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Comparative Evaluation of Roundabout Capacities Methods for Single-lane and Multi-lane Roundabout

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ABSTRACT

A roundabout is a highway engineering concept meant to calm traffic, increase safety, reduce stop-and-go travel, reduce accidents and congestion, and decrease traffic delays. It is circular and facilitates one-way traffic flow around a central point. The first part of this study evaluated the principles and methods used to compare the capacity methods of roundabouts with different traffic conditions and geometric configurations. These methods include gap acceptance, empirical, and simulation software methods. The present aim is to compare different roundabout capacity models for acceptable capacity predictions for single-lane and multi-lane roundabouts. Previous studies such as RODEL, SIDRA, Swiss, HCM6, and IRC overestimate capacity, while the GHCM method underestimates it. Each VISSIM and SIDRA predicted higher capacity than HCM2010, Paramics, and Simtrafic capacity methods. Generally, the precise prediction of capacity value depends on the circulating flow, exiting traffic flow, driver behavior, and geometric variations. Also, a comparison between seventeen methods was made using virtual data. For a single-lane roundabout, Girabase and Swiss models estimated higher capacity values when compared with other models, while HCM 2010 estimated lower capacity. The Shamueli's model provides an estimate of capacity about the same as the lower bound of the HCM 2000 model. Brilon's model estimated lower capacity values for a multi-lane roundabout compared with other methods. At low circulating flow, the Girabase model estimated a higher capacity value, while with the increasing circulating flow, the FHWA2000 estimated a higher capacity than the Girabase model. Also, there is a bit of a difference between SIDRA 5 and 8.0. There is a small interval between models that are implemented in a single-lane roundabout. Therefore, the models are better at predicting the capacity of a single lane than they are at predicting the capacity of multiple lanes.

Keywords: Roundabouts, capacity, traffic simulation, time headway

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مقارنه لتقييم طرق القدرات التقاطع الدائرية للمسار الواحد و دوار متعدد المسارات

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الخلاصة

التقاطعات الدائرية هو مفهوم هندسي للطرق يهدف إلى تهدئة حركة المرور وزيادة السلامة وتقليل السفر المتقطع وتقليل الحوادث والازدحام وتقليل التأخير في حركة المرور. إنه دائري ويسهل تدفق حركة المرور في اتجاه واحد حول نقطة مركزية. هدفت الدراسة الحالية إلى تقييم الأسس والأساليب المستخدمة لمقارنة طرق سعة التقاطعات مع ظروف المرور المختلفة التشكيلات الهندسية. تتضمن هذه الأساليب قبول الفجوة والطرق التجريبية وبرامج المحاكاة. الهدف الحالي هو تقديم مقارنة بين نماذج سعة الدوران المختلفة للتنبؤ بالسعة المقبولة للتقاطعات أحادية المسار ومتعددة المسارات. بينت الدراسات السابقة مثل طريقة RODEL و SIDRA و Swiss و HCM6 و IRC تقديرا" مبالغا فيه للسعة بينما اظهرت طريقة GHCM تدنيا في التقدير. توقعت كلا" من طريقة VISSIM و SIDRA سعة أعلى مما توقعته الطرق HCM2010 و Paramics و Simtrafic. قلل HCM2010 بالقدرة أكثر من طرق FHWA2000 وHCM2000 . بشكل عام ، يعتمد التنبؤ الدقيق لقيمة السعة على التدفق الدوري وتدفق حركة المرور الخارجة وسلوك السائق والتغيرات الهندسية. تم إجراء مقارنة بين سبعة عشر طريقة باستخدام البيانات الافتراضية. بالنسبة للتقاطع أحادي المسار ، قدرت نماذج Girabase و Swiss قيم السعة اعلى مقارنة بالنماذج الأخرى ، بينما قدر HCM 2010 سعة أقل. يعطي النموذج شامويلي تقديراً للقدرة يكون تقريباً نفس الحد الأدنى لنموذج HCM 2000 . بالنسبة للتقاطع الدائري متعدد المسارات ، قدر النموذج بريلون قيم السعة منخفضة مقارنة بالطرق الأخرى. في تدفق التدوير المنخفض ، قدر نموذج Girabase قيمة سعة أعلى ، بينما مع زيادة تدفق التدوير ، قدر FHWA2000 سعة أعلى من نموذج Girabase. أيضًا ، هناك اختلاف بسيط بين SIDRA 5 و 8.0. هناك فاصل زمني صغير بين النماذج التي يتم تنفيذها في تقاطع أحادي المسار. لذلك تعد النماذج أفضل في التنبؤ بسعة حارة واحدة أكثر من التنبؤ بسعة المسارات المتعددة.

الكلمات الرئيسية: التقاطع الدائري (الفلكة), نماذج السعة, المحاكاة

1. INTRODUCTION

Roundabouts are replacing conventional un-signalized intersections and have been successfully implemented worldwide over the past few decades to improve operational efficiency **(Rodegerdts 2007; Tian et al., 2007; Fernandes et al., 2020)**. Compared to an uncontrolled intersection, a roundabout reduces speed and the number of conflict points **(Wang and Yang, 2012; Mallikarjuna, 2014)**. Moreover, compared to other intersection applications such as all-way stop control and traffic signals, roundabouts can achieve sustainability goals by reducing power needs and improving the efficiency of traffic movement **(Suh et al., 2018).** The modern roundabout is a subset of several circular or elliptical intersections. Traffic is slowed and flows almost continuously in one direction around a central island, with many exits onto different intersecting roads **(Qu, et al., 2014)**.

Roundabouts are more advantageous as an intersection alternative than other intersections. Because they have a significant role in improving traffic safety by reducing some sorts of crashes (head-on and right-angle or t-bone crashes) that cause fatalities or injuries. In addition, roundabouts provide pedestrian safety by providing rest areas at medians, facilitating U-turns, increasing capacity, reducing delays and traffic congestion, minimizing maintenance costs, aesthetics, a pleasant landscape, savings on infrastructure investments, and environmental factors such as reduced greenhouse gas emissions and fuel consumption from automobiles by dramatically lowering acceleration, deceleration, and idling **(Ariniello and Przybyl, 2010; Li, et al., 2011; Mallikarjuna, 2014; Qu, et al., 2014; Suh et al., 2018; Alkaissi, 2022)**.
It is essential to comprehend the roundabout's operational performance to ensure vehicles' safe movement. One of the most significant parameters that explain the operational performance of roundabouts and the level of service is the capacity parameter **(Arroju et al., 2015).** The roundabout's capacity is the maximum number of vehicles that can enter a roundabout at a given entrance leg to flow through a circulating lane **(Qu, et al., 2014)**. Due to the rapid growth of traffic volume and estimated capacity having a major role in estimating performance measures, accurately analyzing and predicting the capacity of a roundabout is important **(Luttinen, 2004; Li, et al., 2011; Barry, 2012; Al–Azawee, 2018)**.
The ability of a roundabout to handle traffic largely depends on the traffic flow rate from each approach, geometric elements such as the central island's diameter, exit lane width, entry lane width, circulating lane width, and driver behavior that includes critical gap and follow-up time **(Kusuma and Koutsopoulos, 2011; Mahesh, et al., 2016)**. The critical gap is the minimum gap size that an entering driver would need to enter the roundabout, measured in seconds. In general, the critical gap value is an important factor in improving or designing roundabouts, impacting roundabout capacity modeling and simulation **(Shaaban and Hamad, 2020)**. The critical gap and follow-up time can be calibrated **(Tanyel, et al., 2005)**. The main aim of this paper is divided into two parts; the first is to review the roundabout capacity models that have been done in the literature using different methods and tools. The second part compares other roundabout capacity models for acceptable capacity predictions for single-lane and multi-lane roundabouts using virtual data (traffic volume and geometrical elements).
Roundabouts are classified into three categories (mini, single-lane, and multi-lane roundabouts) based on the number and size of the lanes. This classification facilitates discussion of the specific performance of the roundabout. Roundabouts are designed uniquely by using traffic control features and fundamental geometric elements. These elements include the inscribed circle diameter, the entrance line and sidewalk, the circulatory roadway, the landscape buffer, the track apron, the entry, and exit lanes, the splitter island, and the central island diameter **(Rodegerdts, et al., 2010).** The mini-roundabout type used in settled urban environments and low-speed areas of 30 mph or less is the mini-roundabout. A single-lane roundabout is the most basic and traditional layout for roundabouts used in urban and rural areas; it has a one-entry lane and a one-circulating lane. Compared with a mini-roundabout, a single-lane has a non-mountable central island, a large inscribed circle diameter, and a slightly higher rate of speed. Compared to other intersections, single-lane roundabouts have a low number of conflict points **(Pratelli, et al., 2018).** Roundabouts have developed to include multiple lanes at entry, exit, and circulatory

roadways with increasing traffic demands. The multi-lane roundabouts have two or more lanes and a minimum of one entry.
In some cases, the roundabout has a different number of lanes on one or more approaches, such as two lanes on the main street and one-lane entries on the minor street. When more than one vehicle travels next to each other, wider circulatory roadways are required. Multi-lane roundabouts grant higher capacity and similar or slightly higher speeds than single-lane roundabouts **(Pratelli, et al., 2018; CDOT, 2018; Demir and Demir, 2020)**. **Fig. 1** illustrates the features of three types of roundabouts.

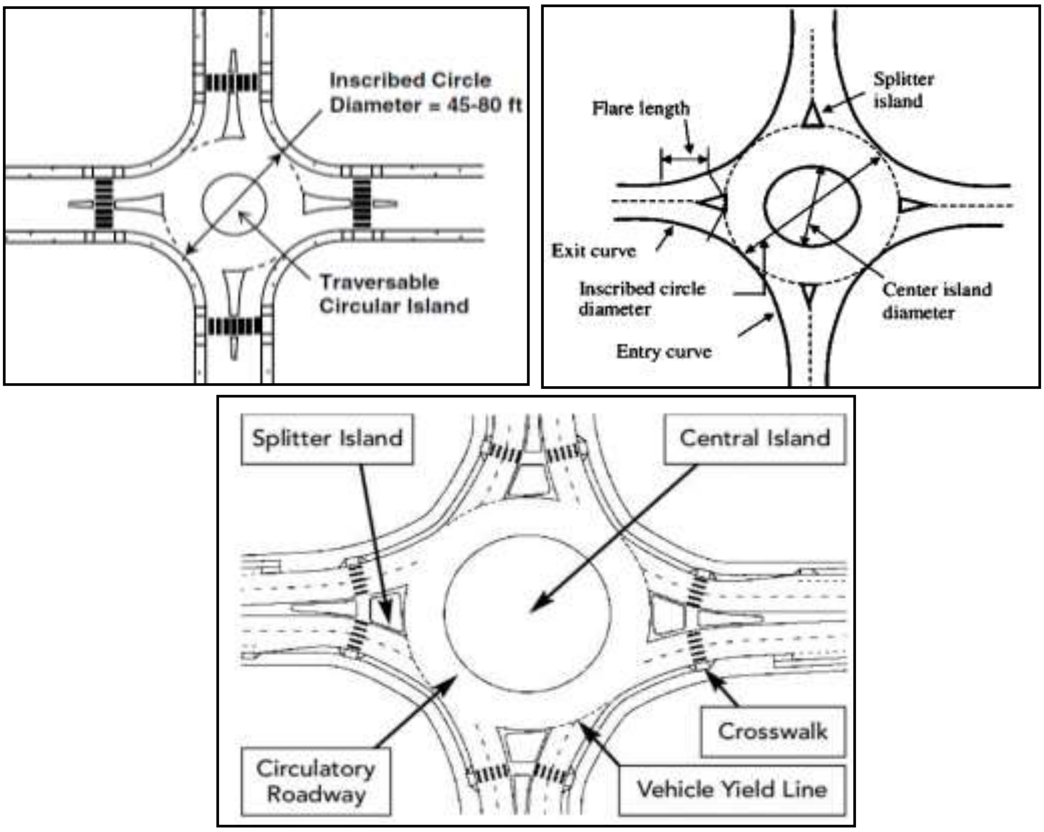


Figure 1. From left: mini roundabout, single-lane roundabout, and multi-lane roundabout.

2. TYPE of CAPACITY ROUNDABOUT MODELS

Regression (empirical) analysis and gap acceptance (analytical) models are two of the most common ways to evaluate and estimate the capacity of roundabouts **(Chandra and Rastogi, 2012)**. Analytical models were generally based on the circulating flow and two gap acceptance parameters (critical gap and follow-up time) to estimate capacity performance in early procedures. Other analyses are carried out using empirical models, which are statistical and use regression to predict the relationship between roundabout capacity and geometric characteristics. The main parameters for these models are entry width, circulating width, inscribed circle diameter, approach half-width, lane width, and splitter island width **(Gallelli and Vaiana, 2008; Lenters and Rudy, 2010; Taeb, 2021; Zehawi and Ahmed, 2018).**

Several models for analyzing the capacity and performance of roundabouts have been developed and used worldwide. These models use roundabout configurations as parameters. With the increasing popularity of roundabouts over the last three decades, the capacity methods of roundabout intersections have been a common research matter. Therefore, researchers developed extensive methodologies for capacity analysis and traffic operation evaluation. Based on field data, the empirical method is used in the United Kingdom, Switzerland, and India. Also, in Iraq, **(Sultan et al., 2015)** developed an empirical model for local roundabouts. Based on the gap acceptance theory, the analytical method is used in the United States, Germany, and Australia. Also, simulation (discrete and stochastic) methods have been used to estimate the capacity of roundabouts.

2.1 Gap Acceptance Models

In many developed countries, the gap acceptance theory is used to estimate roundabout capacity. Early models were developed to fit the native traffic conditions in nations such as the United States, Australia, and Germany. Driver behavior and local habits influence gap acceptance models **(Gazzarri, et al., 2013)**.

2.1.1 Highway capacity manual (HCM) versions

A. Highway Capacity Manual (2000):
The Highway Capacity Manual (HCM2000) was the first version to include a procedure for estimating capacity only for single-lane roundabouts. The HCM2000 is limited to capacity analysis and ignores the wide range of roundabout geometric configurations **(Manual, 2000)**. The HCM2000 assumes the following:

1. Circulating flows are supposed to be random,
2. Because drivers make right turns in both roundabouts and Two-Way Stop Control (TWSC) intersections, the gap acceptance characteristics in roundabouts are expected to be similar to those in TWSC intersections,
3. Based on research conducted in other countries and the limited study conducted in the United States, upper and lower capacity bounds have been established, which are closely related to follow-up time and critical gap values,
4. The 15-minute volumes of vehicles passing in front of the entering vehicles are used to calculate the circulating flows, and the effect of exiting vehicles from the same approach is ignored.

Based on the assumption that there is a negative exponential distribution of headway between circulating vehicles, the capacity is calculated using the equation shown in **Table 1**. Three factors determine the roundabout's capacity: circulating traffic flow, critical gap (t_c), and follow-up time (t_f). Driver behavior and gap acceptance characteristics are used to obtain the critical gap and follow-up time values (HCM, 2000). The equations used to calculate capacity have limitations. When the roundabouts have a lot of pedestrians and bicycles, the capacity of the roundabout could be determined by using other methods. Multi-lane roundabouts with two or more lanes in the circulating lane are not covered in the HCM equations. Therefore, another method of analysis would be required for multi-lane roundabouts. Unless field data for the critical gap and follow-up time have been collected, the HCM2000 method could not be used if the circulating flow exceeds 1200veh/h **(Manual, 2000)**.

B. Highway Capacity Manual (2010):

The Highway Capacity Manual (HCM2010) estimates the capacity of single-lane and multi-lane roundabouts. It was developed as a part of the research conducted by the National Cooperative Highway Research Program (NCHRP). It has a new methodology for the roundabout capacity equation, based on observed data from 31 roundabouts in the United States of America (USA). As illustrated in **Table 1.**, it provides capacity per lane rather than per approach and only requires the circulating flow rate as an input **(Manual, 2010)**. The HCM2010 proposes an exponential function for evaluating roundabout capacity based on gap acceptance theory.

Table 1. Equations for different entry combinations and circulating lanes for HCM2000, HCM2010, and HCM2016

Number of entries lanes	Number of circulating lanes	Entry lane capacity Equations (pcu/h)		
		HCM 2000	HCM 2010	HCM 2016
1	1	$C_e = \frac{(v_c * e^{\left(-v_c * \frac{t_c}{3600}\right)})}{(1 - e^{(-v_c * \frac{t_f}{3600})})}$	$C_e = 1130 * e^{-0.0001 * v_c}$	$C_e = 1380 * e^{-0.000102 * v_c}$
2	1	-	$C_{e,RL} = 1130 * e^{-0.0001 * v_c}$ (For both lane entries)	$C_{e,RL} = 1420 * e^{-0.00091 * v_c}$ (For both entry lanes)
1	2	-	$C_e = 1130 * e^{-0.0007 * v_c}$	$C_e = 1420 * e^{-0.00085 * v_c}$
2	2	-	$C_{e,R} = 1130 * e^{-0.0007 * v_c}$ (For the right entry lane)	$C_{e,R} = 1420 * e^{-0.00085 * v_c}$ (For the right entry lane)
		-	$C_{e,L} = 1130 * e^{-0.00075 * v_c}$ (For left entry lane)	$C_{e,L} = 1350 * e^{-0.00092 * v_c}$ (For left entry lane)
where; t_c is the critical gap, t_f is follow-up time, v_c is circulating traffic flow, C_e is entry capacity (pcu/h), $C_{e,R}$ is right entry lane capacity (pcu/h), $C_{e,L}$ is left entry lane capacity (pcu/h).				

C. Highway Capacity Manual (2016):

The Highway Capacity Manual (HCM6) updated the HCM2010 method's parameter values. According to HCM2016 research, there is a low correlation between geometry and capacity. Therefore, this method does not relate capacity or driver behavior to the roundabout geometric. To calculate the capacity of a roundabout, Eqs. (1) to (3) are used:

$$C = A * \exp^{(-B * vc)} \quad (1)$$

$$A = \frac{3600}{t_f} \quad (2)$$

$$B = \frac{t_c - (\frac{t_f}{2})}{3600} \quad (3)$$

where; C is the capacity (pcu/h), and vc: Circulating flow (pcu/h). The critical gap and follow-up headway are used to calculate the parameters of A and B; see **Table 2.**

Table 2. Critical gap and follow-up time values in seconds

HCM versions	Item	$t_{c\ (Second)}$	$t_{f\ (Second)}$
HCM 2000	Upper bound	4.1	2.6
	Lower bound	4.6	3.1
HCM 2010	Single-lane	5.19	3.19
	Multi-lane two-entry and one circulating lane (both entry lanes)	5.19	3.19
	Multi-lane one entry and two circulating lanes (both entrylanes)	4.11	3.19
	Multi-lane two-entry and two circulating lanes (Right Lane)	4.11	3.19
	Multi-lane two-entry and two circulating lanes (Left Lane)	4.29	3.19
HCM 2016	Single-lane	4.98	2.61
	Multi-lane two-entry and one circulating lane (both entry lanes)	4.55	2.54
	Multi-lane one entry and two circulating lanes (both entry lanes)	4.33	2.54
	Multi-lane two-entry and two circulating lanes (Right Lane)	4.33	2.54
	Multi-lane two-entry and two circulating lanes (Left Lane)	4.65	2.67

2.1.2 Austroad model

According to Australian practice, the roundabout's capacity is determined using the gap acceptance theory. The SR45 model was the first roundabout gap acceptance model to be introduced and developed **(Ren, et al., 2016)**. It is expressed mathematically as follows:

$$C = \frac{\varphi * v_C * exp\left(-\lambda * (t_C - \Delta)\right)}{1 - exp\left(-\lambda * t_f\right)} \quad (4)$$

$$\varphi = 0.75 * \left(1 - \frac{v_C * \Delta}{3600}\right) \quad (5)$$

$$\lambda = \frac{\varphi * v_C}{3600 * \left(1 - \frac{v_C * \Delta}{3600}\right)} \quad (6)$$

where; C is the capacity (pcu/h), φ is the proportion of un-bunched conflicting vehicles with randomly distributed headway, λ is an exponential arrival headway distribution model parameter, Δ is the intra-bunch minimum headway value within each bunch in the circulating flow (s)

2.2 Empirical Regression Models

Geometric design elements affect performance measures. Therefore, empirical regression models are utilized to establish a relationship between the capacity of a roundabout and its geometric characteristics. This model uses capacity as the dependent variable and circulating flow as the independent variable to create a relationship between capacity and circulating flow at each entrance.

2.2.1 Federal highway administration

The Federal Highway Administration (FHWA 2000) developed the informational guide on roundabouts that is primarily based on the Transport and Road Research Laboratory (TRRL) linear regression method. **Fig. 2** illustrates the expected capacity of roundabouts with single-lane and double-lane configurations. The capacity equation simplifies the TRRL-developed British roundabout capacity equations explained in the following section (the UK method equations are displayed in Section 2.2.2). In multi-lane roundabouts, it's important to balance the use of each lane to prevent overloading some lanes and underusing others. FHWA2000 does not explicitly cover roundabouts with more than two lanes **(Robinson and Rodegerdts, 2000)**.

2.2.2 United Kingdom (UK) model

The model used in the United Kingdom is based on a formula developed by TRRL. This linear model is based on statistical principles and utilizes regression analysis. Six geometric parameter variables that affect the capacity, such as the diameter of the inscribed circle, the entry width, the entry angle, the flare length, the flare's sharpness, and the entry bend radius, are mainly considered **(Aty and Hosni, 2001)**

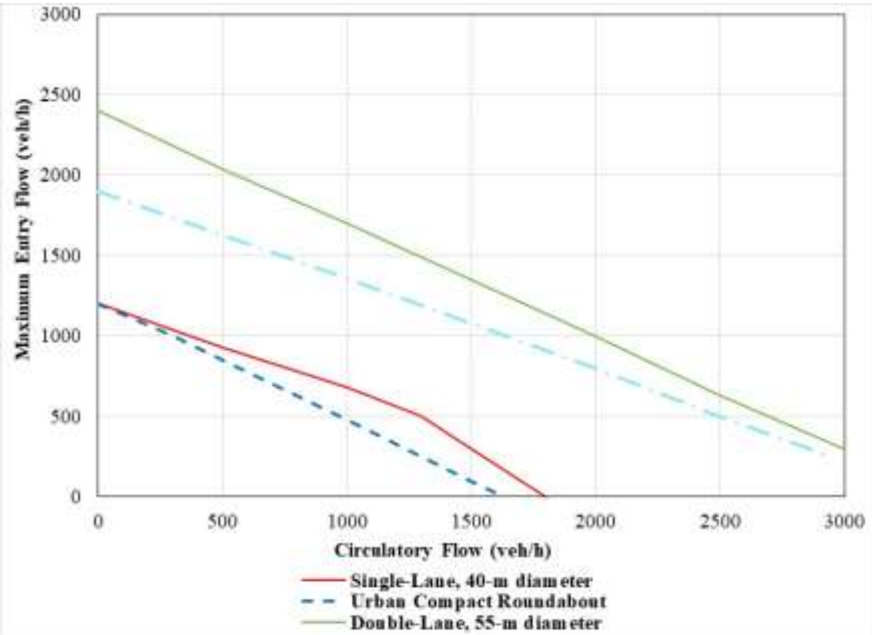


Figure 2. The capacity of single-lane and double-lane roundabouts **(Robinson and Rodegerdts, 2000)**

It used data from 86 sites to develop a direct relationship between capacity and geometrical parameters. Kimber's capacity model was established and named after the head of the research team **(Mathew, 2017).** Geometric parameters such as the width of approach, the width of entry, and effective flare length have a greater impact on capacity than entry radius, entry angle, and diameter. The following is a set of equations for estimating entry capacities in single-lane and two-lane roundabouts based on geometric parameters **(Johnson and Lin, 2018)**:

$$Q_e = k * (F - f_c * Q_c) \qquad f_c * Q_c \leq F \tag{7}$$

$$Q_e = 0 \qquad f_c * Q_c > F \tag{8}$$

$$k = 1 - 0.00347 * (\emptyset - 30) - 0.978 * (\frac{1}{r} - 0.05) \tag{9}$$

$$F = 303 * x_2 \tag{10}$$

$$f_c = 0.210 * t_D * (1 + 0.2 * x_2) \tag{11}$$

$$t_D = 1 + \frac{0.5}{1+\exp(\frac{D-60}{10})} \tag{12}$$

$$x_2 = v + \frac{e-v}{1+2S} \tag{13}$$

$$S = \frac{1.6*(e-v)}{l'} \tag{14}$$

where: Qe is the entry capacity, pcu/h, Qc is circulating flow, pcu/h, e is entry width (3.6 to16.5m), v is approach half-width (1.9 to 12.5m), l' is effective flare length (1.0 to infinite meters), r is entry radius (1.0 to infinite meters), φ is entry angle (0.0 to 77 degree), D is inscribed circle diameter (13.5 to 171.6m), K is constant, F is the intercept, fc is the slope, and S is a measure of the degree of the flaring.

2.2.3 Brilon and Vandehey (1998) model

Brilon and Vandehey determined that driver behavior, especially personal attitudes, and experience, impacts entry capacity in Germany. According to this model, geometrical parameters other than the number of lanes do not affect roundabout capacity. The capacity equations illustrated in **Table 3** indicate that the second and third lanes in the circle only add a small amount of capacity, especially in multi-lane roundabouts. These equations also show the capacity estimated in **Fig. 3**. The curves represent the average capacity values obtained from field data. The regression lines demonstrate the relationship between the capacity of the entry and circulating flow. The circulating flow and capacity of the entry are measured in passenger cars unit per hour (pcu/h) **(Brilon and Vandehey, 1998).**

2.2.4 Brilon and Wu basic and modified models

An analytical model was also developed by the German Highway Capacity Manual (GHCM) based on queuing theory and gap acceptance **(Brilon, 2005).** This model is expressed mathematically as:

Table 3. Roundabout capacity equations **(Brilon and Vandehey, 1998)**

Number of entry lanes/circle	Entry capacity equations
1 entry and 1 circle lane	qe=1218-0.74*qc
1 entry and 2 or 3 circle lane	qc=1250-0.532*qc
2 entry and 2 circle lane	qe=1380-0.5*qc
2 entry and 2 or 3 circle lane	qe=1409-0.42*qc
Where; 1 bus or truck =1.5 passenger car unit (pcu); 1 truck and trailer or articulated bus =2pcu; and 1 motorcycle or bicycle = 0.5pcu	

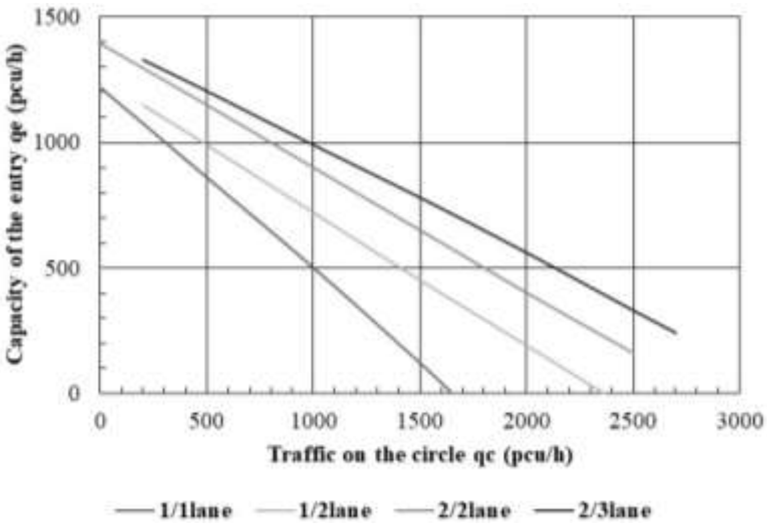


Figure 3. The capacity of roundabouts **(Brilon and Vandehey, 1998)**.

$$C = 3600\left(1 - \frac{v_c * t_{min}}{3600 * n_c}\right)^{n_c} * \frac{n_e}{t_f} * exp[-\frac{v_c}{3600}\left(t_c - \frac{t_f}{2} - t_{min}\right)] \quad (15)$$

where; C is the entry capacity (pcu/h), vc is the conflicting flow (pcu/h), t_{min} is the minimum gap between succeeding vehicles on the circle, n_e is the number of entry lanes, n_c is the number of circulating lanes, t_c, t_f are the critical gap, and follow-up time (sec).

The volumes are measured in passenger car units (pcu), with 1 truck equal to 1.5 pcu, 1 articulated truck equal to 2 pcu, 1 motorcycle equal to 1 pcu, and 1 bicycle equal to 0.5 pcu. The constant values were originally derived from Stuwe's (1992) observations for three parameters: t_c, t_f, and t_{min}. These constant values of parameters could not be applied to all types of roundabouts. Therefore, Brilon and Wu (2008) developed a modified version to introduce the parameters tc, tf, and tmin into the above equation **(Brilon and Wu, 2008)**. **Table 4** indicates the equations to determine these parameters for mini-roundabouts and single-lane roundabouts. Also, the capacity equations for multi-lane roundabouts are given directly without returning to Eq. (15).

Table 4. Compilation of equations for capacity calculation **(Brilon and Wu, 2008).**

Type of roundabout	Outer diameter (m)	ne	nc	t_c (second)	t_f (second)	t_{min} (second)
Mini	13 ≤ D ≤ 26	1	1	Eq. (15) with the following parameters: t_c=3.86+8.27/D t_f=2.84+2.07/D t_{min}=1.57+18.6/D		
Single- lane	26 ≤ D ≤ 40	1	1			
Multilane	40 ≤ D ≤ 60	1	2	C=1440·exp (-v_c /1180)		
Compact two-lane	40 ≤ D ≤ 60	2	2	C=1642·exp (-v_c /1180)		
Multilane	D > 60	2	2	C=1926·exp (-v_c /1405)		

2.3 Simulation Model

An alternative to empirical and analytical methods is a simulation model. It can simulate traffic flow based on drivers' lane-changing, car-following, and gap-acceptance behaviors at intersections. Roundabout simulation software includes two types: deterministic and stochastic simulation models **(Vaiana, et al., 2007). Table 5** shows the most popular software for roundabout feature simulations in different countries worldwide. The necessary parameters for some methods are illustrated in **Table 6**.

Table 5. The most popular roundabout software packages **(Abbood and Al-Tufail, 2018)**

Countries	Name	MODEL-BASED	Model
USA	CORSIM	CORridor SIMulation	Stochastic
USA	SIMTRAFFIC	SIMULATION TRAFFIC	Stochastic
USA	HCS/SYNCHRO	Highway Capacity Software	Deterministic
UK	RODEL	ROundabout DELay	Deterministic
UK	ARCADY	Assessment of Roundabout Capacity And DelaY	Deterministic
UK	PARAMICS	Parallel Microsimulation	Stochastic
Germany	VISSIM	Verkehr In Städten – SIMulationsmodell	Stochastic
Australia	SIDRA	Signalized Intersection Design and Research Aid	Deterministic

3. RELATED WORK

Numerous formulas have been developed to estimate roundabout capacity. Several researchers have developed a new method, and some studies compared these methods to indicate which method is reasonable for estimating capacity. The NCHRP compared the estimated capacity of roundabouts by RODEL and SIDRA to field data collected from multiple roundabouts in the USA. It was noticed that both methods overestimated the field-measured capacities **(Rodegerdts, et al., 2007).**

(Stanek, 2012) compared the different roundabout capacity methods, HCM2000, FHWA2000, HCM2010, SIDRA INTERSECTION, Paramics, SimTraffic, and VISSIM methods. Based on a single-lane roundabout, it was estimated capacity. **Fig. 4** shows the different shapes of the capacity curves for the various methods. It was concluded that when the conflicting flows were from about 400 to 1300 veh/h, the FHWA2000 predicted the highest approach capacity. Also, the HCM2010 had a lower capacity (from about 440 to 700 veh/h) than either the HCM 2000 or FHWA 2000 methods. SIDRA predicted the lowest capacity (from 700 to 1360 veh/h). SimTraffic estimated the lowest capacity for circulating flows under 440 veh/h. When the circulated flow was less than 300 veh/h, the SIDRA and VISSIM methods estimated higher capacity than other methods. It was recommended that calibration be done following local traffic conditions and that multiple analysis methods be used to get a reliable result.

(Gazzarri, et al., 2013) tested the HCM2010 capacity model's applicability in Italy. Field data from seven single-lane and multi-lane roundabouts were used. Maximum likelihood, median, and Raff's methods were used to determine the critical gap. A comparison was made between the results of the Tuscany (Italy) method and previous studies, such as NCHRP 572, the HCM2010 default capacity model, and a study conducted in California by Xu and Tian (2008). The result indicated that the HCM2010 estimated a lower capacity than Tuscany (Italy) capacity model. It was concluded that the methods that used local data for critical gaps and follow-up time had a higher capacity when compared with NCHRP 572 and the HCM2010 methods.

(Ren, et al., 2016) evaluated the capacity estimation for single-lane roundabouts. The field capacity was compared with the German Highway Capacity Manual, HCM2000, SIDRA, HCM2010, and New Roundabout Capacity (NRC) methods to evaluate the accuracy of each method. It was concluded that with low and medium traffic volumes, the SIDRA, GHCM, HCM2000, and NRC methods estimated similar entry capacities. However, for high-traffic conditions, the capacities of the methods were different.

Table 6. Comparison of principal inputs shared by major roundabout capacity models **(Yap, et al., 2013)**

Input variable	HCM	French (Girabase)	SIDRA 8.0	Swiss (Bovy-Tan)	FHWA 2000	German methods
Entry width	/	Included	/	/	Included	/
Circulating flow	Included	Included	Included	Included	Included	Included
Inscribed circle diameter or radius	/	Included	Included	/	Included	Included
splitter width	/	Included	/	Included	/	/
Circulatory width	/	Included	Included	Included	Included	Included
no. of entry lanes	/	/	Included	Included	/	Included
Approach half width	/	/	/	/	Included	/
effective flare length or short lane length	/	/	Included	/	Included	/
entry angle and entry radius	/	/	Included	/	Included	/
exiting flow	/	Included	/	Included	/	/
Critical gap and Follow-up time	Included	Included	Included	/	/	Included
Model parameters	Gap acceptance	Gap acceptance and Geometry	Gap acceptance and Geometry	Geometry	Geometry	Gap acceptance

The capacity of the IRC method was increased under high traffic conditions and a high proportion of exit vehicles. According to the results shown in **Fig. 5**, the capacity was underestimated by SIDRA, HCM 2000, GHCM, and NRC methods. Compared to the GHCM, HCM 2000, and SIDRA methods, the NRC method's capacity was closer to the observed capacity. The NRC method was effective under various circulating traffic flows.

(Chen and Hourdos, 2018) produced a model of a multi-lane roundabout. HCM 2010 and HCM6's default models were compared to the proposed model. When the circulating flow rate was high, the HCM2010 model overestimated the capacity of the left lane while closely estimating the right lane's capacity. The HCM6 model overestimated the capacity of the right lane by up to 28% and the left lane by up to 20%.

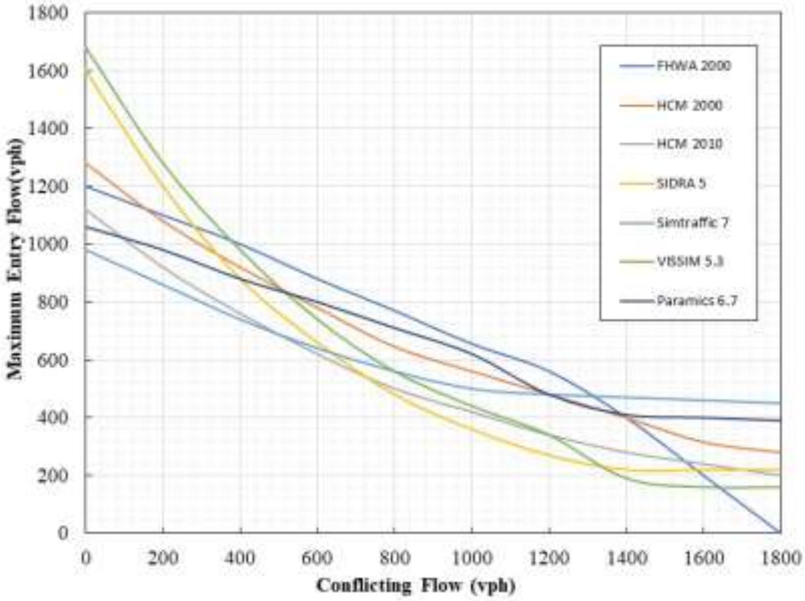


Figure 4. Single-lane roundabout capacity **(Stanek, 2012)**

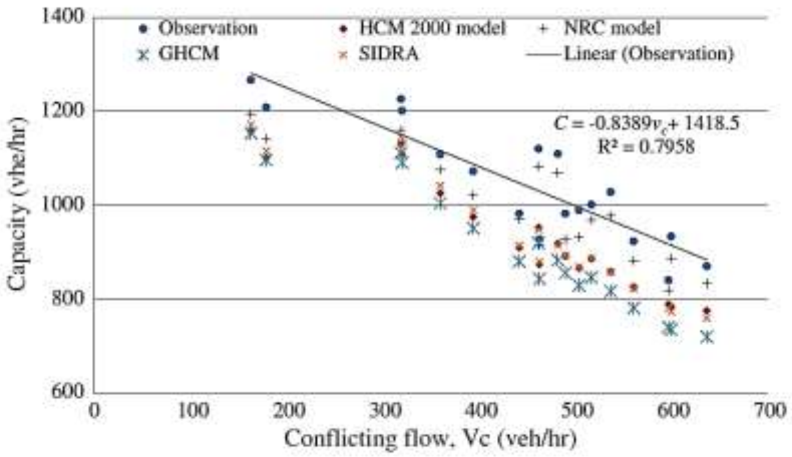


Figure 5. Comparison of entry capacities **(Ren, et al., 2016)**.

(Almukdad, et al., 2021) estimated and compared the capacity of two single-lane roundabouts. The Qatar Highway Design Manual (QHDM 2015) and HCM6 methods were applied. It was realized that the capacity with default gap parameter values (critical gap for QHDM 2015 was 4.98 seconds, and for HCM6, it was assumed between 4.1 to 4.6 seconds) was underestimated compared to the calibrated model at the same circulating flows. The difference in capacity models between calibrated and uncalibrated HCM6 was 36.7 percent, while the difference between calibrated and uncalibrated QHDM was 19.4 percent. The calibrated HCM6 had a significantly higher capacity than the HCM6 default values, QHDM default values, and QHDM calibrated values.

(Hamim, et al., 2021) developed a model to estimate roundabout capacity in the presence of heavy vehicles. Data was collected from six roundabouts with various geometric and traffic compositions. The developed model was compared to the HCM6, TRRL, IRC, and German methods. It was indicated that the HCM6 method underestimated capacity, while the German and the TRRL methods underestimated or overestimated capacities for different circulating flows. The IRC method overestimated capacity when compared to the observed capacity. It was concluded that the new model performed better than other methods in predicting the capacity of a rural roundabout.

One can conclude that predicting the capacity of a roundabout is a complex issue. It needs to establish a model that better represents the roundabout's reality. According to the literature, the software and method based on microscopic models, such as VISSIM, give a better result than reality. VISSIM is based on the car following theory and lane changing model; after reviewing most of the work that has been done relating to different methods and software for predicting the capacity of roundabouts, to fill the gap that exists in the literature and enrich this field of research, in the next section, a set of models for a single-lane and a multi-lane roundabout will be simulated.

4. METHODOLOGY

4.1 Different Capacity Estimation Methods Used for Comparison

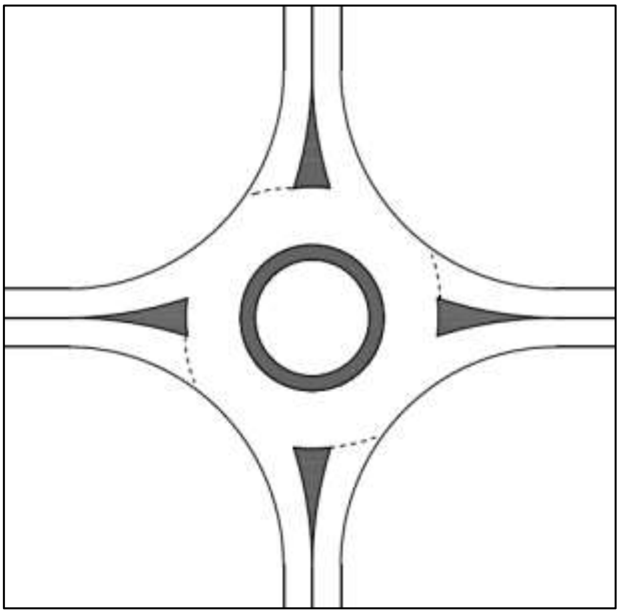
In the present study, the following capacity models have been compared: Brilon and Vandehey (1998), Australia, HCM2000, HCM2010, HCM2016, FHWA2000, and Brilon (2005) methods. Also, the French Model SETRA (1987) and GIRABASE (1997) are based on the existing flow and the width of the splitter island, which are not utilized in most of the other models **(Mauro, et al., 2020)**. **(Polus and Shamueli, 1997)** developed capacity models using the diameter and circulating flows as explanatory variables. The Wu (2001) capacity model is derived from gap acceptance principles and queuing theory and was introduced officially into the German Highway Capacity Manual in 2001. It is based on the numbers of entry (ne) and circulating (nc) lanes. The default values of critical gap (tc=4.1 second), follow-on headway (tf=2.9 second), and intra-bunch minimum headways (Δ=2.1 second) were initially obtained from field observations. In California, Xu and Tian (2008) developed a model based on NCHRP 3-65 study. Also, (**Gazzery, et al., 2013**), based on HCM 2010, developed a capacity model for the local roundabout in Italy (North Tuscany). The SIDRA intersection analysis software package has been developed by the Australian Road Research Board (ARRB), for the design and evaluation of signalized intersections, roundabouts, two-way stop control, and yield-sign control intersection**.** A brief overview and equations of roundabout capacity estimation methods used for comparison purposes are given in **Table 7**.

Table 7. Summary of operational capacity assessment models.

Countries	Author	Type	Equations	Method
France	SETRA (1987)	Single-lane and Multilane	$C = (1330 - 0.7 * Q_d) * (1 + 0.1 * (e - 3.5))$ $Q_d = (Qc + 2/3 * Q_u') * (1 - 0.085 * (ANN - 8))$ $Q_u' = Q_u * (1 - SEP/15)$; $Q_u'=0$ if SEP>15m	Empirical
	Girabase (1997)	Single-lane and Multilane	$C = \left(\left(\frac{3600}{t_f}\right) * \left(\frac{W_e}{3.5}\right)^{0.8}\right) * exp^{(-C_b * Q_d)}$	Gap acceptance and Geometry
Israel	(Polus and Shmueli, 1997)	Single-lane	C = 394 * D^0.31* exp(-0.00095 * Qc)	Empirical
Norway	Aakre (1997)	Single-lane and Multilane	C=275 * x - 0.282 * Qc * (1+ 0.2 * x) x = c+(e-c)/ (1+2 * S) ; S=1.6 * (e-c)/L	Empirical
German	GHCM (2001)	Single lane	$C = (1-(\Delta * Q_c)/n_c)$^$n_c * n_e/t_f * exp(-Q_c*(t_c - t_f/2 - \Delta)$	Gap acceptance
USA	California (Xu and Tian, 2008)	Single-lane and Multilane	C_e =1440 * exp(-1.01* 10^-3 * q_c) for single lane	Gap acceptance
			C_e=1565 * exp(-1.014 * 10^-3 * q_c) for left multilane	
			C_e=1636 * exp(-0.917 * 10^-3 * q_c) for right multilane	
USA	NCHRP 572 (Rodegerdts, 2007)	Single-lane	Ce=1130 * exp(-0.1 * 10^-3) * q_c	Gap acceptance
		Multilane	C_e=1059 * exp(-0.778 * 10^-3 * q_c) for left-multilane	
			C_e=1161 * exp(-0.736 * 10^-3 · q_c) for right-multilane	
Italy	North Tuscany (Gazzery, et al., 2013)	Single-lane and Multilane	C_e=1364 * exp(-0.70 * 10^-3 * q_c) for single lane	Gap acceptance
			C_e=1390 * exp(-0.70 * 10^-3 * q_c) for left-multilane	
			C_e=1369 * exp(-0.646 * 10^-3 * q_c) for right lane	
Australian	SIDRA 5 and 8 (Akcelik)	Single-lane and Multilane	Simulation	Gap acceptance
Swiss Capacity Model	Bovy et al (Bovy et al., 1991)	Single-lane and Multilane	$Q_e = \left(1500 - \frac{8}{9} * Q_b\right) * \beta$ $Q_b = \gamma * q_k + \alpha * q_a$	Gap acceptance

4.2 VIRTUAL DATA

In this work, two cases, shown in **Fig. 6** and **Fig. 7**, are used to compare roundabout capacity using different analytical, empirical, and software-based models. The first case is a single-lane roundabout, and the second one is a double-lane roundabout. The effects of pedestrians and traffic compositions have been neglected in the simulation, and 15 minutes is used as the time step of the simulation. **Table 8** shows the samples of the virtual data used for analysis.



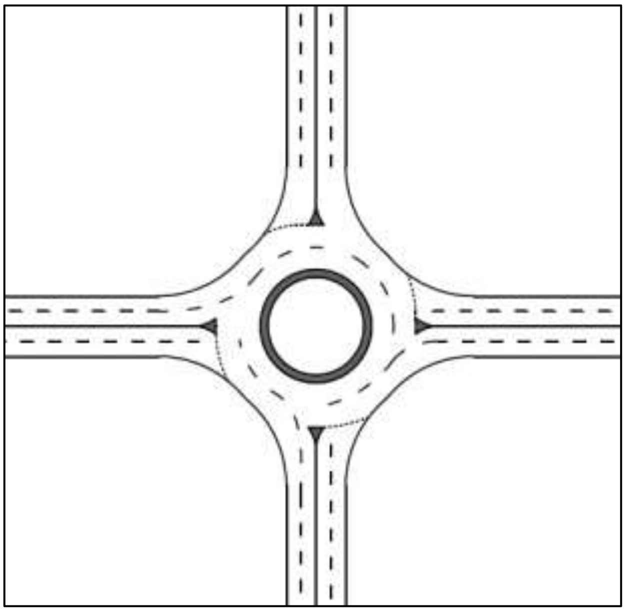


Table 8. Default parameters for estimating capacity

Parameters	Single-lane roundabout	Multi-lane roundabout
Entry radius, r (m)	20	30
Entry angle, phi (deg)	30	30
Approach half-width, v (m)	3.5	7
Entry width, e (m)	4	8
Effective flare length, l' (m)	20	20
Circulating Width, ANN (m)	8	12
Island Diameter (m)	20	30
Inscribed Diameter, D (m)	36	54
Number of circle lane and entry lane, n_e, n_c	1	2
Lane width (m)	4	4
Peak flow period (min)	15	15
Peak flow factor, PHF (%)	100	92
Splitter island width, SEP (m)	6	4

5. RESULTS AND DISCUSSION

The capacity methods have been implemented for each case, as shown in **Figs. 8** and **9**, respectively. The result for each case is described below.

5.1 Single-Lane Roundabout

Fig. 8 shows the results of single-lane capacity models. The following points could be noticed:

- The estimated capacity by NCHRP572 and HCM2010 models are quite close but underestimate the capacity compared to the other models.
- Most models estimate capacity in the middle of the lower and upper limits of HCM2000.
- The Tuscany model overestimates capacity. It is close to the upper limit capacity of HCM2000.
- California and SETRA1987 methods overestimate capacity when circulating flow is low (125 to 250 veh/h); their results are coming to the range of the other models when circulating flow is increased beyond 250 veh/h. In contrast, Aakre (1997) model underestimates capacity when circulating flow is low (125 to 300 veh/h), and beyond 300 veh/h it estimates close to the other models at the normal range.
- GHCM2001 estimates capacity for any value of circulating flow compared to all other models.
- In contrast, the FHWA2000 model does not follow the same tendency as the other models except Aakre (1997) model, which has almost the same line slope as the FHWA2000 model.
- Shamueli (1997)'s model underestimates capacity and is close to the lower limit capacity of HCM2000.
- The results of SIDRA5 and SIDRA8 are quite similar, and both are similar to the HCM 2016 result.
- One can notice a big difference between the result of different versions of HCM's models, and HCM2010 failed to predict capacity precisely.
- It is interesting to mention that underestimating or overestimating capacity when circulating flow is low does not affect the practical work. Still, the problem is when a model overestimates or underestimates capacity when the circulating flow is high. Therefore, we can make this criterion to classify a model's accuracy in predicting capacity.

5.2 Multilane Roundabout

For case 2, the results from the capacity models are given in **Fig. 9.** The following points could be noticed:

- The results of SIDRA 5 and 8 are not identical but quite close to each other. HCM2016 with SIDRA 5 gave the same result, especially when the circulating flow is high.
- Shamueli (1997)'s model same to single-lane capacity, underestimates the capacity
- FHWA2000 overestimates capacity.
- Brilon's models underestimate capacity.
- Most models' results get closer when the circulating flow is high.

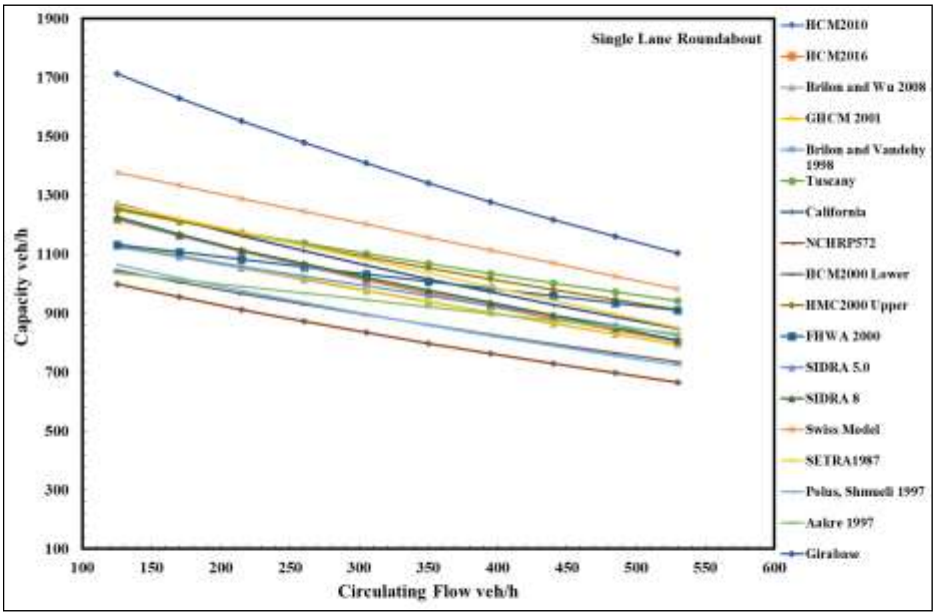


Figure 8. Single-lane capacity models implemented

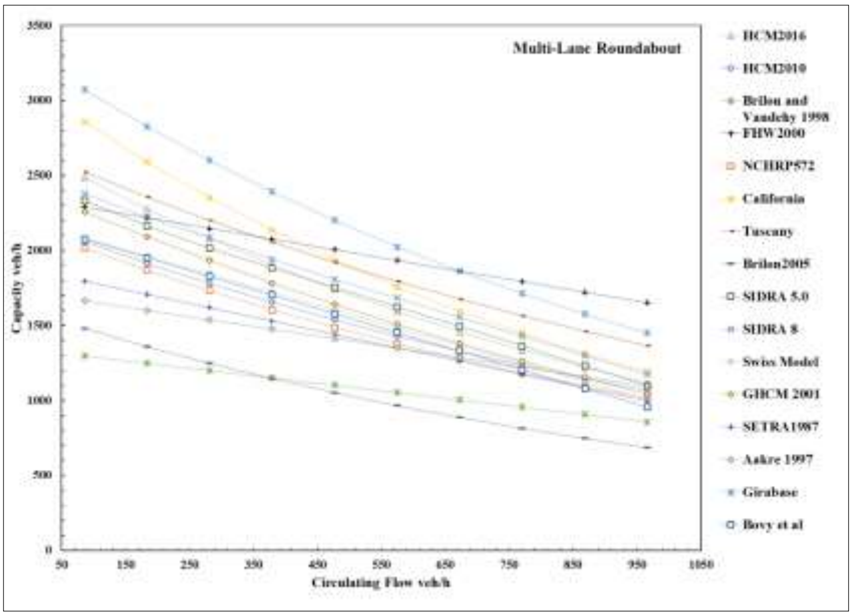


Figure 9. Multi-lane capacity models implemented

6. CONCLUSIONS

In this study, the following points can be concluded:

1. It has been proven that road user behavior and geometric configuration significantly affect the quality of models. Because road user behavior is the main parameter in most capacity estimation models.
2. Gap acceptance parameters influence the capacity of roundabouts.

3. Any model cannot predict capacity precisely if the calibration process is not established. Therefore, one cannot rely on the models that have not considered these two important parameters. This is why the models implemented with microscopic traffic models can better predict capacity. These models and usually software-based models, such as SIDRA and VISSIM.
4. For multi-lane roundabouts, each lane varies depending on the circulating flow rate.
5. With different circulating flows, FHWA 2000 underestimated and overestimated capacity compared to HCM6, Tuscany, California, and Girabase models.
6. At a single-lane roundabout, SIDRA 5, SIDRA 8, and HCM6 predicted the same capacity. While at a multi-lane roundabout, SIDRA 8.0 predicted a higher capacity than SIDRA 5 model.
7. Compared to the HCM6, the empirical (SETRA, Akare, Swiss, GHCM, Brilon, and, Brilon and Vandahy) models underestimated capacities.
8. The range of variation of capacity prediction of multi-lane roundabout models is greater compared to single-lane roundabouts, which means that, generally, the results of the models for single-lane roundabouts are closer to each other compared to the results of multi-lane models. Therefore, it can be concluded that, except for HCM2010, the models can predict the single-lane capacity better than the multi-lane capacity.
9. Since the SIDRA INTERSECTION software can give estimates from the HCM 2010, HCM 2016, and FHWA 2000 geometric models, it can be used to design a roundabout, compare the results from all three methods in the same program, and perform an engineering decision during design.

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