Operational Evaluation of a Throughabout to Give Priority to Public Transport at Standard Roundabouts

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Received 15 April 2021; Revised 10 August 2021; Accepted 31 August 2021; Published 8 September 2021

Abstract

The presence of roundabouts in the central business districts (CBD) of cities can reduce the travel speed of bus rapid transit (BRT) along the radial routes. A throughabout is an unconventional and low-cost design in which the central island is split to provide exclusive lanes for major traffic streams. Although the operation of throughabout has been limitedly investigated for private transport, it has been less considered by designers for public transport and for increasing the speed of the BRT system. The current study aims to evaluate the effects of throughabouts on private and public transports and to compare the design with standard roundabouts and conventional intersections. The calibrated and validated results of the microsimulation tool (AIMSUN) indicated that the throughabout improved the travel time of both public and private transports through better use of the space and kept the traffic flowing at all volume levels. The travel speed of the BRT in the throughabout was remarkably stable in both signal-controlled and unsignalized intersections. The standard roundabout was the second-best design. The throughabout can be very helpful in corridors along which the demand for the bus transit is high and the system needs to receive priority.

1. Introduction

Today, it has been found that private transport solutions are not sufficient to improve urban traffic. Public transportation, as a means of mass transit, plays a key role in relieving traffic jams in cities. The bus rapid transit (BRT), contrary to mass rail transit, is a low-cost rapid system and can be implemented even in medium cities [1].

In Iran, this system is usually implemented along radial routes which start from the outskirts of cities and terminate in the central business districts (CBD). Roundabouts are among geometric elements conventional in Iran and some other Asian countries designed primarily as a tool for landscape and urban planning. However, with the rise in the travel demand over time, BRT lines were implemented along CBD travel corridors, and their routes passed through roundabouts. At roundabouts, the dedicated lanes of BRT line are traditionally terminated for allowing the movement of private transport. Frequent roundabouts along BRT routes can reduce the travel speed and associated attractiveness of this system, and these issues can emerge as serious challenges.

Although traffic control and management systems to give priority to transit flow, such as bus preemption, are common in the literature, the need for low-cost geometric solutions is obviously felt. However, the geometric solutions suitable for standard roundabouts and improving the speed of BRT have been less studied so far [2, 3].

Different roundabout designs have been suggested as alternatives to the standard ones [4]. Some of these designs, such as compact (mini-) roundabouts, have been implemented in numerous locations and are in frequent use all over the world, while some others, like throughabouts, are recent and yet being developed or introduced ([5-7]) (Figure 1). Due to the space limitations and high land prices in the CBDs of cities, implementing grade-separated roundabouts requires a high cost. Therefore, only the at-grade roundabouts were selected to be studied herein [8].
The compact, flower, turbo, and throughabout roundabouts are the different kinds of at-grade roundabouts (Figure 1). To give priority to buses in a roundabout, throughabout is more suitable than other designs provided in Figure 1. In this design, the central island is split to provide exclusive lanes for buses resulting in no delay for buses, while the circulating lanes are reserved for private transport. While having other advantages of a standard roundabout such as the reduction in the number of conflict points and traffic calming [9], a throughabout obviates the need for BRT buses to turn in circulating lanes, prevents bus bunching in the circulating lanes, and avoids interference of movements.

Høsser [10] stated that although all elements of a throughabout were separately known and could be borrowed from the existing standard roundabout, there was no geometric design for it in which all components were combined together. Hence, he proposed a geometric design for throughabouts using the standard roundabouts. For this purpose, the interactions of the road users, including buses, cyclists, and pedestrians, were simulated in SSAM (Surrogate Safety Assessment Model) software, and the design leading to the lowest conflicts was suggested. He remarked that this design could be used for light traffic volumes in which the roundabout entries are single-lane and less than 1800 vph pass through the whole intersection. Thus, he suggested evaluating multilane throughabouts for heavier traffic volumes.

Sangster et al. [11] investigated the performance of several throughabouts designed to give priority to private transport and compared the throughabouts with conventional intersections. The results of this study revealed that although such roundabouts might not show better performance compared to other rivals in all locations, they could be considered as a particular solution in some areas due to giving priority to major movements. By comparing conflict points in throughabout and standard roundabouts, they suggested that the safety of throughabouts should be better than conventional intersections [11].
According to Siraut and Keith [12], some throughabouts built in England to give priority to private transport were significantly prone to accidents. However, they conducted no quantitative analysis on the safety of throughabouts using crash data [11, 12] and failed to provide evidence for this claim.

Extensive studies have been conducted on the capacity, delay, and safety of standard roundabouts. However, the throughabouts or other alternative roundabouts are not common. Although samples of throughabouts have been used in countries such as the United States, England, Ireland, Canary Islands, Spain, Portugal, and Norway [13, 14], these cases have been designed to give priority to private transport. Facilitating movements of buses along BRT routes, in which the frequency of transits system is high, has been less considered in research studies. This design has been studied for light traffic volumes, and its performance has not been evaluated at heavy volumes.

This research aims to investigate the operational performance of throughabouts as an engineering solution and geometric alternative to standard roundabouts. The evaluations were conducted for public and private transports. The operational evaluation was performed for light, medium, and heavy traffic volumes obtained from field data. Since the roundabout could accommodate the observed peak hour volume conveniently, a scenario with higher demand volume was also created to consider the 3–5-year growth of the traffic and evaluate the design in saturated or near-capacity conditions. This study aims to identify which design is suitable for each volume level in signalized and unsignalized intersections.

The structure of this paper is as follows. The first section of this paper, which was devoted to Introduction, explained the necessity of this study. The second section reviews the literature relevant to (un)conventional roundabouts. The third section, Methodology, describes the process of traffic microsimulation and how the software was calibrated/validated. The simulation was the primary tool of this paper for operational analysis. The fourth section, Results, discusses operations of the throughabout, standard roundabout, and conventional intersection designs. The paper ends with concluding remarks and offers some suggestions for future researches.

2. Literature Review

2.1. Roundabout. Standard roundabouts have been used worldwide for more than six decades, and their popularity is increasing nowadays. A standard roundabout is a helpful tool for traffic calming and improving traffic flow [9]. When vehicles approach a roundabout, they have to slow down to enter the ring road. Contrary to other types of intersections, roundabouts do not force vehicles to stop in varying patterns. Hence, they improve traffic flow, promote traffic safety, and reduce fuel consumption and vehicular emissions [15].

Traffic safety is one of the most important advantages of roundabouts. Roundabouts reduce the potential number of conflicts and alleviate hazardous head-on and right-angle conflicts [16]. It has been consistently proven that converting conventional intersections to roundabouts decreases the number of fatal or injury crashes [17, 18].

Standard roundabouts can also cut down emissions and fuel consumption by reducing the vehicle idle time at intersections and therefore creating a positive impact on the environment. After comparing several vehicular emissions measured at six sites in USA for the before and after traffic volumes, Mandavilli et al. [15] concluded that standard roundabouts outperformed stop-controlled intersections in reducing HC, CO, NOx, and CO2 emissions.

Shaaban et al. [19] assessed the environmental impacts of replacing four three-lane unsignalized roundabouts with signalized intersections along a highly congested urban arterial in Qatar. The roundabouts operated at near-capacity conditions. Therefore transportation authorities decided to convert roundabouts into the signalized intersections for a better operation. The conversion resulted in almost 40 percent reduction in vehicular emissions. This reduction is attributed to the extended idling with less coasting and reacceleration along the immediate upstream approaches of signalized intersections.

Fernandes et al. [20] evaluated the impacts of suburban roundabouts lane configuration on air pollution and noise level. They considered three layouts for investigation: one entry lane and one lane on the ring (SL), one entry lane and two lanes on the ring (CTL), and two entry lanes and two lanes on the ring (ML). They reported that SL resulted in the lowest CO2 emissions per vehicle (or unit distance) compared to CTL and ML roundabouts. However, it generated higher equivalent continuous A-weighted sound level (LAeq) at low traffic volumes because vehicles drove at higher speeds in the approach compared to the other layouts. CTL delivered the highest level of CO2 and NOx emissions and the lowest A-weighted sound level (LAeq).

Today, after many decades of experience regarding standard roundabouts, there are still different ideas about the “ideal roundabout” with little agreement on the essential effects of rules on how to cross an intersection [13]. It is important to underline that the development of roundabouts has been in progress since 1902. One of the outcomes of this progress is the invention of “unconventional” or “alternative” types of roundabouts which are in worldwide usage today. Unconventional roundabouts are different from “standard roundabouts” in some design features. The main incentive for the implementation of unconventional designs is the particular shortcomings of standard roundabouts regarding actual specific circumstances. Generally, these shortcomings are underlined by low levels of capacities or traffic safety [21, 22].

Different designs have been recommended as alternatives to the standard ones [4]. Due to the space limitations and high land prices in the CBDs of cities, implementing grade-separated roundabouts requires a high cost. Therefore, only the at-grade roundabouts were considered in this study.

The compact, flower, turbo, and throughabout roundabouts are among the unconventional at-grade roundabouts (Figure 1). A flower roundabout (Figure 1(b)) has four
muscles and provides a loop with an exclusive lane for right turns in the outer lanes of the roundabout [13, 14, 23]. In the compact roundabout (or a mini roundabout), the central island is traversable, and it has a small diameter, which allows buses and trucks to use the whole space of the central island when making their way through the intersections [13]. A turbo roundabout not only provides a separate room for some traffic flows in the central island but also allows for channelizing traffic entrance into (or exit from) the roundabout [13, 14, 23, 24].

Implementing throughabout for the routes with a high demand of bus transit and the necessity of prioritizing public transport can be very helpful. Other countries have taken advantage of such roundabouts to prioritize private transport [13, 14]. However, throughabouts implemented to give priority to bus transit merit attention.

2.2. Microsimulation. Traffic simulation has the potential to provide an objective, cost-effective, and flexible approach to evaluate traffic management systems and design alternatives. However, in order to realize this potential, the traffic microsimulation must represent real-world environment, and it must be valid for the application. It is needed for the simulation to provide results that are credible and reliable. The process of ensuring validity, credibility, and reliability typically consists of three elements—verification, validation, and calibration [25].

Verification determines whether computer codes and programs properly model the behavioral mechanism and logic of the studied system and if it provides the expected outcomes. For instance, the software developer checks in this stage whether a vehicle with a speed of 60 km/h spends one hour to travel through a road with a length of 60 kilometers or not. This step is undertaken by the software developer while developing the software. Validation evaluates to what extent the underlying fundamental rules and relationships used to describe the emergent behavior as specified within the relevant theory properly reflect the observed field conditions [25]. For example, it evaluates the accuracy of car following, lane changing, and gap acceptance models in producing correct capacity, queue length, travel time, and so forth. This step is also made by software developers while establishing the simulation software. The third step, calibration, reveals the extent to which the software user can/should change the software’s default values so that it properly reflects the characteristics of cars and drivers in the studied location. For example, if the default value of the perception-reaction time is 1 s in the software, the calibration procedure evaluates whether it should be 1 s in the studied intersection or the default value should be modified. This step is performed by the user, and there is no need to access the software internal codes. Calibration is the most common task among traffic engineers for tuning the software outputs. If there is no agreement between the model outputs and field values after calibration, traffic engineers may step into the validation process. This step requires access to the software codes and modifications to the underlying behavioral models in the simulator.

Unfortunately, due to the data collection problems, lack of sufficient data, and deficiency in available guidelines, the calibration procedure receives less attention, and sometimes, the simulation outputs are applied directly without calibration. This issue can be resolved by transferring the parameters calibrated for a case study to other sites that are similar in geometry and traffic conditions [26]. This type of transferability is known as spatial transferability, and there are two ways to perform it: the application-based and the estimation-based transferring. In the former approach, the simulation parameters are calibrated for one location and then applied directly to another context without any modifications. In the latter approach, each site is separately calibrated. Then, the calibration parameters are compared. If the drivers’ behavior, vehicles’ performance, and other conditions are presumably identical in the two locations, the calibrated parameters should be similar at the two sites. Gallelli et al. [26] investigated the performance of the two approaches of spatial transferability by considering two standard roundabouts. The research results confirmed that calibration is an essential step in microsimulation for guaranteeing consistency between field data and simulation output. The study also confirmed the goodness of the application-based approach.

Essa and Sayed [27] and Gallelli et al. [28] evaluated calibration effects on the simulation of rear-end collisions in signalized intersections and roundabouts, respectively. They applied two scenarios, that is, simulation based on default VISSIM data (no calibration) and simulation based on calibrated data. After verifying that the trajectory data extracted from the simulation replicate the trajectories obtained by automated computer vision video analysis, they compared the rear-end conflicts obtained from SSAM and real traffic. Gallelli et al. [28] found that although there was a high correlation between the simulated and observed conflicts in the second scenario (calibration), the simulation was unable to replicate forced drivers’ maneuvers. Essa and Sayed [27] suggested performing the parameter calibration in two steps: the first is the calibration of vehicle parameters and the second is the calibration of the driver parameters.

3. Methodology

3.1. Data Collection. This section describes how the four main types of data, the geometric, traffic, signal configuration (timing and phasing), and transit data, were collected.

The studied case was the Basij throughabout, located at the intersection of the Holy Shrine and Bahar streets in Mashhad, Iran. The roundabout is located in the central business district (CBD) of the city, along BRT line #1. Regular buses as well as BRT run along this route and cross this throughabout. Holy Shrine street is the major street extended north-south, and the BRT runs along this street. Bahar street is minor a street that runs east-west. Shrine street connects the intercity bus terminal into a great pilgrimage center.

Table 1 presents the geometric characteristics of the throughabout. All entries of the throughabout are two-lane with a width of 3.25 m, while each bus lane is 4 m in width.
The posted speed limit of the approaches leading to the roundabout is 50 km/h.

Very long ago, the intersection was designed as a nonstandard roundabout, and then it was converted into a conventional intersection. After the prevalence of standard roundabouts, it was reconstructed in the form of a standard roundabout. During the implementation of BRT lines in Mashhad in 2009, the standard roundabout turned into a throughput. Generally, the studied throughput is unsignalized, in which the traffic flow entering the circulating lanes must give way to traffic already in the roundabout. But, on limited days of the year, the traffic signal is activated due to ceremonies and feasts. In this case, the throughput is controlled by the SCATS system (Figure 2).

The hourly changes in the traffic volume were investigated using automatic traffic count data. For a working day in summer, that is, August 19, 2019, the three analysis periods of midday, evening, and morning peaks were recognized. The total traffic volumes in these periods were, respectively, 8200 vph, 6200 vph, and 3200 vph.

To ensure that the installed detectors on the roadbed of each lane were not broken and the traffic volume was accurately counted, automatic count data was compared with manual data. Manual counting was performed by the field survey team on August 19, 2019.

In the midday peak, when the traffic volume of the intersection was 8300 vph, the difference between the manual and automatic traffic counts was 100 vehicles. This fact showed that the automatic count data was very accurate and acceptable. The traffic volumes of other periods were extracted from the SCATS system, and 100 vehicles were added to the total volume of the intersection in each period. Since the SCATS does not provide turning movements, the turning volume percentages were surveyed for the summer midday peak (8300 vph) and assumed they were the same for other periods.

Furthermore, on a working day in October 2019, the traffic volume in midday and evening peaks were extracted from the SCATS to consider the seasonal variations in the traffic volume. The total traffic volumes in these periods were around 7300 vph and 5300 vph, respectively. To account for the near-capacity condition and consider the traffic volume growth in a short-term period of three to five years, the highest observed volume (8300 vph) was increased by 15%, and the volume of 9300 vph was also simulated.

Table 1 illustrates the percentage increase or decrease in traffic volumes of different analysis periods compared to the peak period volume (8300 vph). Readers can use Tables 2 and 3 to get an idea of how an intersection of interest is performing under that volume and compare it with those designs used in this paper.

The vehicles passed through the intersection in three phases as follows (Figure 2(b)):

1. Through and right turn of the major street (north-south)
2. Left turn of the main (north-south) and major (east-west) streets
3. Through and right turn in the minor street (east-west)

The timing of the traffic signals was obtained from the traffic control center. However, this timing might not be optimum and may incur further delays to vehicles. Therefore, the timing for the conventional intersection was optimized using the Synchro software and directly employed in the standard roundabout and throughabouts signal timing.

Field data of the transit system, including the number and location of bus stations, type of stations, the time of arrival of buses to the stops, and the stop time in the bus stops were obtained from the Mashhad Bus Organization (MBO). The service frequency along the BRT route was 48 buses per hour per direction. Meanwhile, 16 buses ran along the minor street per hour per direction.

### 3.2 Development of Model

The AIMSUN software (version 6.2) was used in this paper for microscopic simulation of the throughput operation. There are numerous traffic simulators all around the world. Two or a few of them are generally in everyday use in each country. AIMSUN is the most known traffic simulator in Iran. To apply this software for local cases, traffic and transportation organizations (TTOs) have calibrated AIMSUN parameters considering the vehicle characteristics, driver behavior, and driving environment prevailing in Iran. Therefore, the authors of the article preferred to use AIMSUN for simulation in this study.

The aerial image of the throughput was obtained from Google Earth and imported into the background area of the AIMSUN to create the geometry of the throughput. Table 1 represents the dimensions of the geometric elements of the throughput. To create the geometry of the standard roundabout, the two exclusive bus lanes in throughput were removed. Therefore, the buses move along with other vehicles in circulating lanes when they enter the roundabout area. Finally, the roundabout was removed thoroughly from the central area, while the other features were kept the same to model the conventional intersection design (Figure 3). Note that, along the approaches, the buses still travel in exclusive lanes in all designs.

The traffic demand data can be defined in two ways in the AIMSUN software. The first way is state mode: the total volume and percentage of turning movements are defined for each approach. The second way is O-D matrix: an O/D

| Characteristics | Throughabout | Standard |
|----------------|-------------|----------|
| Radius of central island (m) | 15 | 18 |
| Outer radius (m) | 36 | 36 |
| Number of turning lanes | 5 | 5 |
| Width of turning lanes (m) | 3.8 | 3.8 |
| Width of lanes (m) | 3.25 | 3.25 |
| Width of BRT lane (m) | 4 | 4 |
| Number of entry/exit lanes | | |
| North bound | 2/4 | 2/4 |
| South bound | 2/2 | 2/2 |
| East bound | 2/2 | 2/2 |
| West bound | 2/3 | 2/3 |
node is defined for each intersection approach, and the traffic volume from the origin to the destination node was defined in the software. The second approach was employed in the current research.

The simulation time in all scenarios was equal to one hour, with ten minutes used as the warm-up period. The software calculates the outputs in 10-minute intervals and presents the hourly averages for each iteration. Each scenario was run for ten iterations, and the average results of ten iterations are reported herein.

### 3.3. Calibration

Traffic simulators should be calibrated to ensure the reliability of their outputs. As described in Section 2.2, Gallelli et al. [26] assessed the application-based and estimation-based methods for transferring the calibration parameters from one location to another context. They confirmed the goodness of the application-based approach. Therefore, this approach was adopted in the present study. The calibration parameters and their respective values were mainly obtained from [29, 30] and directly applied in the current study. Since the simulation software and the city where the study cases are located are similar in this work and [29, 30], the studies mentioned above are very suitable for current position. Table 4 shows the calibrated parameters and their corresponding values.

In addition to the characteristics of the drivers and passenger cars, some public transport features were calibrated. The Mashhad Bus Organization (MBO) suggested that the standard deviation of the arrival time of each bus to the station should be considered as 5 s. The mean and standard deviation of stop time in the station should be considered as 10 s and 3 s, respectively. Since the service frequencies along major and minor streets were 48 and 16 buses per hour per direction, the headways were 80 s and 235 s, respectively. The interested readers can refer to AIMSUN 6 user’s manual [32] to see the definition of variables presented in Table 4.

### 3.4. Validation

After model calibration, the queue length and travel time were validated for the throughabout and standard roundabouts to ensure that simulation replicates the real-world traffic. In the following, the validation process is described.
When the throughabout was unsignalized, no queue was observed in the six analysis periods mentioned in Table 1. The traffic flow was smooth in the simulation, and the flow quality was similar to the field situation.

For the validation of travel time, the floating car method was used. The car traveled along the route of each movement five times during the peak period when the intersection volume was 8300 vph. The average travel time of each movement was obtained. Afterward, the travel times of the movements were weighted based on the traffic volume to obtain the average travel time of the entire intersection. The resulting average travel times from simulation and field observation were 118 s and 206 s, respectively, which indicated the simulation travel time was shorter than the observed value by 43%.

Therefore, the speed limit of the approaches was reduced from 50 km/h to 30 km/h to increase simulation travel time. As a result, the simulated travel time reached

![Figure 3](image-url)  
**Figure 3:** The aerial image of Basij throughabout and geometry of proposed designs in AIMSUN. (a) The aerial image of the Basij roundabout. (b) The throughabout. (c) The standard roundabout. (d) The conventional intersection.

| Agent | Parameters | Mean | Std. dev. | Min | Max | Reference |
|-------|------------|------|-----------|-----|-----|-----------|
| Car   | Length (m) | 4.14 | 0.28      | 3.83| 4.52| [29]      |
|       | Width (m)  | 1.65 | 0.04      | 1.6 | 1.75|           |
|       | Give way time (s) | 9.5  | 3.3   | 3   | 15  |           |
|       | Minimum gap (s) | 1.1  | 0.62  | 0.24| 3.5 |           |
|       | Reaction time when stopping (s) | 1    |       |     |     |           |
|       | Reaction time behind lights (s) | 1    |       |     |     |           |
| Driver| Sensitivity for imprudent lane changing (s) | 1    |       |     |     |           |
|       | Red percentage (%) | 12   |       |     |     | [30]      |
|       | Undertaking cases (%) | 70   |       |     |     | [31]      |
|       | Imprudent lane changing cases (%) | 50   |       |     |     |           |
|       | Stay on fast lane after overtaking (%) | 80   |       |     |     |           |

| Bus   | Schedule | N-S | E-W | 0:01:20 | 0:00:05 | n.a. | Mashhad Bus Organization (MBO) |
|-------|----------|-----|------|---------|---------|-----|--------------------------------|
|       | Stop time (sec) | N-S | 10   | 3      |         | n.a. |                                |
|       |           | E-W | 10   | 3      |         | n.a. |                                |

n.a.: not applicable.
202 s, showing a difference of 2% compared to the actual travel time. Similarly, speed limits were reduced from 50 km/h to 30 km/h for other analysis periods in throughabouts.

To validate the travel time of the standard roundabout, the 15 Khordad roundabout, which is the closest roundabout to the studied one, was selected. The two roundabouts, at a distance of 1.5 km, are located along the same major street and BRT line, and there is no other intersection between them. The two roundabouts have similar conditions regarding the number of entry and exit lanes in each approach, number of circulating lanes, type of the area, traffic volume, and so forth.

In the same way, the travel time of movements was measured in the throughabout; the travel time of the 15 Khordad roundabout was measured at a traffic volume of 6300. In this period, the total travel time of the standard roundabout was 186 s, while the simulated travel time was 173 s, showing a difference of 6%. Therefore, the travel time of the standard roundabout was assumed to be valid, and the speed limits of approaches remained unchanged.

In addition to the total travel time of the entire intersection, the difference between the simulated and observed travel times of the movements was less than 10% in the throughabout and standard roundabout. Thus, the travel time of the movements was also reliable. No queue was formed in the six analysis periods in the field and simulation environment.

Similarly, the travel time and queue length of the signalized throughabout and standard roundabout were also validated. Given the calibration and validation of various performance measures, it can be said that the simulation mimics the real-world situation accurately, and it has sufficient reliability for the upcoming analysis.

4. Evaluation of the Traffic Operations

In this section, the total travel/delay time and capacity of three designs are discussed. The operation of public transport is compared as well.

4.1. Private Transport

4.1.1. Travel/Delay Time and Capacity. The suggested design should maintain a series of operational measures at an acceptable level or better than the existing design to replace the existing one. Figure 4 illustrates the travel and delay time of the proposed design. In Figure 4 and other figures of Section 3, the symbols I, S, and T denote the conventional intersection, standard roundabouts, and throughabout, respectively. In Figure 4, the thicker lines demonstrate the travel time (Tr), while the thinner ones denote the delay time (D). Instead of the term “modern roundabout,” the authors preferred to use “standard roundabout,” since the “modern” has already been a long time “standard” in Iran.

When the intersection is unsignalized, the delay in the throughabout varied from 5 s at the volume of 3300 vph to 10 s at the traffic volume of 8300 vph. However, the delay in the conventional intersections started from 5 s, reaching 120 s at 4300 vph (Figure 4(a)). The delay in the standard roundabout was slightly longer than that in the throughabout.

The conventional intersection and standard roundabout designs reached their capacities at the traffic volumes of 4300 vph and 5000 vph, whereas the capacity of the throughabout reached 9300 vph. Due to its higher capacity, the throughabout resulted in a lower delay to private transport.
Whenever a queue is formed in the entry link, AIMSUN does not allow the vehicles to enter the network. In this case, the volume exiting the intersection equals capacity, and the portion of the demand matrix which is more than the capacity is not loaded into the network.

Figure 4(b) depicts the total travel and delay time of the three designs when the intersection was controlled by a traffic signal. The delay in the throughabout varied from 10 s at the traffic volume of 3600 vph to 310 s at its capacity (4600 vph). However, in the standard roundabout, the delay increased from 50 s to 350 s at its capacity (4500 vph). The maximum delay endured by private transport was almost 450 s in the conventional intersection design.

When the intersection is controlled by a signal, the throughabout increased the average travel time of the minor street compared to the standard roundabout (Figure 5(d)). But, as can be seen in Figure 4(b), the intersection travel time was lower in the throughabout. This indicates that the positive effect of the throughabout on the major street travel time was greater than its negative effect on the minor street travel time. The adverse effects of the throughabout on the minor street could be ignored in this particular case, since the main goal of the throughabout was to give priority to the major street, in which the volumes of public and private transports are very high. The intersection signal can be removed and replaced with yield signs to avoid the negative effect of traffic signal on minor street travel time.

Evaluation of the travel time of movements at higher volumes showed that, in all designs, the right turn (R) had the shortest travel time, while the left turn (L) had the longest travel time. The travel time of through traffic (T) was between the travel times of right and left turns (Figure 5).

In summary, in both signalized and unsignalized intersections, the throughabout design was superior in all
4.1.2. Smooth Traffic Flow. The number of stops and the ratio of move-to-total-time are among the most important factors that explain to what extent the traffic is flowing and the driving task is comfortable for drivers. The travel time of vehicles per kilometer of the road segment is also evaluated in the current section. Tables 5 and 6 show these indicators for signalized and unsignalized intersections, respectively.

4.2. Public Transport. The travel speeds of buses in throughabouts were 50 km/h and 60 km/h, respectively, in signal-controlled and uncontrolled intersections and remained almost constant until reaching the capacity (Figure 6). However, in the standard roundabout and conventional intersection, the travel speed decreased with increased traffic volume.

When the intersection was yield-controlled, the travel speed in the standard roundabout started to be 60 km/h at the lowest traffic volume (3300 vph) and then decreased to 40 km/h when the intersection was locked at the volume of 5000 vph. In the conventional intersection, the travel speed of buses was 60 km/h at the lowest volume and decreased to 10 km/h at 4000 vph.

As seen, the travel speed of buses deteriorates with the increase of volume in the conventional intersection and standard roundabout. Still, the throughabout helps keep the travel speed stable and uniform at all volume levels and assists the transit system in moving faster.

Table 5: Travel time and movement smoothness indexes in the signalized intersection.

| Criteria          | Volume | Intersection | Geometric design | Throughabout |
|-------------------|--------|--------------|------------------|-------------|
|                   |        |              | Standard roundabout | Throughabout |
|                   | 3000   | 4            | 2                | 1           |
|                   | 4000   | 7            | 5                | 4           |
|                   | 4500   | 8            | 8                | 8           |
| Stops (/km)       | Average| 7            | 6                | 5           |
| Move/total time   | 3000   | 0.33         | 0.43             | 0.85        |
|                   | 4000   | 0.27         | 0.34             | 0.37        |
|                   | 4500   | 0.21         | 0.28             | 0.31        |
|                   | Average| 0.25         | 0.33             | 0.45        |
| Travel time (s/km)| 3000   | 274          | 137              | 135         |
|                   | 4000   | 456          | 254              | 335         |
|                   | 4500   | 516          | 390              | 424         |
|                   | Average| 445          | 298              | 335         |

Table 6: Travel time and movement smoothness indexes in the unsignalized intersection.

| Criteria          | Volume (vph) | Intersection | Geometric design | Throughabout |
|-------------------|--------------|--------------|------------------|-------------|
|                   |              |              | Standard roundabout | Throughabout |
|                   | 3300         | 0.2          | 0.2              | 0.07        |
|                   | 4300         | 2.4          | 1.8              | 0.09        |
|                   | 5300         | 5.3          | 4                | 0.1         |
| Stops (/km)       | 6300 & 7300  | 0.2          | 0.2              | 0.2         |
|                   | 8300         | 3.9          | 4.3              | 4.3         |
|                   | 9300         | 6.3          | 5.2              | 5.2         |
|                   | Average      | 2.6          | 2                | 6           |
| Move/total time   | 3300         | 0.97         | 0.97             | 0.99        |
|                   | 4300         | 0.39         | 0.72             | 0.99        |
|                   | 5300         | 0.19         | 0.13             | 0.98        |
|                   | Average      | 0.51         | 0.6              | 0.72        |
| Travel time (sec/km)| 6300 & 7300 | 72            | 73               | 113         |
|                   | 8300         | 205           | 173              | 114         |
|                   | 9300         | 377           | 644              | 117         |
|                   | Average      | 218           | 297              | 246         |
5. Conclusion

In this study, the performance of three designs, that is, throughabout, standard roundabout, and conventional intersection, was evaluated under six volume scenarios in signalized and unsignalized intersections using the AIMSUN software. The results of local studies that had calibrated the vehicle and driver parameters of AIMSUN were applied for the calibration. The parameters of queue length and travel time of movements were also validated in this study.

The results confirmed that more than 9300 vehicles per hour could pass through the unsignalized throughabout, having much higher capacity than the standard roundabout and conventional intersection. This volume takes into account the peak hour volume and traffic growth in the next few years. Moreover, in the throughabout design, the travel time decreased in the major and minor streets. The signalized throughabout also allowed for the passage of up to 4600 vehicles per hour, providing a higher capacity compared to the standard roundabout and the conventional intersection. The standard roundabout was the second-best design.

Evaluation of the percent of stops and move-to-total-time revealed the better performance of the throughabout compared to the other two designs. The design also keeps the traffic moving as its name implies; that is, it lowers the stopping time of vehicles negotiating the intersection.

The travel speed of buses in the throughabout for both signalized and unsignalized modes was higher than 50 km/h, remaining constant with the increase in the volume. However, for other designs, the travel speed of the bus was lower than these values, experiencing a significant reduction and reaching 8 km/h with the volume increase.

As stated in Section 3.1., Basij roundabout was a conventional signalized intersection, which has been turned to a standard roundabout and then to a throughabout. The evaluation of the three designs indicated that the changes were reasonable, improving step by step the traffic operation of the intersection.

If the geometric conditions of the roundabout are similar to those presented in Table 1, a yield-controlled throughabout is suggested to be constructed for volumes up to 9300 vehicles per hour. If the roundabout needs to be controlled by traffic signals for any reason, throughabout has again a better performance than the standard roundabout and conventional intersection at volumes up to 4600 vehicles per hour.

It should be noted that the better performance and higher capacity of the unsignalized throughabout compared to the signalized throughabout and other designs were due to the two following factors: (1) The splitting of the central island and dedicating the lanes for exclusive use of buses caused separating the routes of public and private transports and provided stable travel speed for all vehicles. (2) The number of circulating lanes of the roundabout was larger than the number of entry lanes (Table 1). The high number of turning lanes in ring road is typical in Iran and is not specific to this roundabout. Increasing the number of circulating lanes and allocating the lanes of the central island to buses facilitated weaving maneuvers in the ring road and resulted in the better performance of throughabouts.

One may say that the rise in the number of turning lanes or splitting the central island for bus transit might increase collisions. A comparison of the crash data between the throughabout and a standard roundabout for a five-year period indicated that the throughabout approximately halved the number of injury accidents. The throughabout halved the crashes for different vehicles, including passenger cars, motor vehicles, buses, and even pedestrians.

The throughabout design can be very beneficial in corridors along which the demand for bus transit is high, and the system needs to be prioritized. Other countries have implemented this geometric design to give priority to private transport and reduce congestion along heavily congested corridors. However, in the present study, the effects of a throughabout which is intended to give priority to bus transit were investigated. The results were very positive and
promising. The paper showed that dedicating the space of central island in roundabouts to bus transportation improves the operations of throughabouts compared to the standard roundabout in both signalized and unsignalized conditions. This design enhances the traffic performance of both private and public transports.

For future studies, it is suggested to investigate the performance of a combination of flower roundabout and throughabout. In the flower roundabout, turning lanes specific to right turning are designed for private cars, and, in the central island of the throughabout, the through movements of public transport are channelized. This design has the advantages of both flower roundabout and throughabout. The authors expect that the combination of throughabout and flower roundabout can improve the safety and operation of the intersection, since the combination of the two designs provides further channelization of movements.

**Data Availability**

The data are not available.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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