Hindawi
Mathematical Problems in Engineering
Volume 2018, Article ID 4310894, 8 pages
https://doi.org/10.1155/2018/4310894

Research Article

Mathematical Analysis for Roundabout Capacity

Wonho Suh ,[1] Jung In Kim ,[2] Hyunmyung Kim,[3] Joonho Ko,[4] and Young-Joo Lee [5]

[1]*Department of Transportation and Logistics Engineering, Hanyang University, Ansan 15588, Republic of Korea*
[2]*Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, USA*
[3]*Department of Transportation Engineering, Myongji University, Yongin 17058, Republic of Korea*
[4]*Graduate School of Urban Studies, Hanyang University, Seoul 04763, Republic of Korea*
[5]*School of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea*

Correspondence should be addressed to Young-Joo Lee; ylee@unist.ac.kr

Received 3 February 2018; Accepted 9 May 2018; Published 5 June 2018

Academic Editor: Konstantinos Karamanos

This paper investigates roundabout capacity analysis using mathematical modelling and microscopic simulation. The capacity in approach section in roundabout is calculated by estimating the number of vehicles that can enter a roundabout for a given approach given a certain circulating volume. Since roundabouts are working with only yield conditions, capacity is dependent on gap acceptance model. Priority rules are used to simulate the gap acceptance model and define the right-of-way for conflicting movements. In the case of roundabouts, priority rules can be utilized to establish right-of-way at each of the conflict points where the approach traffic merges with the circulating traffic of the roundabout. By altering the minimum acceptable gap and related parameters, it is possible to calibrate a simulation model to be that of a real-life roundabout or that of a theoretical roundabout that meets the operating characteristics defined in current capacity models. The proposed roundabout capacity analysis methodology is expected to assist modelling operational conditions for roundabouts. Results are presented that provide evidence to validate the proposed approach.

1. Introduction

Roundabouts are one of the most environmentally sustainable infrastructure design strategies to significantly reduce greenhouse gas emission [1–3]. The goal of sustainable infrastructure is to protect the environment and conserve resources while taking into consideration intended needs as well as benefits and costs. Roundabouts, compared with other intersection applications including traffic signals and all-way stop control, can accomplish sustainability goals by eliminating power needs and making more efficient traffic flow [2, 3]. As an intersection design, electronic signal requirement is minimal or not required in roundabouts, whereas signalized intersections require electric power and significant infrastructure for signal control, for example, signal post and signal head. Also, roundabouts save fuel and greenhouse gas emission, since roundabouts allow vehicular traffic to move slowly with very little queuing [4, 5]. As a result, vehicles do not sit and idle as much compared to signalized intersections, traffic congestion is reduced, and it can operate without increasing the number or length of lanes leading up to an intersection. Vehicles moving without stopping unlike signalized intersections mean saving more energy use and emissions from vehicles. It was reported that, by reducing idling, ten circular intersections were found to save 200,000 gallons of gas each year. Additionally, roundabouts exhibit lower vehicle delay and fewer traffic accidents.

Environmentally, roundabouts reduce fuel consumption and greenhouse gas emission by significantly reducing acceleration, deceleration, and idling from vehicles [4–7]. For maintenance, roundabouts do not require signal hardware, electrical power, or their related supplies. From operational perspective, roundabouts show lower overall delay than signalized and all-way stop-controlled intersections when they are operating under capacity conditions. As a result, roundabouts are considered much more sustainable infrastructure design in contrast to other conventional intersection designs [8–10]. However, capacity of roundabouts varies from location to location depending on driving behaviours. Therefore, it is critical to objectively estimate the capacity of roundabouts for better infrastructure design selection.

The purpose of this paper is to estimate the capacity of roundabouts using simulation based mathematical analysis and highlight the impacts of priority rules in VISSIM microscopic simulations of a single-lane roundabout on approach capacity. This paper quantifies roundabout capacity to provide comprehensive analysis tools. Using simulation data and mathematical models, roundabout capacity calculation is evaluated to quantify the impact of minimum acceptable gap and related parameters on roundabout capacity.

The approach capacity is accepted to be as the maximum number of vehicles that can enter a roundabout for a given approach given a certain circulating volume. Since roundabouts are unsignalized with only yield conditions, capacity is dependent on gap seeking logic. If a vehicle has an acceptable gap in circulating flow, the vehicle will proceed to enter the roundabout, else it must wait until an acceptable gap is available. In microscopic traffic simulation model VISSIM, the priority rule is used to simulate the gap seeking logic. By altering the minimum acceptable gap (with additional parameters no discussed herein), it is possible to calibrate a simulation model to be that of a real-life roundabout or that of a theoretical roundabout that meets the operating characteristics of the Highway Capacity Manual.

2. Literature Review

Traffic congestion is one of the main problems in major cities [4]. Traffic congestion and pollution are extensively recognized as significant impediments to sustainable economic and societal growth in urban areas worldwide [2–4]. In 2014, congestion in the USA was responsible for 3.1 billion gallons of wasted fuel, 6.9 billion hours of travel delay, and $160 billion in congestion cost. In the past decades, a variety of traffic applications and design have been applied to reduce traffic related problems and improve sustainability of transportation system [2].

Major portion of traffic congestion occurs around intersection areas where multiple roads are intersecting each other. Roundabouts are considered as one of the most environmentally sustainable infrastructure design strategies to significantly reduce greenhouse gas emission and congestion compared to other conventional intersection controls [1–3]. Since roundabouts have operational and environmental advantages over other conventional intersection designs, they are becoming an increasingly appealing alternative intersection treatment [8–10]. One component of determining if a roundabout is a feasible intersection treatment is to perform an operational analysis [11–20]. Loprencipe, Giuseppe, and Primieri proposed three methods to define the best geometrical and functional design solution. Three methods are (1) three-dimensional geometrical modelling of the layout and road elements; (2) visualization, also with dynamic scenes; and (3) functional analysis of traffic flows (traffic microsimulation techniques) [11]. Benekohal and Atlur developed a four-step multicriteria site selection procedure and evaluated software programs to estimate delay and capacity [12]. The factors considered in the process include intersection delay (LOS), roundabout capacity, distribution of traffic volume among approaches, and crash history. Qu et al. analysed different types of intersections by modelling traffic flow using queuing theory and conflict theory [13]. Akcelik et al. utilized an analytical method to develop a formula to estimate traffic flow capacity of roundabout entry [14]. Borkloe et al. analysed different type of intersection designs using microscopic simulation model [15]. Also, transportation agencies and local governments provide guidelines about the intersection design selection [16–20]. The operational performance of an existing or proposed roundabout can be assessed through capacity models [21–29]. However, it is well known that the capacity models vary depending on the driving behaviours [28]. Therefore, it is critical to objectively estimate the capacity of roundabouts for better infrastructure design selection and calibrate the model to better estimate the field traffic conditions.

To better model capacity of roundabout, microscopic traffic simulation models are often utilized. VISSIM is a discrete, stochastic, and time step based microscopic simulation model developed to model urban traffic and public transit operations [30, 31]. The model is a useful tool for the evaluation of various alternatives based on transportation engineering and planning measures of effectiveness. VISSIM models individual vehicles using a psychophysical driver behaviour model developed by Wiedemann [31]. The underlying concept of the model is the assumption that a driver can be in one of four driving modes: free driving, approaching, following, and braking. The model was originally developed at the University of Karlsruhe, Germany.

The VISSIM network and Wiedemann model can be calibrated for local driver behaviours as observed in the field. While this tool is very useful in modelling roadway networks, VISSIM also requires that a model be calibrated to represent the actual traffic conditions and provide accurate and useful data.

In the United States, roundabouts are increasingly being utilized to efficiently handle significant volumes without using a traffic signal. The Highway Capacity Manual 2010 dedicates a portion to the performance of roundabouts in the United States [32]. NCHRP Report 572 discusses safety, operational performance, and design features and analyses these areas using data collected from existing roundabouts in the United States [33].

Given the amount of design documentation and operational guidelines in HCM 2010 and NCHRP Report 572, there are limited documentation regarding methodologies to build a microscopic simulation model for capacity analysis.

Wei discusses the methods of building a roundabout in VISSIM based on a case-study using priority rules and conflict zones to control the right-of-way for entering vehicles [34]. Trueblood and Dale [30] discuss the VISSIM parameters that are used to build the roundabout network: priority rules, reduced speed areas, link, and connectors. While this is helpful in setting up the network elements themselves, it does not provide acceptable “default” values a researcher or engineer can use to estimate capacity relative to expected capacity found in HCM 2010. Shroeder presents a multilane roundabout sensitivity analysis and investigates the impacts that conflict zones and speeds have on capacity analysis [35]. However, his methods differ slightly from the above-mentioned papers. Shroeder uses conflict zones instead of priority rules.

3. Methods

The single-lane roundabout equation is for roundabouts with a single circular roadway and a single-lane on each approach. Equation (1) is the equation for single-lane roundabout capacity. The same equation can be applied to roundabouts with a single circular roadway and two approach lanes [33].

$$c_{e,pce} = 1130e^{(-1.0\times 10^{-3})v_{c,pce}}, \quad (1)$$

where

$c_{e,pce}$ is the capacity of the approach lane under consideration in passenger car equivalents, veh/h,

$v_{c,pce}$ is the conflicting flow in passenger car equivalents, veh/h.

The equations presented above are calibrated to the NCHRP Report 572 data and require only the conflicting flow rate as input. However, the HCM 2010 presents the option of calibrating the above equations with local follow-up and critical headway values. For local conditions, the calibrated capacity equation is in the form found in (2), (3), and (4) for the input parameters. Therefore, follow-up and critical headway data must be collected in order to calibrate the capacity equation [33].

$$c_{pce} = Ae^{-Bv_c} \quad (2)$$

$$A = \frac{3600}{t_f} \quad (3)$$

$$B = \frac{t_c - t_f/2}{3600}, \quad (4)$$

where

$c_{e,pce}$ is the capacity of the approach lane under consideration in passenger car equivalents, veh/h,

v_c is the conflicting flow in passenger car equivalents, veh/h,

t_c is the critical headway, seconds,

t_f is the follow-up headway, seconds.

Critical headway is defined as "the minimum headway an entering driver would find acceptable". Critical headway cannot be measured in the field because drivers will accept all gaps larger than their critical headway. However, it can be estimated by measuring the lengths of gaps in the circulating stream that are either accepted or rejected by entering vehicles. Therefore, critical headway is estimated based on the acceptance and rejection of gaps. The HCM 2000 recommends a critical headway value between 4.1 and 4.6 seconds. The value is selected based on driver behaviour and gap acceptance characteristics. For example, a location with drivers who are familiar with roundabouts would use a critical headway closer to 4.1 seconds [36].

Additionally, lags measured at the roundabout can also be used in the calculation of critical headway. A lag is the time between when a vehicle arrives at the entrance point and the next circulating vehicle. If exiting vehicles are included in the analysis, then they are also used along with circulating vehicles to calculate gaps and lags in the conflicting flow.

Follow-up headway is defined as "the headway maintained by two consecutive entering vehicles using the same gap in the conflicting stream". Thus, if two vehicles enter the roundabout from the same approach with no conflicting event between them, a measure of follow-up headway can be made. The HCM 2000 found that the upper and lower follow-up time values are 2.6 and 3.1 seconds, respectively. Like critical headway, the follow-up time would be selected based on driver behaviour [36].

Even though the HCM capacity equations are the HCM procedure for calculating the capacity of roundabouts in the United States, the HCM recognizes that these equations have limitations and, in certain situations, using other means for determining capacity may be advisable. For instance, roundabouts that have unusually high volumes of pedestrians and bicycles and use signals to accommodate these users could be modelled with other methods. Also, multilane roundabouts that have three or more lanes in the circulating roadway are not covered in the HCM equations and thus another analysis method would be needed to analyse a roundabout with this geometry.

To estimate capacity a roundabout model is defined by links and connectors, routing decisions, reduced speed zones, and priority rules [31]. Each of these parameters must be calibrated to achieve the desired simulation (e.g., matching field conditions).

3.1. Links and Connectors. Links and connectors establish the horizontal geometry of the network. Links represent a direction of travel whereas connectors represent turning movements between the various links.

3.2. Routing Decisions. Routing decisions are the points along the links and connectors where turning movement decisions are made. The goal of the simulation is to match the decision-making timing and processing of real drivers as closely as possible. Decision points are located upstream of the actual movement and when a vehicle crosses that point, it is assigned a turning route based on the turning movement proportions. For instance, 20% of the vehicles may turn left. Then based on the vehicle distribution approximately 20% of the vehicles in the simulation should turn left.

3.3. Reduced Speed Zones. Reduced speed zones are used to reduce the speed of the simulated drivers to match that of an actual driver traveling through the real world field condition. For instance, the physical geometry of roundabout forces the driver to reduce his/her speed to navigate through the tight geometry. In a simulation, however, the geometry of the links and connectors have no physical effects on the digital driver (e.g., the digital driver does not feel the inertia and centripetal forces acting on the vehicle and therefore does not react and therefore change its speed).

3.4. Right-of-Way. Priority rules are used to assign right-of-way. This parameter is unique to each locale. European drivers have different tolerances than drivers in the United States. Rural drivers have different tolerances than urban drivers. Driver education also plays a role in this as well. Drivers unfamiliar with roundabouts, for instance, may desire larger gaps before entering the roundabout. This in turn affects the overall capacity of the roundabout.

3.5. Priority Rules. Priority rules define the right-of-way for unsignalized conflicting movements [31]. In the case of roundabouts, priority rules can be utilized to establish right-of-way at each of the conflict points where the approach traffic merges with the circulating traffic of the roundabout. At roundabouts, there are eight (8) merging conflict points: four (4) are converging and four (4) are diverging. In VISSIM it is only necessary to model the 4 converging conflict points. Right-of-way using priority rules is governed by two input parameters: (1) minimum gap time and (2) minimum headway.

3.6. Minimum Gap Time. Minimum gap time is the minimum gap that a vehicle will accept. During a simulation, the current gap time is calculated based on the distance from the start of the priority rule (the green line) on the mainline to the first vehicle's position and its speed. If the gap time is greater than the minimum gap time then the stopped car will proceed with the merge. If the gap time is less than the minimum time, then vehicle must wait to proceed until another gap of sufficient time occurs.

3.7. Minimum Headway. The minimum headway is "typically defined as the length of the conflict area" [31]. Generally, if the mainline experiences free-flow traffic then the gap time is the controlling parameter. However, if the mainline experiences significant queuing then the headway parameter is the more relevant parameter [31].

The priority rule should be placed on the network such that the red line is placed at the stop/yield bar. The Conflict Marker (green line) should be placed at the end of the conflict zone, i.e., where the theoretical gore of the two links [31]. The minimum headway is the length of the conflict zone, i.e., the distance from the physical gore to the theoretical gore. The end goal of simulating the roundabout is to accurately model the merge point at each leg of the intersection. If this point is modelled correctly, the resulting roundabout should perform as one expects in the field. The red marker of the priority zone in VISSIM represents the point on the link or connector where a vehicle must give right-of-way to an approaching vehicle on another link or connector.

When a vehicle arrives at red marker, it checks two things. It checks the current gap time from the green marker at the end of the conflict zone (area between the two bars) to the next approaching vehicle. It also checks to see if there is vehicle currently in the conflict zone. A waiting vehicle will continue to yield if there is already a vehicle which is present in the conflict zone and/or if the observed gap time for that time step is less than the minimum acceptable gap time set by the designer.

The placement of the mainline portion of the priority rule appears to have effect on the operational performance of the roundabout; it should be noted that this was observed only by watching the simulation and not through empirical data collection and analysis. It is unreasonable that situation may arise in which the conflict area is placed relative to the yield bar such that the upstream approach traffic arrives at the beginning of the conflict area unevenly and a queue vehicle would not advance despite the appearance of an acceptable gap because the minimum headway is not met. The case may also exist where both the minimum gap and minimum headway conditions are met, but a merging movement results in a collision of vehicles, which in VISSIM is hardly cause for alarm, as the two vehicles just simply drive over one another or in the very least the circulating vehicle reacts to the merging vehicle and reduces its speed to avoid a collision. Both result in an anticipated impact on capacity. It is supposed that a higher capacity will result if the conflict area is placed such that the conflict area ends at the physical gore and begins further upstream. This placement would effectively guarantee that if there exists an acceptable gap and the minimum headway condition is met, a merging vehicle will avoid a collision upon completing the merge. For this reason, further investigation into the placement of the conflict area and its impact on the capacity should be untaken.

For the purposes of this research, the priority rules were placed at each leg such that the red bar was located at the yield bar, and the green conflict area bars were placed such that leading bar was at the theoretical merge with the trailing bar 6 meters (the minimum headway distance) upstream.

3.8. Speed Control. There are two methods of controlling speeds at a roundabout in VISSIM. One method is to set up desired speed decision points at critical points in the roundabout. When a vehicle crosses the desired speed decision point, its desired speed is changed based on the user-selected desired speed distribution of the desired speed decision point. For instance, a desired speed decision point could be placed in advance of the yield bar and set to the expected or design operating speed of the circulating flow of the roundabout. Another desired speed decision point should be placed at the egress of the roundabout to set the vehicle's desired speed back to its desired speed before it entered the roundabout. Note that the vehicle does not begin to change its speed until it passes the desired speed decision point.

Reduced speed areas are the other method of controlling speed at a roundabout in VISSIM. While reduced speed areas are generally used on short segments of links and connectors (such as turning movements), they can be used in modelling a roundabout in VISSIM to simulate vehicles decelerating as they approach and circulate through the roundabout and then accelerating back to their desired speed after exiting the roundabout. Reduced speed areas are different from desired speed decision points in that the vehicle will begin to change its speed in advance of the reduced speed area such that by the time the vehicle enters the reduced speed zone, it is already traveling at a reduced speed. Once the vehicle leaves the reduced speed area, it will begin to accelerate back to its original desired speed. Reduced speed areas cannot cross multiple links and connectors; therefore, for use in roundabouts, multiple reduced speed areas must be placed in succession to maintain the appropriate approach and circulating speeds.

4. Results

A baseline VISSIM model was created to simulate the roundabout. This research is to analyse and compare different minimum acceptable gaps and their effects on network operations and simulated capacity. For simplicity, the focus of the data collection for this research was only on the one approach leg of the roundabout. Since it is a roundabout with four legs which are symmetric, it is assumed that the resulting approach capacity of one leg is equal to the approach capacity of the other legs. Therefore, only one leg was analysed for this research.

The VISSIM model was simulated for 70 minutes including the first 10 minutes as warm-up time periods to allow the network volume to build. Each scenario consisted of 400 individual simulation runs using the same parameters only changing the entry volumes for the network. While holding the entry volume of the approach leg in interest constant, the other entry volumes for the other three legs were varied from 100 to 2000 vehicles/hr incremented at 100 vehicles/hr. Then the approach leg volume was increased by 100 vehicles/hr and held constant while the other three legs' entry volumes were varied. The approach leg entry volume was varied from 100 to 2000 vehicles/hr. Also, all volume inputs were inputted as exact volumes, not based on distributions, such as Poisson. This would allow for more control over the input volume eliminating variations from distributions between simulation runs. The same simulation seed number was used for all simulation runs for all parameters. Replications with different seed numbers were not done because of the time constraints. However, further comparison can be done with different seed numbers for the verification purposes.

Scenario 1 with Priority Rules and Conflict Zones. Scenario 1 utilizes both priority rules and conflict zones for right-of-way control. Headway distance is 6 meters and minimum gap time is set to 0.5 seconds to 6 seconds with 0.5-second increment. Figure 1 shows the approach capacity versus circulating flow for Scenario 1.

As shown in Figure 1, the maximum circulating volumes achieved were between 700 vehicles/hr and 800 vehicles/hr. When compared with the HCM 2010 regression model, the simulated capacity from Scenario 1 is significantly lower. This would be the result of using both priority rules and conflict zones at the same time. The regression curves are exponential as expected as suggested in other reports including NCHRP Report 572, but the data significantly underestimates the capacity of the roundabout. From this setup, the predicted levels of the Highway Capacity Manual can not be achieved.

Also, it is noticed that there are little variations between the simulated runs with different minimum gap times. Simulations with gaps between 0.5 seconds and 3 seconds show only slight differences.

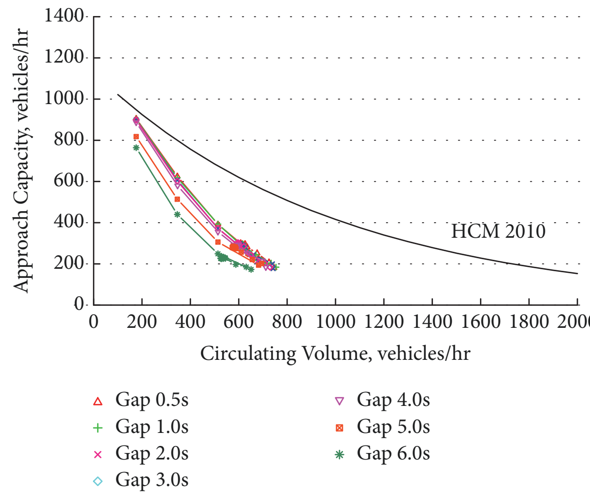

Figure 1: Scenario 1 roundabout approach capacity: priority rules and conflict zones.

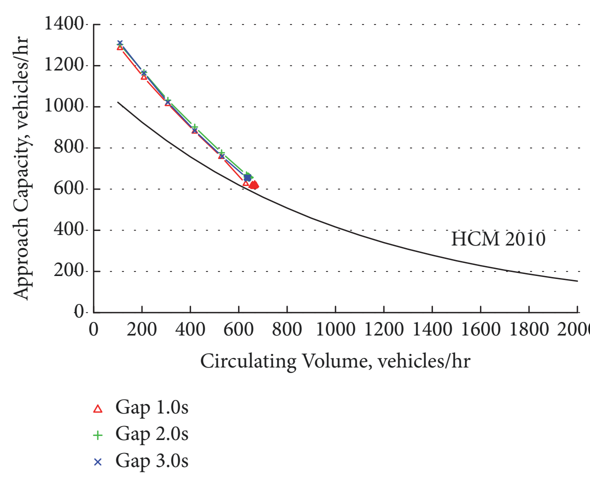

Figure 2: Scenario 2 roundabout approach capacity: priority rules only.

Scenario 2 with Priority Rules. To further understand the role of the gap acceptance in the priority rules, Scenario 2 was designed. Since it was believed that having priority rules and conflict zones at the same time would not work as intended, only priority rules were installed with the exact same network and traffic volume as Scenario 1. Therefore, headway distance remains 6 meters. However, the minimum gap parameter was adjusted with the range of 1.0 seconds to 3.0 seconds with a 1.0-second increment. Figure 2 shows the results from the simulation runs with the HCM 2010 regressions model.

By running simulation with priority rules only, it was observed that the results from Scenario 2 have better matching with the HCM 2010 model. However, there are still discrepancies between the HCM 2010 model and the simulated outputs. Also, the maximum circulating flow obtained is approximately 700 vehicles/hr.

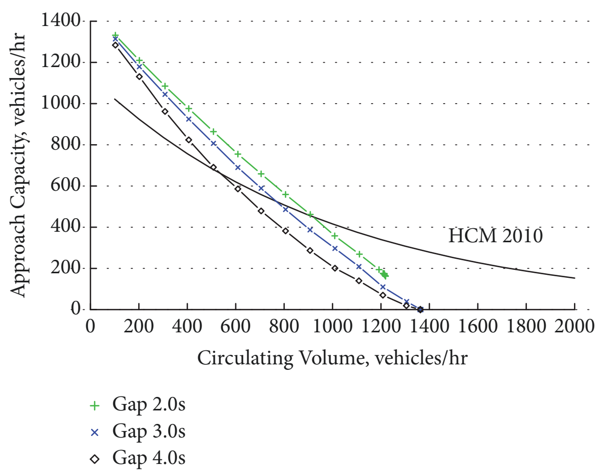

Figure 3: Scenario 3 roundabout approach capacity: priority rules only and adjusted input.

Scenario 3 with Priority Rules and Adjusted Input. The same network was used for Scenario 3. The exact same network and traffic volume with the same headway distance and minimum gap parameter were used as Scenario 2. However, input volumes were inserted on only two approaches. For example, westbound and northbound approaches were given input volumes and all westbound traffic was routed to the thru movement with no left or right turns. Approach capacity was collected on the northbound leg. The northbound traffic volumes were equally split, 33.3% left, 33.3% thru, and 33.3% right movements. Figure 3 demonstrates the results.

Figure 3 shows that there are significant differences in approach capacity with different minimum gap time parameter. For example, there can be as much as a 50% variance in capacity between 2.0-second minimum gap time and 4.0-second minimum gap time when circulating volume is more than 800 vehicles/hr. The approach capacity appears to have larger capacity with smaller minimum gap time.

Compared with Scenarios 1 and 2, the actual simulated circulating volumes reached almost 1400 vehicles/hr, doubling the maximum achieved circulating volumes of the previous results from the two scenarios. Figure 3 also suggests that the HCM 2010 model underestimates the approach capacity for circulating volumes less than 500 vehicles/hr to 800 vehicles/hr depending on the minimum gap time. On the other hand, the HCM 2010 model seems to overestimate the approach capacity for circulating volumes greater than approximately 700 to 900 vehicles/hr depending on the minimum acceptable gap time selected.

5. Discussion

After simulation runs of Scenarios 1 and 2 were completed, it was observed that the circulating flow did not go over a certain traffic flow level as shown in Figures 1 and 2. It appeared that the roundabout reached the capacity and could not handle any higher throughput. After changing input parameters and visual checking, it seemed that merging activities and conflicts between the westbound vehicles and southbound vehicles contributed to the traffic conditions. Therefore, the southbound and westbound traffic inputs were removed to allow for the eastbound traffic to enter the roundabout without conflicting with other traffic. In this setup, the eastbound traffic could enter the roundabout without waiting for a gap. The maximum circulating volume on the approach was controlled by the eastbound traffic volume, the minimum gap time, and the reduced speed inside the roundabout.

As expected, as the minimum gap time increases from 2.0 seconds to 4.0 seconds, the approach capacity drops. A minimum gap of 2.0 seconds seems to have a linear relationship between the approach capacity and the circulating traffic. As the minimum gap increases, the difference between the curves increases as well. This indicates that the change in the minimum gap makes a significant impact on the approach capacity. Also, the steepness of the curve is greater than the HCM 2010 model, implying that the simulated capacity results are more sensitive than the HCM 2010 model.

Additionally, Figure 3 implies that the approach capacity does not change linearly. The results are somewhat expected, since the HCM 2010 curve is an exponential regression. It is observed that the vertical and horizontal translations in the curves from the simulated outputs are not equal from run to run suggesting that the capacity reduction with the increase of the minimum gap time is not linear, either.

In comparing Scenarios 2 and 3, the curves from the simulated outputs demonstrate similar shapes and regimes with respect to the HCM model. However, some discrepancies exist between the two scenarios. The difference between the two scenarios is how vehicles enter the roundabout. When vehicles are entering a roundabout, the headway between the vehicles inside the roundabout is random and individual approaches cannot and do not operate independent of the other approaches. When all the approaches have input volumes as in Scenario 2, the merging of each approach is therefore dependent on the merges of the other approaches. This can be a part of reasons for the differences between Scenarios 2 and 3. To verify this, more simulation and analysis must be undertaken to investigate the difference and relationship between the two scenarios. By comparing Scenarios 2 and 3 it is clear that all of the approaches of a roundabout work together in order to create acceptable gaps. Though the impact of routing percentages was not investigated in this paper, differing percentages for each movement for each approach may impact the capacity of the roundabout approach.

Also, the results in this paper are based on the simplified simulation results. Additional parameters, including different speed inside the roundabout and initial desired vehicles speeds, need to be investigated and their impacts on the capacity need to be analysed.

6. Conclusions

The purpose of this paper is to estimate the capacity of roundabouts using simulation based mathematical analysis and highlight the impacts of priority rules in microscopic traffic simulations of a single-lane roundabout on approach capacity. This paper quantifies roundabout capacity to provide comprehensive analysis tools. Using simulation data and mathematical models, roundabout capacity calculation is evaluated to quantify the impact of minimum acceptable gap and related parameters on roundabout capacity. From the simulated results, it was demonstrated that even though the approaches are simple merges; however together they interact with one another to provide gaps for the other legs.

The results suggest that the minimum gap time has significant impact on the approach capacity. By solely calibrating the roundabout using the minimum gap time of the priority rules, the approach capacity of the roundabout can be increased or decreased by as much as 50%. This is a significant difference when trying to achieve a calibrated roundabout that should match the actual field conditions. Therefore, to effectively model a roundabout, the gap time must be calibrated to represent local traffic conditions. With an operating speed of 19.5 km/hr, the simulated roundabout model should have a minimum gap time set to approximately 2.28 seconds. The results also suggest that the HCM 2010 model underestimates the approach capacity for circulating volumes less than 500 vehicles/hr to 800 vehicles/hr depending on the minimum gap time and overestimates the approach capacity for circulating volumes greater than approximately 700 to 900 vehicles/hr depending on the minimum acceptable gap time selected. However, further analysis should be needed to understand the impacts of other network features and parameters.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was supported by a grant from Smart Civil Infrastructure Research Program (18SCIP-B138406-03) funded by Ministry of Land, Infrastructure and Transport (MOLIT) of the Korean government and Korea Agency for Infrastructure Technology Advancement (KAIA). This work was also supported by the 2015 Research Fund of UNIST (Ulsan National Institute of Science and Technology) (1.180015.01).

References

[1] J. Helmer and G. Gough, "Best Practices in Sustainable Transportation," *Institute of Transportation Engineers Journal*, vol. 80, no. 3, pp. 26–35, 2010.

[2] J. Schmale, E. von Schneidemesser, and A. Dörrie, "An integrated assessment method for sustainable transport system planning in a middle sized German city," *Sustainability*, vol. 7, no. 2, pp. 1329–1354, 2015.

[3] P. Maheshwari, R. Khaddar, P. Kachroo, and A. Paz, "Dynamic modeling of performance indices for planning of sustainable transportation systems," *Networks and Spatial Economics*, 2014.

[4] M. Guerrieri, F. Corriere, G. Rizzo, B. Lo Casto, and G. Scaccianoce, "Improving the sustainability of transportation: Environmental and functional benefits of right turn by-pass lanes at roundabouts," *Sustainability*, vol. 7, no. 5, pp. 5838–5856, 2015.

[5] H. Isebrands and S. Hallmark, "Assessing the air quality benefits of roundabouts," in *Proceedings of 2006 Air and Waste Management Association Annual Meeting*, New Orleans, LA, USA, 2006.

[6] US DOT Report to Congress, Transportation's Role in Reducing US Greenhouse Gas Emissions, 2010.

[7] S. Mandavilli, M. J. Rys, and E. R. Russell, "Environmental impact of modern roundabouts," *International Journal of Industrial Ergonomics*, vol. 38, no. 2, pp. 135–142, 2008.

[8] T. Tollazzi, G. Tesoriere, M. Guerrieri, and T. Campisi, "Environmental, functional and economic criteria for comparing "target roundabouts" with one- or two-level roundabout intersections," *Transportation Research Part D: Transport and Environment*, vol. 34, pp. 330–344, 2015.

[9] A. Klibavičius and G. M. Paliulis, "Increasing the capacity of intersections by short traffic lanes," *Transport*, vol. 27, no. 1, pp. 67–72, 2012.

[10] A. S. Huzayyin and H. Salem, "Analysis of thirty years evolution of urban growth, transport demand and supply, energy consumption, greenhouse and pollutants emissions in Greater Cairo," *Research in Transportation Economics*, vol. 40, no. 1, pp. 104–115, 2013.

[11] G. Loprencipe and F. Primieri, "The Integrated Design of Urban Road Intersections: A Case," in *Proceedings of the International Conference on Sustainable Design and Construction (ICSDC'11)*, pp. 722–727, 2011.

[12] R. Benekohal and V. Atluri, "Roundabout Evaluation and Design," A Site Selection Procedure CT-R27-21, Illinois Center for Transportation, Urbana, Illinois, 2009.

[13] Z. Qu, Y. Duan, H. Hu, and X. Song, "Capacity and delay estimation for roundabouts using conflict theory," *The Scientific World Journal*, vol. 2014, Article ID 710938, 12 pages, 2014.

[14] R. Akcelik, E. Chung, and M. Besley, "Analysis of roundabout performance by modelling approach flow interactions," in *Proceedings of the third international symposium on intersections without traffic signals*, pp. 15–25, Portland, Ore, USA, July 1997.

[15] J. Borkloe, E. Nyantakyi, and G. Mohammed, "Capacity analysis of selected intersections on mampong road, kumasighana using micro simulation model," *International Journal of Structural and Civil Engineering Research*, vol. 2, no. 3, pp. 39–61, 2013.

[16] Institute of Transportation Engineers, Selection of Appropriate Control, 2015.

[17] Sweroad., Principles for Selection of Intersection Type, 2000.

[18] Mainroads Western Australia, *Roundabouts and Traffic Signals: Guidelines for the Selection of Intersection Control*, 2015.

[19] Washington Department of Transportation, WSDOT Design Manual, 2017.

[20] Indiana Department of Transportation. Intersection Decision Guide,.

[21] R. Akçelik, "Roundabout Design and Capacity Analysis in Australia and New Zealand," in *Proceedings of the International*

Roundabout Design and Capacity Seminar6th International Symposium on Highway Capacity & Quality of Service, Stockholm, Sweden, 2011.

[22] H. Al-Madani and M. Saad, "Analysis of roundabout capacity under high demand flows," *Urban Transport*, vol. 107, 2009.

[23] X. Qu, L. Ren, S. Wang, and E. Oh, "Estimation of entry capacity for single-lane modern roundabouts: case study in Queensland, Australia," *Journal of Transportation Engineering*, vol. 140, no. 7, Article ID 05014002, 2014.

[24] L. Ren, X. Qu, H. Guan, S. Easa, and E. Oh, "Evaluation of roundabout capacity models: An empirical case study," *Journal of Transportation Engineering*, vol. 142, no. 12, Article ID 04016066, 2016.

[25] Z. Qu, Y. Duan, X. Song, H. Hu, H. Liu, and K. Guan, "Capacity prediction model based on limited priority gap-acceptance theory at multilane roundabouts," *Mathematical Problems in Engineering*, vol. 2014, Article ID 490280, 2014.

[26] S. Tanyel, T. Baran, and M. Özuysal, "Determining the capacity of single-lane roundabouts in Izmir, Turkey," *Journal of Transportation Engineering*, vol. 131, no. 12, pp. 953–956, 2005.

[27] S. Tanyel, T. Baran, and M. Özuysal, "Applicability of various capacity models for single-lane roundabouts in Izmir, Turkey," *Journal of Transportation Engineering*, vol. 133, no. 12, pp. 647–653, 2007.

[28] F. Xu and Z. Z. Tian, "Driver behavior and gap-acceptance characteristics at roundabouts in California," *Transportation Research Record*, vol. 2071, no. 1, pp. 117–124, 2008.

[29] W. Suh, C. Barry, L. Schmitt, J. Anderson, M. O. Rodgers, and M. Hunter, "Impact of including exiting vehicles in single-lane roundabout capacity models," *Transportation Research Record*, vol. 2517, pp. 87–95, 2015.

[30] M. Trueblood and J. Dale, "Simulating Roundabouts with VISSIM," in *2nd Urban Street Symposium*, Anaheim, Calif, USA, 2003.

[31] PTV, *VISSIM 5.40-03 User Manual*, Karlsruhe, Germany, 2012.

[32] Transportation Research Board. Highway Capacity Manual,.

[33] Transportation Research Board, *Appendixes to NCHRP Report 572: Roundabouts in the United States*, NCHRP, Washington, DC, USA, 2007.

[34] T. Wie, Hardik S. r., and R. Ambadipudi, "VISSIM Calibration for Modeling Single-Lane Roundabouts: Capacity-Based Strategies," in *Transportation Research Board Annual Meeting*, Washington, Wash, USA, 2012.

[35] B. Schroeder, *Modern Roundabout Operations in VISSIM: Calibration Guidance and Evaluation of Pedestrian Crossing Treatments*, Institute for Transportation Research & Education (ITRE) North Carolina State University, Raleigh, NC, USA, 2011.

[36] M. Hunter, M. Rodgers, J. Bansen, L. Schmitt, C. Barry, and W. Suh, *Calibration of the HCM 2010 single-lane roundabout capacity equations for Georgia conditions*, Georgia Department of Transportation, 2013.