volume (veh/h); (**B**) queue length (m); and (**C**) travel time (s).

(A) Traffic Volume at the Sixth and Fifth Roundabouts (Greater Amman Municipality, 2018)					
Roundabout	**Street Name**	**Volumes of Vehicles in the Circulating Roadway (veh/h)**	**Volumes of Left-Turning Vehicles in the Subject Entry (veh/h)**	**Volumes of Right-Turning Vehicles (veh/h)**	**Volumes of U-Turning Vehicles (veh/h)**
Sixth roundabout	Prs. Alia Street (South)	704	1373	874	0
	K. Faysal Ben Abdul Aziz Str. (North)	2383	1152	316	0
	Zahran Street (East)	4231	1147	340	0
	Zahran Street (West)	43	3450	0	548
Fifth roundabout	Ali Mohammad Junah Street (South)	3132	135	86	0
	Kindi Street (North)	636	1122	515	269
	Zahran Street (East)	947	240	1410	0
	Zahran Street (West)	156	710	0	1159

(B) Avg. Observed Queue Length (m)		
Time	**Sixth Roundabout (North Approach)**	**Fifth Roundabout (South Approach)**
7:30–7:35	635	413
7:35–7:40	851	723
7:40–7:45	407	593
7:45–7:50	941	638
7:50–7:55	505	403
7:55–8:00	326	810
8:00–8:05	541	509
8:05–8:10	399	412
8:10–8:15	435	449

Table A1. *Cont.*

(B) Avg. Observed Queue Length (m)									
Time				**Sixth Roundabout (North Approach)**			**Fifth Roundabout (South Approach)**		
8:15–8:20				358			286		
8:20–8:25				242			250		
8:25–8:30				179			185		
(C) Average Observed Travel Time at Sixth and Fifth Roundabouts (s)									
Roundabout	**Approach**	**Distance (m)**	**The Avg. (sec)**	**Obs. 1**	**Obs. 2**	**Obs.3**	**Obs.4**	**Obs. 5**	**Obs.6**
Sixth round-about	From east of Zahran Street to Prs. Alia Street	206.06	148.28	144.45	143.26	153.6	154.49	144.95	148.93
	From K.Faysal Ben Abdul Aziz Street to east of Zahran Street	212.94	217.01	207.43	209.48	223.9	241.21	204.69	208.72
	From west of Zahran Street to K.Faysal Ben Abdul Aziz Street	201.56	96.17	102.06	77.43	103.2	114.6	91.41	88.33
	From Prs. Alia Street to west of Zahran Street	204.2	191.53	196.81	192.01	186.66	195.97	191.13	186.61
Fifth round-about	From east of Zahran Street to Ali Mohammad Junah Street	271.56	105.93	125.31	82.85	97.35	135.67	80.78	113.64
	From Kindi Street to east of Zahran Street	272.5	203.09	178.54	186.28	220.19	268.46	187.32	177.76
	From west of Zahran Street to Kindi Street	253.74	77.13	74.82	80.54	68.23	74	85.76	78.73
	From Ali Mohammad Junah Street to west of Zahran Street	244.95	96.84	101.65	95.43	86.49	83.21	123.18	91.09

Appendix C

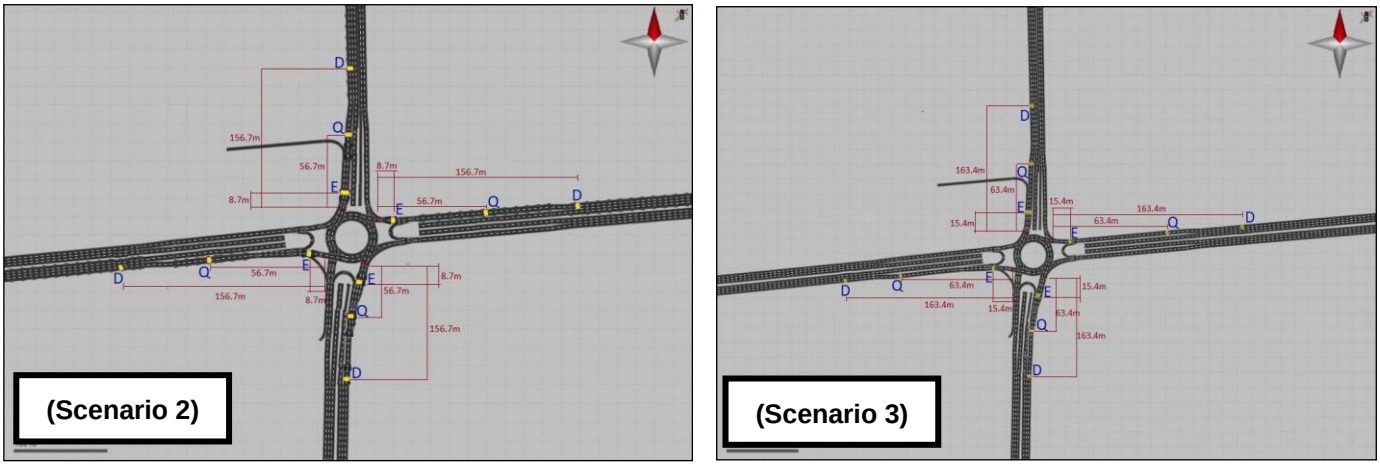


Figure A3. *Cont.*

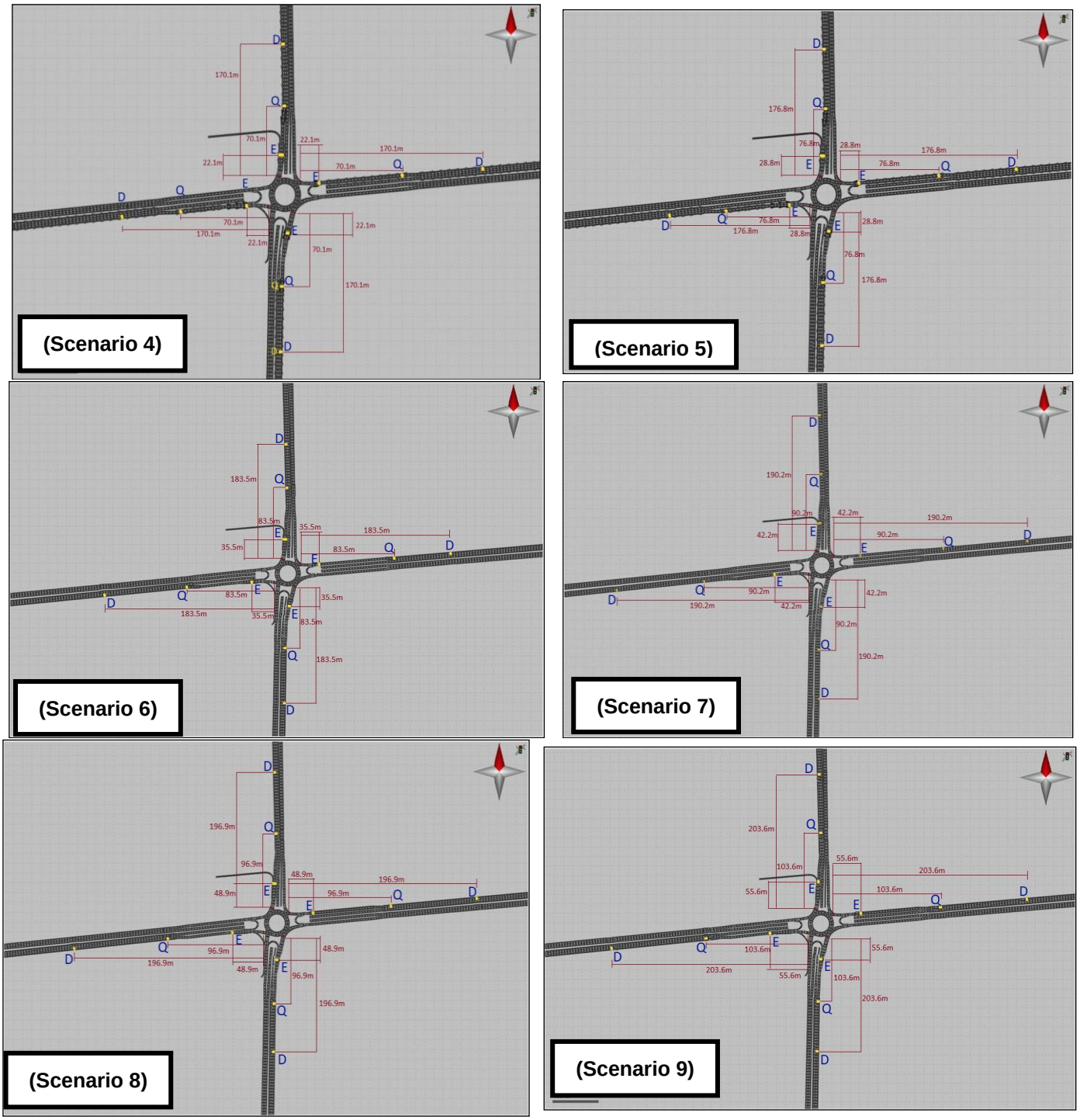


Figure A3. *Cont*.

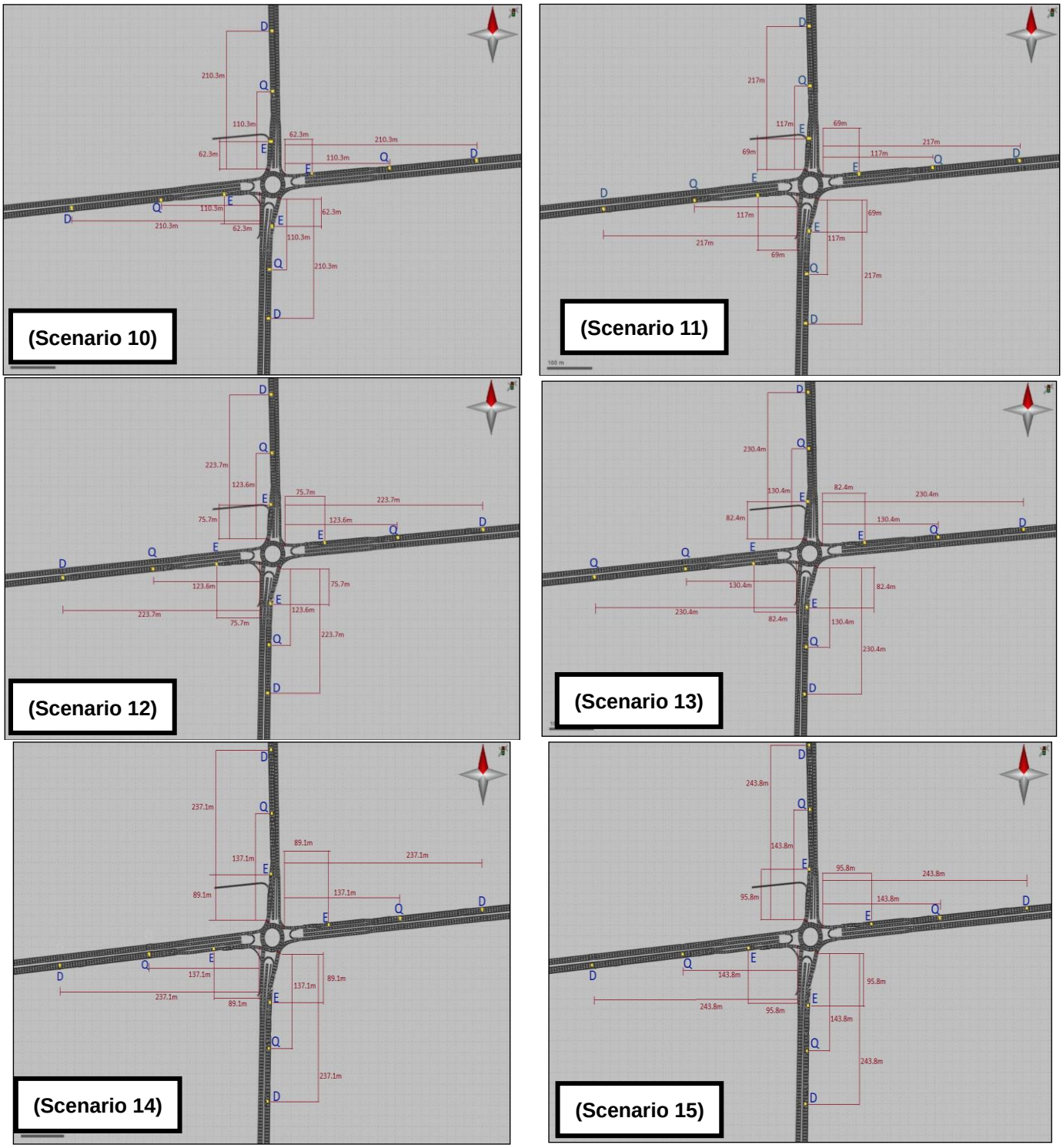


Figure A3. Different scenarios from scenario 2 to scenario 15 at the 6th roundabout.

Appendix D

Table A2. Comparison of Average travel time and simulated travel time of the un-signalized sixth and fifth roundabouts during the peak traffic hour (7:30–8:30) (2018).

	Approach	Distance (m)	Average Observed Travel Time (s)	Average Simulated Travel Time (s)	Variation	(80–120) % of Field Value
Sixth roundabout	From east of Zahran Street to prs. Alia Street	206.06	148.28	145.48	1.89	**YES**
	From K. Faysal Ben Abdul Aziz Street to east of Zahran Street	212.94	217.01	219.01	−0.92	**YES**
	From west of Zahran Street to K. Faysal Ben Abdul Aziz Street	201.56	96.17	93.51	2.76	**YES**
	From prs. Alia Street to the west of Zahran Street	204.2	191.53	202.73	−5.85	**YES**
Fifth roundabout	From east of Zahran Street to Ali Mohammad Junah Street	271.56	105.93	118.32	−11.69	**YES**
	From Kindi Street to east of Zahran Street	272.5	203.09	188.75	7.06	**YES**
	From west of Zahran Street to Kindi Street	253.74	77.13	83.32	−8.03	**YES**
	From Ali Mohammad Junah Street to the west of Zahran Street	244.95	96.84	88.54	8.57	**YES**

Appendix E

Table A3. Calculation of validation model of the average queue length at the sixth and fifth roundabouts during the peak traffic hour (7:30–8:30) (2018).

Number of Runs	Observed Average Queue Length (m)		VISSIM Simulated Average Queue Length (m)		$GEH=\sqrt{\frac{2x(Q_{sim}-Q_{observed})^2}{(Q_{sim}+Q_{observed})}}$	
	Sixth Roundabout	Fifth Roundabout	Sixth Roundabout	Fifth Roundabout	Sixth Roundabout	Fifth Roundabout
Run 1	484.84	472.54	510	500.41	1.1279	1.2636
Run 2	484.84	472.54	475.84	443.11	0.4106	1.3754
Run 3	484.84	472.54	549	526.22	2.8218	2.4021
Run 4	484.84	472.54	478	443.32	0.3118	1.3655
Run 5	484.84	472.54	440.7	528.06	2.052	2.4822
Run 6	484.84	472.54	542.84	415.19	2.5586	2.7221
Run 7	484.84	472.54	513.5	518.08	1.2826	2.0462
Run 8	484.84	472.54	453	395.15	1.4705	3.7155
Run 9	484.84	472.54	540.5	549.4	2.458	3.4002
Run 10	484.84	472.54	460	447.01	1.14299	1.1906
Run 11	484.84	472.54	502.84	536.71	0.8099	2.8566
Run 12	484.84	472.54	429	428.67	2.6124	2.0667
Run 13	484.84	472.54	470	507.75	0.6793	1.5904
Run 14	484.84	472.54	540	443.38	2.4366	1.3625
Run 15	484.84	472.54	401.5	490.88	3.9589	0.8358
The avg. value of GEH:					1.7423	2.04502

References

1. Szczuraszek, T.; Klusek, R. Influence on the Type of Intersection on Road Traffic Safety in Poland. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *471*, 062021. [CrossRef]
2. Pilko, H.; Mandžuka, S.; Barić, D. Urban single-lane roundabouts: A new analytical approach using multi-criteria and simultaneous multi-objective optimization of geometry design, efficiency and safety. *Transp. Res. Part C Emerg. Technol.* **2017**, *80*, 257–271. [CrossRef]
3. Shah, R.; Khan, T.N.; Ullah, N.; Khan, M.T. Traffic Analysis Evaluate and Signalize the Existing Roundabout using PTV Vissim Software. In Proceedings of the 1st International Conference on Resent Advances in Civil and Earthquake Engineering (ICCEE-2021)—OCT 08, Peshawar, Pakistan, 8 October 2021.
4. Owais, M.; Abulwafa, O.; Abbas, Y.A. When to decide to convert a roundabout to a signalized intersection: Simulation approach for case studies in Jeddah and Al-Madinah. *Arab. J. Sci. Eng.* **2020**, *45*, 7897–7914.
5. Shatnawi, A.; Drine, A.; Al-Zinati, M.; Althebyan, Q. Analyzing the Effect of Driving Speed on the Performance of Roundabouts. *Int. Arab. J. Inf. Technol.* **2022**, *19*. [CrossRef]
6. Zhou, L.; Zhang, L.; Liu, C.S. Comparing Roundabouts and Signalized Intersections Through Multiple-Model Simulation. *IEEE Trans. Intell. Transp. Syst.* **2021**, *23*, 7931–7940. [CrossRef]
7. Fatimah, S.; Matondang, S.A. Simulation Model to Reduce the Traffic Jams with a Stochastic Program. *WSEAS Trans. Environ. Dev.* **2022**, *18*, 37–41. [CrossRef]
8. AlKofahi, N.; Khedaywi, T. Trends and Modeling of Traffic Accidents in Jordan. *Int. J. Eng. Technol. (IJET)* **2019**, *11*, 1166–1181. [CrossRef]
9. Hazim, N.; Hassan, M.R. Improving Traffic Incident Management Using Intelligent Transportation Systems, A Case of Amman City. *Turk. J. Comput. Math. Educ.* **2021**, *12*, 4343–4352.
10. Abid, R.I.; Tortum, A.; Atalay, A. Fractal Dimensions of Road Networks in Amman Metropolitan Districts. *Alex. Eng. J.* **2021**, *60*, 4203–4212. [CrossRef]
11. Hazim, N.; Bazlamit, S.M.; ABU Salem, Z.; Alghazawi, O.; Odeh, I. Determinations of critical gap and follow-up time at roundabouts in Jordan. *Roads Bridges-Drog. I Mosty* **2019**, *18*, 227–234. [CrossRef]
12. Alsaleh, N.M.; Shbeeb, L. Turbo, flower and conventional roundabouts in Jordan. In Proceedings of the 6th Annual International Conference on Architecture and Civil Engineering (ACE 2018), Singapore, 14–15 May 2018. [CrossRef]
13. Khliefat, I.; Naser, M.; Alhomaidat, F.; Hanandeh, S. Improving the Capacity and Level of Service at the Sixth Circle in Jordan by Using Traffic Signals and Roundabout Metering Approach. *Open Transp. J.* **2021**, *15*, 69–80. [CrossRef]
14. Rashed, O.; Imam, R. A Functional and Operational Comparison between Signalized and Unsignalized Roundabouts. *Int. J. Eng. Res. Technol.* **2020**, *13*, 1448–1454. [CrossRef]
15. Osei, K.K.; Adams, C.A.; Ackaah, W.; Oliver-Commey, Y. Signalization options to improve capacity and delay at roundabouts through microsimulation approach: A case study on arterial roadways in Ghana. *J. Traffic Transp. Eng. (Engl. Ed.)* **2019**, *8*, 70–82. [CrossRef]
16. Iscan, N. Evaluation the Level of Service at a Roundabout: A Case Study on Al-Ibrahimeya Roundabout in Alexandria, Egypt. 2019. Available online: https://semanticscholar.org/paper/72100880d7e5063ebede73e1931fad10dc5a44b6 (accessed on 1 March 2023).
17. Sarir, E.M.; Khan, E.M.T. Evaluation of Capacity at Signalized Roundabout Using VISSIM. Bachelor's Thesis, Abasyn University, Peshawar, Pakistan, 2020. [CrossRef]
18. Ma, X.; Yi, P.; Bolla, V. Priority metering control for an urban circular intersection. *Civ. Eng. J.* **2019**, *2*, 24. [CrossRef]
19. Qadri, S.S.S.M.; Gökçe, M.A.; Öner, E.; Gökçe, E.G. Analysis of various scenarios to mitigate congestion at a signalized roundabout using microsimulation. In Proceedings of the 2019 Innovations in Intelligent Systems and Applications Conference (ASYU), Izmir, Turkey, 31 October–2 November 2019.
20. Van, N.H.; Can, V.X.; Thuat, V.T. A fuzzy traffic signal control method for a single intersection under mixed traffic conditions. *Technology* **2020**, *11*, 1715–1723.
21. Hamim, O.F.; Hossain, S. Hadiuzzaman Developing empirical model with graphical tool to estimate and predict capacity of rural highway roundabouts. *Int. J. Transp. Sci. Technol.* **2022**, *11*, 726–737. [CrossRef]
22. Murat, Y.S.; Guo, R.-J. Signalized Roundabouts. In *International Encyclopedia of Transportation*; Elsevier: Amsterdam, The Netherlands, 2021. [CrossRef]
23. Murat, Y.S.; Cakici, Z.; Tian, Z. A signal timing assignment proposal for urban multi lane signalised roundabouts. *J. Croat. Assoc. Civ. Eng.* **2019**, *71*, 113–124. [CrossRef]
24. Fernandes, P.; Teixeira, J.; Guarnaccia, C.; Bandeira, J.; Macedo, E.; Coelho, M. The Potential of Metering Roundabouts: Influence in Transportation Externalities. *Transp. Res. Rec. J. Transp. Res. Board* **2018**, *2672*, 21–34. [CrossRef]
25. An, H.K.; Liu, Y.; Kim, D.S. Operational optimization at signalized metering roundabouts using cuckoo search/local search algorithm. *Meas. Control* **2022**, *55*, 1110–1123. [CrossRef]
26. An, H.K.; Yue, W.L.; Stazic, B. Estimation of vehicle queuing lengths at metering roundabouts. *J. Traffic Transp. Eng. (Engl. Ed.)* **2017**, *4*, 545–554. [CrossRef]
27. An, H.K.; Yue, W.L.; Stazic, B. An analysis of a partially signalized roundabout using SIDRA 6 software. *Asian Transp. Stud.* **2016**, *4*, 314–329.

28. Duan, Y.; Qu, X.; Easa, S.; Yan, Y. Optimising total entry delay at roundabouts with unbalanced flow: A dynamic strategy for smart metering. *IET Intell. Transp. Syst.* **2019**, *13*, 485–494. [CrossRef]
29. Kabit, M.R.; Tan, M.C.N.; Ibrahim, W.I.W. An Evaluation of Signal Metering Application to Mitigate Roundabout's Unbalanced Flow Conditions: A Case Study In Kuching. *Malays. Constr. Res. J.* **2019**, *27*, 1.
30. Qadri, S.S.S.M.; Gökçe, M.A.; Öner, E. State-of-art review of traffic signal control methods: Challenges and opportunities. *Eur. Transp. Res. Rev.* **2020**, *12*, 1–23. [CrossRef]
31. Xu, H.; Zhang, K.; Zhang, D. Multi-level traffic control at large four-leg roundabouts. *J. Adv. Transp.* **2016**, *50*, 988–1007. [CrossRef]
32. Mao, C.; Wang, Q.; Xu, W.; Cheng, X.; Yang, S.; Li, P. Combined Phase Design Model for Multileg Roundabout Intersections. *J. Adv. Transp.* **2022**, *2022*, 8946794. [CrossRef]
33. Toledo, T.; Balasha, T.; Keblawi, M. Optimization of actuated traffic signal plans using a mesoscopic traffic simulation. *J. Transp. Eng. Part A* **2020**, *146*, 04020041. [CrossRef]
34. Pratama, B.; Christanto, J.; Hadyantama, M.T.; Muis, A. Adaptive Traffic Lights through Traffic Density Calculation on Road Pattern. In Proceedings of the 2018 International Conference on Applied Science and Technology (iCAST), Manado, Indonesia, 26–27 October 2018; pp. 82–86. [CrossRef]
35. Ye, F.; Hao, P.; Wu, G.; Boriboonsomsin, K.; Gao, Z.; Laclair, T.; Barth, M. *Dynamic Queue Prediction at Signalized Intersections with Fusing Sensory Information and Connected Vehicles*; Oak Ridge National Lab. (ORNL): Oak Ridge, TN, USA, 2020.
36. Afezolli, A.; Shehu, E. The analysis of Performance and Capacity at a Roundabout with metering signals. In Proceedings of the 3rd International Balkans Conferenceon Challenges of Civil Engineering, 3-BCCCE, Tirana, Albania, 19–21 May 2016.
37. Mahmood, K. *Improving Roundabout Performance Using Roundabout Metering Technique*; University of Akron: Akron, OH, USA, 2016.
38. An, H.K.; Abdalla, A.N. Prediction of queuing length at metering roundabout using adaptive neuro fuzzy inference system. *Meas. Control* **2019**, *52*, 432–440. [CrossRef]
39. Nikitin, N.; Patskan, V.; Savina, I. Efficiency Analysis of Roundabout with Traffic Signals. *Transp. Res. Procedia* **2017**, *20*, 443–449. [CrossRef]
40. TRUM. *Taffic and Road Use Management*; Department of Transport and Main Roads: Brisbane City, Australia, 2022.
41. Martin-Gasulla, M.; Garcia, A.; Moreno, A.T.; Llorca, C. Capacity and Operational Improvements of Metering Roundabouts in Spain. *Transp. Res. Procedia* **2016**, *15*, 295–307. [CrossRef]
42. Martin-Gasulla, M.; García, A.; Moreno, A.T. Benefits of metering signals at roundabouts with unbalanced flow: Patterns in Spain. *Transp. Res. Rec.* **2016**, *2585*, 20–28. [CrossRef]
43. Al-Obaidi, M.K.J. Improvement of the Traffic Management of Deactivated Al-Faris Al-Arabi Signalized Roundabout in Baghdad City. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *518*, 022016. [CrossRef]
44. Adegbaju, O.A. Establishing Delay-Based Criteria for Installing Traffic Signals at Two-Lane Roundabouts. Master's Thesis, Western Michigan University, Kalamazoo, MI, USA, 2018. Available online: https://scholarworks.wmich.edu/cgi/viewcontent.cgi?article=4821&context=masters_theses (accessed on 1 May 2023).
45. Jiang, Z.-H.; Wang, T.; Li, C.-Y.; Pan, F.; Yang, X.-G. Investigation on Two-Stop-Line Signalized Roundabout: Capacity and Optimal Cycle Length. *J. Adv. Transp.* **2019**, *2019*, 5720290. [CrossRef]
46. Jalil, K.; Xia, Y.; Zahid, M.N.; Kamal, A.S. Two Stop-Line Method for Modern T-Shape Roundabout: Evaluation of Capacity and Optimal Signal Cycle. *J. Adv. Transp.* **2022**, *2022*, 7679496. [CrossRef]
47. Fernandes, P.; Rouphail, N.M.; Coelho, M.C. Turbo roundabouts along corridors: Analysis of operational and environmental impacts. *Transp. Res. Rec.* **2017**, *2627*, 46–56. [CrossRef]
48. Hill, M.; Pittenger, J.; Ceifetz, A. *Development of a Michigan-Specific VISSIM Protocol for Submissions of VISSIM Modeling*; Michigan Department of Transportation, Research Administration: Cadillac, MI, USA, 2020.
49. Choudhury, A.; Maszczyk, T.; Math, C.B.; Li, H.; Dauwels, J. An Integrated Simulation Environment for Testing V2X Protocols and Applications. *Procedia Comput. Sci.* **2016**, *80*, 2042–2052. [CrossRef]
50. Hunter, M. *VISSIM Simulation Guidance*; Department of Transportation, Office of Performance-Based Management & Research: Atlanta, GA, USA, 2021.
51. Macioszek, E.; Akçelik, R. A comparison of two roundabout capacity models. In Proceedings of the 5th International Roundabout Conference, Transportation Research Board, Green Bay, WI, USA, 8–10 May 2017.
52. Muhammad, S.; Jamaludin, S.A. Evaluating the Performance of Traffic Flow using SIDRA for Roundabouts in Ip-oh, Perak. *J. Kejuruter.* **2022**, *34*, 421–427. [CrossRef]
53. Yagoop, N.K.; Ahmad, N.; Abbood, A.K.N. Improvements of some roundabout Intersections using capacity model Analysis. *IOP Conf. Series: Mater. Sci. Eng.* **2020**, *928*, 022083. [CrossRef]
54. Bie, Y.; Cheng, S.; Easa, S.M.; Qu, X. Stop-Line Setback at a Signalized Roundabout: A Novel Concept for Traffic Operations. *J. Transp. Eng.* **2016**, *142*, 05016001. [CrossRef]
55. Demir, H.G.; Demir, Y.K. A Comparison of Traffic Flow Performance of Roundabouts and Signalized Intersections: A Case Study in Nigde. *Open Transp. J.* **2020**, *14*, 120–132. [CrossRef]
56. Alozi, A.R.; Hussein, M. Multi-criteria comparative assessment of unconventional roundabout designs. *Int. J. Transp. Sci. Technol.* **2021**, *11*, 158–173. [CrossRef]
57. Boualam, O.; Borsos, A.; Koren, C.; Nagy, V. Impact of Autonomous Vehicles on Roundabout Capacity. *Sustainability* **2022**, *14*, 2203. [CrossRef]

58. Stević, Ž.; Pamučar, D.; Subotić, M.; Antuchevičiene, J.; Zavadskas, E.K. The Location Selection for Roundabout Construction Using Rough BWM-Rough WASPAS Approach Based on a New Rough Hamy Aggregator. *Sustainability* **2018**, *10*, 2817. [CrossRef]
59. Davidović, S.; Bogdanović, V.; Garunović, N.; Papić, Z.; Pamučar, D. Research on Speeds at Roundabouts for the Needs of Sustainable Traffic Management. *Sustainability* **2021**, *13*, 399. [CrossRef]
60. Leonardi, S.; Distefano, N. Turbo-Roundabouts as an Instrument for Improving the Efficiency and Safety in Urban Area: An Italian Case Study. *Sustainability* **2023**, *15*, 3223. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.