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Comparison of Traffic Flow Characteristics and Environmental Impacts between a Cross Intersection and a Roundabout Intersection: A VISSIM Simulation-based Approach

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Abstract

Urban areas face numerous challenges due to high population density and traffic congestion. Countless man-hours are lost on the roads due to traffic congestion which eventually leads to reduced efficiency or even failure of the whole transportation system. Without proper planning for the future, this congestion problem will only increase. In this paper, an attempt has been made to compare the traffic flow characteristics and environmental impacts in two types of intersections: Cross and Roundabout. Bijoy Sarani intersection has been used for the case study which is notoriously known for its traffic congestion and delay issues. After developing the microscopic simulation model in PTV VISSIM software through calibration and validation procedures, the intersections were compared regarding delay times, emissions, and fuel consumption. The study suggests that a roundabout intersection with a 2-phase control system exhibits substantial improvements over the traditional 4-phase cross intersection. The findings of this paper will provide valuable insight to traffic engineers and transportation planners about the selection of intersections and management strategies in densely populated urban cities.

Keywords: *Intersections; Roundabouts; VISSIM; Simulation; Congestion*

1. Introduction

Growing traffic congestion experienced on transportation networks, particularly at major city intersections, leads to significant inconveniences in the form of delays and poor level of service. Traffic intersections are complex components of transportation networks, where vehicles from different directions converge, requiring users to make quick decisions while considering factors such as route, geometry, operational speed, and other vehicles' movements. The performance of intersections plays a pivotal role in determining the overall efficiency of the transportation network and is often measured by delay and capacity (Liu et al., 2019; Li, 2018). Two common approaches are usually considered to improve the aforementioned characteristics of an intersection: grade separation and at-grade solutions. Grade separation, though the optimal solution with minimal delays and conflict points, is not always feasible due to high initial costs. Hence, at-grade solutions, such as roundabouts, have gained popularity as a favorable alternative to grade-separated interchanges for controlling vehicular movements at intersections. Roundabouts have demonstrated exceptional performance in various regions, including the USA, Australia, and Europe. Since their meticulous design allows for relatively higher speed in merging and weaving incoming vehicles (FHWA, 2000). A study was conducted by converting cross intersections to roundabouts which showed that the total crash rate decreased by 60%, fatal crashes were eliminated and injury crashes were reduced by 82% (Cunningham, 2007). Another study found that such conversions typically result in a 30% to 50% reduction in the number of injury accidents and a 50 % to 70 % reduction in fatal accidents (Elvik, 2003). But given the cost and temporary traffic disruptions associated with constructing a roundabout intersection, it is vital to assess its long-term viability and effectiveness. This study assesses the performance of the Bijoy Sarani intersection, a cross intersection in Dhaka city involving the convergence of four inbound roads from the Airplane crossing, Jahangir Gate, Tejgaon, and Farmgate, in comparison to a theoretical roundabout.

Additionally, in the realm of signal processing, it is imperative to recognize that signals exhibit diverse phase systems, characterized by the presence of varying numbers of phases, such as two-phase, three-phase, four-phase, multi-phase, etc. Among these, two-phase and four-phase are used widely in four-legged intersections. The performance of the intersection also varies with variations in the phase configurations. In this study, the performance of the existing cross intersection, which utilizes a four-phase signaling system, is initially compared with a roundabout intersection under a four-phase system, followed by an assessment under a two-phase system.

In recent times, traffic simulation has increasingly become the preferred approach for analyzing traffic problems because of its capability to accurately depict real-life scenarios. One prominent software in this field is PTV VISSIM, which has gained popularity in recent years. Numerous studies have encompassed a wide range of areas employing PTV-VISSIM, such as modeling of speed limits on freeways (Yu & Abdel-Aty, 2014), investigation of ramp meter strategies (Chang et al., 2007), examination of driver behavior effects (Habtemichael & Picado-Santos, 2013), simulation of pedestrian movement (Fellendorf & Vortisch, 2010), and estimation of expected traffic emissions (Stevanovic et al.,2009). It has also been employed in analyzing intersection and roundabout operations and enabling comparisons and calibration between analytical and microsimulation models. This study aims to provide policymakers and transportation professionals with valuable insights regarding the functional capacities of cross intersections and roundabouts in the context of delay times, emissions, and fuel consumption.

2. Methodology

This study analyzed traffic performance and environmental effects of signalized cross intersections versus roundabouts. A VISSIM 2023 simulation model was calibrated, validated with real traffic data, and used to assess the base model and a hypothetical signalized roundabout.

2.1 Data Collection

The collection of precise traffic data is essential for the development of an accurate microscopic model. Video cameras were installed at various locations of the study site to acquire traffic data which were then processed manually. The traffic volume data along with the road geometric data, vehicle speed data, and vehicle composition data were collected from the field on a weekday during peak hours. The total traffic volume of 2 hours in the intersection was collected and an average vehicle composition was obtained which is given in Table 1. Buses aren't added to this composition as they were input separately into the model as they used different routes.

Table 1. Average Vehicle Composition

Vehicle Type	Relative Flow
Car	0.55
Truck	0.02
Motorcycle	0.19
Microbus	0.07
CNG	0.17

2.2 Calibration and Validation of the Simulation Model

The study utilized detailed network geometry data from a corridor survey and Google Earth images to build the VISSIM model through the graphical user interface (GUI). This simulation tool employs a link-and-connector method to depict road sections and merge/diverge points, with adjusted lane widths for accurate site representation. After building the base model, individual components were refined and adjusted to replicate the field-measured or observed conditions. The full calibration process consisted of two segments – systemic calibration and operational calibration. The systemic calibration included customizing 3D models to represent the types of vehicles on the test site and distribution of kinematic parameters such as desired speed, acceleration, and deceleration of different vehicle types as provided in Table 2. Furthermore, to precisely reproduce the actual traffic behavior of the test corridor, the driving behavior parameters of the VISSIM model were modified which included the standstill distance, headway time, etc. in the operational calibration part of the model. Several iterations were used to identify the optimal combination of parameters for this particular calibration procedure.

Table 2. Distribution of Kinematic Parameters of Different Vehicle Types

Vehicle Type	Desired Speed (km/h)	Acceleration (m/s^2)		Deceleration (m/s^2)	
		Maximum	Desired	Maximum	Desired
Car	40	3.5	3.5	7.5	2.8
Truck	30	3.5	2.3	6.5	2.5
Bus	30	1.2	1.2	7.5	0.9
Motorcycle	45	3.5	3.5	7.5	2.8
CNG	35	3.3	2.0	6.5	2.5
Microbus	40	6.8	4.0	5.5	1.3

In this step of model development, the Wiedemann 99 version of the car following parameters were taken as base and the values were necessarily adjusted until the difference between the simulated flow and the observed traffic flow was within 10%. Along with these, lane changing and lateral behavior parameters were also adjusted to fit the existing traffic scenario as described in Table 3.

Table 3. Calibrated Driving Behavior Parameters

Parameters	**Calibrated Value**
Lane Changing	
Waiting Time Before Diffusion (sec)	40
Overtake Reduced Speed Area	Allowed
Lateral	
Desired Position at free flow	Any
Observe vehicles in next lane(s)	Allowed
Diamond Shape Queuing	Allowed
Consider the next turning direction	Allowed

The calibrated model was validated by comparing field data with simulation results using the Geoffrey E. Heavers (GEH) measurement for volume comparison. GEH value is a statistical measure used in traffic simulation and analysis to quantify the differences between observed and predicted traffic flow or travel time values. GEH value is defined as:

$$\text{GEH} = \sqrt{\frac{(\text{simulated - observed})^2}{0.5*(\text{simulated} + \text{observed})}}$$

As a general guideline for model validation, GEH values less than 5 indicate a good fit; values between 5-10 require further investigation, while values above 10 indicate a poor fit. This study obtained average GEH values of 7.310, 7.896, 8.314, and 9.159 for four links converging into the Bijoy Sarani intersection which suggests further investigation is needed. This can be due to poor lane discipline and a wide variety of vehicle classes roaming on these particular roads whereas the previously mentioned guideline is for homogeneous traffic following strict lane discipline. For non-lane-based heterogeneous mix, owing to the wide variation in the operating and performance characteristics of vehicles, the thresholds of the GEH values are more lenient. However, the GEH values can also be reduced in such cases through increased efforts but it may not match the marginal improvements obtained. Hence, there can be a trade-off between accuracy and effort (Oketch, 2005). which suggests that the developed model can replicate field traffic conditions with acceptable accuracy. The comparative plot of field data and VISSIM data for the link coming from Farmgate to the intersection is shown in Figure 1. Similar analyses were conducted for all the other inbound roads and the respective GEH values were calculated to measure the accuracy of the simulation model.

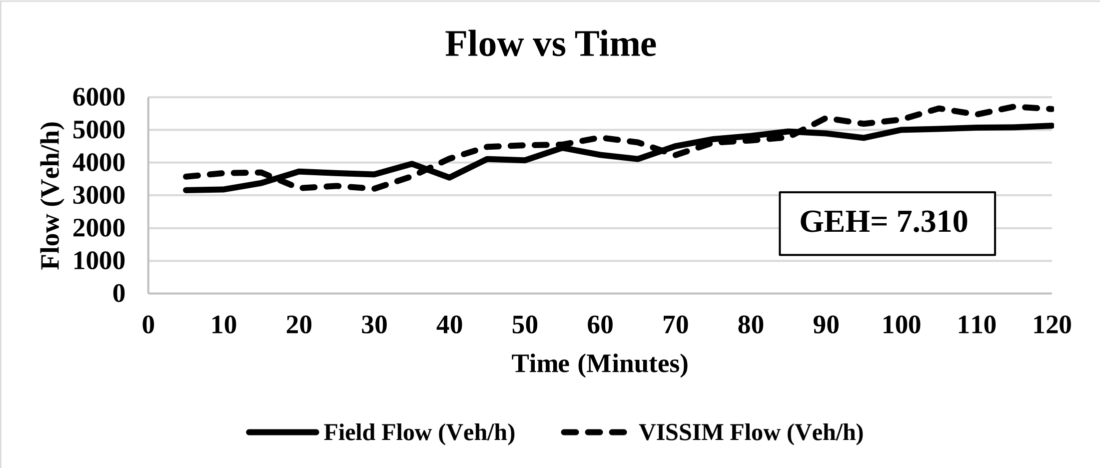

Figure 1. Validation of Farmgate to Bijoy Sarani Link

2.3 Development of Roundabout Intersection

This study required the design of a hypothetical signalized roundabout intersection at the study area to compare the traffic performance with the existing infrastructure. Maintaining consistency with the land acquired by the current traffic geometric condition, the diameter of the inscribed island and circle for the roundabout has been determined to fit the study site. A central island of diameter 4 meters along with a diameter of 28 meters for the inscribed circle has been appointed to the simulated model to develop the roundabout. Consequently, the roundabout being designed falls into the category of an urban compact roundabout (Robinson et al., 2000). This hypothetical roundabout has been meticulously designed by the guidelines provided by Highways England (National Highways, 2020). Given that all approach roads have a speed limit of 40 mph or below, configurations of a normal roundabout have been employed. The four dual carriageways are 13m wide in each direction. However, as the entry to the intersection flares out, the width gradually increases. The developed model of the existing cross intersection and the roundabout intersection has been shown in Figures 2 & 3 respectively.

Figure 2. Developed Cross Intersection Model

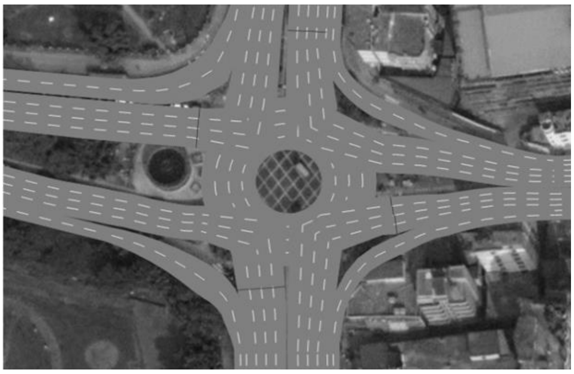

Figure 3. Developed Roundabout Intersection Model

3 Results and Analysis

The developed VISSIM microsimulation model was utilized to simulate two hours of peak traffic in the study corridor under three different situations. The first situation included the existing four-phase signal control system and geometric infrastructure. The second situation consisted of a roundabout intersection with four phase signal control system and finally, the third situation had a roundabout intersection with a two-phase signal control system along with proper priority rules on different lanes to avoid conflict. The VISSIM evaluation function makes it possible to determine the level of service of different scenarios along with average vehicle delay, average person delay, CO emission, NO_x emission, VOC emission, and fuel consumption. In this study, the existing situation is considered to be the base scenario and by using this, the other scenarios will be compared to identify positive or negative effects of infrastructure change. This study did not focus on link performance rather it prioritized the performance of the intersection node and thus the characteristics of the node have been analyzed. Table 4 provides an overview of the level of service achieved by the node under different scenarios.

Table 4. Level of Service Comparison

Scenario	Signal Control	Level of Service
Cross Intersection	Four Phase	D
Roundabout	Four Phase	D
Roundabout	Two Phase	C

In Table 4, level of service C indicates superior service quality than level of service D. A wide range of parameters including traffic and environmental parameters were compared to fully grasp the overall impact of the changes to the infrastructure and management system. Through the use of the VISSIM node evaluation tool, the average, standard deviation can be automatically generated for each of the aforementioned parameters. Having the existing scenario as the base situation, the percentage increase or decrease in the parameters in the different scenarios is summarized in Table 5. In the table, the positive percentage values indicate an increase and a negative percentage value indicates a decrease in the parameter.

Table 5. Traffic and Environmental Parameter Comparison

Parameters	**Scenario**		
	Cross Intersection	Roundabout – 4 Phase (%)	Roundabout – 2 Phase (%)
Average Vehicle Delay	-	14.53281	-54.605
Average Person Delay	-	1.476194	-52.7397
Stop Delay	-	24.96145	-59.4152
CO Emission	-	3.919559	-25.1614
NO_x Emission	-	9.691068	-24.1311
VOC Emission	-	8.541019	-27.7548
Fuel Consumption	-	13.761395	-24.1513

Compared to the base scenario of the cross intersection, the delay times increased in the roundabout when the signal control had a 4-phase system. The major cause behind this increase is the additional length of the path that has to be covered by the vehicles to traverse the intersection area. This additional path meant that the vehicles had to stay in the intersection for a longer period resulting in higher amounts of emission and fuel consumption. Conversely, in the case of a roundabout intersection with 2 phase signal control system, the average delays for both vehicles and persons along with stop delays decreased. This could be because, in this scenario, vehicles from opposing signals were allowed to pass through the intersection at the same time given that appropriate priority rules were maintained. The 2-phase signal control system had a total cycle time lesser than the 4-phase system resulting in more vehicle movement in the total span of the simulation. More movement of vehicles meant that the approaching vehicles spent less time in the intersection area compared to other scenarios and thus the total emission also decreased. Although the average speed of the vehicles tends to be lower in roundabouts, these reduced speeds lead to smooth driving patterns and consequently reduce emissions and delays.

4. Conclusion

This paper investigates intersection efficiency and sustainability by comparing three different scenarios in the study area. Microscopic traffic simulation through VISSIM was employed which can be used to analyze various traffic management strategies, policies, signal control, and environmental impacts. The study aimed to utilize this method for evaluating different scenarios and seeking innovative approaches to enhance intersection performance. Evaluation results show that, with the view of improving intersection efficiency, the roundabout intersection with 2 phase signal control system performs notably better than the existing cross intersection with 4-phase signal control in Bijoy Sarani given that appropriate priority rules are set in the roundabout along with total compliance of the drivers. The average vehicle delay, average person delay, and stop delay in the roundabout decreased by 54.605%, 52.7397%, and 59.4152% respectively when the roundabout was active under 2 phase signal control system. The emission of pollutants also decreased as the number of vehicles spending time in the intersection node was also reduced. On the other hand, the average vehicle delay, average person delay, and stop delay values for the roundabout with 4 phase signal control system increased by 14.53281%, 1.476194%, and 24.96145%. The subsequent emissions of the vehicles in the intersection node also increased as vehicles were forced to travel a larger path and spend more time in the intersection.

This study replicated the existing traffic conditions in the VISSIM model but as seen in the validation phase of model development, accurate representation was not possible due to the complex travel pattern of vehicles in mixed traffic conditions of Dhaka and hence there was a tradeoff between accuracy and effort. Although a close match to the existing traffic situation could not be achieved, the comparison can still be deemed to be satisfactory.

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