Developing Empirical Capacity Estimation Model for Highway Roundabouts in Bangladesh

by

Md. Saddam Hossain

MASTER OF SCIENCE IN CIVIL ENGINEERING (TRANSPORTATION)

Department of Civil Engineering

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY,

DHAKA, BANGLADESH

April 2021

Developing Empirical Capacity Estimation Model for Highway Roundabouts in Bangladesh

A thesis submitted to the Department of Civil Engineering,

Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING (TRANSPORTATION)

by

Md. Saddam Hossain
Department of Civil Engineering
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
Dhaka, Bangladesh

April 2021

The thesis titled 'Developing Empirical Capacity Estimation Model for Highway Roundabouts in Bangladesh', submitted by Md. Saddam Hossain, Roll No: 0417042424 (F), Session: April 2017 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Transportation) on April 3, 2021.

BOARD OF EXAMINERS

Dr. Md. Hadiuzzaman Professor Department of Civil Engineering Bangladesh University of Engineering and Technology (BUET) Dhaka 1000, Bangladesh	Chairman
Dr. Md. Delwar Hossain Professor and Head Department of Civil Engineering Bangladesh University of Engineering and Technology (BUET) Dhaka 1000, Bangladesh	Member (Ex-officio)
Dr. Md. Mizanur Rahman Professor Department of Civil Engineering Bangladesh University of Engineering and Technology (BUET) Dhaka 1000, Bangladesh	Member
Dr. Mohammed Russedul Islam Associate professor Department of Civil Engineering, Military Institute of Science and Technology	Member (External)

DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

April 3, 2021

Md. Saddam Hossain

DEDICATED

To

My mother Dulu Begum and my father Matiur Rahman. Their continuous inspirations made this effort possible.

ACKNOWLEDGEMENT

I am deeply indebted to and want to express my utmost gratitude to my thesis supervisor, Dr. Md. Hadiuzzaman, Professor, Department of Civil Engineering, BUET, for his guidance, generous help, constructive comments, invaluable suggestions what has made it possible to prepare this concerted thesis. I would like to thank Omar Faruqe Hamim, Assistant Professor, Department of Civil Engineering, BUET for his untiring support throughout the progress of the thesis work. His endurance, consistent efforts, ceaseless inspiration have helped me to work diligently for the completion of this research work. Without his continuous support and guidance, this thesis would not have materialized.

I want to thank the Department of Civil Engineering, BUET for providing me an opportunity to work on this contemporary thesis work.

My special thanks to, Md. Nazmul Haque, Assistant Professor (Transportation Engineering), Director of Weekend Program (In-Charge), Department of Civil Engineering, Presidency University for his outstanding support of data extraction process. I would like to thank Dr. Asif Raihan, Assistant Professor, ARI, BUET for his untiring support throughout the progress of the thesis work. Also, thanks to Dr. Asif M Zaman, Managing Director, Esolve International Limited for his inspiration and allowing me a flexible work schedule during this study. I am grateful to my family, friends, and colleagues for their constant encouragement and cooperation in pursuing my goals.

ABSTRACT

Transportation infrastructure plays a significant role behind economic growth of a country. Particularly, in developing countries, heavy vehicles act as the backbone in transporting goods and people via highways while sharing the same carriageway with other vehicles. However, presence of heavy vehicles in traffic stream lowers operating speed and flow in rural highways especially at the vicinity of intersections. With the increasing portion of heavy vehicles in a traffic stream, the capacity of roundabouts decreases drastically. This research aims at developing an empirical model for estimating and predicting capacity of highway roundabouts considering both geometric and traffic parameters. Six roundabout intersections along the national highways owned by Roads and Highways Department (RHD), Bangladesh have been selected as the study area, and relevant geometric and traffic data have been collected. The collected traffic flow data was extracted by using pixel-based heterogeneous traffic flow measurement technique. The geometric data was extracted by applying AutoCAD and ArcGIS.

Using multivariate regression method, an empirical model for capacity estimation and prediction of roundabout has been developed as a function of entry width, circular road width, distance between entry and nearest exit, central island diameter, and circulating traffic flow. The presence of heavy vehicles in traffic stream has been incorporated in estimating and predicting capacity of roundabouts by converting all types of vehicle to passenger car equivalent units. The developed model was evaluated with observed capacity collected from the selected six roundabouts. The evaluation has shown that the model performed well with the shortlisted explanatory variables. The model was based on negative exponential with circulating flow (Q_c) and positively linear with geometric parameters. In the developed empirical model, circular road widths and central island diameters were found to be more useful predictor variables compared to others used in the established models (e.g., flare length, entry radius, and entry angle). A negative exponential relationship was found between entry capacity and circular flow. The entry width and entry to the nearest exit distance of roundabouts were found to have a positive linear relationship with entry capacity.

A comparative study with HCM 2016 model, TRRL model, IRC model, and German model for estimating roundabout capacity has been performed to assess the suitability of the developed model for estimating capacity of highway roundabouts. The comparison results reveal that the entry capacity of a roundabout estimated using HCM 2016, German, TRRL, and

IRC model differs significantly from the observed capacity values but the estimation using the developed regression model does not differ significantly from the observed values. Hence, the developed regression model is statistically better in estimating entry capacity of highway roundabouts in Bangladesh.

Microscopic simulation model was developed in a state-of-art microsimulation tool VISSIM for further investigation of the effect of independent variables. The VISSIM coded model was calibrated and validated with the field collected data of selected sites. The calibrated VISSIM model then used to exploring the developed model with different traffic flow scenario and geometric configurations. The extracted capacity from VISSIM was compared with predicted capacity of developed empirical model capacity. This analysis was important as the variability of traffic and geometric data had not been explored through analytical approach. The capacity variability within the VISSIM simulated roundabouts has proved the accuracy of the empirical model. Furthermore, a Python language-based program called PyNomo has been executed with the help of several add-on packages (e.g., numpy, scipy etc.) to generate a compound parallel scale nomograph consisting of multiple variables using the developed empirical model to aid the practitioners and engineers as a quick tool to estimate and predict roundabout capacity. Considering the impact of heavy vehicles in social and economic development of a country, the model developed in this study will be useful for policymakers and practitioners while planning and designing roundabouts in rural highways to keep in pace with the ever-increasing future traffic demand.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
$C_{e, pec}$	Entry lane capacity (pc/h)
D	Diameter of central Island (m)
DC	Data collection
E	Entry width (m)
EN	Entry Number
FHWA	Federal Highway Administration
GHE	Geoffrey E. Havers
HCM	Highway Capacity Manual
IRC	Indian Road Congress
L	Entry to nearest exit distance (m)
NCHRP	National Cooperative Highway Research Program
NMV	Non - Motorized Vehicle
n_c	Number of circulating lanes
n_e	Number of entry lanes
PCU	Passenger Car Unit
Q_e	Entry capacity (pcu/h)
Q_c	Circulating flow (pcu/h)
R	Circular road width (m)
RHD	Roads and Highways Department
t_c	Critical headway (sec.)
t_f	Follow-on headway (sec.)
t_q	Queue duration (sec.)

TRRL	Transportation and Road Research Laboratory
Vph	Vehicle per hour
$V_{c,\,pec}$	Conflict flow capacity rate (pc/h)
α	Proportion of free vehicles
Δ	Headways
λ	Decay constant (sec^{-1})

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Roundabout is a type of circular junction where road traffic is permitted to flow in one direction (clockwise in Bangladesh) around a central island, and priority is typically given to the traffic already in the junction. Roundabouts are commonly used to facilitate low to moderate traffic flows in an orderly manner while providing a traffic control mechanism. The safety and traffic operational benefits of roundabouts for automobiles and small trucks have been well documented which prove the fact that roundabouts are quite safer and an efficient form of traffic control for most intersections (Russell et al., 2002, 2005; Rodegerdts et al., 2010; Godavarthy and Russell, 2015; Mandavalli et al., 2008; Godavarthy et al., 2018). Compared to signalized and stop-controlled intersections, roundabouts offer better overall safety, less delay, small queues, safe speed management, and scopes for several community enhancement features (Godavarthy et al., 2018). Also, in some instances, the expensive widening of an intersection approach required for signalization can be addressed using the available space of the roundabouts (Rodegerdts et al., 2010; Brilon, 2016).

Considering the advantages of roundabouts, many developed countries have adopted this tool for providing safe and efficient traffic movement at intersections. A study by Rasheed (2010) highlights the fact that over 150 roundabouts are in operation in Canada. Kittleson and Associates (2020) recognized more than 10,600 active roundabouts in the United States. In Japan, roundabouts are adopted more often since this type of intersection provides greater efficiency at low to medium traffic flow along with increased safety (Arshi, 2018). The benefits of using roundabouts are protruding from the facts that in the United States the total number of crashes are decreased by 35% and crashes involving injuries are decreased by 76%; and similar outcomes have been recognized in Australia, France, Germany, Netherlands, and in the United Kingdom (Rodegerdts et al., 2010). Bangladesh, a low-middle income developing country has followed the same trend set internationally and adopted a traffic control, calming and safety tool in the form of roundabouts on both rural and urban roads.

Traffic control at intersections is a complex process; thus, considerations, such as, capacity and delay along with safety and geometrical constraints are concerning features towards efficiency (Arshi, 2018). The capacity of an intersection in a way defines the capacity of the whole road network; hence, has a significant impact on the efficiency of the road network (Arshi, 2018). Intersections thus have a significant role in the operation of road networks, especially in urban settings. Although, intersections usually do not affect the capacity of rural highways due to the intersections' sparse placement along the road network; however, in Bangladesh, closely spaced intersections on rural highways influence the efficiency of the overall road network. Furthermore, the highway network in Bangladesh is dominated by heavy vehicles (i.e., large buses and trucks) which may demand the use of roundabouts as speed calming devices to provide better safety on rural highways.

The capacity of a roundabout is the maximum number of vehicles that can enter the roundabout in one hour. However, this capacity is defined for each entry and not for the entire junction (Polus and Shumeli, 1997). This concept is similar to the analysis method of the Highway Capacity Manual (TRB, 1985) for signalized junction, whereby the capacity of each minor traffic stream is defined separately, depending on the critical gap and the conflicting stream volume.

The capacity estimating method of a roundabout can be classified broadly into three groups: (1) empirical method; (2) analytical method; and (3) microscopic traffic simulation method. Among them, the empirical methods are based on the geometric properties of roundabouts including entry width, entry angle, entry radius, circular road width, inscribed circle diameter, etc. For example, the UK empirical method proposed by Transport and Road Research Laboratory (TRRL) utilizes several geometric parameters for roundabout capacity estimation: entry width, flare length, the sharpness of the flare, entry bend radius, entry angle, and inscribed circle diameter (Kimber, 1980). The Swiss method is similar to the UK method but considers the effect of existing traffic in the direction opposite to the entering traffic (De Aragao et al., 1991; Al Masaeid and Faddah, 1997) developed a roundabout capacity estimation model by using empirical analysis. According to HCM 2000 (TRB, 2000), the capacity of a roundabout entry is a function of the one flow variable, i.e., circulating flow in a negative exponential regression setting, while the HCM 2010 (TRB, 2010) proposes an analytical approach based on the critical gap and follow-up time to determine the entry capacity of a roundabout. Mathew et al. (Mathew et al., 2017) modified and calibrated the HCM equation for heterogeneous traffic conditions. In another study, a new microscopic simulation technique, where a coordinated approach to modeling vehicle location is adopted and was applied to model the traffic flow at the roundabout under mixed traffic conditions (Hossain, 1999).

The capacity of a roundabout depends on its geometric features as well as on the behavior of existing traffic (Mahesh, 2016). Geometric characteristics of a roundabout are represented by parameters such as the diameter of the central island, entry angle, entry width, exit width, the width of circulating roadway, weaving width, weaving length, etc. whereas parameters like critical gap and follow-up headway represent the traffic behavior affecting the performance of a roundabout. Traffic composition and volume at the approach and circulating section of roundabouts greatly influence the critical gap and follow-up headway of the traffic stream.

Research studies have been conducted to estimate the capacity of roundabouts in developed countries with traffic stream full of passenger cars (Brilon et al., 1997; Fitzpatrick, 2015; Rodegerdts et al., 2010), and in developing countries with heterogeneous traffic stream (Arroju et al., 2015; Mahesh, 2016; Arshi, 2018). Most of the estimation models have been developed for urban roundabouts using either an empirical or analytic approach. Very few researches have focused on estimating the capacity of rural highway roundabouts with traffic streams dominated by heavy vehicles (Dahl and Lee, 2012; Mohamed et al., 2020). Rural highway roundabouts in Bangladesh have the dominant presence of heavy vehicles which has a significant impact on the capacity of roundabouts. Often, these roundabouts become a source of bottlenecks due to failure in accommodating the traffic demand which focuses on the fact that these roundabouts are not being appropriately designed. The absence of design guidelines in line with the local traffic and geometric conditions attributes to these failures of designers and engineers in Bangladesh. The scenario of rural highway roundabouts in Bangladesh stimulates the need for a study to develop a capacity estimation and prediction model of roundabouts under rural highway settings while considering the impact of the presence of heavy vehicles in traffic streams. Further research can be conducted to deal with urban roundabouts and highway roundabouts around the periphery of cities with moderate surrounding development activities.

1.2 Objectives and Scope

This thesis is concerned with the development of an empirical capacity estimation model for highway roundabouts under heterogeneous traffic conditions. The specific objectives are:

I. To identify traffic and geometric parameters which affect the roundabout entry capacity;

II. To develop an empirical model as a function of circulating traffic and geometric parameters to estimate roundabout entry capacity;

III. To calibrate and validate a microscopic simulation model to investigate the accuracy of the developed model;

IV. To develop a nomograph to determine design parameters for a known capacity as well as to predict capacity for known variables;

V. To compare the developed model's performance against the selected previous models.

The outcome of this research will help traffic engineers to accurately estimate and design highway roundabout capacity under heterogeneous traffic conditions which will improve traffic operation.

1.3 Organization of the Thesis

In harmony with preceding objectives and scope, the structure of this thesis is as follow:

Chapter 1 presents the background of the study and describes the specific objectives of the thesis along with the problem statement.

Chapter 2 discusses roundabouts and their types also discusses different parameters related to the capacity of a roundabout. It also reviews the literature on roundabout capacity modeling, outlining issues and limitations with present methodologies. And discuss the different capacity estimation methods for different types of roundabouts.

Chapter 3 explains the methodology and collection of new capacity data for the analysis and development of an empirical capacity model. It will discuss the characteristics of data and limitations arising from the actual sample/data used. It also presents a short assessment of comparing different methods of capacity data measurement, to address one of the limitations of empirical modeling.

Chapter 4 describes the technique and method of data extraction collected from the field. It will discuss the analysis of data in different categories. It also presents a summary sheet of data.

Chapter 5 sets out the modeling methodology and development empirical capacity model by the multivariate regression method. It will develop microscopic traffic simulation models and nomograph of roundabouts. It will investigate the impact of different variables identified from the empirical model.

Chapter 6 discusses the result of the developed capacity model and nomograph in this thesis.

Chapter 7 presents the conclusion drawn from the work in this thesis and discusses the potential approaches to extend research.

CHAPTER 2

LITERATURE REVIEW

2.1 Roundabout

Modern roundabouts are a major type of junction on the road network, where entering vehicles give-way to vehicles circulating one-way around a central island. Modern roundabouts were initially introduced in England during the year 1960 to resolve some existing problems with the traffic circles and rotaries. Among the at-grade road intersections, roundabout proved to be much more operationally efficient. Also, roundabouts are considered safer than other traffic controlled intersections because there is no chance to have a direct impact at the right angle due to the geometric nature of roundabouts.

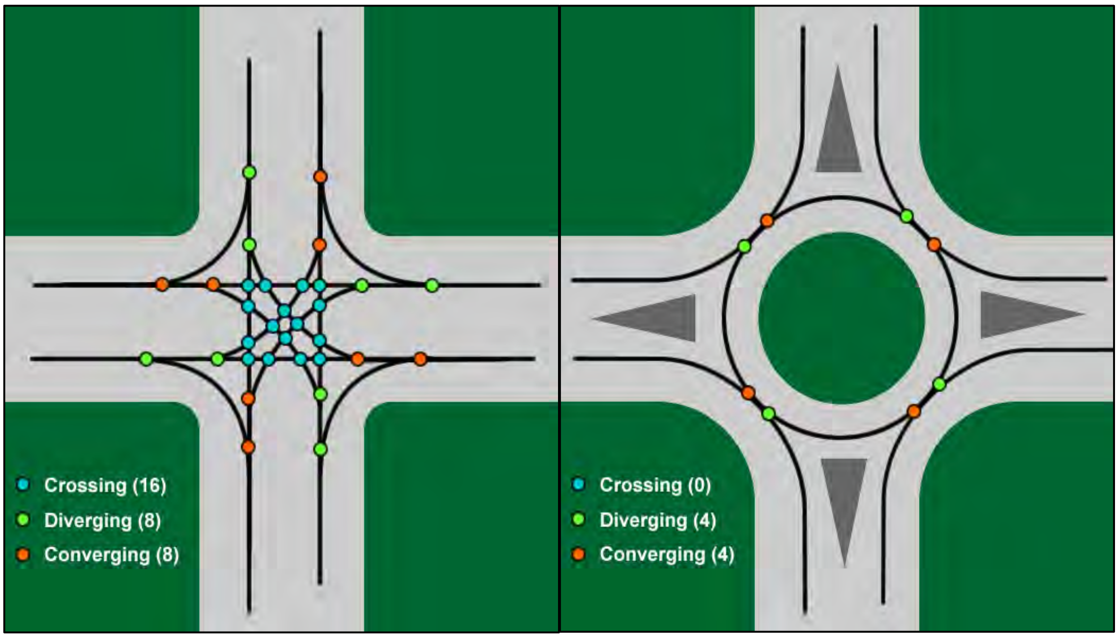

Figure 2.1 Comparisons of vehicle-vehicle conflict points for intersections with four single-lane approaches (TRB, 2000)

2.2 Types of Roundabout

There are various types of roundabout in use, differing in terms of size, geometry, and overall capacity. Of these, turbo roundabouts have become increasingly popular in continental Europe, particularly in Holland and Germany (De Baan, 2012). This study will however focus on normal roundabouts, as the other types may be regarded as derivatives arising from space, safety, capacity, or other constraints, but they all operate on the same fundamental principle. The basic types of roundabouts:

I. Conventional roundabout: A clockwise, one-way circular roadway around a raised-curb central island for circulating traffic, with more than two approaches that have multiple vehicle entries.

II. Mini-roundabout: A one-way circular roadway around a flush central island of up to 4 meters in diameter, usually without flared entries.

III. Turbo roundabout: A new type of roundabout that minimizes the conflicts at roundabouts by forcing the motorists to know their direction at the entry approach before entering the roundabout. Figure 2.2 shows the basic shape of the Dutch turbo as well as other types of roundabouts.

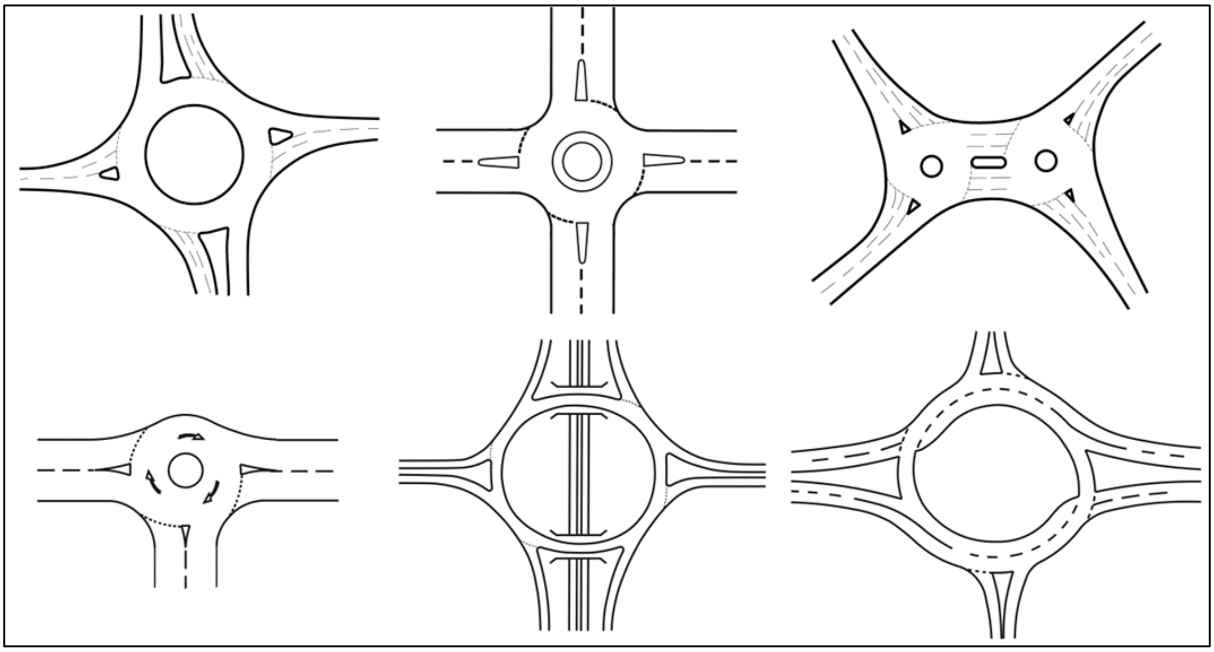

Figure 2.2 Clockwise from top left: Conventional roundabout, compact roundabout, double roundabout, turbo-roundabout, at-grade, and mini-roundabout (DOT, 2007)

From the design point of view, roundabouts are categorized into three types as follows:

2.2.1 Mini Roundabout

Mini-roundabouts are small roundabouts with a fully traversable central Island They can be useful in such environments where conventional roundabout design is precluded by right-of-way constraints. In retrofit applications, mini-roundabouts are relatively inexpensive because they typically require minimal additional pavement at the intersecting roads and minor widening at the corner curbs.

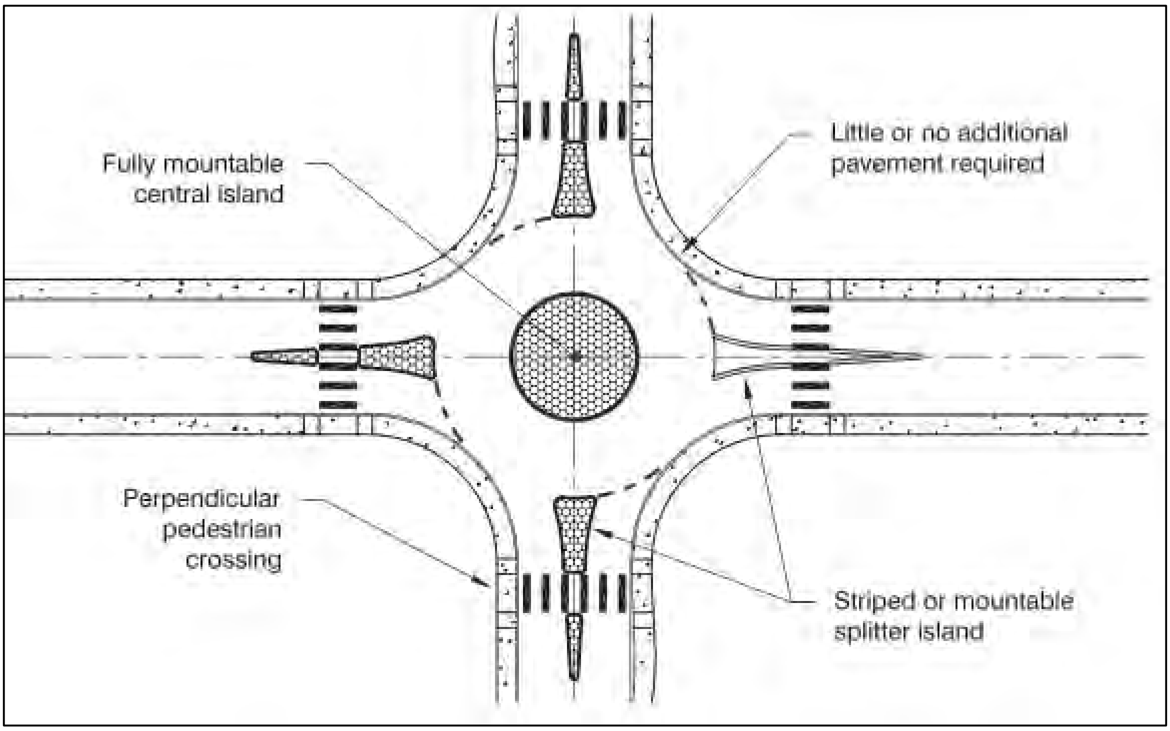

Figure 2.3 Mini roundabout (NCHRP, 2010)

They are mostly recommended when there is insufficient right-of-way to accommodate the design vehicle with a traditional single-lane roundabout. Because they are small, mini-roundabouts are perceived as pedestrian-friendly with short crossing distances and low vehicle speeds on approaches and exits.

2.2.2 Single Lane Roundabout

This type of roundabout is characterized as having a single-lane entry at all legs and one circulatory lane. Figure 2.4 shows the features of typical single-lane roundabouts. They are distinguished from mini-roundabouts by their larger inscribed circle diameters and non-traversable central islands. Their design allows slightly higher speeds at the entry, on the circulatory roadway, and at the exit. The geometric design typically includes raised splitter islands, a non-traversable central island, crosswalks, and a truck apron. The size of the roundabout is largely influenced by the choice of design vehicle and available right-of-way.

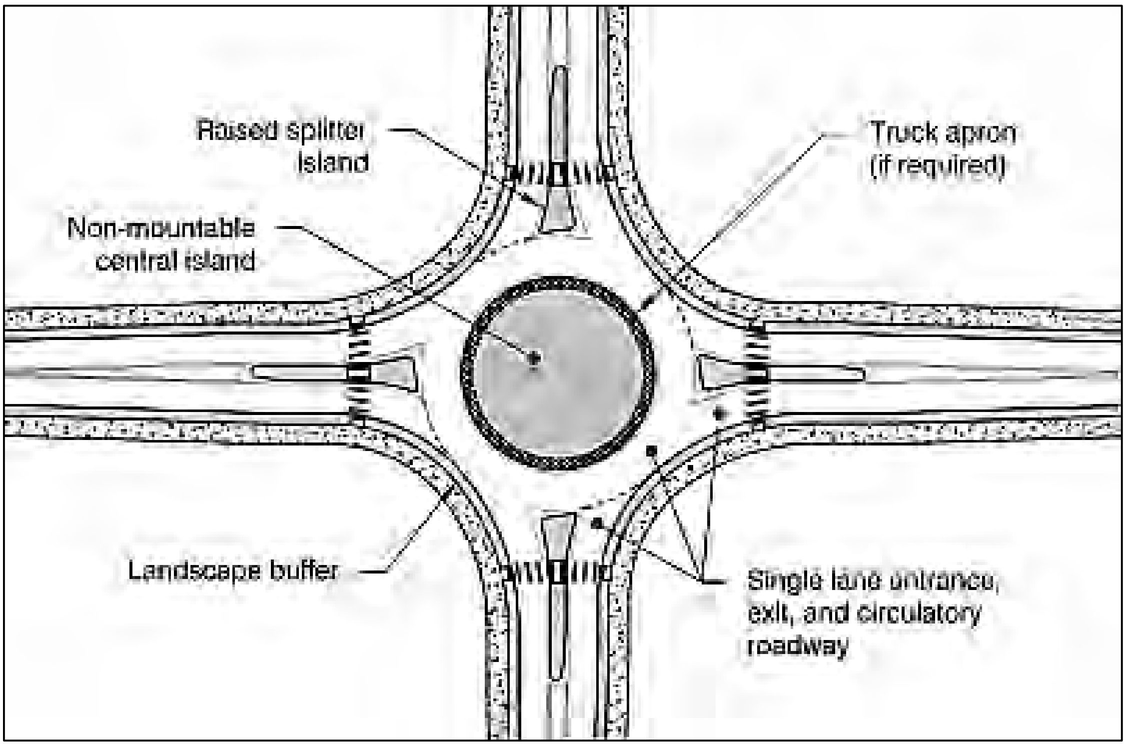

Figure 2.4 Single-lane roundabout (NCHRP, 2010)

2.2.3 Multilane Roundabouts

Multilane roundabouts have at least one entry with two or more lanes. In some cases, the roundabout may have a different number of lanes on one or more approaches (e.g., two-lane entries on the major street and one-lane entries on the minor street). They also include roundabouts with entries on one or more approaches that flare from one to two or more lanes.

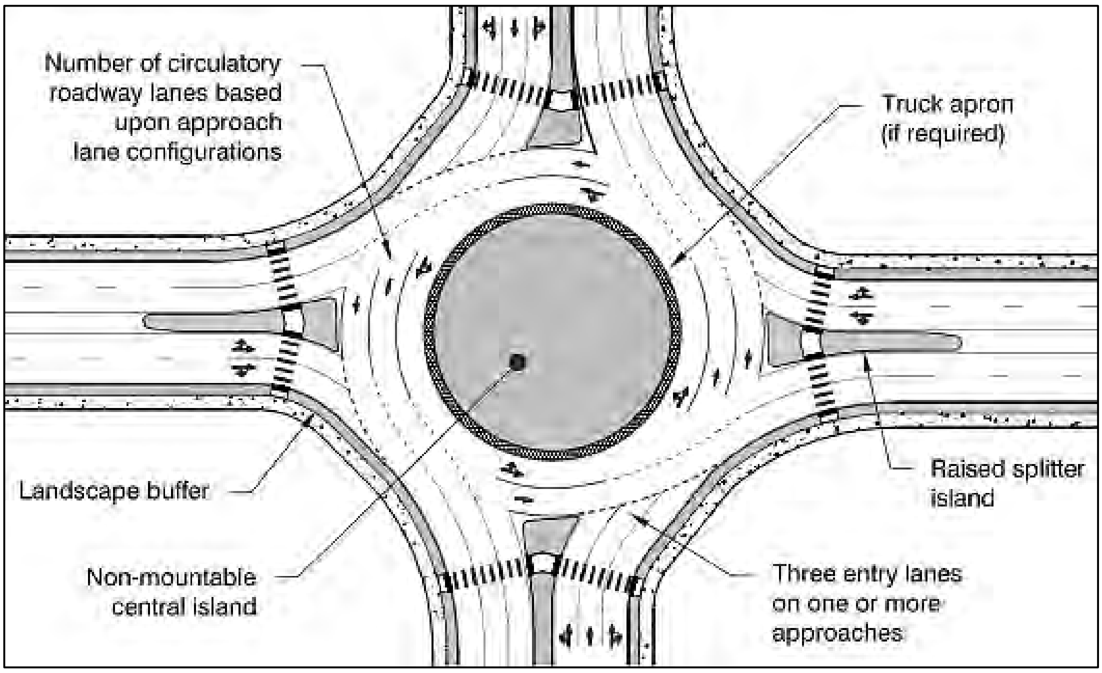

Figure 2.5 Multilane roundabout (NCHRP, 2010)

These require wider circulatory roadways to accommodate more than one vehicle traveling side by side. Figure 2.5 provides examples of typical multilane roundabouts. The speeds at the entry, on the circulatory roadway, and at the exit are similar or maybe slightly higher than those for the single-lane roundabouts. The geometric design will include raised splitter islands, truck aprons, a non-traversable central island, and appropriate entry path deflection.

2.3 Roundabout Traffic Performance

Delays on roundabouts are a key measure of their operational performance, comprise geometric delays and queuing delays. The former mainly arise from ethics slowing down to safely negotiate the junction in free-flow conditions (Macdonald, et al., 1984), but the latter result from a combination of random arrivals and oversaturated conditions and are typically estimated using time-dependent queueing models such as those of (Kimber and Hollis, 1979; Akcelik et al., 1998). The ratio of demand flow to capacity (RFC) determines queue lengths and queuing delays in these models, and thus entry capacity is a key variable as it essentially reflects the queue discharge rate. Other methods to determine queues and delays include those based on equivalent blocked/unblocked periods in gap acceptance or back-of queue estimation in SIDRA (Akelik and Chung, 1994), those based on gap acceptance variables (Flannery et al., 2005), or those in microscopic simulation models. However, as a rule, greater capacity leads to smaller queues and delays.

It is important to understand what factors and variables influence capacity and how it may be calculated. The capacity analysis uses appropriate models – such as those are as follows; operational performance in terms of capacity, queues, and delays can be achieved with the given geometric layout of the roundabout. It typically forms the core of any assessment of proposed and existing roundabouts.

The geometric design of a roundabout must typically conform to statutory standards and guidelines such as TD 16/07 (DOT, 2007), the AASHTO Geometric D 2010 (TRB, 2010b), or Austroads design guides (Austroads, 2009) which specify criteria for geometry, visibility and cross-sectional features to satisfy safety and operational requirements. The geometric design must also satisfy spatial limitations which can be particularly onerous in densely-developed areas, as well as accommodate the swept path of design vehicles, design Policy (AASHTO, 2011), and FHWA roundabout Guide.

Given the complexity of the roundabout form and its relationship with capacity, the typical design process for a roundabout usually involves alternating between geometric design and capacity analysis until an optimal solution in terms of performance and cost is achieved. The state-of-the-art software can considerably speed up this process (Savoy Computing Services Ltd., 2012); an early example was ROBOSIGN (Irani et al., 1993) but current solutions such as Auto-Track Junctions-ARCADY (Savoy Computing Services Ltd, 2010); (TRL Software, 2012) and TORUS-SIDRA (Transoft Solutions Inc, 2012) and Akcelik and Associates Pty Ltd (2013) include automated vehicle swept path analysis and allow near-simultaneous geometric design and capacity analysis.

The good roundabout design prioritizes operational performance and safety for all its users, including pedestrian and cycle traffic. However, the success of any design is usually determined by its traffic performance and thus accurate modeling of its capacity is essential for better and more economic roundabout designs.

2.3.1 Geometric Parameters and Terms

The main geometric terms at roundabouts are related to entry and exit radii, circulating roadway widths, approach and entry lane widths, central island diameters, and inscribed circle diameters. Figure 2.6 illustrates the main geometric terms of the roundabout.

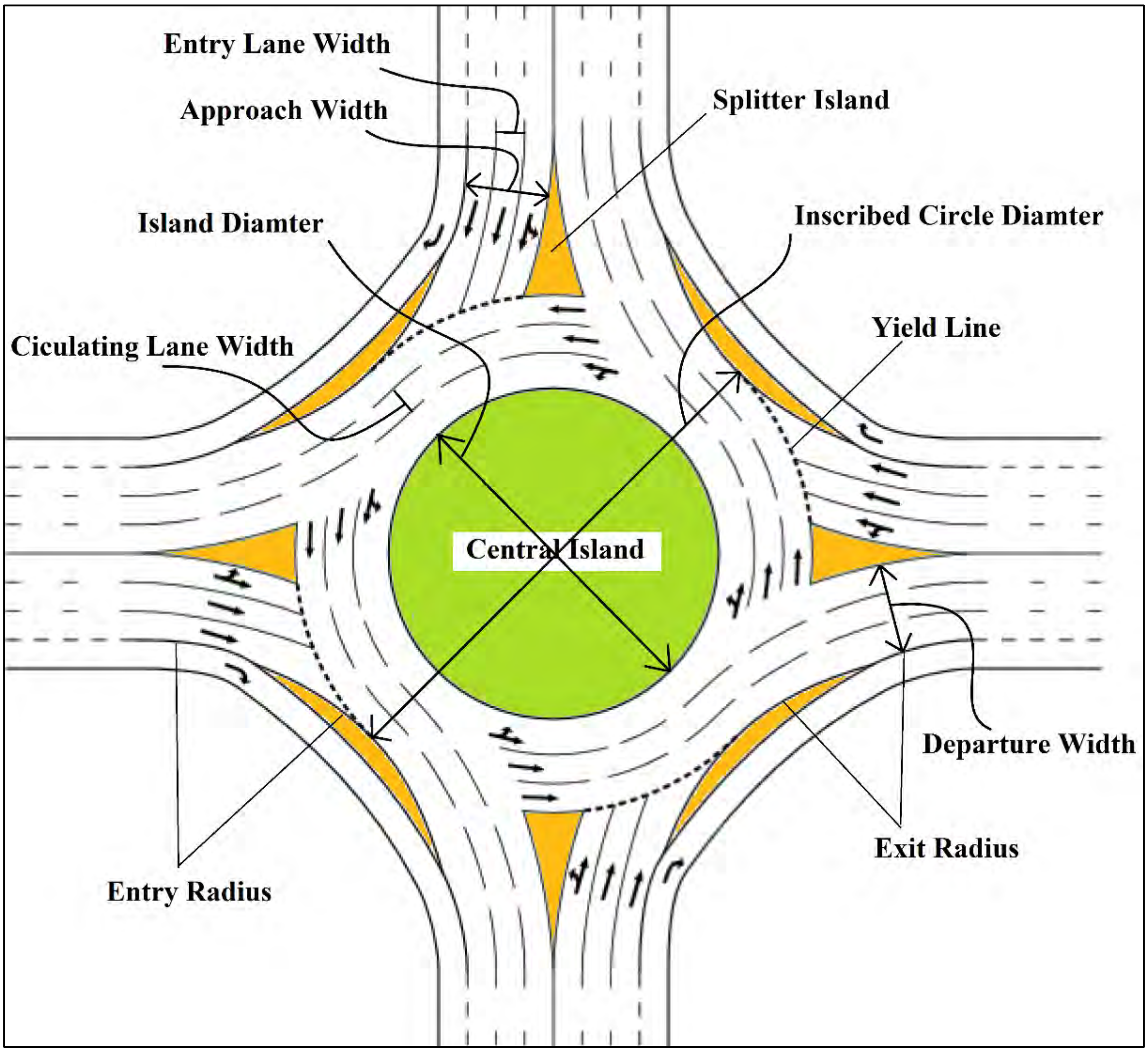

Figure 2.6 Basic geometric parameters of roundabouts (Mohamad, 2015)

2.3.2 Driver Parameter

The critical gap is the gap that motorists wait at the entry lane or approach to enter the roundabout. Critical gap size (in seconds) depends on the drivers' behavior as some drivers accept smaller gaps than others. Figure 2.7 illustrates the gap concept.

The follow-up time is the headway between two successive vehicles entering from the entry approach as shown in Figure 2.7. The follow-up time is usually measured when there is a queue at the entry lane or approach.

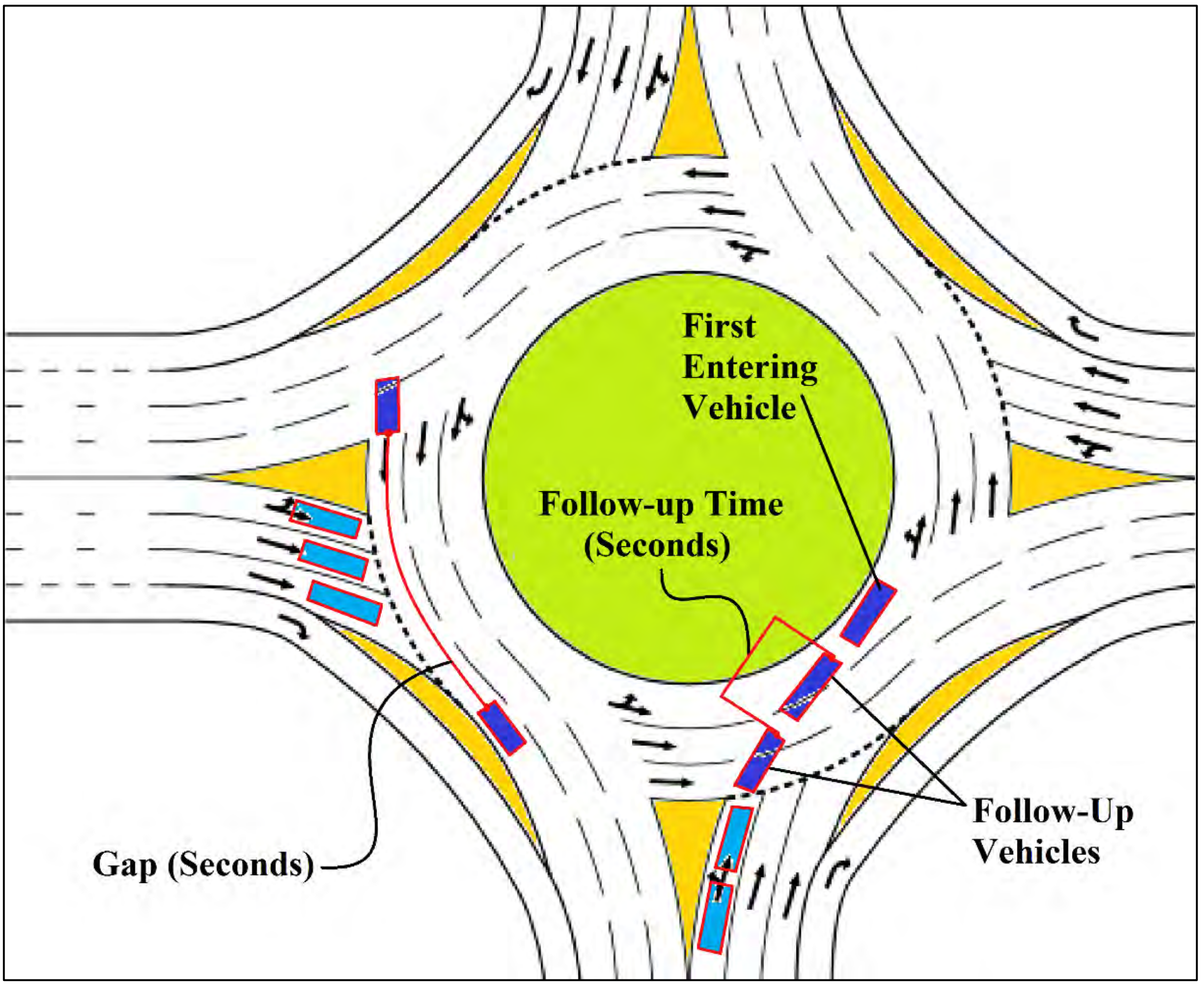

Figure 2.7 Critical gap and follow-up headway (Mohamad, 2015)

2.4 Roundabout Capacity

Capacity in the context of traffic engineering is defined as the “maximum hourly rate at which vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions” (TRB, 2010a). The capacity of a roundabout entry can thus be defined as the “maximum inflow when the demand flow is large enough to cause steady queuing in the approach” (Kimber, 1980), which reflects the queue discharge rate.

This flow is averaged over the applicable analysis time interval to account for inherent short-term (i.e., minute-by-minute or vehicle-by-vehicle) variability resulting from the gap acceptance process. Although the capacity should be based on an upper-bound envelope to observed entry flow data points, most roundabout capacity research use a mean value from saturated conditions (TRB, 2007) as this is more likely to repeatable and achievable with typical analysis time periods.

With the offside-priority rule, the entry capacity varies with the prevailing circulating flow across the entry as a result of the gap acceptance process. Entry capacity also depends on geometry as, for example, a wider multi-lane entry enables more vehicles to enter the same available gap, while bypass lanes increase capacity for traffic turning towards the first arm downstream (Mauro and Guerrieri, 2013). Capacity has also been found to be affected by environmental factors including rain and darkness (Tenekeci and Montgomery, 2010), as well as other traffic factors aside from circulating flow, such as origin destination demand patterns (Hagring, 2000). Pedestrian crossings and exit blocking also reduce entry capacity, either by interrupting demand flows at the entry or causing queues inside the circulatory carriageway (Marlow and Maycock, 1982). The capacity of flared multi-lane entries also depends on the length of the additional lane and lane utilization.

Several viable capacity models have been developed worldwide which can be used to estimate roundabout entry capacity. The existing models can be classified by their primary methodologies. Different types of capacity models have been discussed in the following sections.

2.5 Empirical Model

Among the roundabout capacity modeling, empirical capacity models based on the calibration of relationships between geometry and actual measured capacity are the longest established form. Empirical regression models are created through statistical multivariate regression analyses to fit mathematical relationships between measured entry capacity (Q_e), circulating flows (Q_c), and other independent variables which significantly affect entry capacity. The relationship between Q_e and Q_c is usually assumed to be linear or exponential. Entry capacity can be directly measured from observed entry flow during continuous queuing at the entry, which is typically recorded with the corresponding circulating flows over time intervals of 0.5, 1, 5, or more minutes.

2.5.1 TRRL Linear Regression Model

The TRRL model is widely acknowledged to be the best example of fully-empirical roundabout capacity models, this method is being selected as the standard model in the U.K. (DOT, 1981) and the core of the ARCADY / Junctions 8 (TRL Software, 2012) and (Rodel Software Ltd, 2012) capacity analysis software. The model was derived from extensively collected field data in the 1970s, with over 11,000 minutes of capacity data covering over 86 public roundabout entries (Kimber, 1980)

The TRRL model is approach-based (rather than lane-based) and thus explicitly considering the effects of flaring, albeit with the assumption of relatively balanced lane usage with insignificant entry starvation. Given the lack of evidence for non-linearity from the data, the model is linear in the relationship between entry capacity (Q_e) and circulating flow (Q_c), both in pcu/h units:

$$Q_e = k\,(F - f_c Q_c) \qquad \text{……… (2.1)}$$

Where k was a function of entry radius and entry angle, while F and f_c were functions of flare geometry (i.e. half-with of the approaching road, entry width, and effective flare length), with external inscribed circle diameter at entry also being included in f_c.

The sensitivity of the LR942 model to these six geometric parameters can be attributed to its inclusion of results from track experiments where geometry and traffic conditions could be controlled. Enabling detailed investigations of the impact of flare geometry on capacity (Kimber and Semmens, 1977) an extensive review in 1995 found that the core principles and the form of the relationship remained valid (Barnard et al., 1995)

2.5.2 French Girabase Model

There were several early linear regression models in France, including those by SETRA (Louah, 1988) and CETUR (Alphaned et al., 1991). CETE Mediterranean's model was based on the Harders gap acceptance model (Brilon, 1988) for multilane roundabouts but had limited validation (Louah, 1992). Following on from these, the Girabase model by CETE West was based on data obtained from 507 saturated intervals of 5 to 10 minutes on 45 roundabouts (Guichet, 1997). Although it was based on the Siegloch gap acceptance model, it is classified here as an empirical regression model as the critical gap and follow-on headways were selected to calibrate the model, rather than being obtained from the field measurements (Louah, 1992). Through the statistical analysis, the entry capacity (pcu/h) is:

$$Q_e = \left[\frac{3600}{tf}\left(\frac{w_e}{3.5}\right)^{0.8}\right] e^{-C_b Q_d} \qquad \dots\dots\dots (2.2)$$

Where t_f is the follow-on headway, w_e, was the entry width, C_b is an adjustment factor between urban and rural areas and the Q_d is a function of circulating flow, exiting flow leaving at the same arm and geometric parameters.

2.5.3 Neural Networks

Statistical regression approaches are constrained by the need for a priori knowledge on the form of the relationships between independent and dependent variables. These relationships can be difficult to identify from exploratory data analyses due to the large scatter of measured at-capacity entry flows in public roundabouts (TRB, 2007).

Artificial neural networks have thus been used as an alternative for complex and highly non-linear relationships (Karlafits and Vlahoginni, 2011; Dougherty, 1995). They are mathematical models based on an architecture consisting of one or more hidden layers with several artificial neural cells with activation functions. Using a large set of input-output data, they are trained through learning algorithms to optimize weights and biases. Provided that it is suitably-structured and not been over-trained, a neural network can be used to produce good predictions from new input data. An example developed by (Ozuysal et at., 2009) produced better-estimated capacities from a sample of Turkish roundabout data compared to those of gap acceptance and regression models. However, the effect of individual inputs on capacity cannot be easily interpreted from the optimized weights and biases, which could limit the use of neural networks for design purposes as the application to any design types not included in the original training dataset can be unpredictable.

2.5.4 Limitations of Empirical Modelling

Empirical models map the relationship between input parameters and capacity but do not necessarily prove causality nor provide a complete theoretical understanding of those relationships. Although this does not obviate their use as predictive tools, it is important to understand the underlying principles as there may be atypical scenarios where engineering judgment is needed to assess the validity of the predicted capacities. This is a particular issue with the roundabout design, which may need to conform to unusual site constraints with different arm sizes or orientations.

The parameters included in a model should adequately describe all the key features of a roundabout that might affect capacity, as the omission of any significant parameter could result in poorer predictive performance. However, bearing in mind that data collection costs typically increase with the number of parameters, the selection of the initial parameters to be investigated is usually based on intuitive reasoning, previous research, pilot studies, and the practicality of measurement. The final parameters in the model are then based on statistical significance, which in turn depends on experimental design and sampling considerations. Strong correlations between certain roundabout parameters (e.g., entry width and circulation width) can also affect their statistical significance.

Many empirical models are likely to have been constrained by the sample sizes used for model development, which would have been limited by the number of congested roundabout entries available. Statistically significant relationships between capacity and geometric parameters could also have been difficult to identify due to the limited range of observable parameter values. For example, saturated conditions at a roundabout entry usually correspond with a limited range of circulating flows during peak hours, and this has partly led to the ambiguity over the Q_e and Q_c relationships being linear or non-linear. The above issues probably explain why despite examining a range of geometric parameters, no other parameter aside from Q_c was found to be consistently significant across various regression models found in published literature (Leemann and Santel, 2009; TRB, 2007; Al-Masaeid and Faddah, 1997; Polus and Shmueli, 1997; Brilon and Stuwe, 1993; Louah, 1992; Stuwe, 1991; Semmens, 1988; Semmens, 1982; Kimber, 1980; Glen et at., 1978; Kimber and Semmens, 1977). The results of any empirical model are also likely to be reliable only within the range of parameters in the original database used to develop it. An example was the inability of the LR942 model to satisfactorily model entries with heavily-unbalanced lane utilization (Chard, 1997), which has since been rectified with simulation-based lane modeling in ARCADY, Junctions 8 (TRL Software, 2012). Also, entry capacities at very high circulating flows likely involve extrapolation and may thus be less accurate, since regression 16c models are best-suited to ‘average’ conditions relative to the original dataset.

The issue of extrapolation may also affect the transferability of regression-based models to other countries due to differences in roundabout layouts or driver behavior (Brilon, 2011; TRB, 2007; Troubeck, 1998; Kimber, 1989). To compensate, calibration of the models through changes to coefficients such as slopes and intercepts could be used if actual capacity data is available. However, such adjustments are acceptable only to a limited extent, as major changes to the layouts would involve other changes to the model parameters which may not be clearly understood.

2.6 Gap Acceptance Model

The capacity of roundabouts can be estimated using different types of capacity models developed based on the gap acceptance theory. It is an alternative approach to modeling capacity based on theoretical models. The model is developed around parameters obtained from the measurement of individual headways between circulating and entering vehicles. The data collection for this method is thus less contingent on heavily-congested entries with continuous queuing compared to that for empirical models (Acelik et at., 1998). The gap acceptance models estimate the entry capacity based on the following driving behaviors:

2.6.1 Critical Headway and Follow up Time

Critical gap (t_c) is the minimum time headway in the circulating stream which an entering driver will accept, and sometimes it is also called critical headway. As critical gap cannot be observed directly, many methods have been developed for its estimation from observed rejected and accepted headways/gaps, such as those of Siegloch, Raff, Harders, Wu, and others (Brilon et at., 1999; WU, 2012).

Follow-on headway (t_f) is the time headway between two constructive queued vehicles entering the same gap in the circulating flow.

2.6.2 Headway Distribution

The gap acceptance models assume that the headways (i.e. the time between consecutive vehicles passing the conflict point) of the circulating flow follows a certain distribution. Typically, the distribution follows an M1 (negative exponential), M2 (shifted negative exponential), or M3 (bunched exponential) (Cowan, 1975). The distributions are expressed as follows:

$$\text{M1}: F(t) = 1 - e^{-\lambda t} \text{ for } t \geq 0 \qquad \dots\dots\dots (2.3)$$

$$M2: F(t) = 1 - e^{-\lambda(t-\Delta)} \text{ for } t \geq 0 \qquad \dots\dots\dots (2.4)$$

$$M3: F(t) = 1 - \alpha \,.\, e^{-\lambda(t-\Delta)} \text{ for } t \geq 0 \qquad \text{………(2.5)}$$

where F(t) is the cumulative probability that the headway is less than or equal to t, Δ is the minimum headway between the circulating vehicles (sec^{-1}), λ is the decay constant (sec^{-1}), α is the proportion of free vehicles (i.e. vehicle maneuver is not affected by the lead vehicle). The decay constant λ is calculated using the following expression (Cowan, 1975):

$$\lambda = \frac{qc.\alpha}{1 - qc\Delta} \qquad \text{………(2.6)}$$

Where q_c is the circulating flow (pcu/h). All distributions were developed based on the assumption that the arrival of vehicles follows a Poission distribution. The M1 distribution is the simplest form but does not assume a minimum headway. The M2 distribution is the M1 distribution with headways shifted by a minimum non-zero headway. The M3 distribution has an additional assumption of "bunching'' of vehicles within the circulating flow in congested conditions. (Troutbeck, 1993) suggested that the proportion of free (Unbunched) vehicles at a roundabout is dependent on the circulating flow as follows:

$$\alpha = 0.75(1 - \text{qc}) \qquad \text{………(2.7)}$$

Alternatively, Akcelik (2003) suggested that α can be estimated using the following equation:

$$\alpha = \max(\frac{(1 - qc).\alpha}{1 - (1 - kd)qc\Delta}, 0.001) \qquad \text{………(2.8)}$$

Where k_d is a constant (= 2.2 for roundabouts). Eq. 2.7 and 2.8 assume that the proportion of free vehicles decreases as the circulating flow increases due to shorter headways.

The M1 and M2 distributions are often favored due to their simplicity and in some cases the M3 distribution of Cowan (1975) in particular has been widely used to model the circulatory headways for roundabouts (Akcelik, 2007) but its parameters have to be estimated from field data as they vary according to driver behavior (Tanyel and Yayla, 2003).

2.6.3 Capacity model

From the above-described variables, the entry capacity can then be calculated through appropriate models. Early models included those by Tanner (1962), Armitage and McDonald (1974), and Ashworth and Laurence (1978), but the Siegloch model has been more widelya dopted, being the basis for the HCM 2010 (Akçelik, 2011a), early German models (Stuwe,

1991) and the French Girabase model (Certu, 2006). It is based on negative exponential headways, with critical gap and follow-on headways regressed from measurements in saturated conditions:

$$Qc = \frac{3600}{tf} e^{-Qc(tc - \frac{tf}{2})} \quad \ldots\ \ldots\ \ldots\ (2.9)$$

The diversity of gap acceptance models available is the result of differences in assumed headway distributions, and the formulation of the relevant parameters such as the proportion of bunching in the major priority flow (Akcelik, 2007; WU, 2012). Besides, several models such as SIDRA and that of McDonald and Armitage (1978) use a traffic signal analogy with either lost times and saturation flows, or equivalent green and red times based on the distribution of gaps in the circulating flow (Akcelik, 1994). Comparisons by (Akcelik, 2007) of several of these gap acceptance capacity models showed that there was generally little difference in the model outputs except at larger circulating flows where bunching became more significant.

2.6.3.1 U.S. Highway Capacity Manual (HCM) 2016

Given the scarcity of congested roundabouts in the 1990's, roundabout capacity modeling in the U.S. was initially based on the LR942 model with default geometric parameters (FHWA, 2000), although the Harders gap acceptance model was also adopted in the 2000 Highway Capacity Manual (HCM) with default upper- and lower-bound critical gap and follow-on headways (TRB, 2000).

Later research identified equivalence between the coefficients of an exponential model regressed from capacity data from 18 single-lane and 7 two-lane approaches and those corresponding to the field-measured critical gap and follow-on headway values using the Siegloch model form (TRB, 2007) and (Akcelik, 2011a). These findings thus formed the basis of the HCM 2010 model (TRB, 2010a), which could be calibrated with measured gap acceptance parameters. However, inadequate evidence of statistically-significant relationships between capacity or gap acceptance parameters and other geometric variables meant that the exponential model coefficients depended only on the number of entry and circulating lanes and whether the entry lane is nearside or offside.

The latest edition of HCM 2016 has considered the vehicle types developing the capacity model. The specific parameter has been considered for different types of roundabout. Capacity models for various types of roundabouts are shown in Figure 2.8 to Figure 2.11.

Equation 22-1

$$c_{e,pce} = 1{,}380e^{(-1.02\times10^{-3})v_{c,pce}}$$

where

$c_{e,pce}$ = lane capacity, adjusted for heavy vehicles (pc/h), and

$v_{c,pce}$ = conflicting flow rate (pc/h).

Exhibit 22-2
Example of One-Lane Entry Conflicted by One Circulating Lane

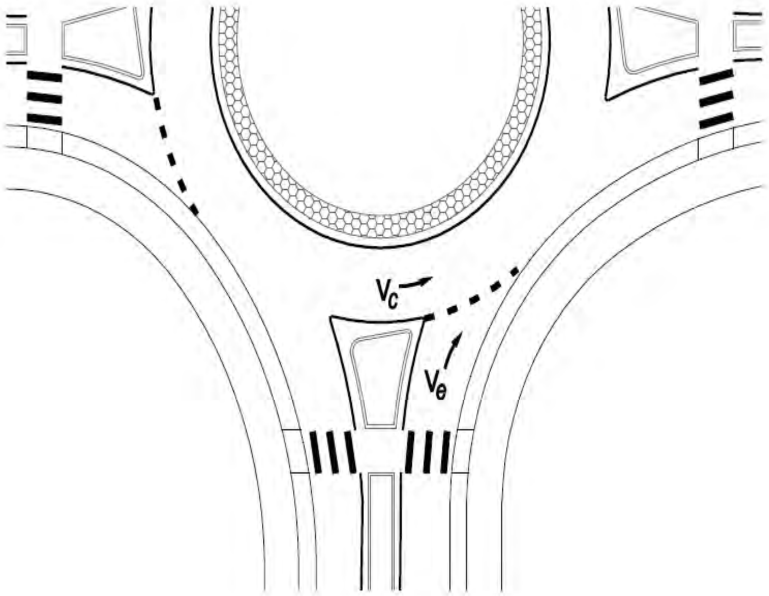

Figure 2.8 Capacity model for two lane entries conflicted by one circulating lane (HCM, 2016)

$$c_{e,pce} = 1{,}420e^{(-0.91\times10^{-3})v_{c,pce}}$$ **Equation 22-2**

Exhibit 22-3
Example of Two-Lane Entry Conflicted by One Circulating Lane

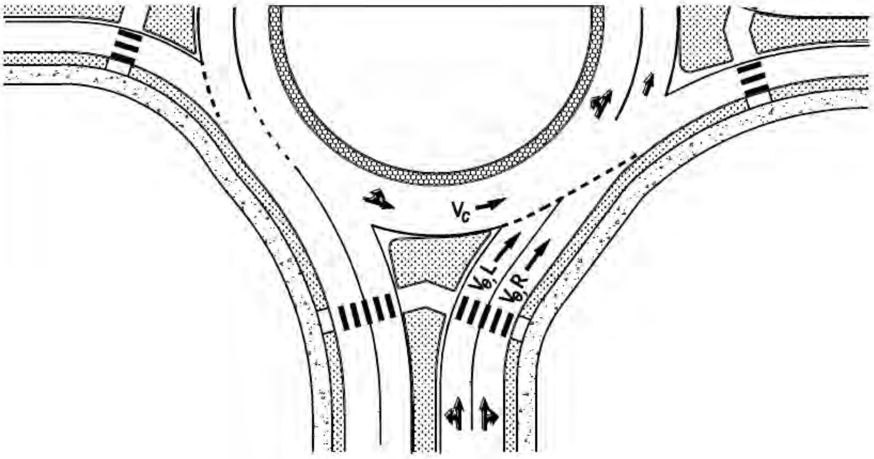

Figure 2.9 Capacity model for one lane entries conflicted by two circulating lanes (HCM, 2016)

Equation 22-3

$$c_{e,pce} = 1{,}420e^{(-0.85\times10^{-3})v_{c,pce}}$$

where all variables are as defined previously ($v_{c,pce}$ is the total of both lanes).

Exhibit 22-4
Example of One-Lane Entry Conflicted by Two Circulating Lanes

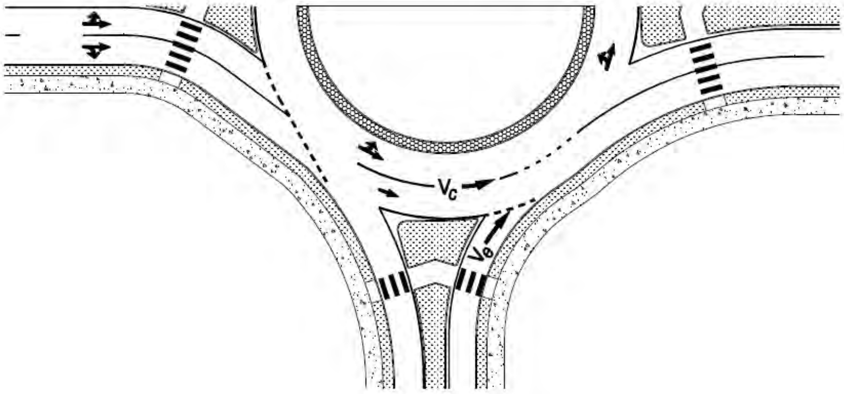

Figure 2.10 Capacity model for two-lane entries conflicted by two circulating lanes (HCM, 2016)

Equation 22-4	$c_{e,R,pce} = 1{,}420e^{(-0.85\times10^{-3})v_{c,pce}}$
Equation 22-5	$c_{e,L,pce} = 1{,}350e^{(-0.92\times10^{-3})v_{c,pce}}$

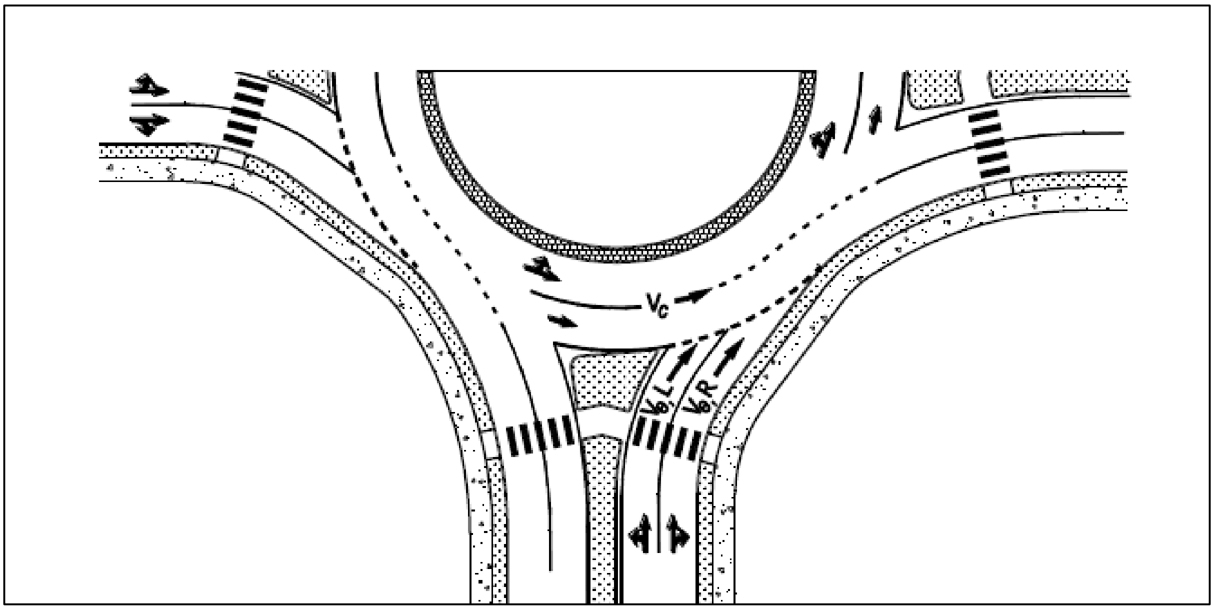

Figure 2.11 Capacity model for single-lane roundabout (HCM, 2016)

2.6.3.2 Garman HBS 2001 / Brilon-Wu

Early studies into German roundabout capacities were initially based on gap acceptance models but had difficulties such as the definition of the major stream at multilane roundabouts (Stuwe, 1991). Later approaches used regression analyses with an exponential form with a total sample size of 4898 one-minute intervals from one- and two-lane entries entering roundabouts with 1- to 3-lane circulation (Brilon and Stuwe, 1993). This was later changed to a better-fitting linear form when the sample size was increased to 7252 data points (Brilon et al., 1997). However, the linear model was rejected as it did not have a clear theoretical basis, while there was doubt over its validity at flows where few measurement points were available.

The model as used in the German Highway Capacity Manual 2001 was derived from gap acceptance principles and queuing theory (Wu, 2001) and based on the numbers of entry (n_e) and circulating (n_c) lanes:

$$Q_e = 3600\left(1-\frac{\Delta Qc}{nc\,3600}\right)^{nc}\frac{ne}{3600}\left(tc-\frac{tf}{2}\Delta\right) \qquad \dots\dots\dots \; (2.10)$$

The default values of critical gap (t_c), follow-on headway (t_f) and intra-bunch minimum headways (Δ) were initially obtained from field observations (Brilon, 2005), but the draft of the upcoming German Highway Capacity Manual will use diameter-dependent values for single-lane roundabouts of 26 to 40 m diameters (Brilon, 2014). Larger roundabouts will use exponential model coefficients which are directly regressed instead of using the above equation.

2.6.3.3 SR45/ SIDRA Gap Acceptance Model

The best-known gap acceptance model for roundabouts was developed in Australia, introduced initially in the form of the SR45 model (Troutbeck, 1989). Using data from 55 roundabout entry lanes in Australia, regression equations were developed for critical gaps (t_c) and follow-on headways (t_f) of the dominant and sub-dominant lanes of an entry (Troutbeck, 1989). The dominant lane in a multi-lane entry was defined as the lane with the larger demand flow, the larger turning flow, or else that in the offside position (Akcelik et al., 1997).

The circulating headway distribution was the Cowan M3 distribution, where a proportion of vehicles (α) was assumed to be bunched with a fixed intra-bunch headway (Δ), while remaining vehicles had exponentially-distributed headways. The intra-bunch headway was taken to be 1 second for multilane circulation, and 2 seconds for single lane circulation, while the proportion of bunched vehicles was calculated from the circulating flow using regressed equations. The entry capacity for each lane was then calculated from (Troutbeck, 1989):

$$Qe = \frac{\alpha Qce^{-\lambda(tc-\Delta)}}{1-e^{-\lambda tf}} \qquad \ldots\ldots\ldots (2.11)$$

where λ is a scale parameter or decay rate which depends on Δ, α, and Q_c. The SIDRA model (Akcelik and Associates Pty Ltd, 2013) is a further development of the SR45 model using a traffic signal analogy (Akcelik, 1994) and revised versions of the empirical follow-on headway and critical gap equations from SR45. Other revisions to the circulating headway and capacity models included additional factors for priority-sharing, origin-destination patterns, and queuing on upstream approaches (Akcelik and Besley, 2004); which were calibrated from studies based on the microscopic simulator Model (Akcelik et al., 1997). The latest version of SIDRA Intersection now includes adjustment factors for entry radius and entry angle (Akcelik, 2011c).

2.6.4 Limitation of Gap Acceptance Model

Priority-sharing occurs when circulating vehicles slow down to accommodate and avoid colliding with vehicles that forcibly enter smaller gaps; in extreme cases, priority-reversal occurs where some circulating vehicles are temporarily stopped due to gap-forcing by entering vehicles or blocked exits. These phenomena occur to varying extents at many roundabouts, particularly when circulating vehicles travel at relatively slow speeds with lower braking distances. Their occurrence contradicts the common assumption in gap acceptance methods of circulating headway distributions not being affected by entering vehicles (Kimber, 1989), but modifications to headway distributions (Troutbeck and Kako, 1999; Akelik, 2011b) and flow-dependent critical gap models Troutbeck (1989) have been developed to overcome this problem.

One criticism of gap acceptance-based models is that they do not directly quantify the relationship between geometry (the only factor which can be controlled by the roundabout designer) and capacity. Instead, they require the formulation and calibration of an intermediary vehicle-vehicle interaction model, which then has to be related separately to geometry and entry capacity. This is an issue as capacity models are sensitive to the values of critical gap and follow-on headway, as well as differences in headway distributions at higher circulating flows (Akçelik, 2007). However, the inherent variability of driver behavior results in fairly weak relationships between these parameters and geometry due to the influence of other factors. For example, critical gap at roundabouts has been found to vary with delay (Polus and Lizar, 2003; Polus et al., 2005) and circulating speed (Xu and Tian, 2008), while Hagring, (2001) suggested that the critical gap could be overestimated if the proportion of vehicles exiting just before the entry was large. By including only more tractable geometric and flow parameters, the regressed equation for critical gap in the SR45 model explained less than half of the observed variation (Troutbeck, 1989). And in contrast to SR45 / SIDRA and CAPCAL models (Linse, 2010; Hagring, 1997a), the critical gap in most other gap acceptance models is insensitive to geometry.

There are also difficulties with defining the parameters from field-measurements. For example, gap acceptance headways can be difficult to define in multilane circulation flows as vehicles on the inner circulating lane may be perceived to conflict with drivers entering the outer lane (Hagring, 2000b; Troutbeck, 1990); likewise, arrival times at the give-way line for lag measurements are difficult to measure since approaching drivers can adjust their speed on the approach to intercept gaps in the circulating flow without having to stop at the give-way line (Louveton et l., 2012a; Louvton et al., 2012b; Weinert, 2000; Hewitt, 1983). Furthermore, there are many methods of calculating critical gaps, but they do not give consistent answers (Tupper et al., 2013; WU, 2012; Lindenmann, 2006 and Brilon et al., 1999). Similarly, the intra-bunch headway (Δ) and the proportion of bunched vehicles (α) used in bunched headway models cannot be measured directly, given that the distinction between free-flowing and platooned vehicles is not always clear from their headways. Δ is usually based on various functions of circulating flow and Δ (Akcelik, 2007). Multilane circulation has typically been approximated as a single stream (Acelik et al., 1998; Hagring, 1996; Troutbeck, 1989), where Δ is taken to be a fixed value depending on the number of circulating lanes (Troutbeck, 1989) or in SIDRA's case, a function of circulating lane flows, origin-destination and approach queuing patterns (Acelik et al., 1998). These approximations have been justified by the need to model larger gaps more accurately compared to smaller gaps and for greater tractability (Luttinen, 1999; Troutbeck, 1991), but they can also mean that calibrating the models with new field-measured values for a different layout or context may not be trivial (Tanyel and Yayla, 2003).

2.7 Microscopic Traffic Simulation Model

Microscopic simulation models are based on modeling the movements and interactions of individual vehicles on a network consisting of links and nodes or connectors. Vehicle movements are controlled by gap acceptance, car-following, lane-changing, and other models. The movement of vehicles is typically calculated for each vehicle at every specified time-step. The parameters of driver behavior such as critical gaps and processes such as vehicle generation are stochastically assigned through Monte Carlo methods using specified probability distributions; the resulting variability of outputs attempts to reflect the characteristics of real-world traffic. There are several proprietary microscopic simulation programs are available for the modeling of general traffic networks, including S-Paramics (Paramics Microsimulation, 2011b), Aimsun (TSS-Transport Simulation Systems, 2011), Vissim (PTV Group, 2021) and SUMO. Several roundabout-specific microsimulation models have also been developed and used for research (Chin, 1985; Chung et al. 1992; Krogscheepers and Roebuck, 1999, and Tan, 1991), while other simulation programs such as INSECT (Tudge, 1988) OCTAVE (Louah, 1988) and KNOSIMO (Grossmann, 1988) have been used for analysis unsignaled junctions in general.

The advantage of the microscopic simulation model is that demand flows and turning movements can be controlled for parametric studies. They are thus used in roundabout research which requires such effects to be modeled (Vandez et al., 2011; Fortuijn, 2009b; Krogcheepers and Roebuck, 2000), as well as for the development and the validation of macroscopic models such as SIDRA (Akcelik et al., 1997; Bared and Afshar, 2009; Hossain , 1999) also derived macroscopic capacity model through regression of data from microscopic simulation models rather than from field data. Simulation models have also played an important role in the modeling of the effects of flaring on capacity (Burtenshaw, 2012; WU N., 1999).

2.7.1 Limitations to Microscopic Simulation

The most widely-acknowledged limitation of microscopic simulation modeling of roundabouts is the priority-reversal and priority-sharing phenomena. While the former may arise due to capacity restrictions of other junctions downstream and is thus beyond the scope of this research, the more-subtle issue of priority-sharing, which occurs especially at high circulating flows, does need to be considered. Relatively simple gap acceptance algorithms used in common microscopic simulation programs may not adequately model the effect of priority (Chevallir and Leclercq, 2009a) resulting in the under-prediction of entry capacities at high circulating flows. Hence, more complex multi-level gap acceptance algorithms, or alternatives such as the probabilistic gap acceptance algorithm of Chevallier and Leclercq (2009b), may be required to model roundabout capacity more accurately in congested conditions.

CHAPTER 3

RESEARCH METHODOLOGY AND DATA COLLECTION

3.1 General

As discussed in the preceding chapter, there is a need to develop an empirical capacity estimation model with a graphical tool for highway roundabout in Bangladesh. This required collection and analysis of ground truth data from the field, which would also allow existing capacity models to be evaluated. Any significant potential shortcomings in their predictive ability would then warrant the development of better alternative models, and the data could then also form the basis of these new models. This chapter thus describes the design of the sampling and data collection methods and justifies why an empirical methodology was used as opposed to gap acceptance. It then describes the characteristics of the resulting final dataset and discusses the possible limitations arising from the data collection process.

3.2 Hypothesised Explanatory Variables

The first step in the development of an empirical capacity estimation model is identifying candidate independent variables affecting capacity, as they govern the sample design, data collection, and hypothesis testing. At the microscopic level, the gap acceptance decision made by an individual driver at a roundabout entry will likely depend on various perceptual, cognitive, physiological, and psychological factors, the characteristics of his/her vehicle and those of the immediate environment including nearest conflicting vehicles. For example, various studies have shown that gap acceptance could be influenced by individual waiting time (Ashworth and Bottom, 1977), driver age and/or gender (Yan et al., 2007; Teply et al., 1997; Wennell and Cooper, 1981), oncoming vehicle size and color (Alexander et al., 2002), vehicle type (Teply et al., 1997), conflicting vehicle speeds (Hancock et al., 1991; Cooper et al., 1977), sight distance obstruction by other vehicles (Yan et al., 2007), driver distraction (Cooper and Zheng, 2002), risk aversion (Pollatschek et al., 2002), presence of passengers or queued vehicles behind the subject coupled with the delay at the front of the queue (Teply et al., 1997). Human perception and cognition studies have also shown how factors such as the angle or curvilinearity of vehicle trajectories, visual references such as stop signs, and inherent perceptual styles could impact time-to-collision estimates (Berthelon et al., 1998; Berthelon and Mestre, 1993), and thus possibly gap acceptance decisions. These factors may also influence follow-on headways, although gap interception likely plays an important role at roundabout entries since approaching drivers can control their speeds to merge into gaps in the circulating flow without having to stop at the give-way line (Louveton et al., 2012a; Louvton et al., 2012b).

Measuring and estimating many of these variables at a disaggregated level for capacity prediction is difficult, even if aggregated measures could be used to develop a more parsimonious model (in which the desired predictive performance was achieved with as few explanatory variables as possible). Macroscopic level variables are thus more commonly used in practice; for example, the critical gap model in SIDRA and SR45 is based on flow and geometric variables (Troutbeck, 1989; Acelik et al., 1998) rather than the factors described above. However, any of these variables (particularly geometry) do not yet have a clearly understood effect on the gap acceptance process at the disaggregated level. Therefore, in the context of developing an empirical model with a limited dataset, including a very large number of such variables could increase the possibility of spurious results being obtained and over-fitting of the model. Model validation would thus be essential, but it was also important to shortlist the more important explanatory variables to be investigated for inclusion in the final model; this was based on previous models and causal mechanisms suggested by existing literature. The shortlisted variables to be investigated and the rationale for their inclusion are described below and in Figure 3.1.

3.2.1 Circulating Flow

Circulation flow is the most important variable due to the offside priority rule; essentially, the more the flow, the less the headways and therefore the lower the frequency of gaps or lags of the adequate size which can be accepted by entering vehicles. The relationship between entry flow and circulating flow is exponentially negative.

3.2.2 Queue Duration

Proxy for average queue delay, where drivers may be more motivated to enter the roundabout when delayed. Larger driver delays or waiting times decreased critical gaps (Polus et al., 2005; Polus et al., 2003; Polus and Lazar, 1999; Ashworth and Bottom, 1977). However, Rodegerdts (2006) found no evidence that queue duration was correlated with gap acceptance parameters.

3.2.3 Entry Lane Width

Entry lane width is also an important parameter as it reflects the available freedom of movement for approaching vehicles. For single entry lanes, flaring may allow zipper-like queue splitting and thus greater driver awareness for higher capacity, but this is likely to depend on a higher number of receiving circulation lanes than entry lanes. Effective flare length (l’), entry parameter in LR942 to represent the time-averaged number of queues (Kimber, 1980), but this was likely to be less relevant to individual lanes. The sharp curvature of most roundabout entries mean that the lane entry width at the give-way line may not be representative of the conditions experienced by a driver during the approach and gap acceptance process. Transportation Research Board (2007) did not find entry width to significantly affect lane capacity. An alternative measure which indirectly takes both flaring and lane widths into account is the entry width (E) and approach half-width (V) were combined into the measured 10 m upstream from the give-way line. This is comparable to the lane width 4 m upstream used in Girabase (Certu, 2006) or the 20m-section-average lane width used in PICADY (Semmens, 1985; Semmens, 1980). Subsequent regression analyses with E generally showed better model fits compared to approach width.

3.2.4 Inscribed Circle Diameter

Inscribed circle diameter of a roundabout increases circulation speeds, possibly affecting perceived gaps and priority sharing. LR942 has a logistic relationship which suggests increased entry capacity at larger ID, but (Marstrand, 1988; Akcelik, 2011c) found that entry capacity could reduce at large diameters.

3.2.5 Central Island Diameter

The central island diameter has a strong influence on the entry capacity of roundabout. Brilon and Stuwe (1993) reported that entry capacity depends on central island diameter. An increase in the diameter of the central island improves the entry capacity.

3.2.6 Entry to Nearest Exit Distance

The distance between entry to nearest exit has a positive relationship with entry capacity. An increase of entry-exit distance decreases the complexity of weaving of roundabout circulating flow and thus improve the capacity.

3.2.7 Entry Angle

Larger conflict angle requires greater turning motion and possibly limits acceleration i.e. less of a merging movement. May be offset by poorer driver visibility due to skew, but LR942 and SIDRA both show monotonous decrease in entry capacity with larger angles.

3.2.8 Entry Curvature

Higher curvature means entering vehicles may have to limit their approach speed or maximum merging speed and increase their minimum acceptable gap. Used in lieu of entry radius (r), since capacity is more likely to be sensitive to small radii than straight entries. LR942 and current SIDRA (Akcelik, 2011c) models show monotonous increase in entry capacity with straighter entries.

3.2.9 Entry-Exit Separation

Separation distance or splitter island width was thus included in French (Guichet, 1997; Louah, 1992) and Swiss (Simon, 1991) models, while part of the exiting flow was concomitantly included in the conflicting flow. The conflicting flow also included exiting flows in the HCM 2010 and PICADY priority junction models (TRB, 2010a; Kimber and Coombe, 1980), although this may have been due to their higher approach speeds. It has been found that the entry capacity of a roundabout is increased with the increasing of entry-exit distance L.

3.2.10 Distance to Upstream Entry

This is also a proxy for the separation point between circulating and exiting vehicles originating from the upstream entry, where larger d_{upe} could facilitate earlier identification of an acceptable gap. The preceding entry is the nearest source of conflicting vehicles so the presence of a vehicle queued there could inhibit gap acceptance if d_{upe} was small; however, a vehicle departing from the preceding entry may also trigger gap acceptance since it is initially slower moving than other circulating vehicles.

3.2.11 Circulation Road Width

The circulation width could alter the distribution of headways in the circulation flow by influencing the degree to which vehicles in adjacent lanes interfere with each other and hence whether the circulating stream was closer to a single-lane or multilane stream in terms of headway distributions (Troutbeck, 1989). It could also determine the distance between the give-way line and the merge conflict point, which may be a factor in deciding the minimum acceptable gap.

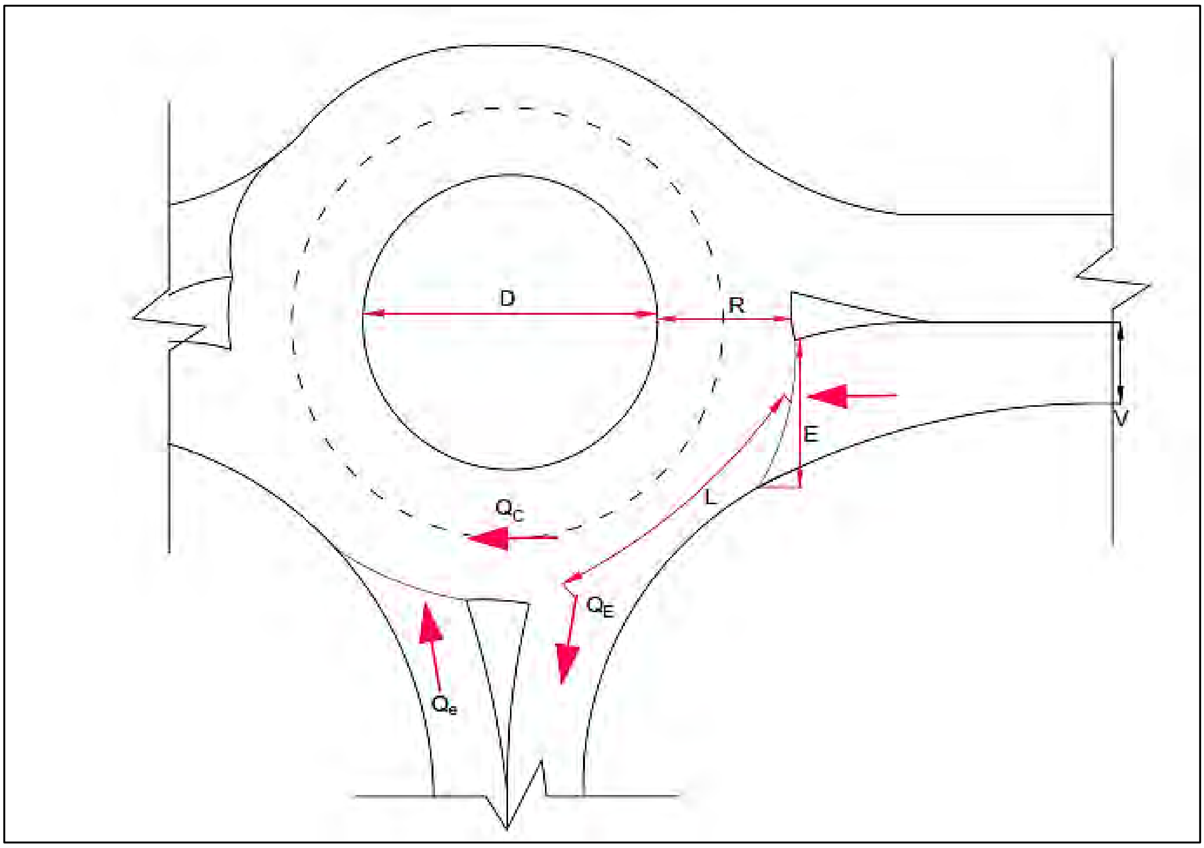

Figure 3.1 Measurement positions for predictor variables (traffic flows and geometric parameters)

3.3 Parameter Selection for Capacity Estimation Model Development

In previous studies by Faddah (1996); Aagaard (1996), and Bilon et al. (1991), it has been revealed that entry capacity and circulating traffic flow in front of the entry of a roundabout follows an exponential relationship. In addition, width of entry and circulating roadway, diameter of central island, and distance from an entry to closest exit also has a strong effect on capacity of a roundabout (Faddah, 1996; Brilon and Stuwe, 1993). Kang and Nakamura (2017) found that with the increase in percentage of heavy vehicles in traffic stream, the capacity of roundabout decreases. Since, in this study, highway roundabouts with dominance of heavy vehicles in traffic flow are being analyzed to develop a capacity model, the presence of heavy vehicles will certainly have a significant impact on capacity estimation. So, in order to develop a model for estimating entry capacity of a roundabout, geometric parameters i.e., entry width, circulating roadway width, central island diameter, distance between an entry and the closest exit, and traffic flow parameter i.e., circulating traffic flow expressed in passenger car units (PCU) per hour have been selected.

3.4 Methodology of Capacity Modeling

Capacity of a roundabout can be determined in two ways: (1) directly from field measured entry flows under saturated conditions and (2) by combining field-measured headways with theoretical gap acceptance models. The literature shows that the gap acceptance method is popular among roundabout capacity researchers worldwide, although this may have been necessitated to some extent by the lack of heavily-saturated roundabout sites in their countries (Rodegerdts, 2006). However, the limitations of the gap acceptance approach discussed in the previous section mean that additional uncertainty could be introduced through the use of headways rather than flows, obfuscating the actual relationship between capacity and explanatory variables.

For example, a change in central Island diameter may impact in different ways on circulating headway distribution, critical gap and follow-on headway; these three in turn determine the entry capacity in existing theoretical models. However, given that there is little consensus over the form and validity of these theoretical models among gap acceptance researchers, while quantifying the headway parameters typically involve various approximations, it would be far better to directly measure the capacity flows and relate them to differences in diameter. Furthermore, traffic flows can be easily and accurately measured compared to the time-of-arrival measurements necessary to calculate lags, so empirical modelling based on direct measurements of capacity flow has a clear advantage for quantifying the effects of factors and variables on capacity.

Aside from the analytical framework, there was also a need to consider whether to model capacity using lane capacities or arm capacities. To determine the entry capacity of a roundabout, the total entry flows should be measured when the queues formed and the lane significantly starved of maximum demand; however, these full arm-capacity conditions are commonly observed particularly in the peak hours. The individual entry flow of entries is measured easily in Bangladesh context because the lane usage patterns are not followed. The data collection for gap acceptance model is difficult in Bangladesh because the drivers are rarely follow the lane use pattern. Given the limited resources available and the wider availability of lane capacity flow data, this study thus focused on the factors and variables which affect gap acceptance capacity at the give-way line. The main limitation of basing the roundabout model on lane capacity is that the effects of flaring, entry angle and entry curvature. Considering all the limitation, the empirical capacity model will have to be modelled using the collected data from field.

3.5 Selection of Roundabout

Roundabouts are frequently used in urban and rural roads as a speed calming device at important intersections. In our research, an attempt has been made to develop a capacity estimation and prediction model of rural highway roundabouts with significant presence of heavy vehicles in the traffic stream, and a pilot survey was performed to find out suitable sites for data collection to carry out this research. While selecting the roundabout sites, the following criteria were considered:

1. Roundabouts are located at highways under rural settings
2. Traffic stream having dominant presence of heavy vehicles
3. Approaches which are reasonably mutually perpendicular
4. Un-signalized and uncontrolled intersection i.e., not having a traffic signal or police-controlled signal
5. Negligible longitudinal gradient at the entries
6. Insignificant presence of pedestrians and cyclists
7. Availability of vantage points for video recording purpose

The selected roundabout sites for this thesis work of Google Earth images are shown in Figure 3.2 to Figure 3.7.

Figure 3.2 Google Earth location image of Bangabandhu bridge east roundabout

Figure 3.3 Google Earth location image of Bangabandhu bridge west roundabout

Figure 3.4 Google Earth location image of Hatikumrul roundabout, Sirajganj

Figure 3.5 Google Earth location image of Bishawroad roundabout, Tarabo, Narayanganj

Figure 3.6 Google Earth location image of Panchdona roundabout, Narshingdi

Figure 3.7 Google Earth location image of Shahprotap roundabout, Narshingdi

3.6 Data Collection

For this study, six roundabouts are selected for necessary data collection. These roundabouts are a parts of two national highways of Bangladesh, i.e., Dhaka-Sylhet Highway (N2) and Dhaka-Rangpur Highway (N5). The details of these roundabouts are shown in Table 3.1.

Table 3.1 List of selected roundabouts

Serial No.	Name of Roundabouts	Highway No.	Locations
R1	Bangabandhu Bridge East Roundabout	N405	Tangail, East side of Bangabandhu bridge approach road
R 2	Bangabandhu Bridge West Roundabout	N405	Sirajganj, West side of Bangabandhu bridge approach road
R 3	Hatikumrul Roundabout	N405	Bridge Approach Road, Sirajganj
R 4	Bishwaroad Roundabout	N2	Demra, Dhaka-Sylhet highway
R 5	Panchdona Roundabout	N2	Ghorashal, Narshindhi, Dhaka-Sylhet highway
R 6	Shaheprotab Bus Stand Roundabout	N2	Narshindhi, Dhaka-Sylhet highway

A pilot survey was conducted at the selected roundabout sites prior to final data collection phase in order to have a rough estimation of the traffic flow, predict the peak flow timeframe, and counteract any difficulties in collecting data.

3.6.1 Geometric data

The geometric parameters (except entry radius, entry angle and entry curvature) of the roundabouts were collected following manual method using measuring tapes. For carrying out these inventory surveys, a team of trained surveyors were employed. Entry radius of roundabouts was measured by analyzing aerial images with the aid of ArcGIS 10.2 and AutoCAD 2019 software.

Geometric variables were collected by inventory survey and measured of high resolution aerial or satellite photographs (Google Earth Pro, 2019) or up-to-date site plans imported into AutoCAD. Scaling of the aerial/satellite photographs to overlaid showed that any distortion caused by the camera perspective was not an issue, as the mapped features matched in position and size after appropriate uniform scaling. One reason for the use of aerial photographs, aside from their relative accessibility, was that as-built survey plans may no longer reflect their current geometry of the roundabouts due to their age and changes in lane markings or layout. In contrast, the available aerial/satellite imagery was more recent based on their known dates; their currency was also confirmed through judicious detailed comparisons with on-site photographs in terms of the condition and positions of roadway markings, surfaces and appurtenances, supplemented by historical street-level and aerial imagery to identify any changes in roundabout layouts.

Figure 3.8 Example of Google Earth image used for geometric data measurement

Measurement with aerial/satellite photographs was particularly suited to variables such as entry radius, entry angles and entry to nearest exit distance as they depend on accurate determination of kerb-line or lane-marking alignments. On-site surveys for such measurements would require adequate safe access to the roadway if they were to produce major improvements in accuracy; this was not a practical alternative due to the potential traffic disruption. The inventory surveyed and measured geometric data is shown in Table 3.2.

Table 3.2 Inventory survey and measured geometric data

SL.	Roundabout Name	Highway Name	Entry Name	Entry width (m)	Circular Road Width (m)	Dia. of Central Island (m)	Entry/Exit Distance (m)
R1	Bangabandhu Bridge East	Dhaka-Rangpur	EN1	9.21	8.64	28.79	45.89
			EN2	9.57	9.58	28.79	56.20
R2	Bangabandhu Bridge West	Dhaka-Rangpur	EN3	11.05	10.71	33.77	63.6
		Dhaka-Rangpur	EN4	9.85	9.91	33.77	58.56
R3	Hatikumrul	Dhaka-Rangpur	EN5	9.35	9.27	31.51	40.66
		Dhaka-Rangpur	EN6	9.45	9.57	33.51	40.88
		Dhaka-Rangpur	EN7	10.85	10.5	33.51	59.73
		Dhaka-Rangpur	EN8	6.75	6.5	20.25	19.72
R4	Bishwaroad Tarabo	Dhaka-Sylhet	EN9	9.5	9.25	30.28	53.57
		Dhaka-Sylhet	EN10	8.09	8.5	30.28	49.49
R5	Panchdona	Dhaka-Sylhet	EN11	8.95	8.83	31.71	42.65
		Dhaka-Sylhet	EN12	10.15	10.12	31.71	58.42
R6	Shaheprotab Bus Stand	Dhaka-Sylhet	EN13	9.43	10.56	29.41	44.54
		Dhaka-Sylhet	EN14	9.31	10.4	29.41	42.48

3.6.2 Traffic Flow

Hypothesised explanatory variables which fluctuate temporally (e.g. circulating flows) should be measured during periods of queuing which reflect capacity conditions, so that their relationships with capacity can be determined. However, depending on the RFC and the level of platooning of arriving vehicles (caused by upstream traffic signals), roundabout entries may not have extensive and uninterrupted queues even during peak traffic periods and this limits the amount of capacity data which could be extracted from them. To maximize the data yield for empirical analysis and therefore improve the robustness of the statistical analyses, it was necessary to investigate methods to extract as much usable capacity flow data from each site as possible. This was also important to yield useful flow data from entries which were not heavily saturated but had desired geometric or other properties to be included in the sample for better empirical modeling.

Video method was adopted for collecting traffic data i.e., flow and headway. In order to capture quality video data, high-resolution video camera mounted at nearby high-rise buildings and lamppost was used, and CCTV footages were collected from concerned authorities where possible. Video data was collected on typical weekdays covering peak hours two times a day each having two hours of time-period (9 AM to 11 AM, and 3:15 PM to 5:15 PM). Manual data collection method was conducted in two sites where video data collection was difficult, costly and time consuming. Manual flow counting also conducted for cross-verification of collected video data vice versa. Figure 3.9 shows the data measurement position of entry and circulating traffic flows.

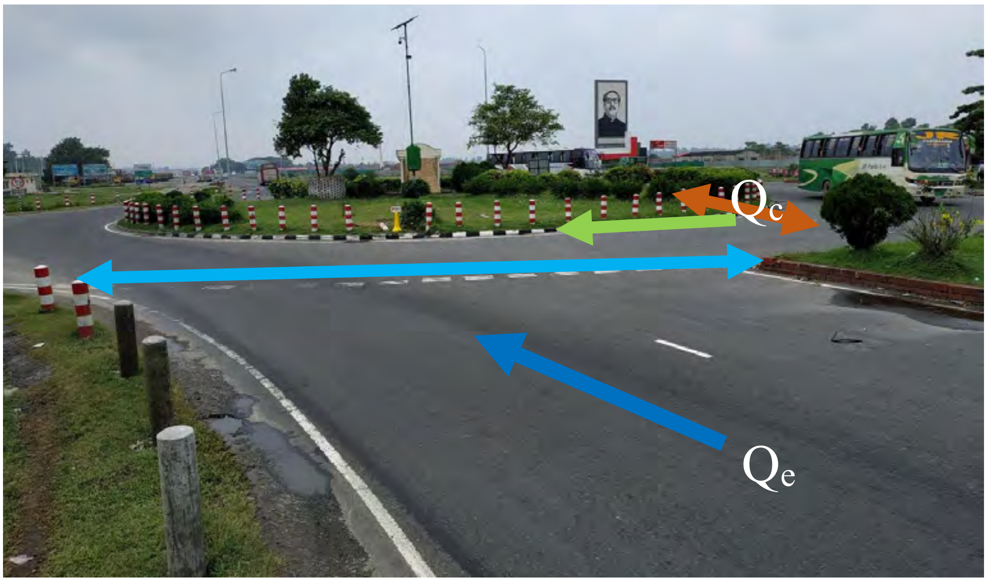

Figure 3.9 Measurement Position of entry flow (Q_e) and circulating flow (Q_c)

CHAPTER 4

DATA EXTRACTION AND ANALYSIS

4.1 Introduction

All the required data for developing the capacity model has collected by video recording, manual counting and inventory survey. The extraction of collected data is necessary for data analysis and developing the desired model. Standard technique is applied for extracting the collected data to maintain the quality of data. Among the selected roundabouts, three have four legs and other three have three legs. Video recording is conducted for four selected roundabout. A total of 2400 minutes of video was recorded for entry and circulating flow. In the following chapter data extraction method and technique and data analysis will be discussed.

4.2 Data Extraction Technique and Quality Assurance

The entry and circulating traffic volume data were extracted from recorded video using two techniques: through pixel-based heterogeneous traffic measurement considering shadow and illumination variation methodology (Haddiuzzam et al., 2017) using MATLAB coding, and another by manually reviewing the videos by multiple people. In the coding, the area and type of data needed were defined and the coding provided the classified traffic as output. Fifteen - minutes interval was defined in the coding and data extracted from approximately 2400 minutes of recording video. Manual extraction was completed by reviewing the video by playing them at slow speed. The result obtained from both techniques were compared and repeated if there were any significant discrepancies (i.e., difference of ±20 vehicles) (Mohamad, 2015).

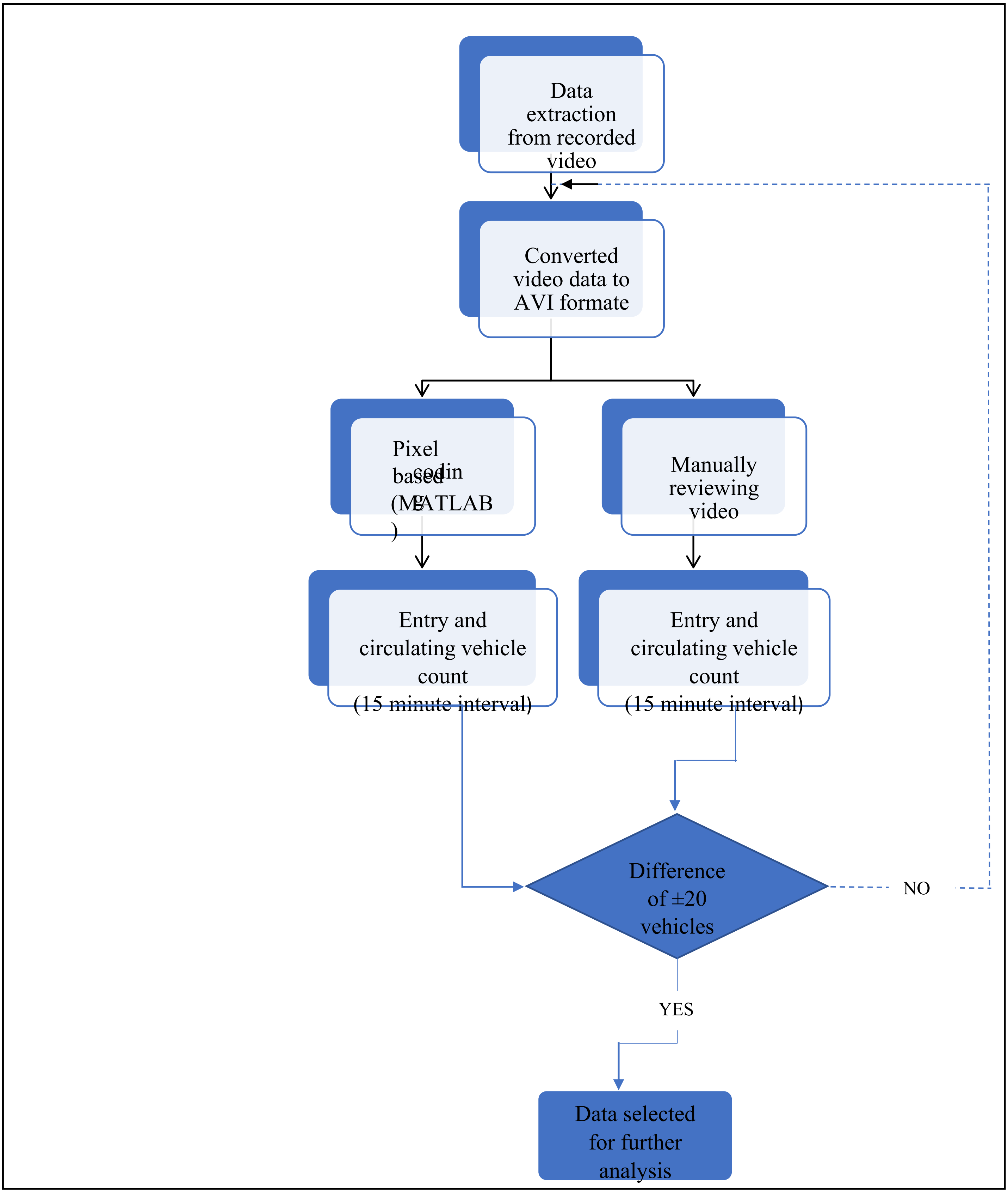

Figure 4.1 Flow chart of data extraction methodology

According to the above described methodology the data was extracted by pixel-based methodology. The screenshot of the coding and data extraction interface is shown in Figure 4.2 to Figure 4.5.

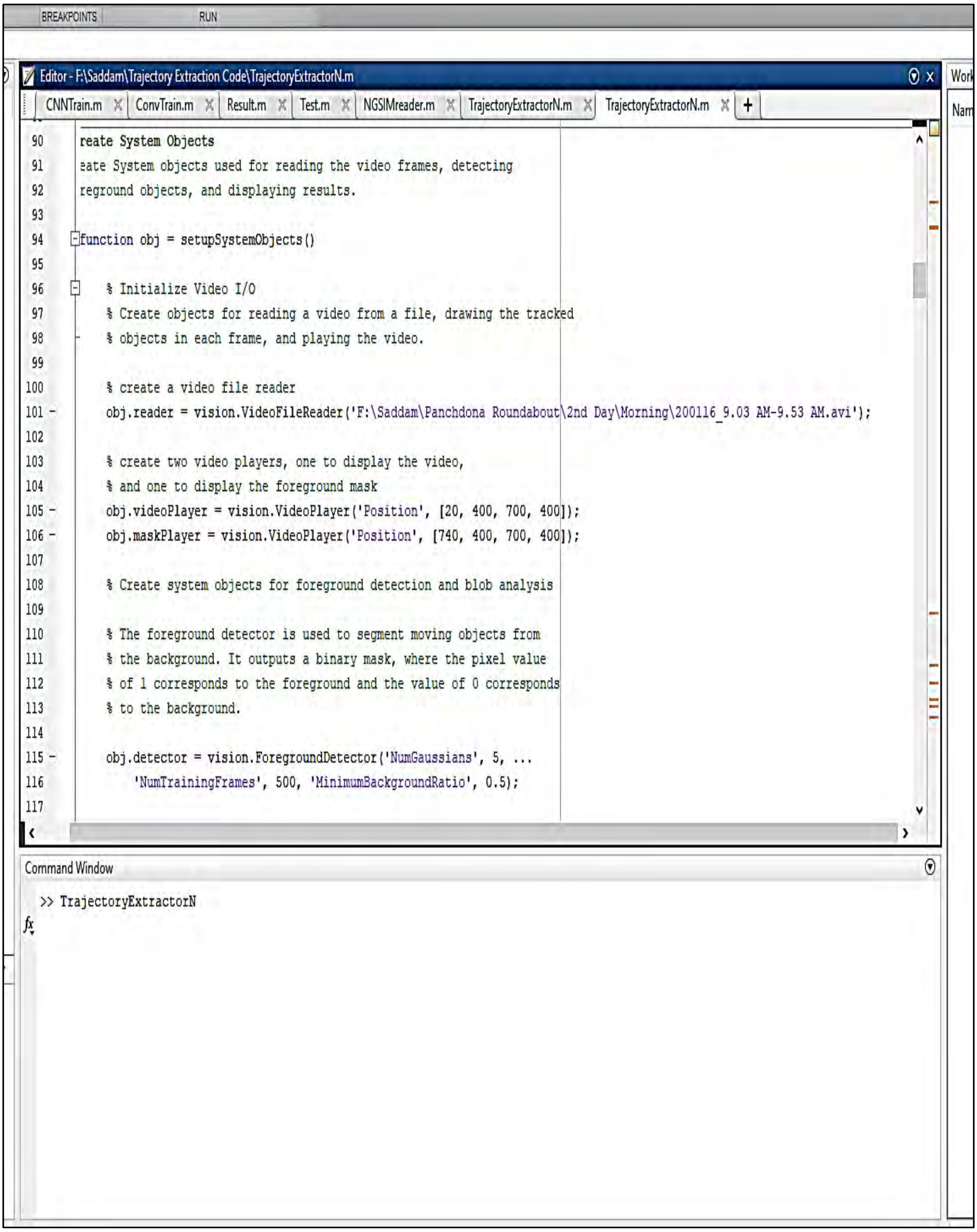

Figure 4.2 Screenshot of data extraction trajectory

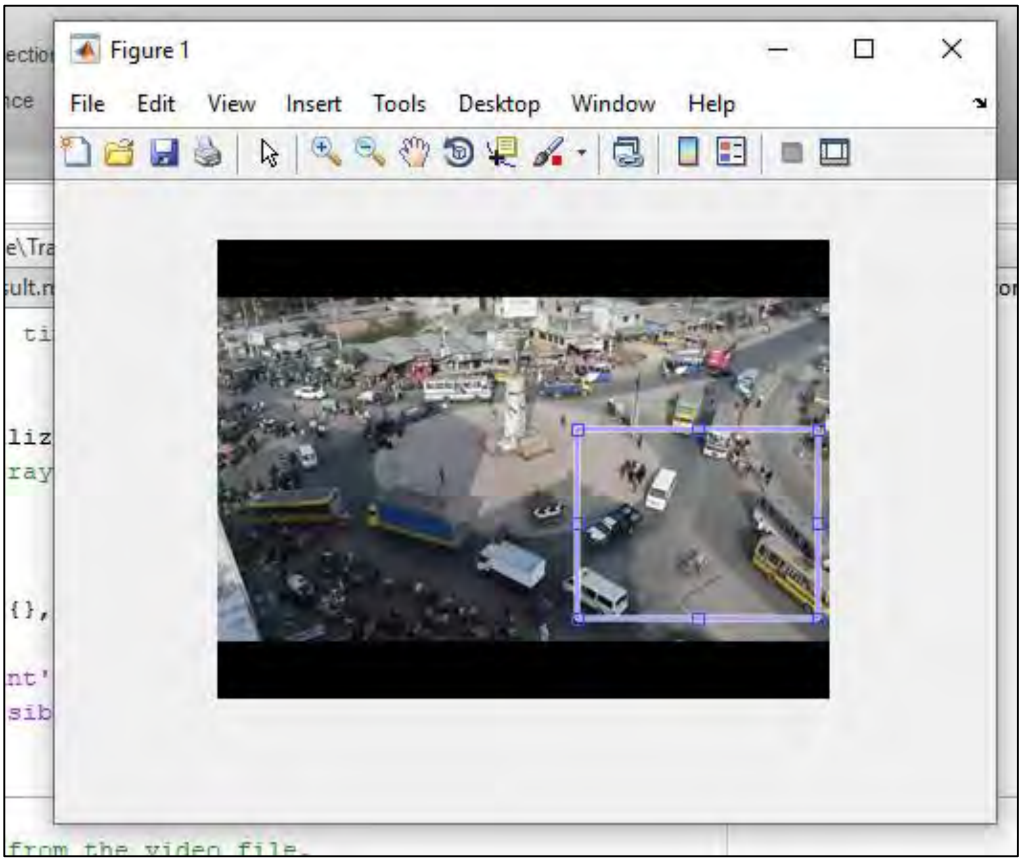

Figure 4.3 Screenshot of area selection for data extraction

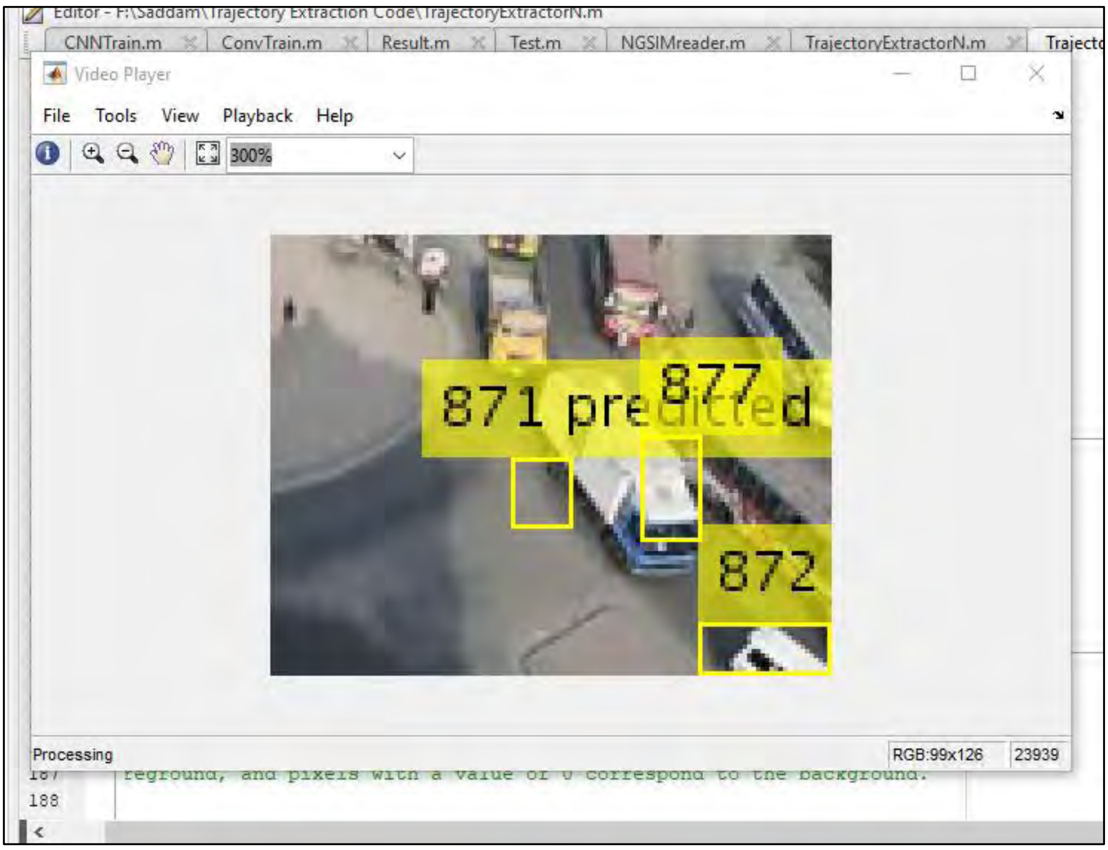

Figure 4.4 Screenshot of vehicles detection and counting block

Figure 4.5 Screenshot of illumination of vehicles

4.3 Extracted Data

From data extraction, entry flows and circulating flows were calculated for each entry of the selected roundabouts with classified vehicle. All types of vehicle present in the traffic stream were then converted to PCU according to Geometric Design Standards Manual of RHD (2005). The PCU values used for different vehicle types such as truck, bus, minibus, utility, car, baby taxi, and motorcycle are 3.0, 3.0, 3.0, 1.0, 1.0, 0.75, and 0.75 respectively.

The sample of extracted data is given in the Table 4.1.

Table 4.1 Example of extracted traffic flow data

Entry Name	Time (AM, PM)	Entry Flow (PCU/h)	Circulating Flow (PCU/h)
EN9	8:30-8:45	1522	405
	8:45-9:00	1492	699
	9:00-9:15	1615	408
	9:15-9:30	1347	586
	9:30-9:45	1382	511

Contd. Table 4.1

Entry Name	Time (AM, PM)	Entry Flow (PCU/h)	Circulating Flow (PCU/h)
	9:45-10:00	1294	611
	10:00-10:15	1384	595
	10:15-10:30	1390	505
EN10	3:00-3:15	1096	822
	3:15-3:30	1121	785
	3:30-3:45	1128	773
	3:45-4:00	1022	847
	4:00-4:15	1126	769
	4:15-4:30	1048	827
	4:30-4:45	1046	845
	4:45-5:00	1001	879

Geometric data also was extracted by digitizing google earth image and inventory survey information. AutoCAD and ArcGIS was used to extract geometric parameters of the selected roundabouts. The AutoCAD drawing of roundabouts and corresponding geometric data shown from Figure 4.6 to Figure 4.11.

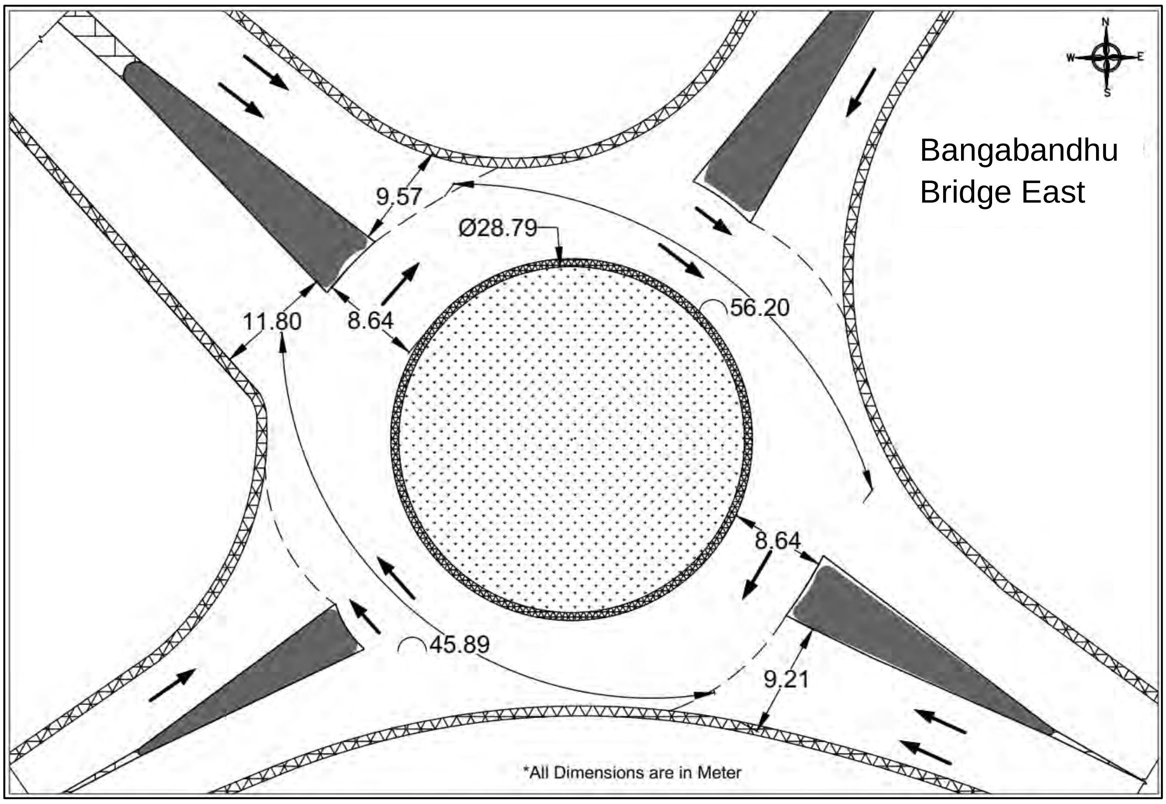

Figure 4.6 Geometric layout of R1 roundabout with geometric parameters

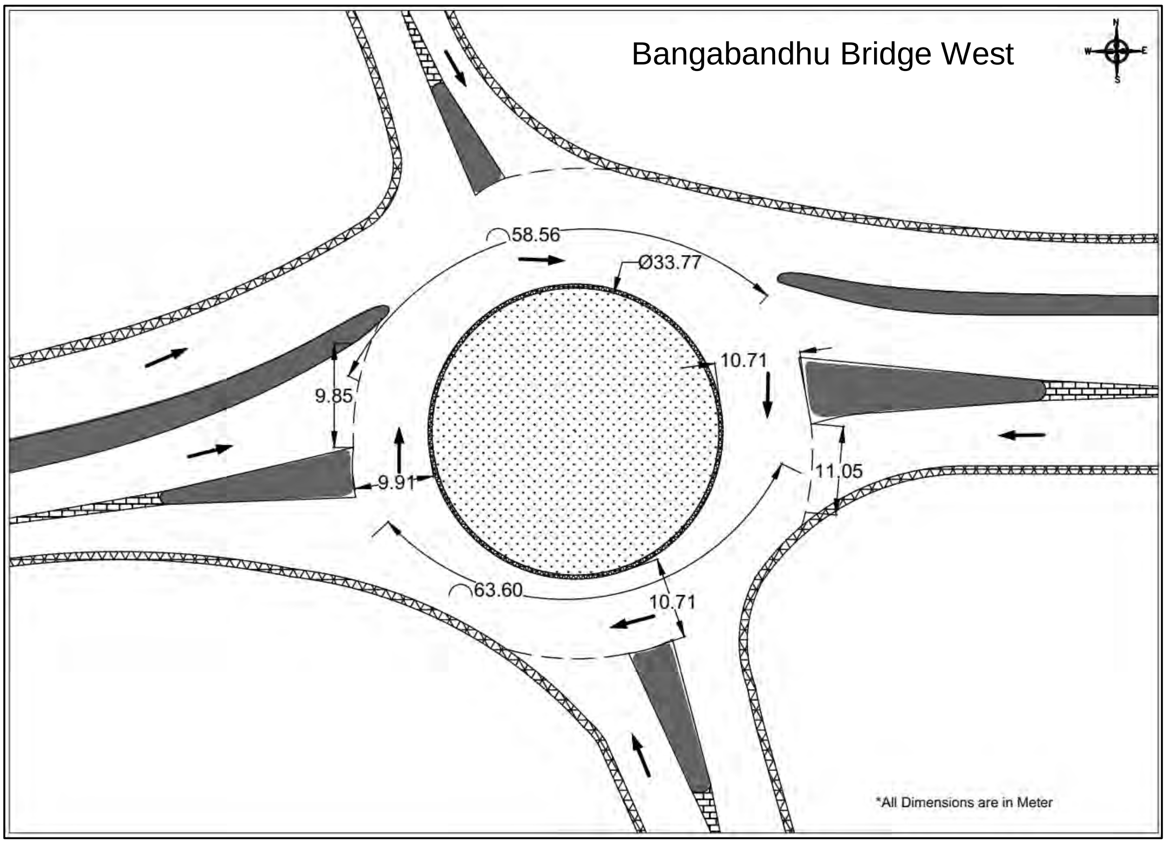

Figure 4.7 Geometric layout of R2 roundabout with geometric parameters

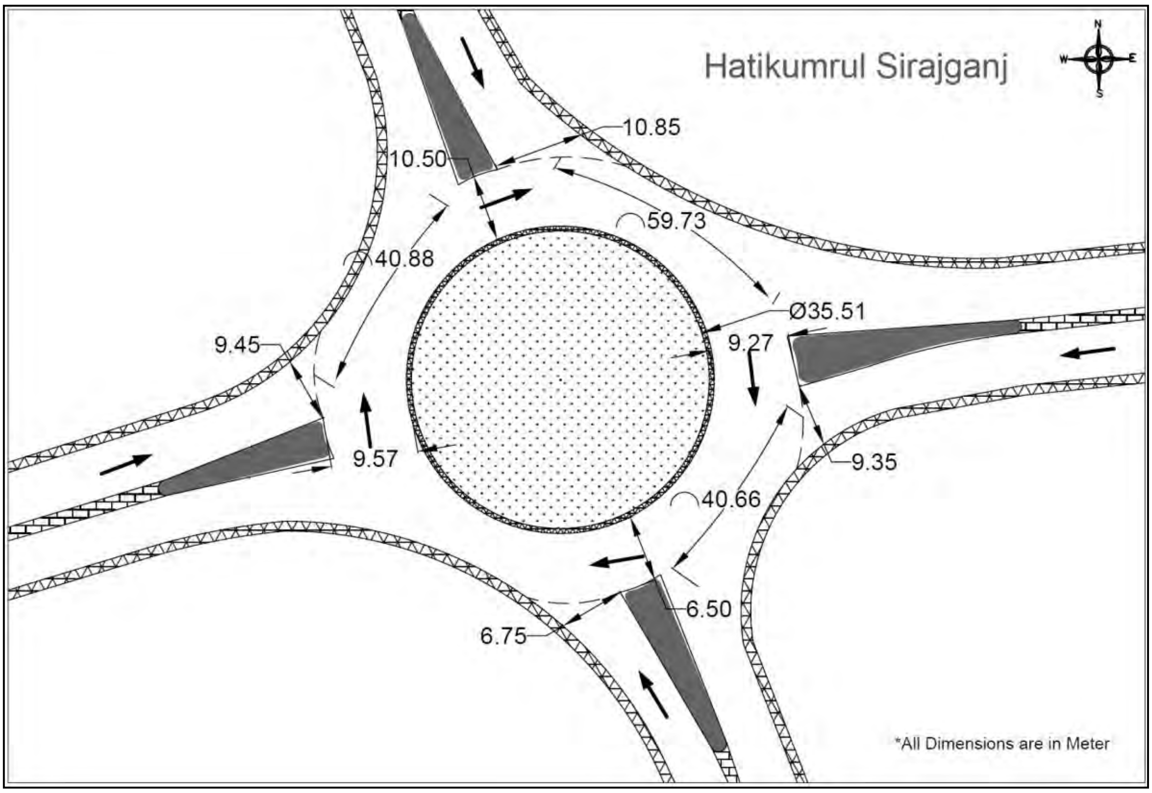

Figure 4.8 Geometric layout of R3 roundabout with geometric parameters

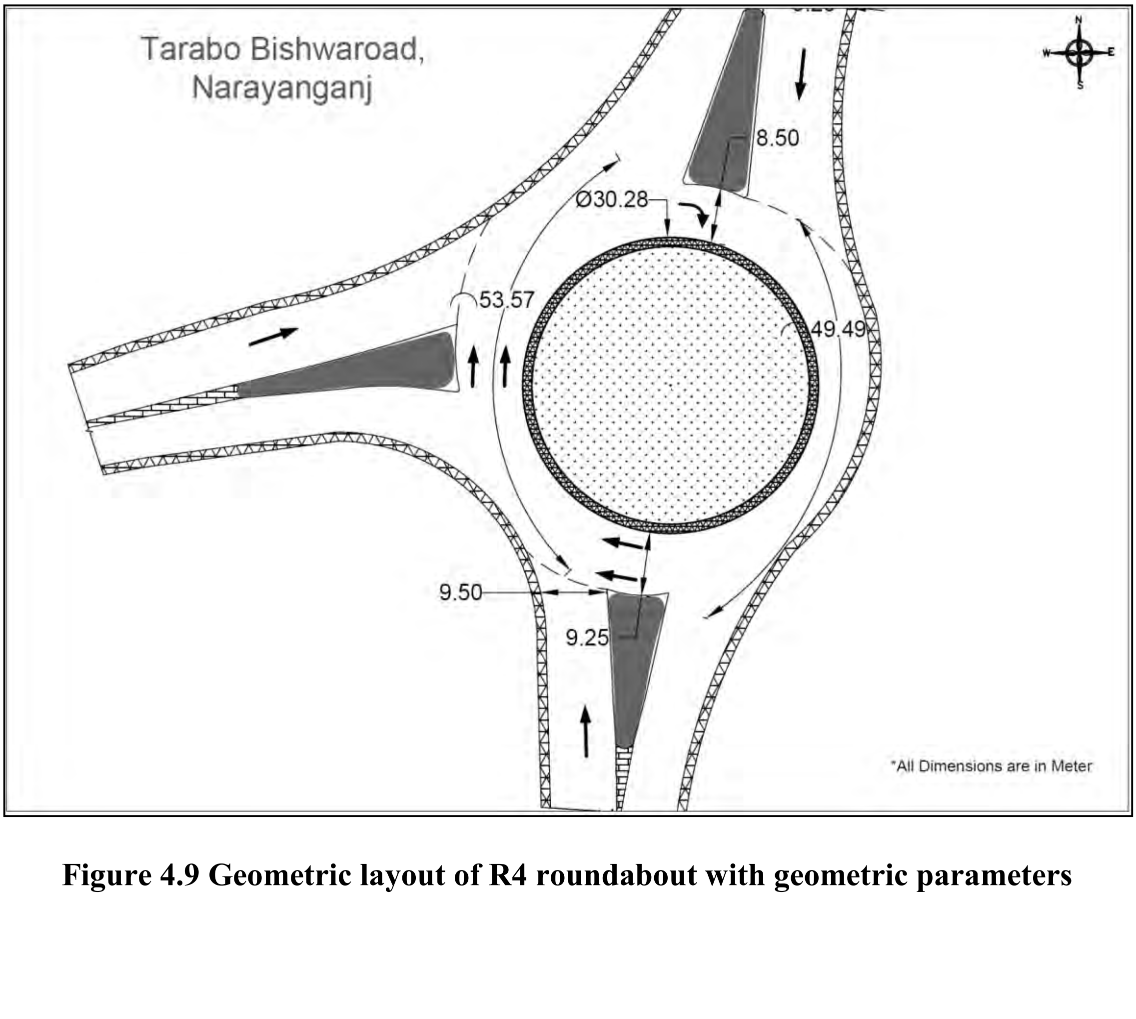

Figure 4.9 Geometric layout of R4 roundabout with geometric parameters

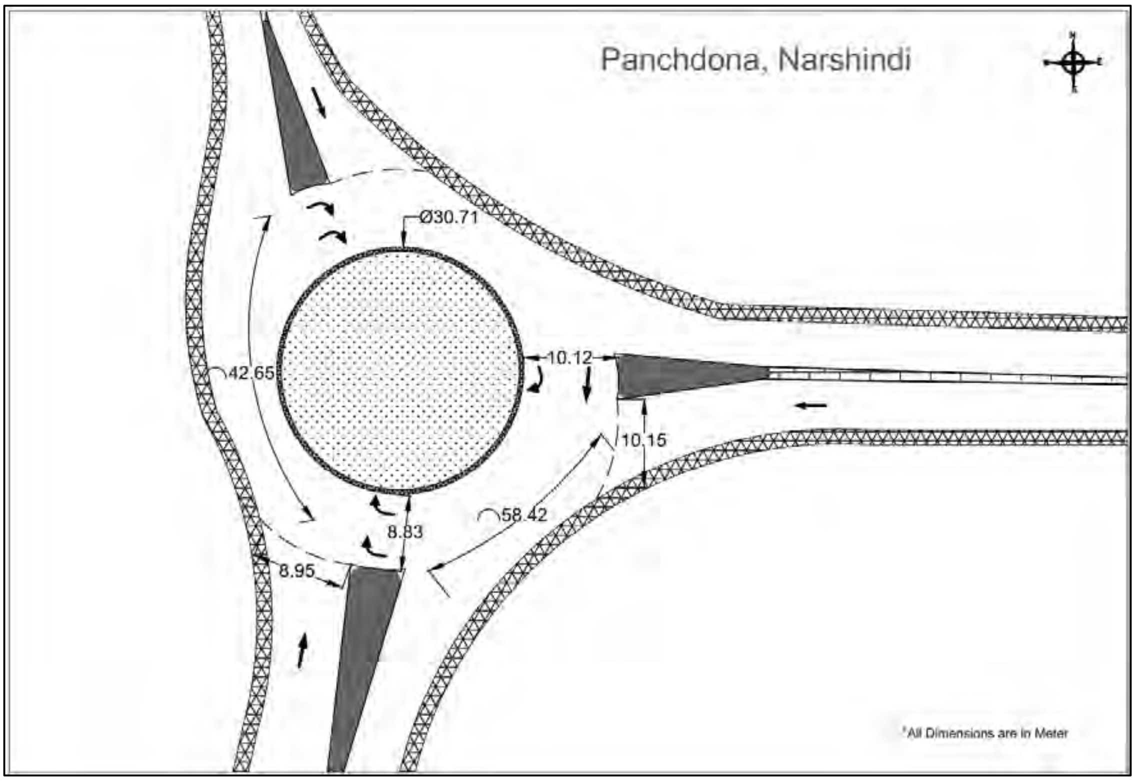

Figure 4.10 Geometric layout of R5 roundabout with geometric parameters

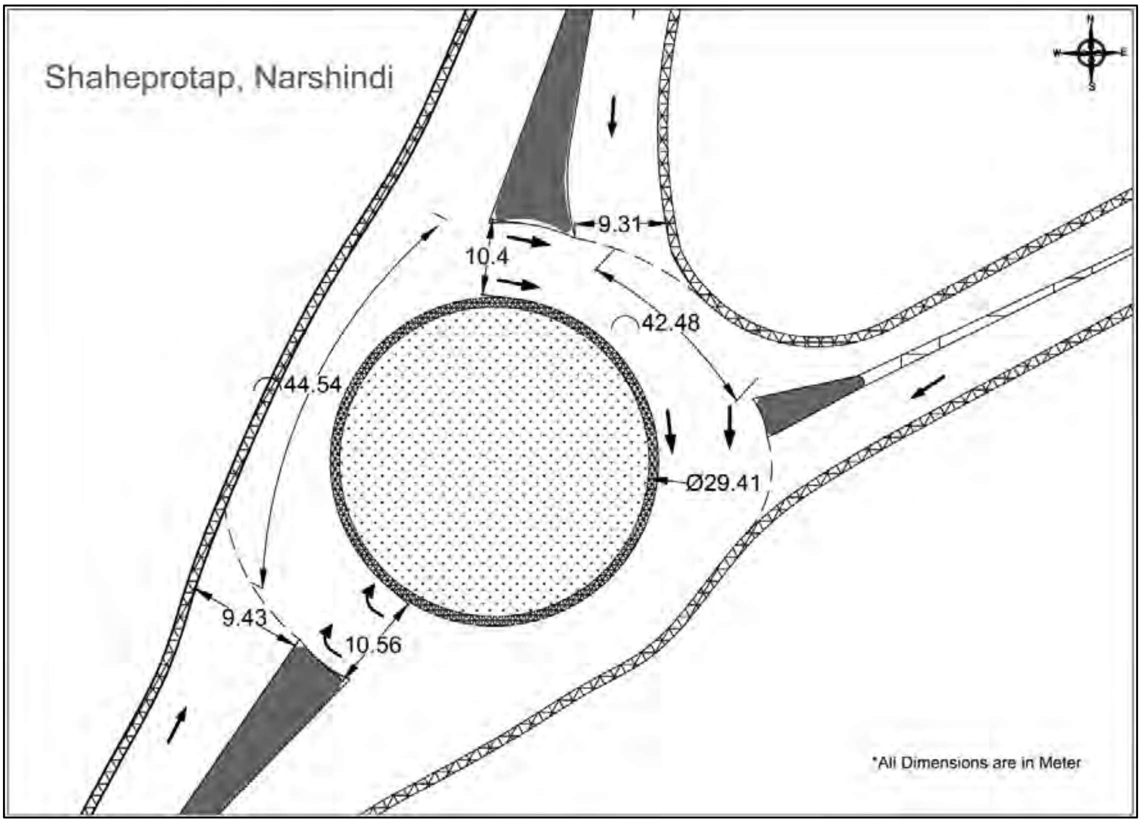

Figure 4.11 Geometric layout of R6 roundabout with geometric parameters

4.4 Data Analysis

The extracted data was analyzed to develop empirical capacity estimation model for highway roundabouts. The traffic flow data were categorized into two types; (1) entry flow, and (2) circulating flow. The analysis of these traffic data are presented in the following sections:

4.4.1 Entry Traffic Flow

Extracted entry flow for each selected entry of roundabouts were categorized based of time interval of data collection time. From the categorized data, it has been observed that the entry flow is little fluctuating with time. The graphical representation entry flow of each roundabout is shown in the Figure 4.12 to Figure 4.17.

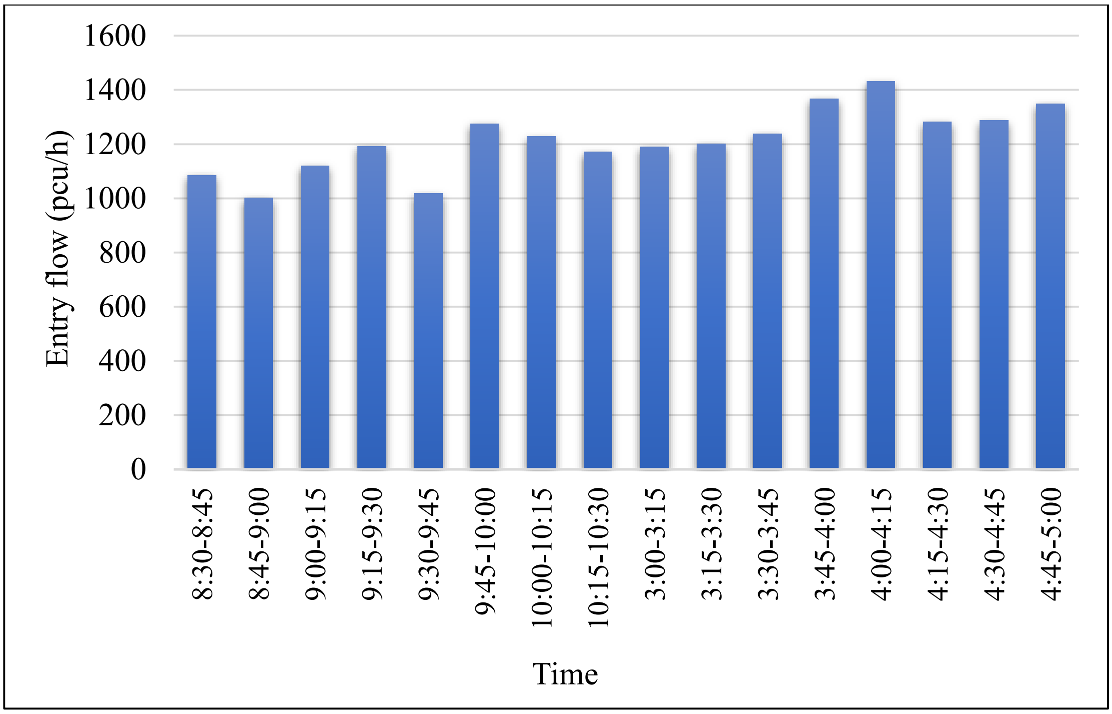

Figure 4.12 Entry flow of roundabout R1

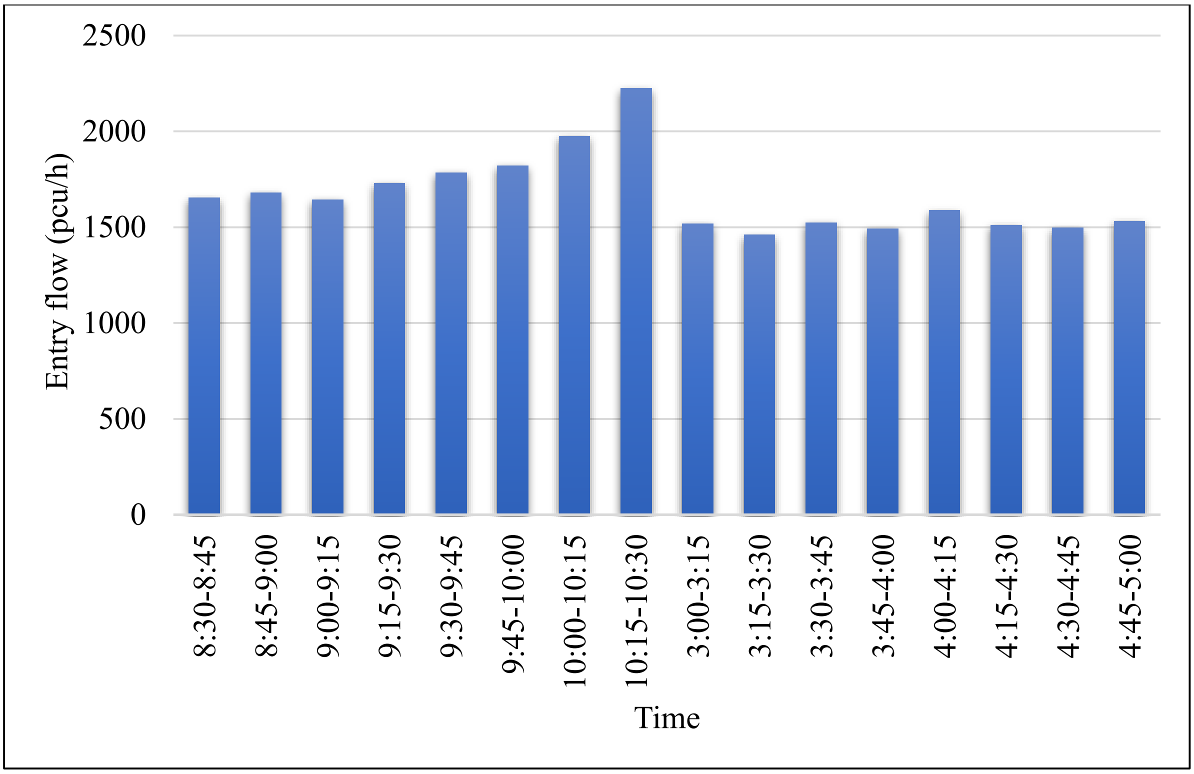

Figure 4.13 Entry flow of roundabout R2

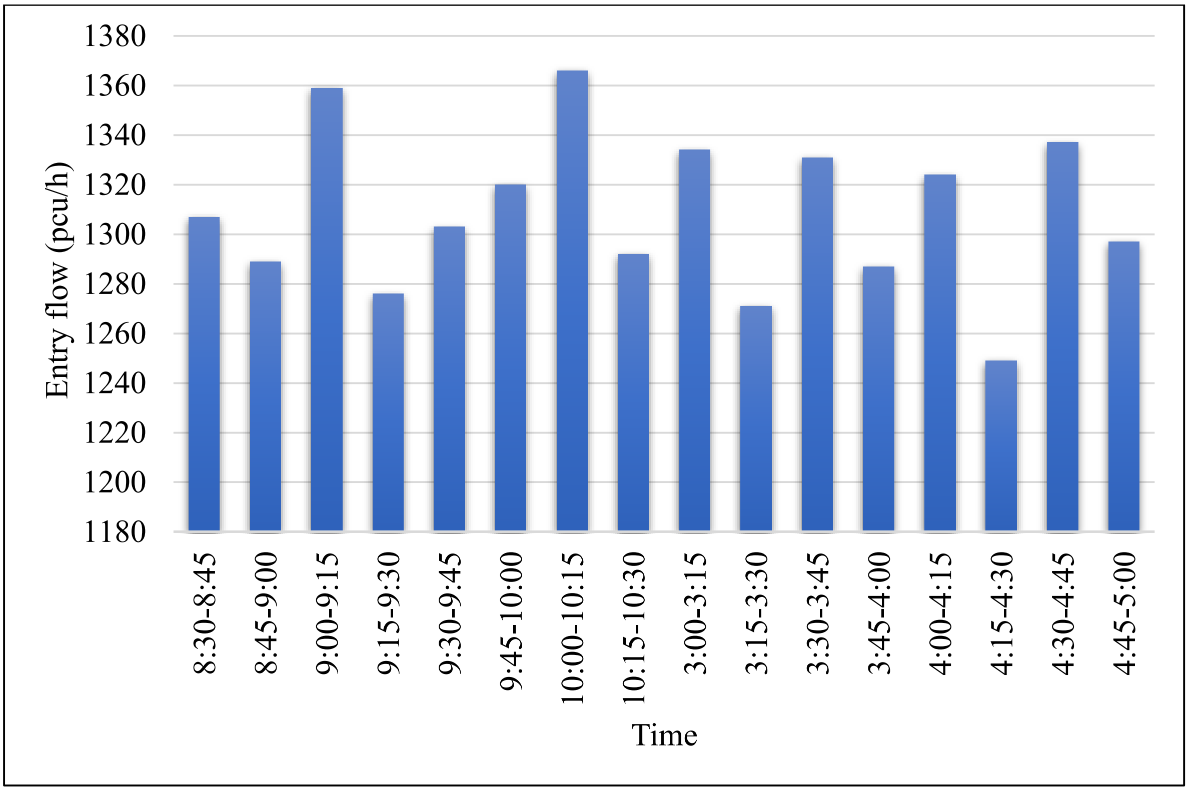

Figure 4.14 Entry flow of roundabout R3

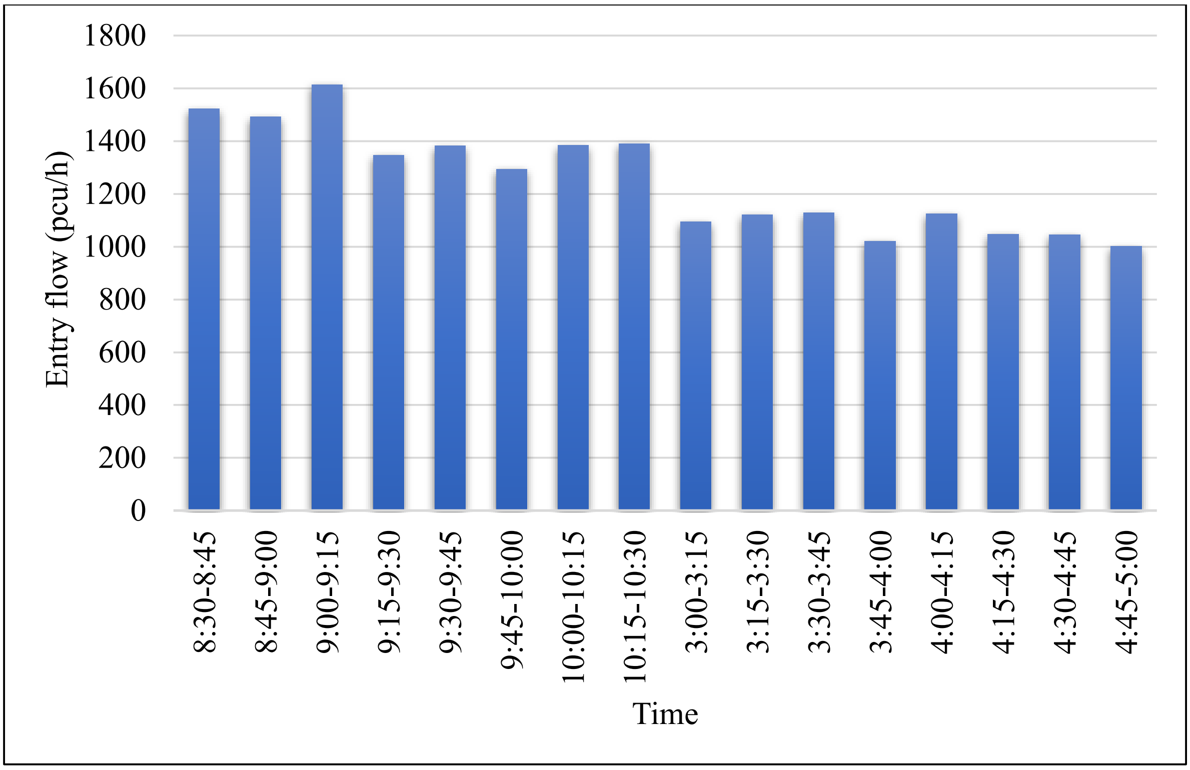

Figure 4.15 Entry flow of roundabout R4

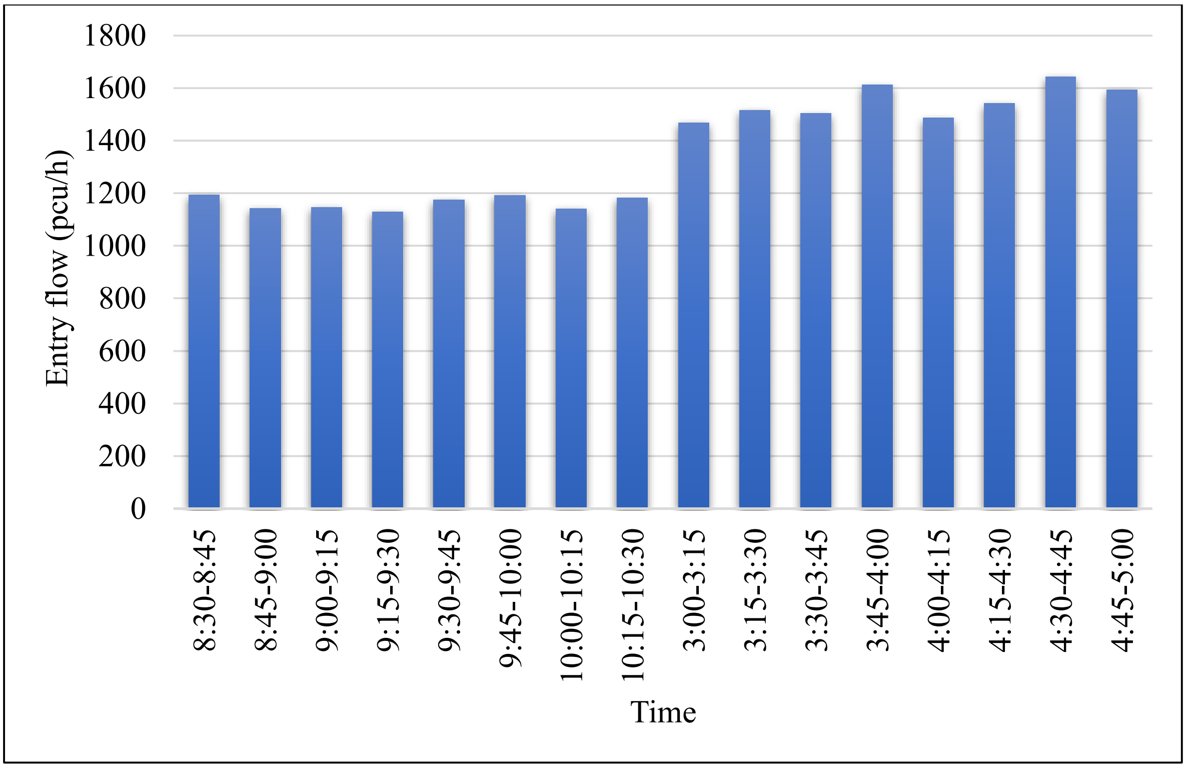

Figure 4.16 Entry flow of roundabout R5

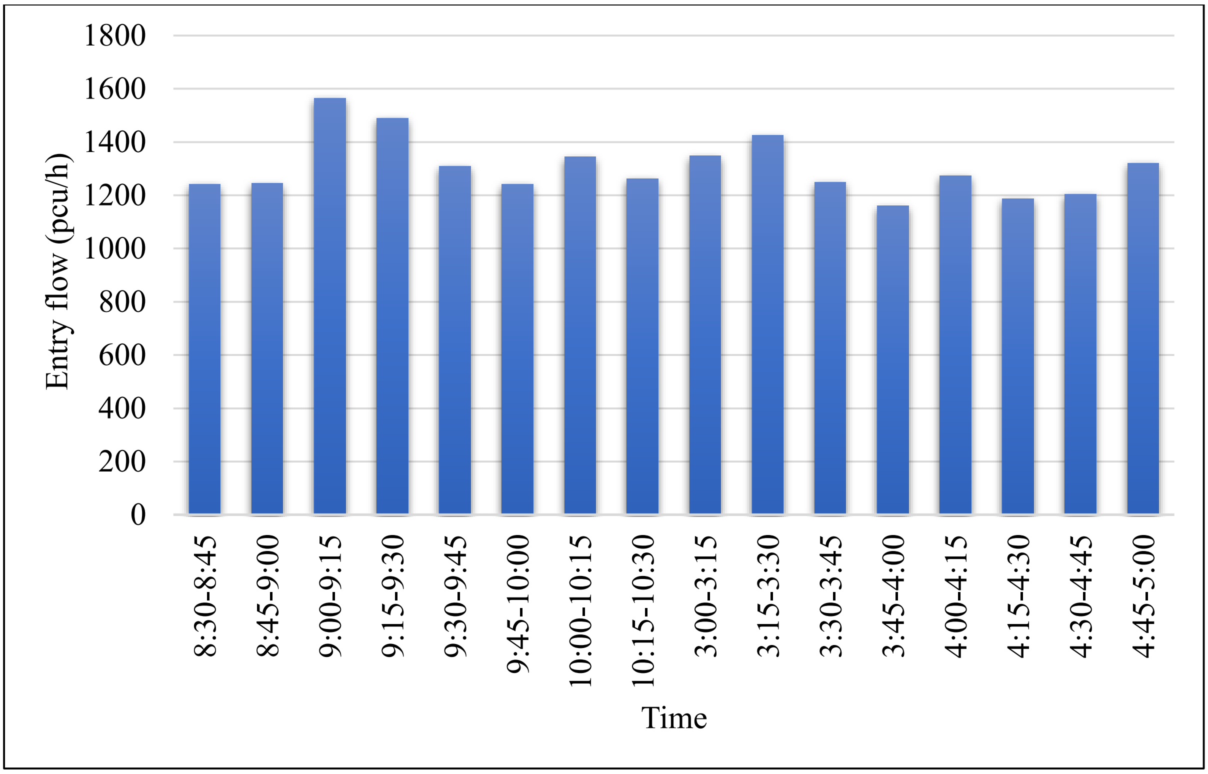

Figure 4.17 Entry flow of roundabout R6

4.4.2 Circulating Traffic Volume

The circulating traffic flows were hypothetically collinear with entry flows. The circulating flows were changed with data collection time and entry flow of corresponding roundabout legs. Circulating flow of selected sites is shown from the Figure 4.18 to Figure 4.23.

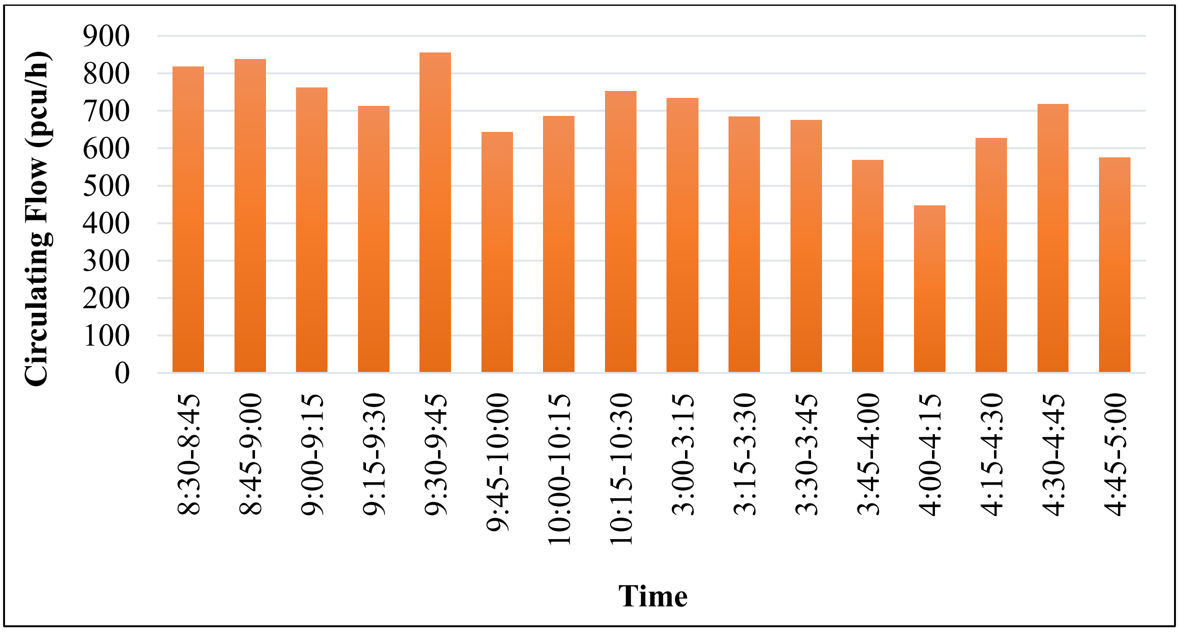

Figure 4.18 Circulating flow of roundabout R1

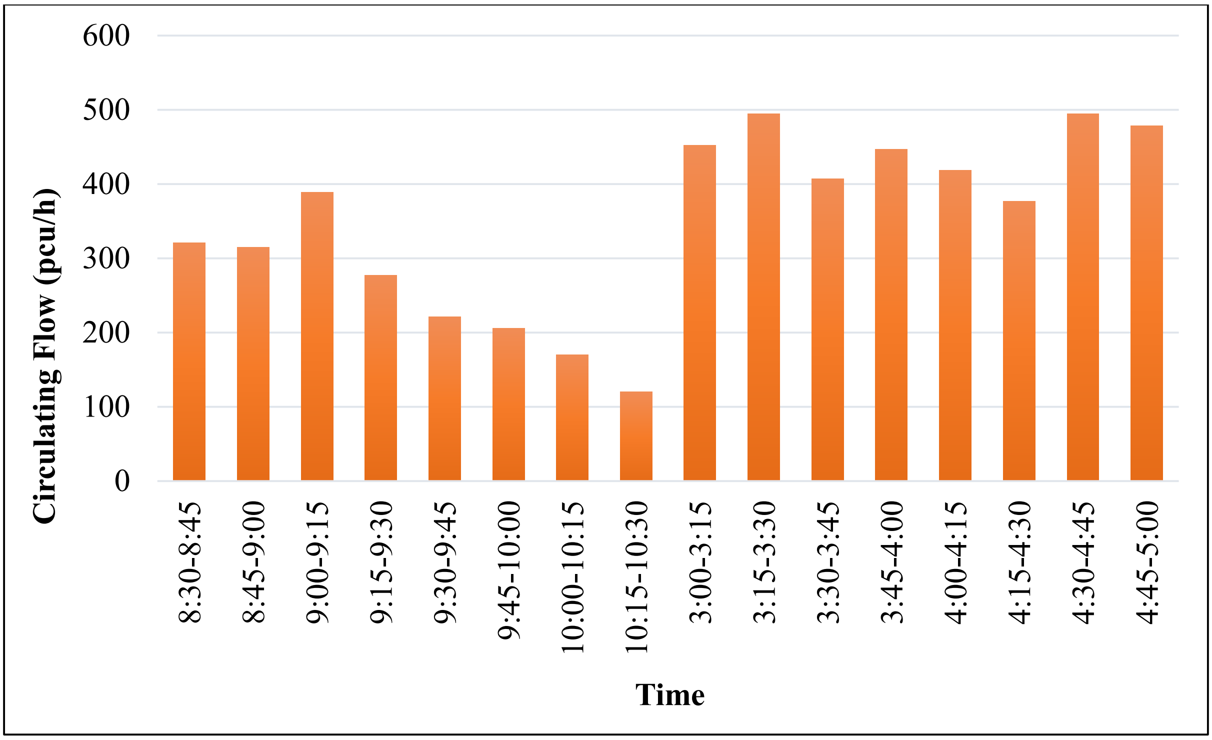

Figure 4.19 Circulating flow of roundabout R2

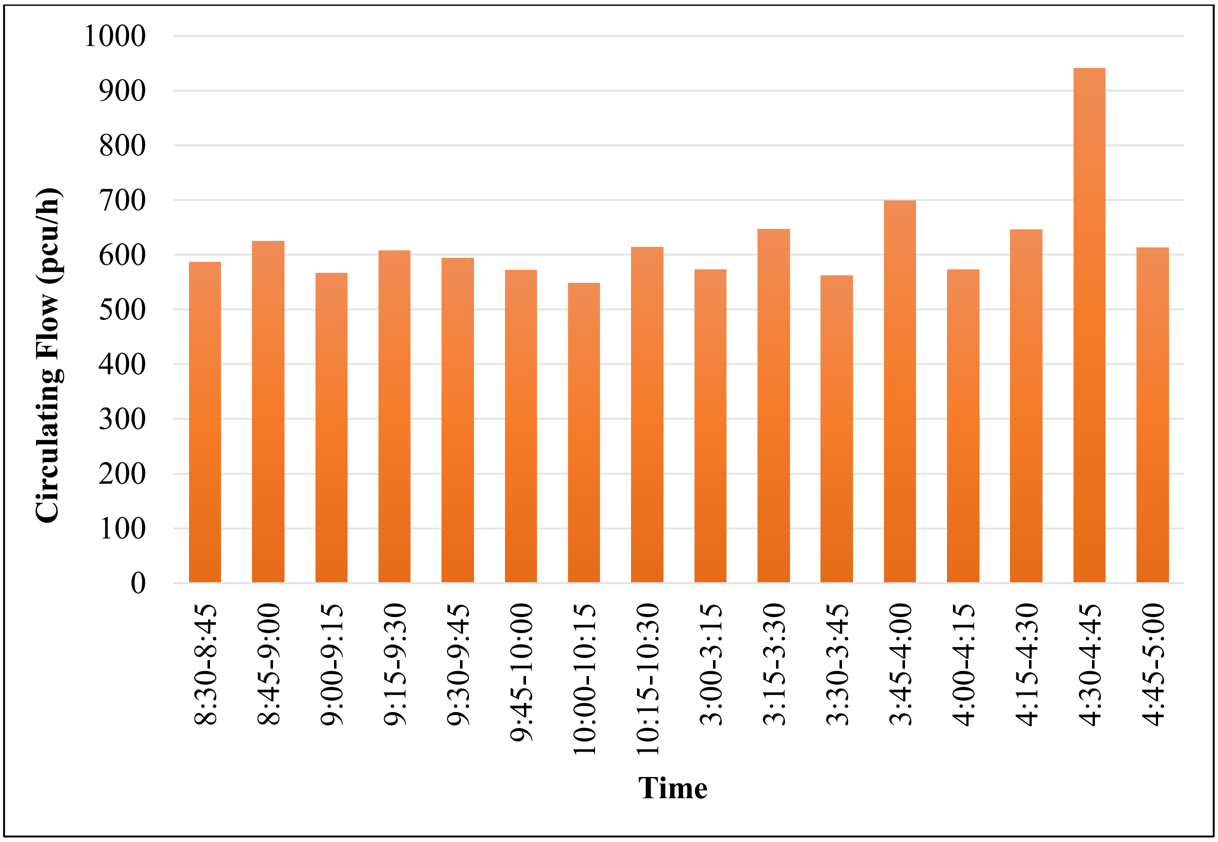

Figure 4.20 Circulating flow of roundabout R3

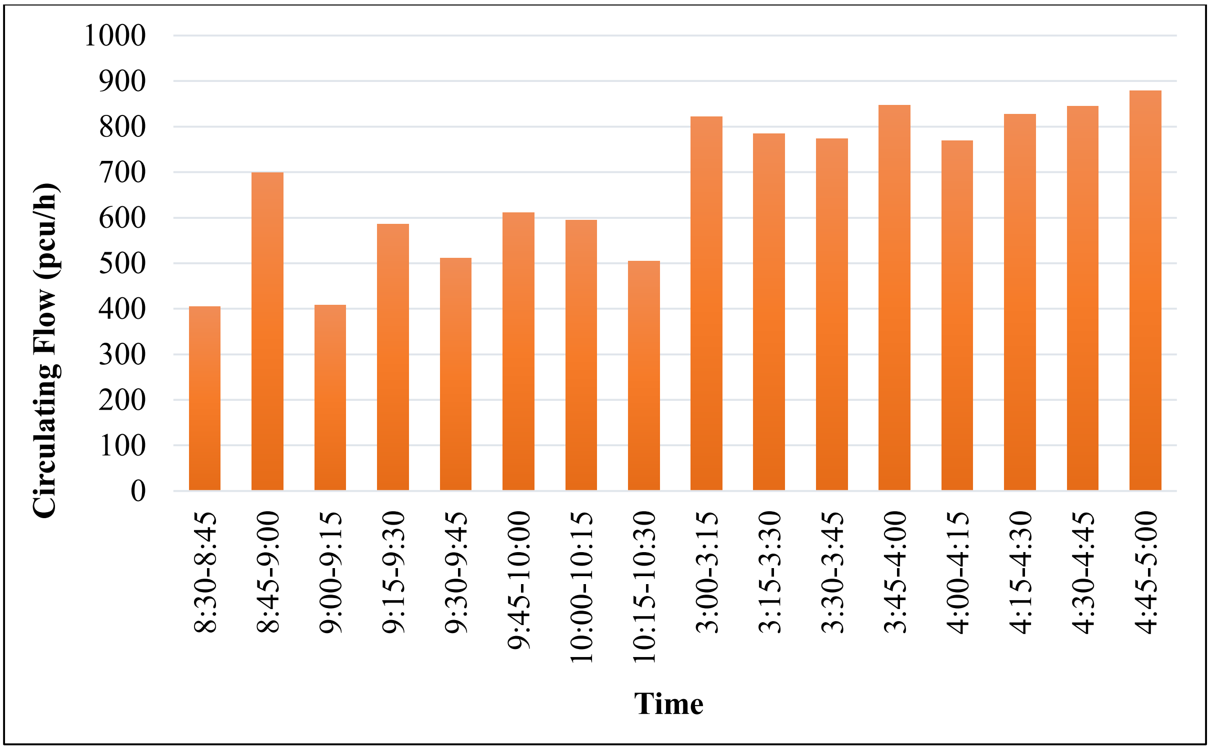

Figure 4.21 Circulating flow of roundabout R4

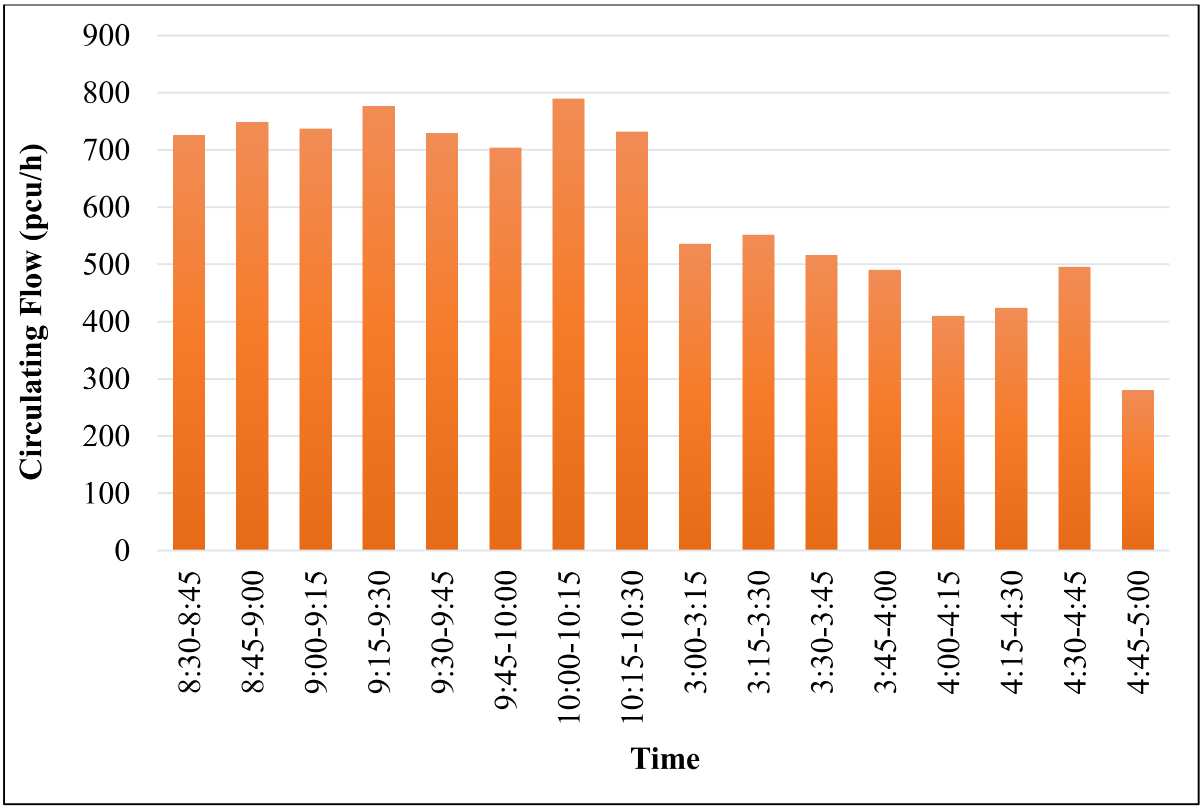

Figure 4.22 Circulating flow of roundabout R5

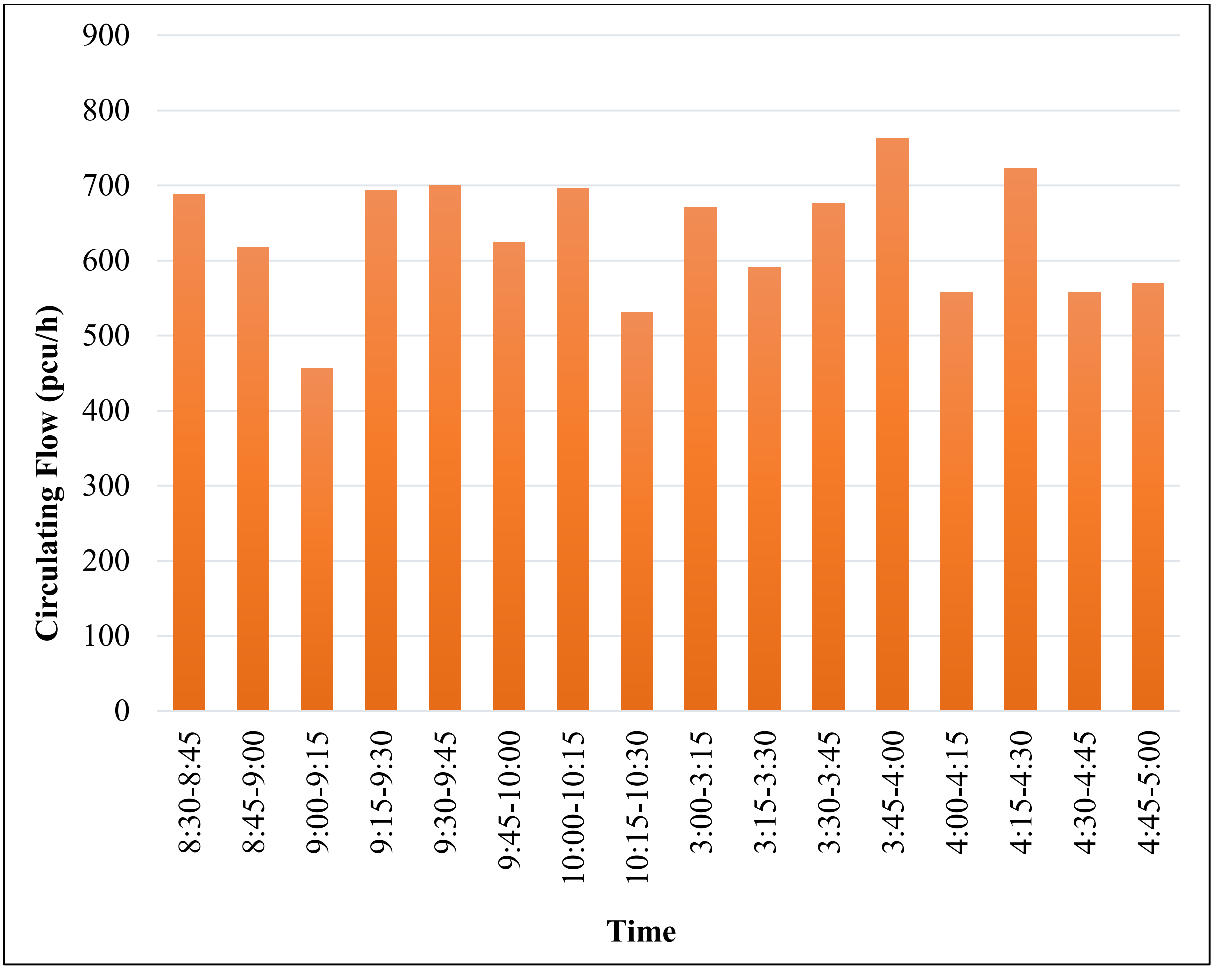

Figure 4.23 Circulating flow of roundabout R6

CHAPTER 5

MODEL DEVELOPMENT

5.1 Introduction

The data extracted from collected field data are categorized into two types (1) geometric data and (2) traffic flow data. Geometric data variables are: diameter of the central island, distance between entry and the nearest exit, entry width, and circulating road width. The traffic flow data variables consisting of entry flow and circulating flow. Statistical multivariate regression was used for developing empirical entry capacity model with the above mentioned variables. It is importance to check that the developed model explains hypothetical relation with entry flow among other variables. The data was used to assess the impact of variables and factors, so the analyses and results are described and discussed. Microscopic traffic simulation modelling was also developed to justify the accuracy of developed model in different geometric and traffic flow conditions. Further, a graphical tool has developed (Nomograph) for estimating and predicting roundabouts entry capacity.

5.2 Data Setup

The extracted data set was coded in the Statistical Package for Social Science (SPSS) (Wanger and William, 2014). The data coded in SPSS was divided into two major categories; (1) independent variables and (2) dependent variables. The entry flow (Q_e) is the dependent variable and other parameters; i.e., Circulating flow, diameter of the central island, distance between entry and the nearest exit, entry width, and circulating road widths are independent variables. Further, the data set was divided into entry leg of selected roundabouts.

5.3 Hypothesis Checking for Model Development

Any type of capacity models, for example, linear and multiple regression, depend on certain assumptions related to independent and dependent variables. If these assumptions are not met, then the results or outputs of the models are not reliable and have Type I or II errors. As discussed in the previous section, entry volumes were considered as dependent variable, whereas circulating flow, diameter of the central island, distance between entry and the nearest exit, entry width, and circulating road width were considered as independent variables. Basic assumptions were checked, the correlation between independent and dependent variables.

5.3.1 Multicollinearity Check

Multicollinearity occurs when two or more independent variables in the models are correlated to each other. The Multicollenearity increases the standard error of the estimates and instability in the predication of models. On the other hand, correlation is required between dependent and independent variables. Table 5.1 shows the correlation matrix between entry and circulating volumes. It is clear that a significant correlation exists between the entry and circulating volumes. Moreover, circulating volumes on each lane also have significant correlation among themselves. Therefore, circulating flows for each lane cannot be used together in the model for the prediction of entry volumes. Note that the correlation between entry and circulation volume are negative; that is, both are inversely proportional to each other. Significant correlations among geometric variables and entry flow is observed from the table.

Table 5.1 Correlation matrix among variables

	Entry Flow (pcu/h)	**Circulating Flow (pcu/h)**	**Entry width (m)**	**Circular Road Width (m)**	**Dia. of Central Island (m)**	**Entry/Exit Distance (m)**
Entry Flow, (pcu/h)	1.00					
Circulating Flow, (pcu/h)	-0.95	1.00				
Entry width, (m)	0.93	-0.92	1.00			
Circular Road Width, (m)	0.86	-0.86	0.89	1.00		
Dia. Of Central Island, (m)	0.78	-0.81	0.78	0.73	1.00	
Entry/Exit Distance, (m)	0.85	-0.85	0.83	0.72	0.68	1.00

5.4 Model Development

Using the available data, new empirical models were developed using statistical methods such as multiple linear or nonlinear regression; Further information on these methods can be found in many statistical textbooks (Kutner et al., 2005; Cohen et al., 2003), but they essentially involved estimating parameters in hypothesized relationships between independent explanatory variables and dependent variable through least-squares minimization of errors (residuals). The importance of each explanatory variable was determined by evaluating the statistical significance of its coefficient, and the improvement in model fit resulting from its inclusion; this also applied to any two-way interactions between explanatory variables where the impact of one variable depended on another. The form of the hypothesized relationship between each independent variable and capacity was typically assumed to be linear by default, unless theory or scatterplots suggested otherwise.

Previous empirical studies (TRB, 2007; Polus and Shmueli, 1997; Brilon and Stuwe, 1993; Louah, 1992; Semmens, 1988; Kimber, 1980; Glen et al., 1978; Kimber and Semmens, 1977) variously used linear or negative exponential relationships between Q_e and Q_c.

5.4.1 Multi -Linear Regression Model

At roundabouts, the least value of traffic flow at the approach causing permanent formation of queue at the entry is called the capacity of the entry, and the sum of all entry capacities under saturated condition is referred to as the total capacity of the roundabout (Mauro, 2010; Arroju et al., 2015). Al-Masaeid (1995) performed a comparative analysis between empirical and gap-acceptance models for estimating roundabout capacity and found that empirical models provide better capacity estimates in comparison with gap-acceptance models. Empirical approach has been adopted for this research keeping in mind that empirical models require a large number of capacity data from different locations.

Based on the geometric characteristics and traffic flow at the entry and circulating roadway, using multivariate regression analysis, an empirical entry capacity estimation model has been developed as a function of central island diameter, distance between entry and near-side exit, entry width, rotary width, and circulating traffic flow. The general form of the capacity estimation model is:

$$Q_e = a \times D^b \times L^c \times exp(d \times E + e \times R) \times exp(-f \times Q_c) \qquad \text{.........} (5.1)$$

where,

a, b, c, d, e, f = regression constants

Q_e = entry capacity (pcu/hr)

D = diameter of central island (m)

L = distance from entry to nearest exit (m)

E = width of entry (m)

R = width of rotary section (m)

Q_c = circulating traffic flow (pcu/hr)

Traffic flow parameters (i.e., entry flow, and circulating flow), and geometric parameters (i.e., entry width, circular road width, central island diameter, and distance from entry to nearest exit) collected from the selected roundabouts are presented in Table 5.2.

Table 5.2 Traffic flow and geometric parameters extracted from field data

Roundabout	Traffic Flow Parameters		Geometric Parameters			
	Entry Flow (pcu/hr)	**Circulating Flow (pcu/hr)**	**Entry Width (m)**	**Circular Road Width (m)**	**Central Island Diameter (m)**	**Entry to Exit Distance (m)**
Bangabandhu Bridge East Roundabout (R1)	1085	817	9.21	8.64	28.79	45.89
	1002	838	9.21	8.64	28.79	45.89
	1120	762	9.21	8.64	28.79	45.89
	1192	712	9.21	8.64	28.79	45.89
	1017	856	9.21	8.64	28.79	45.89
	1275	643	9.21	8.64	28.79	45.89
	1228	686	9.21	8.64	28.79	45.89
	1172	752	9.21	8.64	28.79	45.89
	1190	734	9.21	8.64	28.79	45.89
	1202	685	9.21	8.64	28.79	45.89
	1239	675	9.57	9.58	28.79	56.2
	1367	569	9.57	9.58	28.79	56.2
	1431	447	9.57	9.58	28.79	56.2
	1282	627	9.57	9.58	28.79	56.2
	1287	718	9.57	9.58	28.79	56.2
	1350	575	9.57	9.58	28.79	56.2
	1486	425	9.57	9.58	28.79	56.2
	1327	580	9.57	9.58	28.79	56.2
Bangabandhu Bridge West	1654	321	11.05	10.71	33.77	63.6
	1680	315	11.05	10.71	33.77	63.6

Contd. Table 5.2

Roundabout	Traffic Flow Parameters		Geometric Parameters			
	Entry Flow (pcu/hr)	Circulating Flow (pcu/hr)	Entry Width (m)	Circular Road Width (m)	Central Island Diameter (m)	Entry to Exit Distance (m)
Roundabout (R2)	1643	389	11.05	10.71	33.77	63.6
	1730	277	11.05	10.71	33.77	63.6
	1786	221	11.05	10.71	33.77	63.6
	1822	206	11.05	10.71	33.77	63.6
	1976	170	11.05	10.71	33.77	63.6
	2225	120	11.05	10.71	33.77	63.6
	1519	452	9.85	9.91	33.77	58.56
	1460	495	9.85	9.91	33.77	58.56
	1523	407	9.85	9.91	33.77	58.56
	1493	447	9.85	9.91	33.77	58.56
	1589	419	9.85	9.91	33.77	58.56
	1512	377	9.85	9.91	33.77	58.56
	1497	495	9.85	9.91	33.77	58.56
	1532	479	9.85	9.91	33.77	58.56
Hatikumrul Sirajganj Roundabout (R3)	1307	587	9.35	9.27	31.51	40.66
	1289	625	9.35	9.27	33.51	40.66
	1359	567	9.35	9.27	33.51	40.66
	1276	607	9.35	9.27	33.51	40.66
	1303	594	9.35	9.27	33.51	40.66
	1320	572	9.35	9.27	33.51	40.66
	1366	548	9.35	9.27	33.51	40.66
	1292	614	9.35	9.27	33.51	40.66
	1214	632	9.35	9.27	33.51	40.66
	1325	545	9.35	9.27	33.51	40.66
	1343	589	9.35	9.27	33.51	40.66
	1334	573	9.45	9.57	33.51	40.88
	1271	647	9.45	9.57	33.51	40.88
	1331	562	9.45	9.57	33.51	40.88
	1287	699	9.45	9.57	33.51	40.88
	1324	573	9.45	9.57	33.51	40.88
	1249	646	9.45	9.57	33.51	40.88
	1337	941	9.45	9.57	33.51	40.88
	1297	613	9.45	9.57	33.51	40.88
	1572	460	10.85	10.5	33.51	59.73
	1645	369	10.85	10.5	33.51	59.73
	1597	454	10.85	10.5	33.51	59.73
	1692	324	10.85	10.5	33.51	59.73
	1742	293	10.85	10.5	33.51	59.73
	1615	330	10.85	10.5	33.51	59.73
	1567	454	10.85	10.5	33.51	59.73
	1596	540	10.85	10.5	33.51	59.73
	525	1235	6.75	6.5	20.25	19.72

Contd. Table 5.2

Roundabout	Traffic Flow Parameters		Geometric Parameters			
	Entry Flow (pcu/hr)	Circulating Flow (pcu/hr)	Entry Width (m)	Circular Road Width (m)	Central Island Diameter (m)	Entry to Exit Distance (m)
	536	1296	6.75	6.5	20.25	19.72
	693	1383	6.75	6.5	20.25	19.72
	574	1222	6.75	6.5	20.25	19.72
	512	1261	6.75	6.5	20.25	19.72
	596	1422	6.75	6.5	20.25	19.72
	565	1347	6.75	6.5	20.25	19.72
	530	1398	6.75	6.5	20.25	19.72
Bishwarod, Tarabo Narayanganj Roundabout (R4)	1522	405	9.5	9.25	30.28	53.57
	1492	699	9.5	9.25	30.28	53.57
	1615	408	9.5	9.25	30.28	53.57
	1347	586	9.5	9.25	30.28	53.57
	1382	511	9.5	9.25	30.28	53.57
	1294	611	9.5	9.25	30.28	53.57
	1384	595	9.5	9.25	30.28	53.57
	1390	505	9.5	9.25	30.28	53.57
	1363	512	9.5	9.25	30.28	53.57
	1316	567	9.5	9.25	30.28	53.57
	1274	651	9.5	9.25	30.28	53.57
	1584	548	9.5	9.25	30.28	53.57
	1096	822	8.09	8.5	30.28	49.49
	1121	785	8.09	8.5	30.28	49.49
	1128	773	8.09	8.5	30.28	49.49
	1022	847	8.09	8.5	30.28	49.49
	1126	769	8.09	8.5	30.28	49.49
	1048	827	8.09	8.5	30.28	49.49
	1046	845	8.09	8.5	30.28	49.49
	1001	879	8.09	8.5	30.28	49.49
	1146	767	8.09	8.5	30.28	49.49
	1176	734	8.09	8.5	30.28	49.49
Panchdona, Narshindi Roundabout (R5)	1193	726	8.95	8.83	31.71	42.65
	1143	748	8.95	8.83	31.71	42.65
	1146	737	8.95	8.83	31.71	42.65
	1130	776	8.95	8.83	31.71	42.65
	1174	729	8.95	8.83	31.71	42.65
	1192	704	8.95	8.83	31.71	42.65
	1141	789	8.95	8.83	31.71	42.65
	1182	732	8.95	8.83	31.71	42.65
	1468	536	10.15	10.12	31.71	58.42
	1516	551	10.15	10.12	31.71	58.42
	1504	516	10.15	10.12	31.71	58.42
	1612	491	10.15	10.12	31.71	58.42
	1487	410	10.15	10.12	31.71	58.42

Contd. Table 5.2

Roundabout	Traffic Flow Parameters		Geometric Parameters			
	Entry Flow (pcu/hr)	Circulating Flow (pcu/hr)	Entry Width (m)	Circular Road Width (m)	Central Island Diameter (m)	Entry to Exit Distance (m)
	1541	424	10.15	10.12	31.71	58.42
	1643	496	10.15	10.12	31.71	58.42
	1592	281	10.15	10.12	31.71	58.42
Shaheprotap, Narshindi Roundabout (R6)	1242	689	9.43	10.56	29.41	44.54
	1245	618	9.43	10.56	29.41	44.54
	1565	457	9.43	10.56	29.41	44.54
	1490	693	9.43	10.56	29.41	44.54
	1310	701	9.43	10.56	29.41	44.54
	1242	624	9.43	10.56	29.41	44.54
	1344	696	9.43	10.56	29.41	44.54
	1263	531	9.43	10.56	29.41	44.54
	1348	671	9.31	10.4	29.41	42.48
	1425	591	9.31	10.4	29.41	42.48
	1249	676	9.31	10.4	29.41	42.48
	1160	763	9.31	10.4	29.41	42.48
	1274	557	9.31	10.4	29.41	42.48
	1187	723	9.31	10.4	29.41	42.48
	1205	558	9.31	10.4	29.41	42.48
	1320	569	9.31	10.4	29.41	42.48

Scatterplots of regression analysis of dependent and independent variables are found hypothetically significant and R-square values are also found statistically significant. The scatterplot of every independent vs dependent variables is discussed in Figure 5.1 to Figure 5.5.

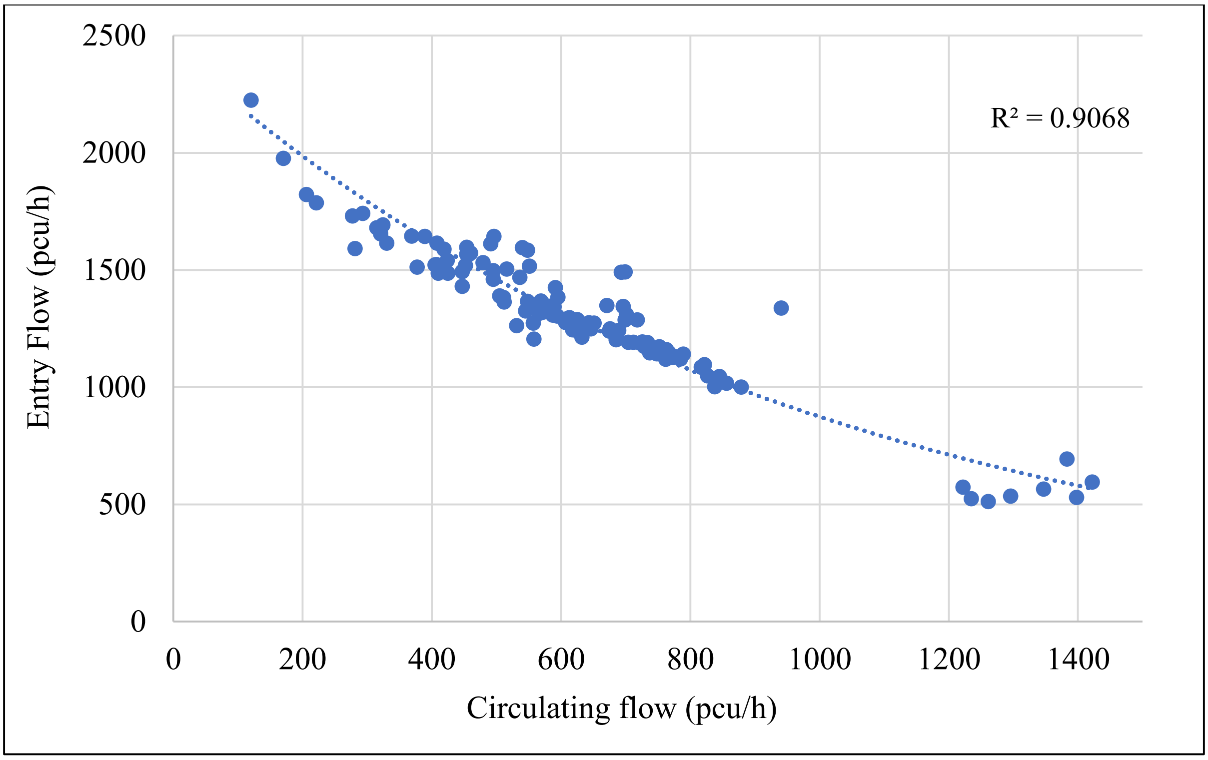

Figure 5.1 Entry and circulating flow curve of modeling data

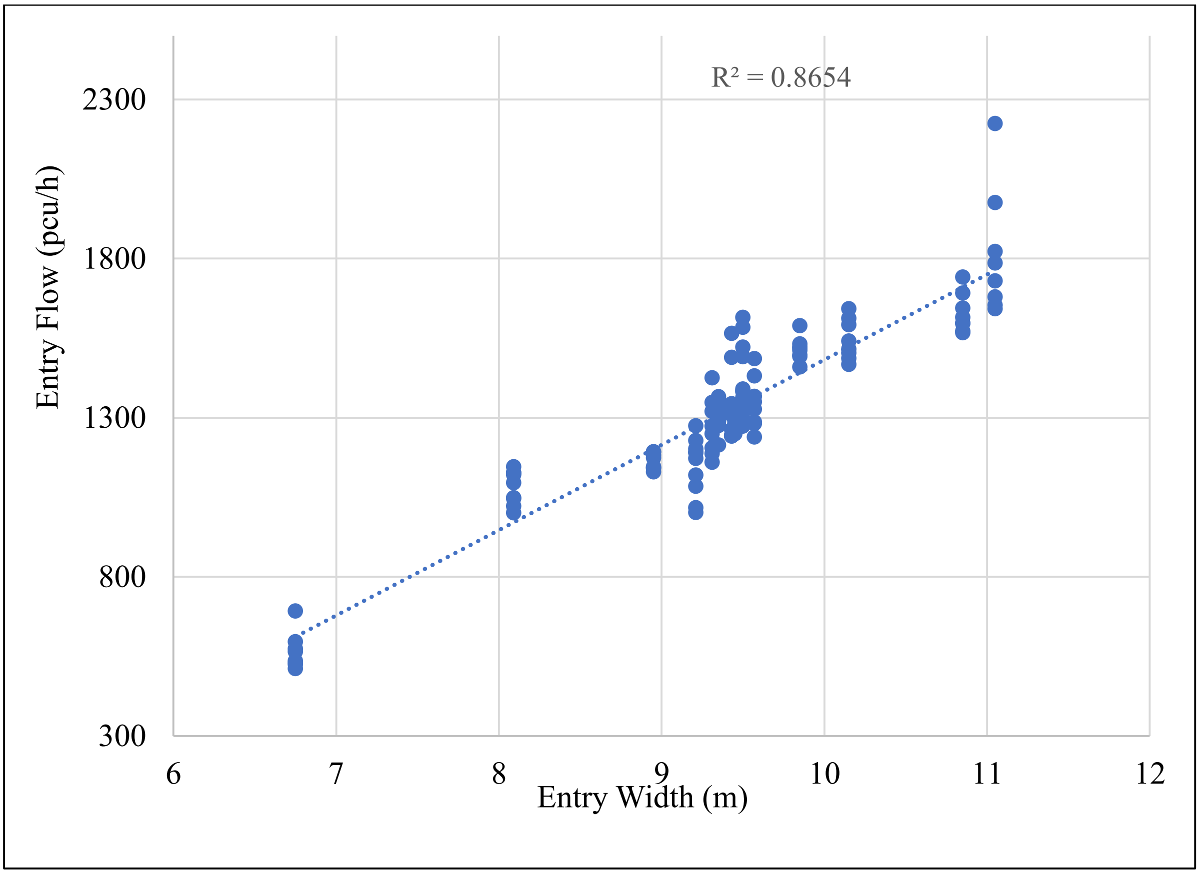

Figure 5.2 Entry flow and entry width curve of modeling data

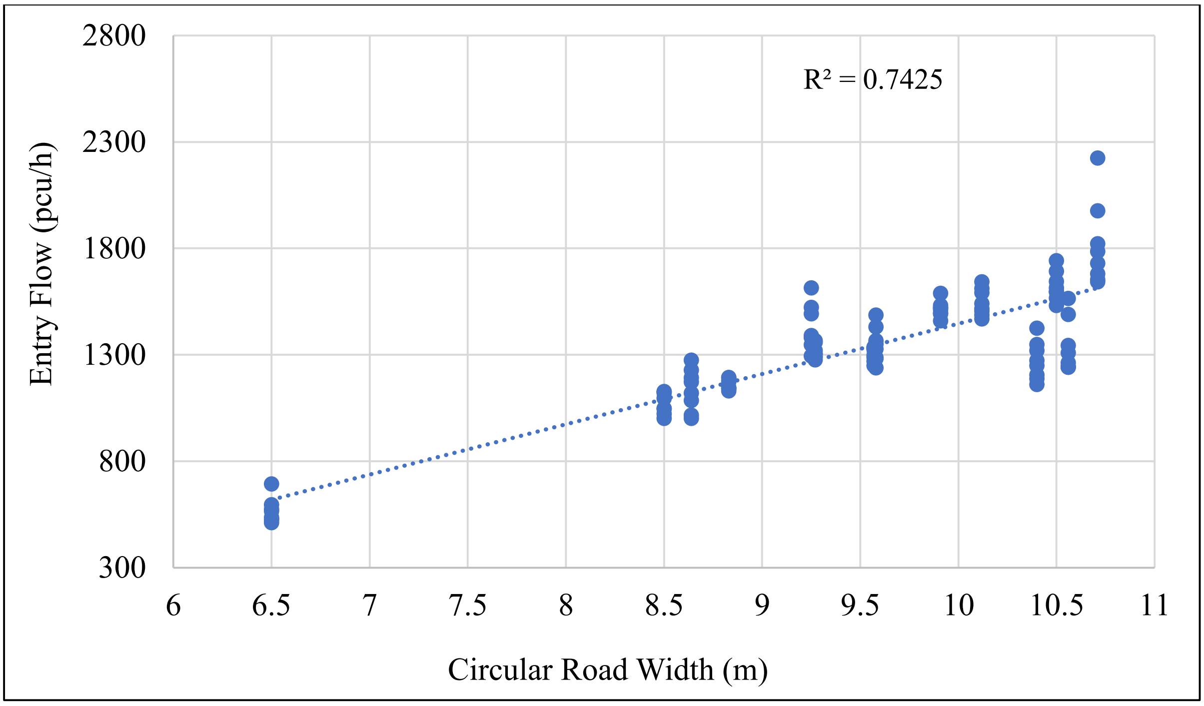

Figure 5.3 Entry flow and circular road width curve of modeling data

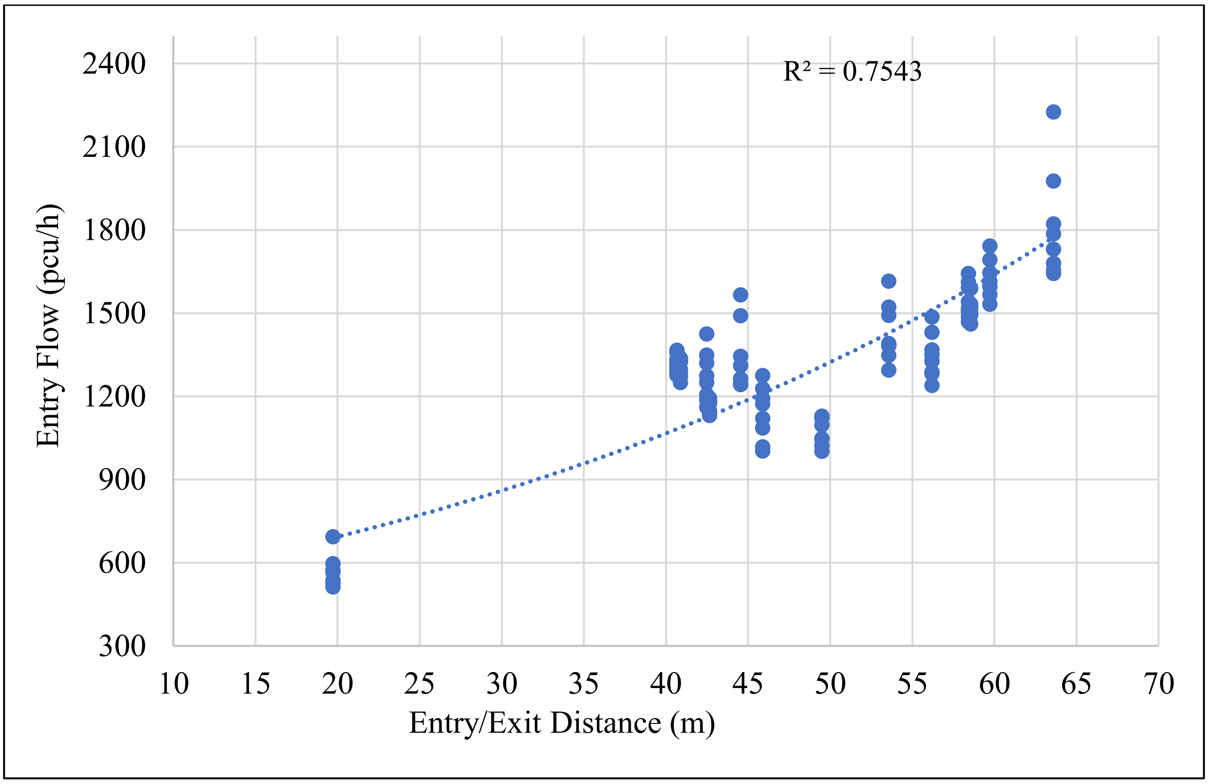

Figure 5.4 Entry flow and entry/exit distance curve of modeling data

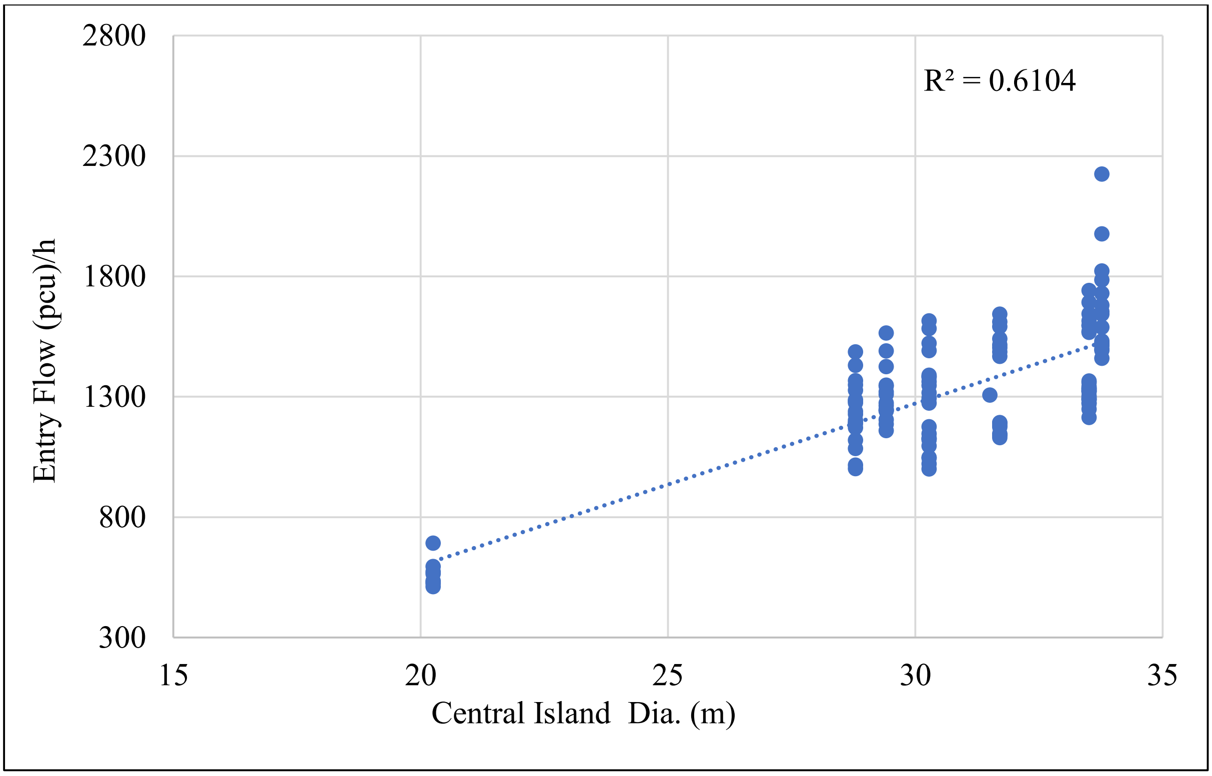

Figure 5.5 Entry flow and central Island Diameter curve of modeling data

5.4.1.1 Comparison of Developed Model with Different Capacity Model

Since, the selected roundabouts are located at highways, stable queue is difficult to be observed, so the entry capacity was observed during the peak period. The performance of the developed model in estimating capacity of roundabout was compared with the observed entry capacity, and capacities estimated using HCM 2016 method, TRRL (UK) linear regression method, Indian Roads Congress Method (IRC 65-1976) and German method. Parameters required for models (HCM 2016 and German method) based on gap-acceptance theory e.g., critical gap was calculated using Raff's method using graphical representation of cumulative distribution functions of accepted and rejected gaps (Fitzpatrick, 2013). Based on the different combinations of leader and follower vehicles among the various vehicle types existing in the traffic stream, the follow-up headway was calculated. The critical gap and the follow-up headway were computed using weighted average approach depending on the composition of traffic stream. A brief overview of roundabout capacity estimation methods used for comparison purpose is given in Table 5.3.

Table 5.3 List of different comparison capacity model

Method Name	Capacity Equation	Parameters
HCM 2016	$C = 1420 \times e^{(-0.85 \times 10^{-3})*V_c}$ for two lane entry and two-lane circulating roundabout $C = 1420 \times e^{(-0.85 \times 10^{-2})*V_c}$ for one lane entry and two-lane circulating roundabout	where, C is entry lane capacity (pcu/hr), and v_c is circulating flow (pcu/hr)
TRRL (UK) linear regression method (Kimber, 1980)	$Q_e = \begin{cases} K(F - f_c \times Q_c), & f_c \times Q_c \leq F \\ 0, & f_c \times Q_c > F \end{cases}$ where, $K = 1 - 0.00347(\varphi - 30) - 0.978(\frac{1}{r} - 0.05)$ $F = 303 \times x_2$ $f_c = 0.210 \times t_D (1 + 0.2 \times x_2)$ $t_D = 1 + \frac{0.5}{1+\exp(\frac{D-60}{10})}$ $x_2 = v + \frac{e-v}{1+2\times S}$ $S = \frac{1.6\,(e-v)}{l'}$	where, Q_e is the entry capacity (pcu/hr), Q_c is the circulating flow, (pcu/hr), e is the entry width (m), v is the approach half width (m), l' is the effective flare length (m), S is the sharpness of flare (m/m), D is the inscribed circle diameter (m), φ is the entry angle (degree), and r is the entry radius (m)
Indian Roads Congress (IRC	$Q_p = \frac{280 \times w\left(1+\frac{e}{w}\right)(1-\frac{p}{3})}{1+\frac{w}{l}}$	where Q_p is the practical capacity of the weaving section (pcu/hr), w is the width of weaving section (m), e is the average entry

Contd. Table 5.3

Method Name	Capacity Equation	Parameters
65-1976) method	$w = \frac{e_1+e_2}{2} + 3.5$ $e = \frac{e_1+e_2}{2}$ $p = \frac{b+c}{a+b+c+d}$	width (m), l is the length of the weaving section (m), p is the proportion of weaving traffic, a, b, c, and d is the parameters for a weaving section
German method (Brilon et al., 1997)	$C = 3{,}600 \times \frac{n_e}{T_f} \times \exp[-\frac{Q_c}{3{,}600} \times (T_c - \frac{T_f}{2})]$	where, C is the capacity (pcu/hr), Q_c is the circulating flow (pcu/hr), n_e is the parameter related to number of entry lanes, T_c is the critical headway (sec), and T_f is the follow-up time (sec)

5.4.2 Microscopic Traffic Simulation Model

A number of software products are available in the market to code the roundabouts, for example, SIDRA, Synchro, CORSIM, Aimsun, and VISSIM. For validation purposes, software was needed that can code the roundabout, code the priority rules, and be flexible enough to code traffic parameters per the requirements. VISSIM (PTV, 2021) microscopic simulation software was selected for the calibration of proposed capacity models. VISSIM is one of the leading software products in the market for microscopic simulation. Most scholars used VISSIM as their first choice for the microscopic simulation task within their studies.

5.4.2.1 Feature Interface of VISSIM

VISSIM has multiple features related to roundabouts such as priority rules (PR) and conflict areas (CA). Because the microscopic simulation task within this research work was based on the CA, the features of CA and its attributes are discussed next.

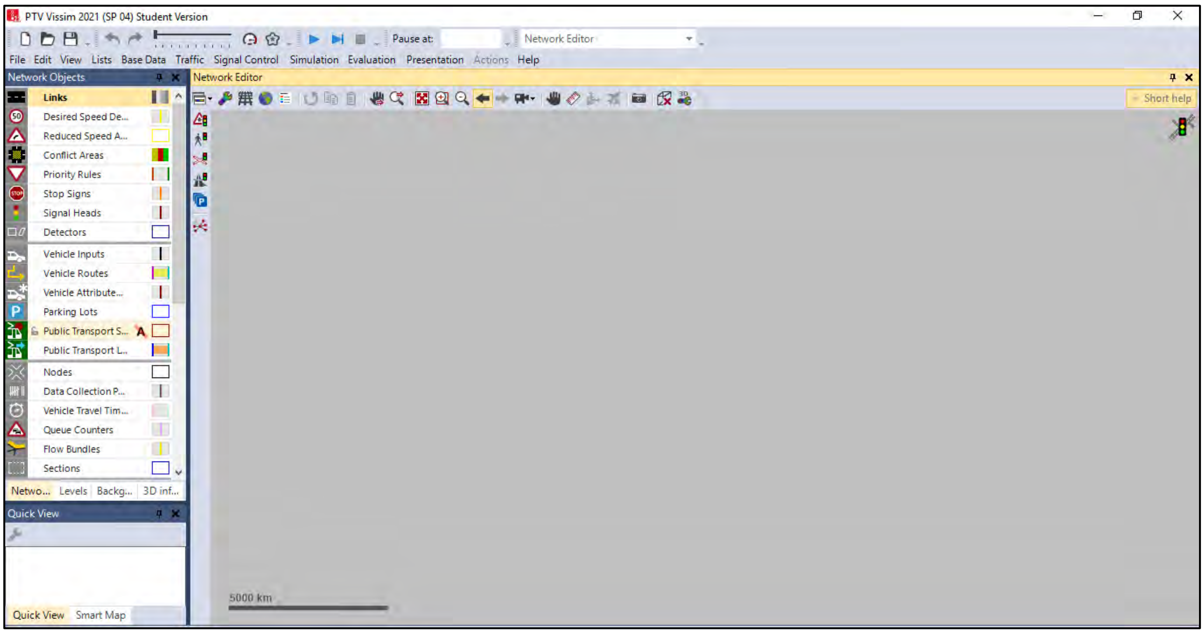

Figure 5.6 User interface of PTV VISSIM 2021 student version

5.4.2.2 Conflict Areas Features

Instead of using the priority rules feature, VISSIM recommends using conflict areas because they are easier to handle, and driving behavior during simulation can be controlled. The conflicting area appears automatically when two intersecting links are coded in VISSIM (PTV, 2021). Figure 5.7 shows the possible scenarios that could be used for conflicted areas. The details of the color coding in the conflicting area are listed here:

I. Green: main traffic flow (right of way)
II. Red: minor traffic flow (yield)
III. Both red: undetermined, both vehicles will see each other and will remain within their original sequence
IV. Both yellow: inactive conflict area without right of way/undetermined

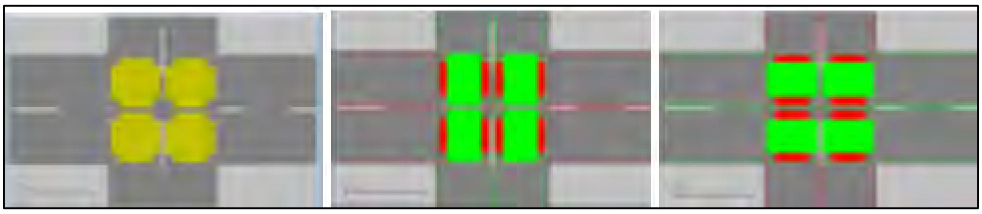

Figure 5.7 Different settings of conflict area (PTV, 2021)

5.4.2.3 Conflict Area Attributes

VISSIM is used different attributes related to the conflicting area. Each attribute's definition and details are provided here:

Front gap: The least time difference in seconds between the back end of the vehicle and the vehicle front end for the major and minor traffic streams, respectively. The front gap is also defined "for the merging conflict" as the time needed for the waiting vehicle to enter the conflict area after the vehicle that has the priority has entered it. Figure 5.8 illustrates the position of the cars before and after for the major and minor traffic streams as they are approaching the conflict area and with the gap of 0.5 seconds.

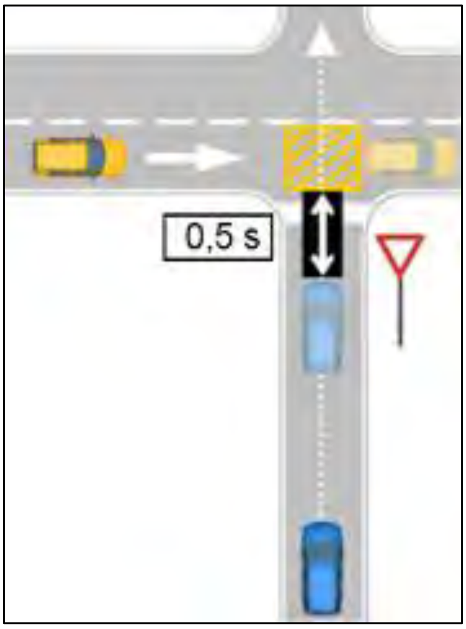

Figure 5.8 Front gap in VISSIM SP04 (PTV, 2021)

Rear gap: The least time gap in seconds between the back end of the vehicle and the front end of the vehicle in the minor and major traffic streams, respectively. This rear gap is used for the crossing conflicts and not for the merging conflicts. Figure 5.9 shows the rear gap with a minimum gap of 0.7 seconds (PTV, 2021).

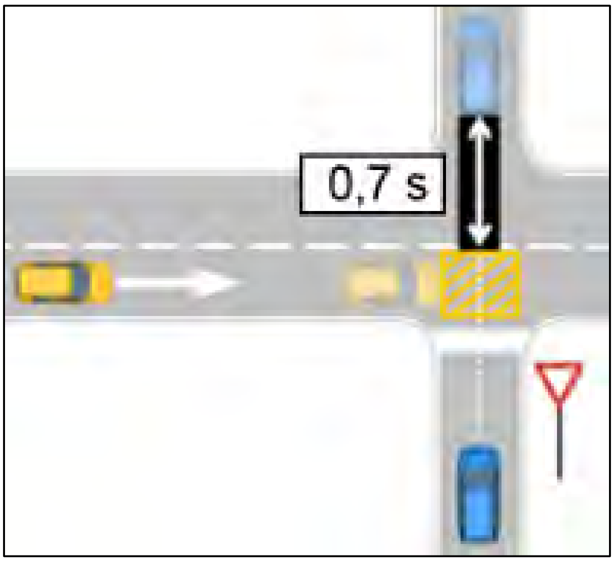

Figure 5.9 Rear gap in VISSIM SP04 (PTV, 2021)

Safety Distance Factor: VISSIM suggests that this attribute should be used only for the merging conflict. It is defined as the factor to be multiplied by the preferred safety distance of the major stream vehicle so that the minimum distance of the yielding vehicle is calculated and known. Figure 5.10 shows the same scenarios with different safety distance factors (i.e., 1.0 and 0.5 seconds for top and bottom cases, respectively) (PTV, 2021).

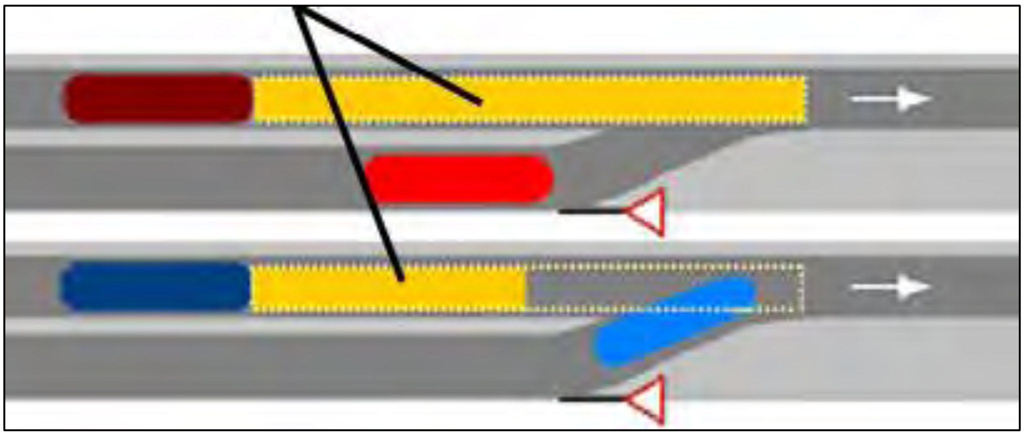

Figure 5.10 Different safety factor values (PTV, 2021)

5.4.2.4 Coding of Roundabouts

The main purpose of using microscopic simulation was to replicate the actual field and estimate the capacity of each targeted entry approach. The following steps were used to code the roundabouts in VISSIM (PTV, 2021):

I. AutoCAD pdf drawing of roundabouts were imported as background to model the geometry of the roundabout.

II. Links and connectors were coded to build the roundabout, as shown in Figure 5.11-Figure 5.16

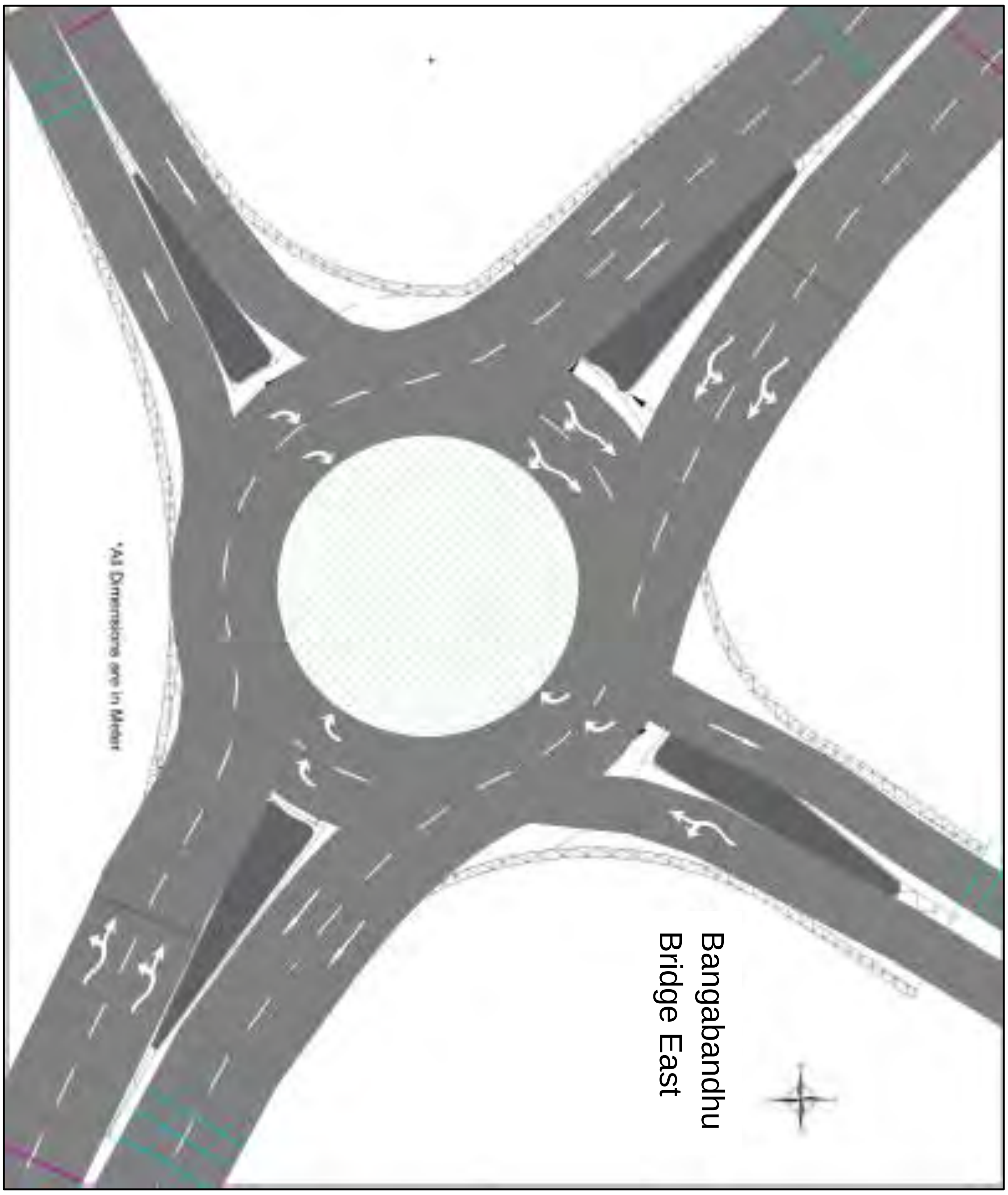

Figure 5.11 VISSIM model coding of roundabout R1

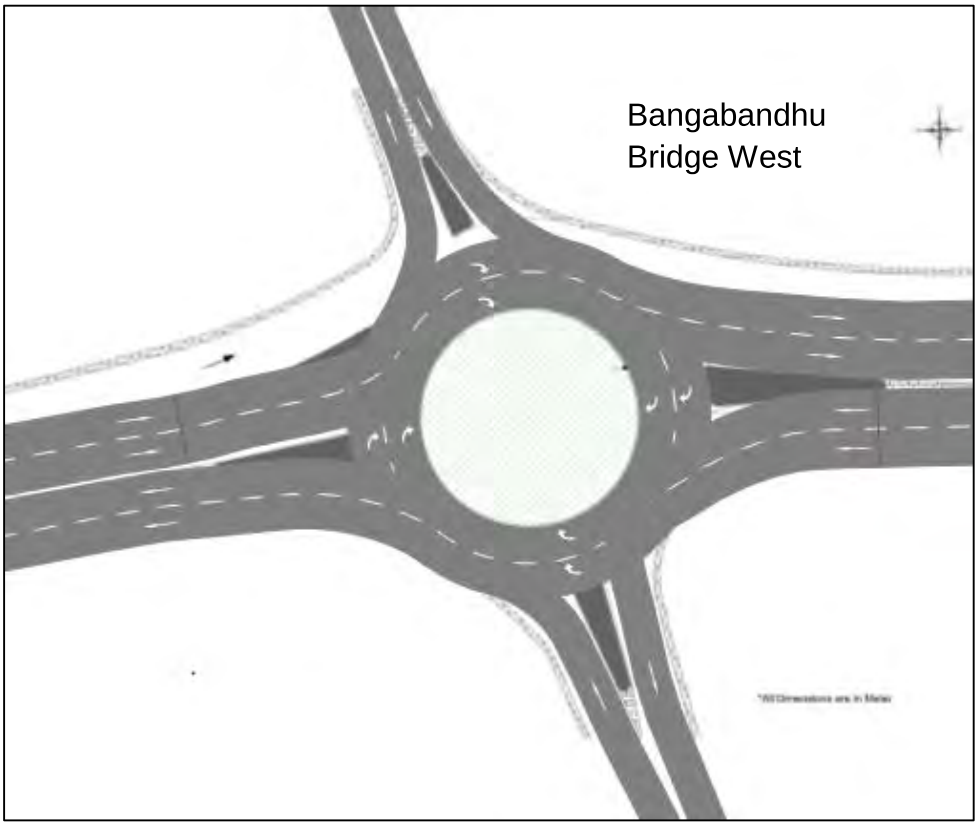

Figure 5.12 VISSIM model coding of roundabout R2

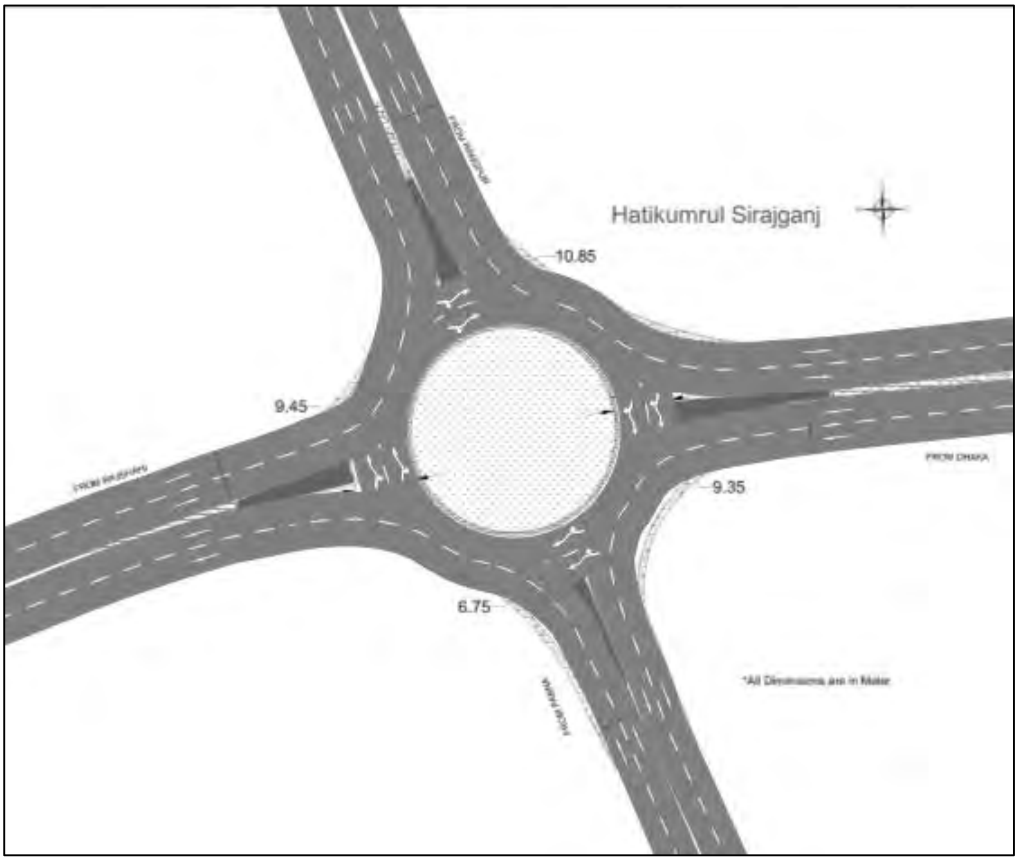

Figure 5.13 VISSIM model coding of roundabout R3

Figure 5.14 VISSIM model coding of roundabout R4

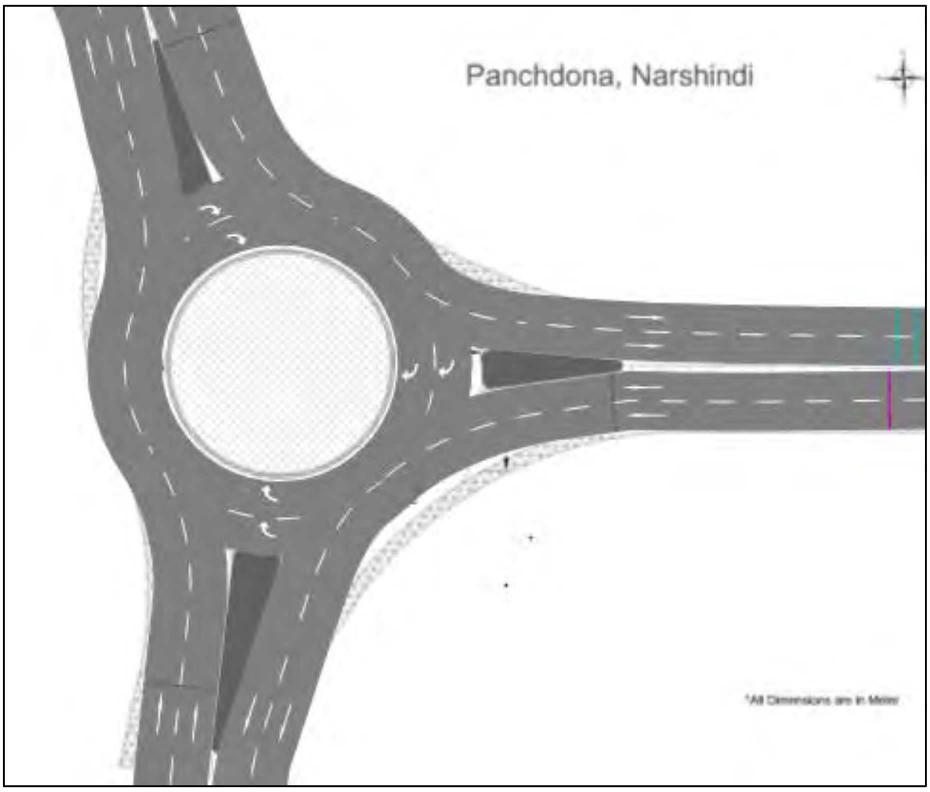

Figure 5.15 VISSIM model coding of roundabout R5

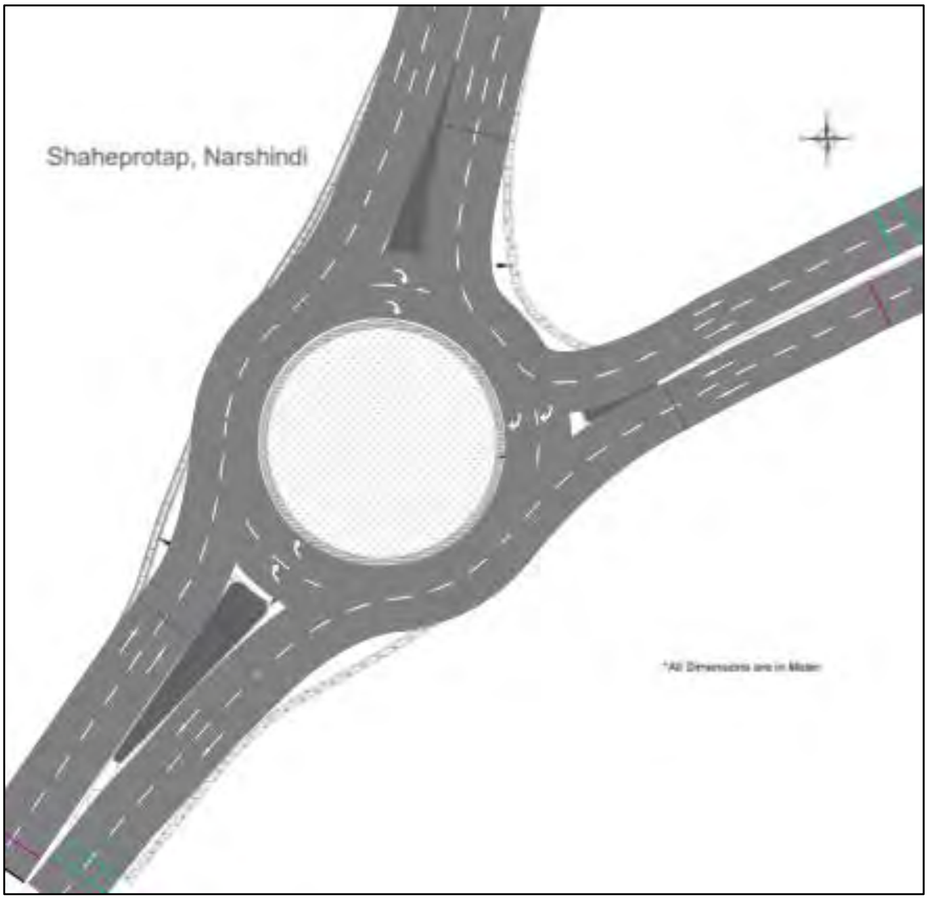

Figure 5.16 VISSIM model coding of roundabout R6

III. Traffic volume, vehicle type, and composition were coded on the links. Note that each lane volume was input separately.

Routing rules were assigned for each lane. Vehicle speed of different types of vehicles was input at dedicated link separately. Conflict areas were also defined, as shown in Figure 5.17-Figure 5.22. Conflict areas were highlighted in yellow, by default, which means the yield is undetermined. The priority was given to the circulating lanes as this is how modern roundabouts work. Red crossing bars indicate that the entering vehicles shall yield and give priority to the green crossing bars for circulating vehicles. This was the only change that was performed manually; the rest of the parameters have VISSIM's default values.

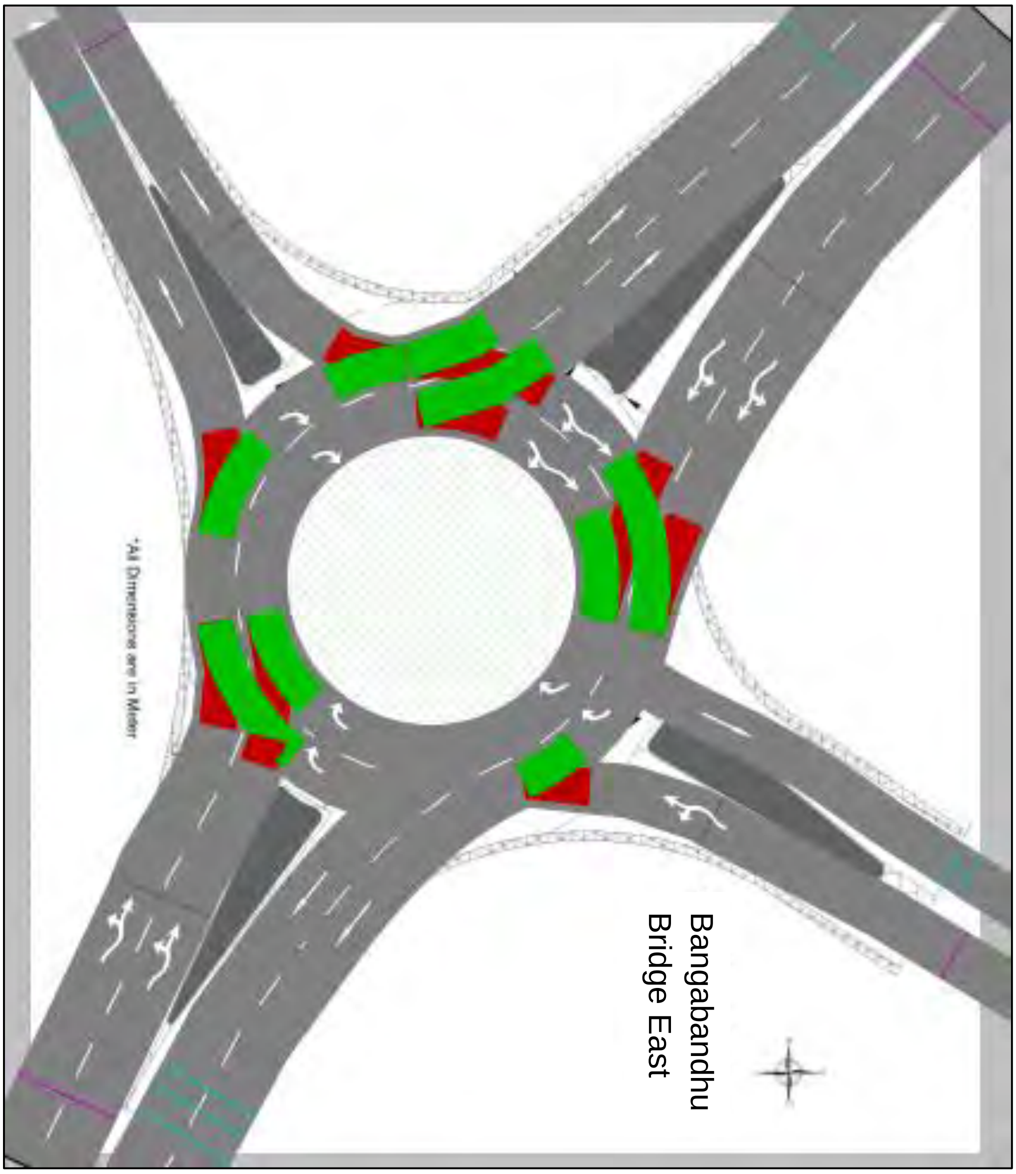

Figure 5.17 Conflict area and priority rules of roundabout R1

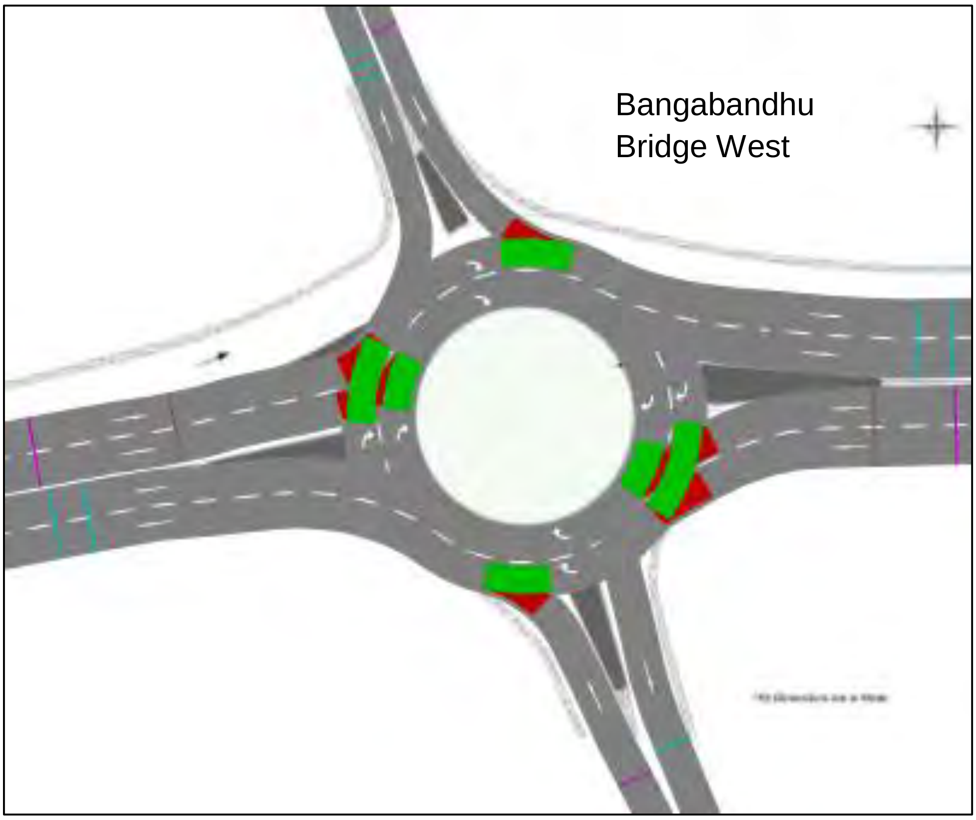

Figure 5.18 Conflict area and priority rules of roundabout R2

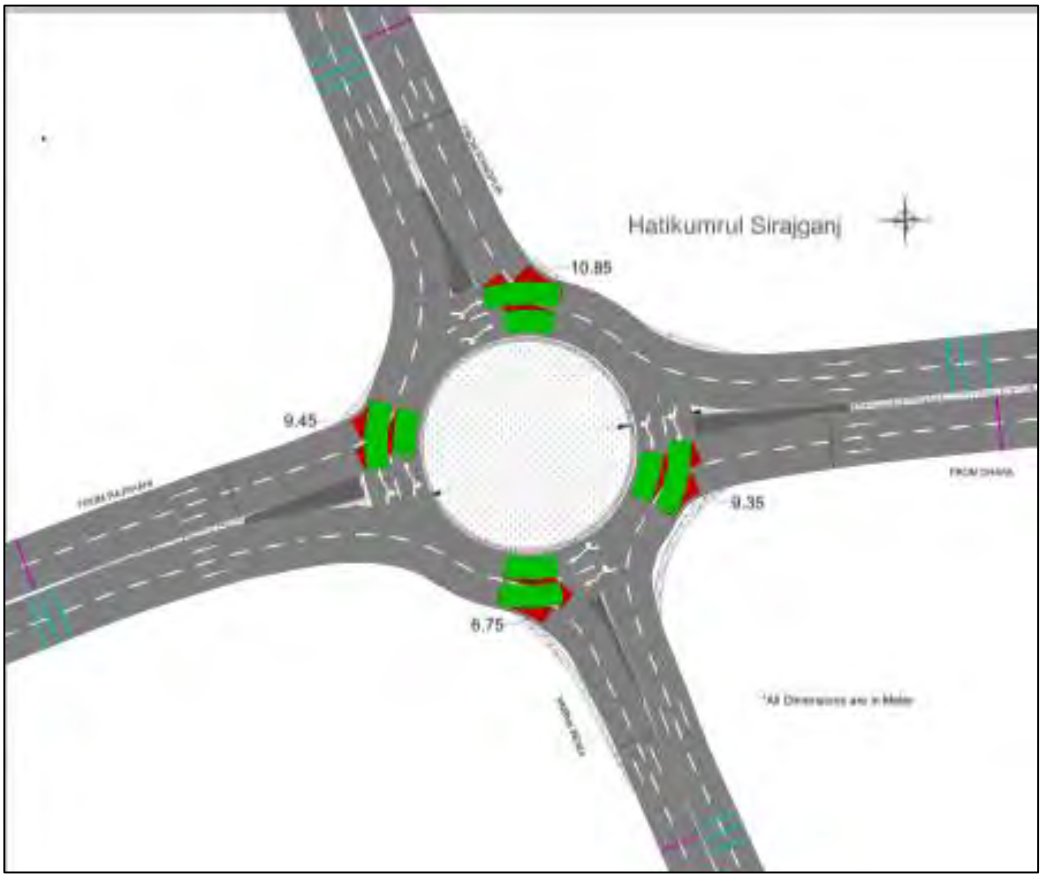

Figure 5.19 Conflict area and priority rules of roundabout R3

Figure 5.20 Conflict area and priority rules of roundabout R4

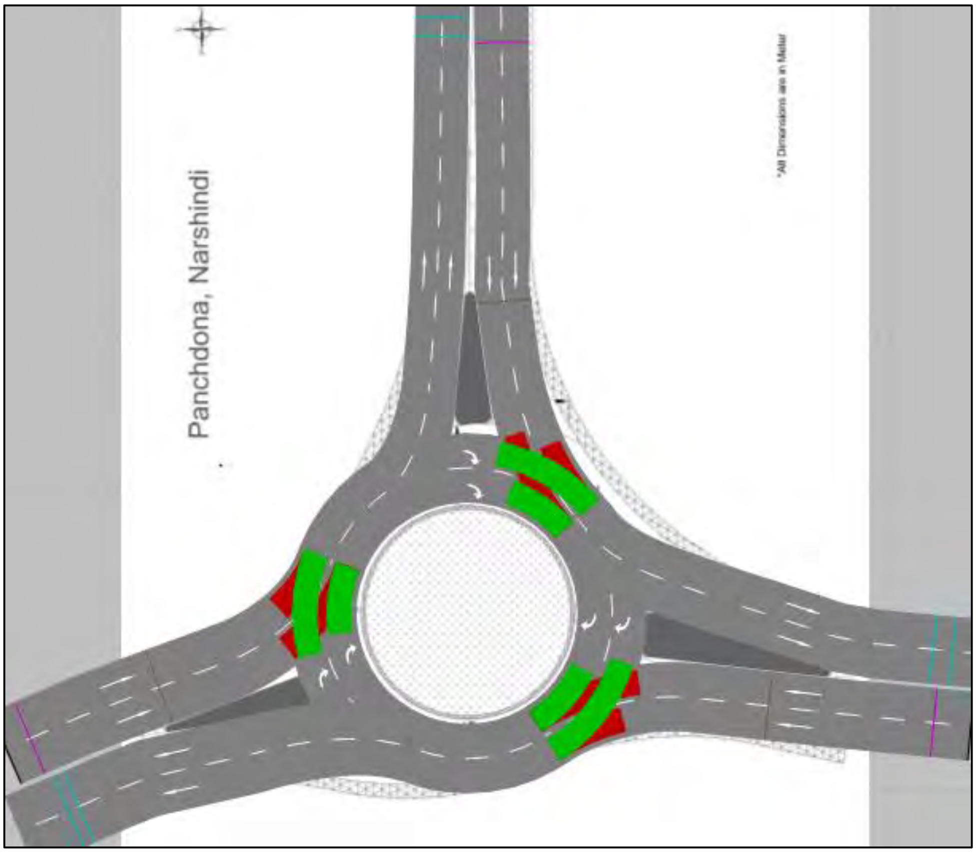

Figure 5.21 Conflict area and priority rules of roundabout R5

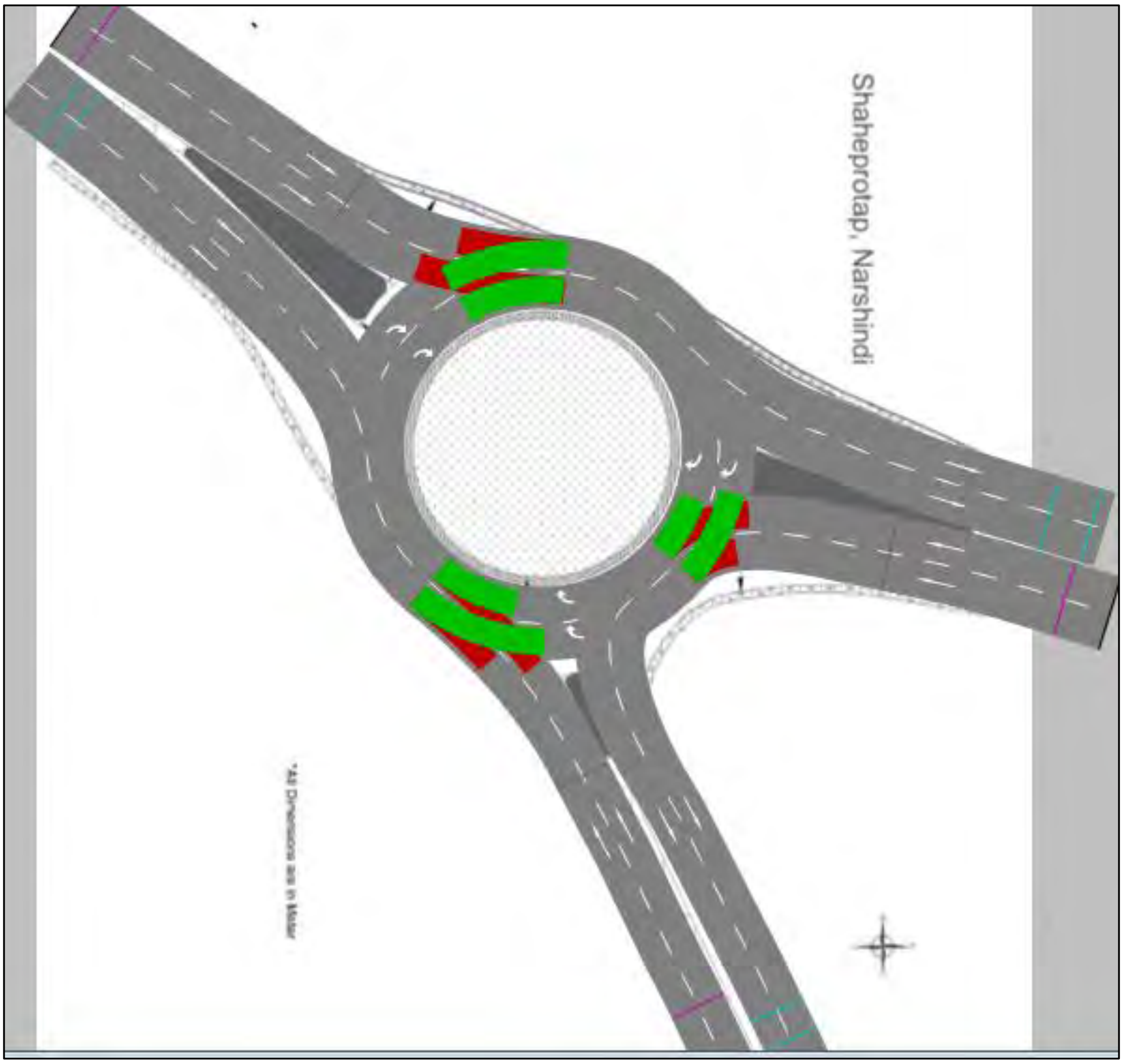

Figure 5.22 Conflict area and priority rules of roundabout R6

5.4.2.5 Data Collection Location

The main outputs from the simulation required were the entry approach traffic flow. The location of Data Collection (DC) points/detectors were named as lane wise and denoted by numeric number; i.e., 1, 2,3 etc. These DCs were used to count the vehicles crossing those points in the same manner that was done on the field data when analyzing the videos either manually or using the software as discussed earlier. After coding the model of the roundabout, a period of ten minutes was coded for each individual run.

5.5 Development of Nomograph

Further, in order to introduce a graphical way of calculating the capacity of roundabouts, a nomograph corresponding to the empirical model has been developed using PyNomo (Glasser and Doerfler, 2019) software which is independent of operating system as it is written in Python language and can generate nomographs having multiple variables.

A nomogram is a diagram that provides a graphical way of calculating the result of a mathematical formula. Sometimes called an alignment chart, a nomogram consists of a set of numbered scales, usually one for each variable in the formula, arranged so that a straightedge can be placed across known values to find the unknown value that solves the formula. Since an equation in two variables is usually represented by a graph, most nomograms represent formulas that involve three or more variables. These graphical calculators were invented in 1880 by Philbert Maurice d'Ocagne and used extensively for many years to provide engineers with fast graphical calculations of complicated formulas to a practical precision. Electronic calculators and computers have made nomograms much less common today, but when a fast, handy calculator of a particular formula is needed they can be very useful. The cost to produce one is a sheet of paper, and they are fun to design, easy to use, and can be beautiful designs that engage people.

The simplest nomogram, one we often encounter, is a single scale with numbers on both sides of it. This is called a conversion scale, and some people would hesitate to call it a nomogram at all. It provides conversion between two functions such as units of measurement.

The most common type of multi-scale nomogram consists of three parallel straight scales. It is used to solve an equation in which functions of three variables are added. The simplest such formula is

$$u1+u2+u3 = 0 \quad \text{.......... (5.2)}$$

for the three variables u1, u2 and u3 .An example of this type of nomogram from the PyNomo website is shown in Figure 5.23 below, annotated with terms used to describe the parts of a nomogram. A line (called an index line or isopleth) or a straightedge will cross the three scales at values that solve this equation, so if you know the values of any two of the variables you can find the third very easily.

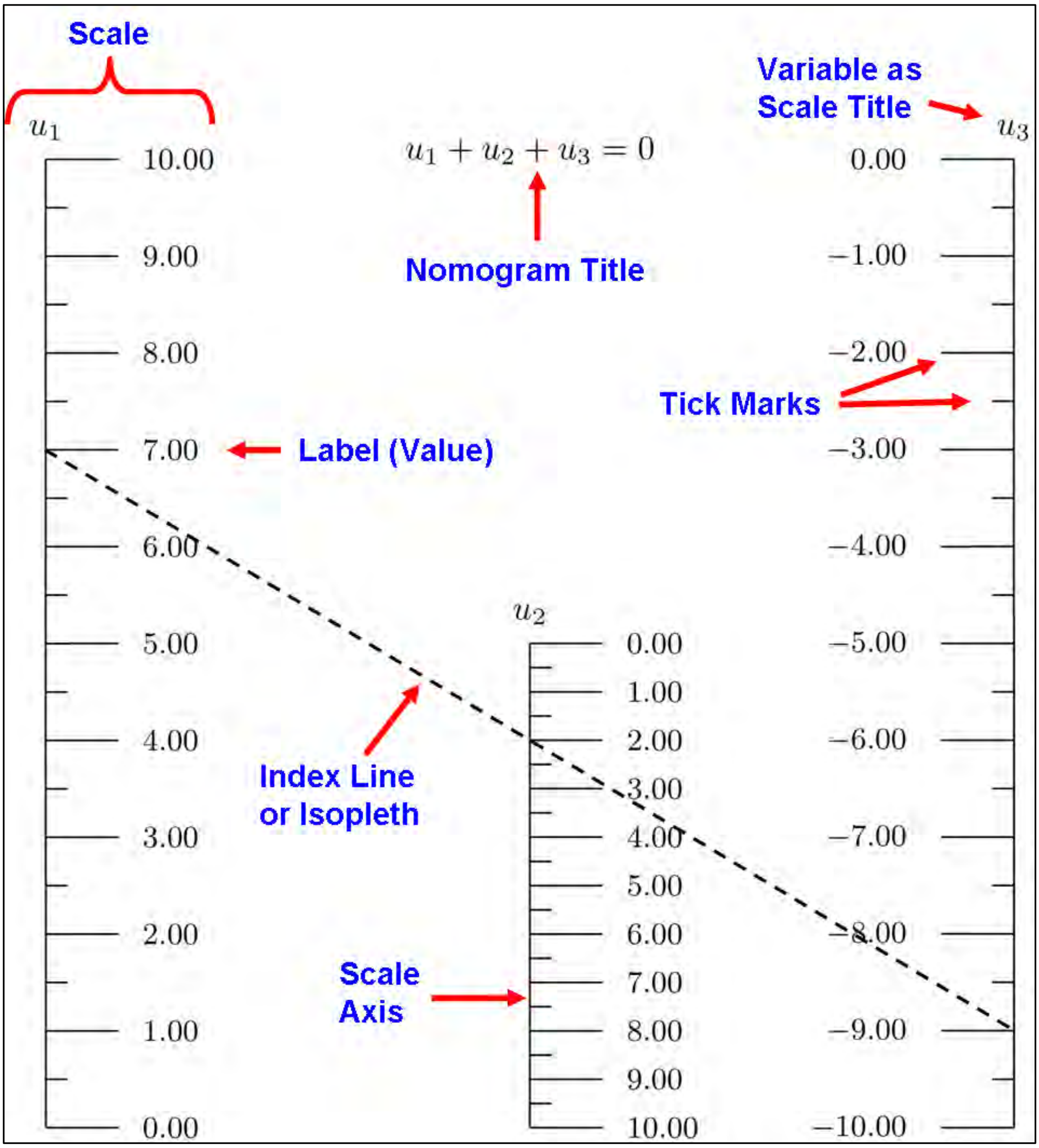

Figure 5.23 Basic element of a nomograph

There are many (out-of-print) books on the mathematics of nomography, but PyNomo allows us to design nearly all nomograms with very little mathematics background. A knowledge of algebra is necessary in order to arrange the formula into a standard type of equation that PyNomo supports. Then a PyNomo script for creating the nomogram can be copied from a standard example of that type and edited to match the terms in the formula. The script is run and a PDF file is created with the nomogram laid out for printing. Copying and modifying a standard example is easy and fast. The spacing of tick marks on the scales, the scale titles, the location of the nomogram title can be modified. Drawing of isopleth and add color to the scales and their labels can easily be modified. PyNomo offers many such features, and in this study tries to cover them all, but don't be put off by these extra details sprinkled in the examples here. They may make the scripts appear more complicated, but they are totally optional and can be ignored until the day you decide you really would like that one scale to be red.

Nomographs (Evesham, 1986) act as a graphical solution for functions having multiple variables which can be used by connecting points with a straight-line on scales representing independent variables, which then crosses the corresponding datum point for the dependent variable; it is flexible to choose among independent and dependent variable so that each variable may be determined in terms of the others. PyNomo version 0.2.2 has been used with Python 2.6 and four Python add-on packages i.e., NumPy, SciPy, PIL, and PyX along with MiKTeX distribution of the typesetting language LaTeX to generate the multi-variable compound parallel scale type nomograph having the form of equation:

$$f_1(u_1) + f_2(u_2) + \ldots\ldots + f_n(u_n) = 0 \qquad \ldots\ldots\ldots (5.3)$$

5.6 Model Calibration and Validation

The calibration of the simulation models was based on comparing the observed entry flow against entry flow derived from ten-minute flows during periods of continuous simulation. It was found that the parameters above produced was not matched with the actual capacity, but overestimated capacities for the selected roundabouts. There was thus a need for further calibration of the VISSIM model.

A review of the literature showed little consensus among researchers, industrial practitioners and public organizations on calibration methods for VISSIM roundabout models. Calibration approaches used by researchers were generally on a case-by-case basis, where the measures used for calibration through comparisons with empirical data have included critical gaps and/or follow-on headways (Li et al., 2013; Cicu et al., 2011; Peterson et al., 2008), speeds (Vaiana and Iuele, 2012; Vaiana and Gallelli, 2011; Keen et al., 2008); travel times (Valdez et al., 2011), headway distributions (Fortuijn, 2009b); capacity (Hummer et al., 2014; Wei and Grenard, 2012).

In addition, several car-following and gap acceptance parameters in VISSIM have been found to affect the entry capacity of roundabouts (Li et al., 2013; Wei and Grenard, 2012; Cicu et al., 2011). Computational approaches to calibrate multiple parameters (e.g. genetic algorithms or neural networks) have previously been used (Vasconcelos and Seco, 2014a; Vasconcelos et al., 2014b; Istoka et al., 2011; Duong et al., 2011; Park and Qi, 2005), but there was a real risk in this case of over-fitting the models given the relatively limited field data (less than 100 capacity data points for each roundabout entry lane) and the large number of model parameters. Another problem was that it was not possible to determine whether the optimized parameter values were suitable without detailed data such as vehicle kinematics. It was thus decided to select specific parameters for calibration based on measures which could be determined using available resources from field data.

Towards this, one possible approach considered was to calibrate priority rule time gaps using critical gaps estimated from field data (Li et al., 2013; Cicu et al., 2011). However, field observations in this and other studies (Wei and Grenard, 2012; Xu and Tian, 2008) suggested that exiting flows likely impact on rejected headways and therefore critical headway estimates. In particular, critical gaps become significantly overestimated due to the inhibition caused by exiting vehicles (Suh et al., 2015; Fortuijn, 2009b; TRB, 2007; Hagring, 2001). There is yet to be an estimation method which adequately allows for this without incommensurate approximations such as assuming every exiting vehicle would have circulated at an average speed (Zheng et al., 2012; Mereszczak et al., 2006).

In addition, the maximum likelihood method of Troutbeck (1992) widely agreed to be the best method of estimating mean critical gaps from the field (Brilon et al., 1999) typically assumes a log-normal gap distribution, which contrasts with the constant time gaps of VISSIM. The critical gap and VISSIM time gap are thus not directly comparable, so it was decided to leave the time gaps unchanged across the models.

Li et al. (2013) and Wei et al. (2012) calibrated VISSIM'S default car-following model parameters using mean follow-on headways between successive vehicles entering the same gap. To a certain extent, as suggested by Suh et al. (2015), Wei and Grenard (2012) and Xu and Tian (2008), follow-on headways could also be partly affected by exiting vehicles, since drivers can make their gap acceptance decisions during their approach. However, they had the key advantage over critical gaps of being directly measurable and directly comparable between the model and the field.

By comparing follow-on headway distributions from each model with at least 123 actual follow-on headway measurements for all site, the Wiedemann 1999 additive and multiplicative car-following parameters were changed from the defaults values. The changed default values are shown for each site in Table 5.4 to Table 5.6

Table 5.4 Default and changes values for calibration of roundabout R1 and R2

Roundabout	**R1**		**R2**	
Parameter Name	**Changed Values**	**Default Values**	**Changed Values**	**Default Values**
Following				
Look ahead distance (m)				
Max.	250	250	250	250
Min.	30	0	30	0
Car following model				
CCO (standstill distance), m	1.5	1.5	0.9	1.5
CC1 (gap time distribution, sec)	5	0.9	5	0.9
Lane change				
Waiting time before diffusion (s)	600	60	600	60
Min. Clearance (front/rear), m	1	0.5	1	0.5
Lateral				
Minimum lateral distance (m)				
Distance standing	0.1	0.2	0.1	0.2
Distance driving	1.5	1	2.5	1

Table 5.5 Default and changes values for calibration of roundabout R3 and R4

Roundabout	**R3**		**R4**	
Parameter Name	**Changed Values**	**Default Values**	**Changed Values**	**Default Values**
Following				
Look ahead distance (m)				
Max.	250	250	250	250
Min.	30	0	30	0
Car following model				
CCO (standstill distance), m	0.6	1.5	0.9	1.5
CC1 (gap time distribution, sec)	0.9	0.9	5	0.9
Lane change				
Waiting time before diffusion (s)	600	60	600	60
Min. Clearance (front/rear), m	1	0.5	1	0.5
Lateral				
Minimum lateral distance (m)				
Distance standing	0.1	0.2	0.1	0.2
Distance driving	2.5	1	2.5	1

Table 5.6: Default and changes values for calibration of roundabout R5 and R6

Roundabout	R5		R6	
Parameter Name	**Changed Values**	**Default Values**	**Changed Values**	**Default Values**
Following				
Look ahead distance (m)				
Max.	250	250	25	250
Min.	25	0	30	0
Car following model				
CCO (standstill distance), m	1.5	1.5	0.9	1.5
CC1 (gap time distribution, sec)	5	0.9	5	0.9
Lane change				
Waiting time before diffusion (s)	600	60	600	60
Min. Clearance (front/rear), m	1	0.5	1	0.5
Lateral				
Minimum lateral distance (m)				
Distance standing	0.1	0.2	0.1	0.2
Distance driving	1.5	1	2.5	1

Adjusting the Wiedemann 1999 default values and continuous simulation was performed for 600s., the output the simulation model was analyzed and compared with the standard calibration targeted shown in Table 5.7. By trial and error method the calibration process was completed.

Table 5.7 List of calibration targets

Criteria and Measures	Acceptability Targets
Hourly Flows, Model vs Observed	
Individual Link Flows	
Within 15%, for 700 vph < Flow < 2700 vph	> 85% of Cases
Within 100 vph for Flow < 700 vph	> 85% of Cases
Within 400 vph for Flow > 2700 vph	> 85% of Cases
Total Link Flows	
Within 5%	
GHE Statistic – Individual Link Flows	All Accepting Link

Contd. Table 5.7

Criteria and Measures	Acceptability Targets
GHE < 5 GHE Statistic – Total Link Flows GHE < 4	> 85% of Cases All Accepting Link
Travel Time, Model vs Observed Journey Time Networks Within 15% (or one minute, if higher)	 > 85% of Cases
Visual Audits **Individual Link Speeds** Visually acceptable Speed-Flow relationship **Bottlenecks** Visually acceptable Queuing	 To Analyst's satisfaction To Analyst's satisfaction

The calibrated VISSIM capacity and observed capacity of the selected sites is shown in Table 5.8. From the table it is found that the developed VISSIM model was calibrated by maintaining the standard calibration target.

Table 5.8 Calibrated VISSIM model capacity and observed capacity

Roundabout	Highway Name	Entry Name	Observed Capacity (pcu/h)	VISSIM Capacity (pcu/h)	% of Deference	GEH
R1	Dhaka-Rangpur	EN1	1085	1108.5	2%	0.71
		EN2	1190	1245	4%	1.58
R2	Dhaka- Rangpur	EN3	1654	1567.5	-6%	2.16
		EN4	1460	1407	-4%	1.40
R3	Dhaka- Rangpur	EN5	1307	1465.5	11%	4.26
	Dhaka- Rangpur	EN6	1334	1161	-15%	4.90
			1271	1360.5	7%	2.47
	Dhaka- Rangpur	EN7	1572	1599	2%	0.68
	Dhaka- Rangpur	EN8	693	810	14%	4.27
R4	Dhaka-Sylhet	EN9	1522	1562	3%	1.01
	Dhaka-Sylhet	EN10	1121	1098	-2%	0.69
R5	Dhaka-Sylhet	EN11	1193	1161	-3%	0.93
	Dhaka-Sylhet	EN12	1468	1431	97%	0.97
R6	Dhaka-Sylhet	EN13	1565	1490	-5%	1.93
	Dhaka-Sylhet	EN14	1348	1305	-3%	1.18

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Capacity Estimation Model for Existing Conditions

Capacity for existing roundabout was estimated by applying the developed equation. Multiple linear regression analysis has been performed to develop a general entry-capacity model for highway roundabouts in Bangladesh. The following capacity estimation equation has been developed:

$Qe = 119.28 \times 0.3571D \times 0.1945L \times \exp(0.0318 \times E + 0.0396 \times R) \times \exp(-0.0004 \times Qc)$ **....** (6.1)

The results of the regression analysis are presented in Table 6.1.

Table 6.1 Result of multiple linear regression analysis

Regression Statistics				
R Square	0.9527			
Adjusted R Square	0.9507			
Standard Error	0.0581			
Number of Observations	123			
Analysis of Variance				
	df	Sum of Squares	Mean Square	F-value
Regression	5	7.9595	1.5919	471.2722***
Residual	117	0.3952	0.0034	
Total	122	8.3547		
Regression Parameter Estimates				
	df	Coefficients	Standard Error	t-Stat
Intercept	1	4.7815	0.3081	15.5204***
Circulating Flow	1	-0.0004	0.0001	-6.6528***
Entry Width	1	0.0318	0.0157	2.0235*
Circular Road Width	1	0.0395	0.0114	3.4694***
ln (Dia. Of Central Island)	1	0.3571	0.0779	4.5842***
ln (Entry to Exit Distance)	1	0.1945	0.0403	4.8310***

Note: $^{***}p< 0.001$, $^{**}p< 0.01$, $^{*}p<0 .05$

From the results showed in Table 6.1, the coefficient of determination, R^2 of the developed model was found to be 0.9527 which indicates that the parameters used i.e., circulating flow, entry width, circular road width, diameter of the central island, and distance between entry to nearest exit account for 95.27% of the variation in entry flow of a highway roundabout. The F-value for this regression model was found to be 471.2722 which is significant at p<0.001, hence the regression model overall predicts entry flow significantly well. The observed significance of entry width is less than 0.05, and for the other regression parameters it is less than 0.001, therefore, all of the parameters make a significant contribution to predicting entry flow. From the observation of the regression parameter coefficients, it can be concluded that an increase in circulating flow will decrease the entry flow whereas an increase in entry width, circular road width, diameter of the central island, or distance between entry to nearest exit will increase the entry flow of a highway roundabout, such findings are practically feasible phenomenon and also supported by the results obtained in several previous studies (Al-Masaeid and Faddah (1997; Polus and Shmueli, 1997; Brilon and Stuwe, 1993).

Sensitivity analysis has been performed on the developed empirical capacity model and the result is shown in Table 6.2.

Table 6.2 Results of sensitivity analysis

Serial Number	Parameters	Changed of Variable Value (%)	Changed of Entry Capacity (%)
1	Circulating Flow (PCU/h)	1	-0.09%
2	Entry width, (m)	1	0.05%
3	Circular Road Width, (m)	1	1.92%
4	Dia. of Central Island, (m)	1	1.20%
5	Entry/Exit Distance, (m)	1	0.45%

The results of the above table reveal that 1% increment in circulating flow resulted in 0.09% decreased of the entry capacity. Like-wise, 1% increment of circular road widths caused 1.92% increment of the entry capacity. Whereas, 1% increment of entry road widths, central island diameters, and entry to nearest exit distances resulted in increment of capacity by 0.05%, 1.2%, and 0.45% respectively.

Capacity of the existing roundabout was predicted by using the developed empirical model. From the predicted capacity, it has been observed that the predicted capacity was very close to existing observed capacity. The estimated capacity is shown in the Table 6.3.

Table 6.3 Empirical model estimated capacity and observed capacity

Roundabout	Highway Name	Entry Name	Observed Capacity (pcu/h)	Estimated Model Capacity (pcu/h)	Difference (%)
Bangabandhu Bridge East (R1)	Dhaka-Rangpur	EN1	1085	1112	-2.44
			1002	1102	-9.94
			1120	1138	-1.59
			1192	1162	2.49
			1017	1093	-7.50
			1275	1197	6.13
			1228	1175	4.30
			1172	1143	2.50
		EN2	1190	1151	3.24
			1202	1176	2.19
			1239	1289	-4.07
			1367	1349	1.33
			1431	1421	0.72
			1282	1316	-2.65
			1287	1266	1.63
			1350	1345	0.34
			1486	1434	3.50
			1327	1343	-1.17
Bangabandhu Bridge West (R2)	Dhaka-Rangpur	EN3	1654	1782	-7.73
			1680	1786	-6.33
			1643	1731	-5.36
			1730	1815	-4.94
			1786	1859	-4.10
			1822	1871	-2.70
			1976	1900	3.85
			2225	1941	12.77
	Dhaka-Rangpur	EN4	1519	1546	-1.81
			1460	1518	-4.00

Contd. Table 6.3

Roundabout	Highway Name	Entry Name	Observed Capacity (pcu/h)	Estimated Model Capacity (pcu/h)	Difference (%)
			1523	1576	-3.50
			1493	1550	-3.80
			1589	1568	1.30
			1512	1597	-5.60
			1497	1518	-1.43
			1532	1529	0.21
Hatikumrul Roundabout Sirajganj (R3)	Dhaka-Rangpur	EN5	1307	1273	2.58
			1289	1281	0.64
			1359	1313	3.40
			1276	1291	-1.14
			1303	1298	0.40
			1320	1310	0.76
			1366	1323	3.12
			1292	1287	0.41
			1214	1277	-5.19
			1325	1325	-0.01
			1343	1301	3.16
	Dhaka-Rangpur	EN6	1334	1331	0.25
			1271	1289	-1.45
			1331	1337	-0.44
			1287	1261	2.00
			1324	1331	-0.50
			1249	1290	-3.28
			1337	1138	14.89
			1297	1308	-0.86
	Dhaka-Rangpur	EN7	1572	1630	-3.72
			1645	1695	-3.03
			1597	1635	-2.36
			1692	1728	-2.10

Contd. Table 6.3

Roundabout	Highway Name	Entry Name	Observed Capacity (pcu/h)	Estimated Model Capacity (pcu/h)	Difference (%)
			1742	1750	-0.49
			1615	1723	-6.70
			1567	1635	-4.32
			1596	1576	1.26
	Dhaka-Rangpur	EN8	525	592	-12.68
			536	576	-7.54
			693	555	19.85
			574	595	-3.63
			512	585	-14.27
			596	546	8.33
			565	564	0.17
			530	552	-4.14
Bishwaroad Roundabout Tarabo (R4)	Dhaka-Sylhet	EN9	1522	1437	5.60
			1492	1268	15.02
			1615	1435	11.15
			1347	1330	1.24
			1382	1373	0.62
			1294	1316	-1.72
			1384	1325	4.24
			1390	1377	0.94
			1363	1373	-0.73
			1316	1341	-1.91
			1274	1294	-1.58
			1584	1352	14.64
	Dhaka-Sylhet	EN10	1096	1100	-0.34
			1121	1117	0.34
			1128	1123	0.45
			1022	1088	-6.47
			1126	1125	0.10

Contd. Table 6.3

Roundabout	Highway Name	Entry Name	Observed Capacity (pcu/h)	Estimated Model Capacity (pcu/h)	Difference (%)
			1048	1097	-4.72
			1046	1089	-4.12
			1001	1073	-7.24
			1146	1126	1.76
			1176	1142	2.92
Panchdona Roundabout Narsingdi (R5)	Dhaka-Sylhet	EN11	1193	1178	1.25
			1143	1167	-2.11
			1146	1173	-2.32
			1130	1153	-2.07
			1174	1177	-0.22
			1192	1189	0.23
			1141	1147	-0.52
			1182	1175	0.55
	Dhaka-Sylhet	EN12	1468	1485	-1.14
			1516	1475	2.69
			1504	1497	0.44
			1612	1513	6.12
			1487	1566	-5.34
			1541	1557	-1.04
			1643	1510	8.09
			1592	1655	-3.94
Shaheprotab, Roundabout, Narsingdi (R6)	Dhaka-Sylhet	EN13	1242	1278	-2.86
			1245	1317	-5.76
			1565	1410	9.90
			1490	1275	14.40
			1310	1271	2.97
			1242	1313	-5.75
			1344	1274	5.22
			1263	1366	-8.20

Contd. Table 6.3

Roundabout	Highway Name	Entry Name	Observed Capacity (pcu/h)	Estimated Model Capacity (pcu/h)	Difference (%)
	Dhaka-Sylhet	EN14	1348	1263	6.33
			1425	1306	8.32
			1249	1260	-0.88
			1160	1214	-4.68
			1274	1325	-4.04
			1187	1235	-4.05
			1205	1325	-9.95
			1320	1319	0.10

Capacities were also estimated using the VISSIM computerized models. The VISSIM model was run using three sets of 10-minute entry flow for each targeted approach. After running the model, the entry flows were collected for each targeted approach, and the entry capacity for each approach was determined the capacity. In order to validate the VISSIM model, the flow times in the simulation were compared to the observed flow times for each approach. In general, observed and simulated flows for each approach were similar. However, the difference in standard deviation between the observed and simulated data was low. The simulation capacity was in acceptable limits of calibration targets which is discussed in the previous chapter.

The calibrated and validated VISSIM models of each sites were continuously simulated for ten minutes. The simulated results of each entry was recorded in Microsoft excel file and used for further analysis. The screenshot during simulation is shown in figures Figure 6.1 and Figure 6.2.

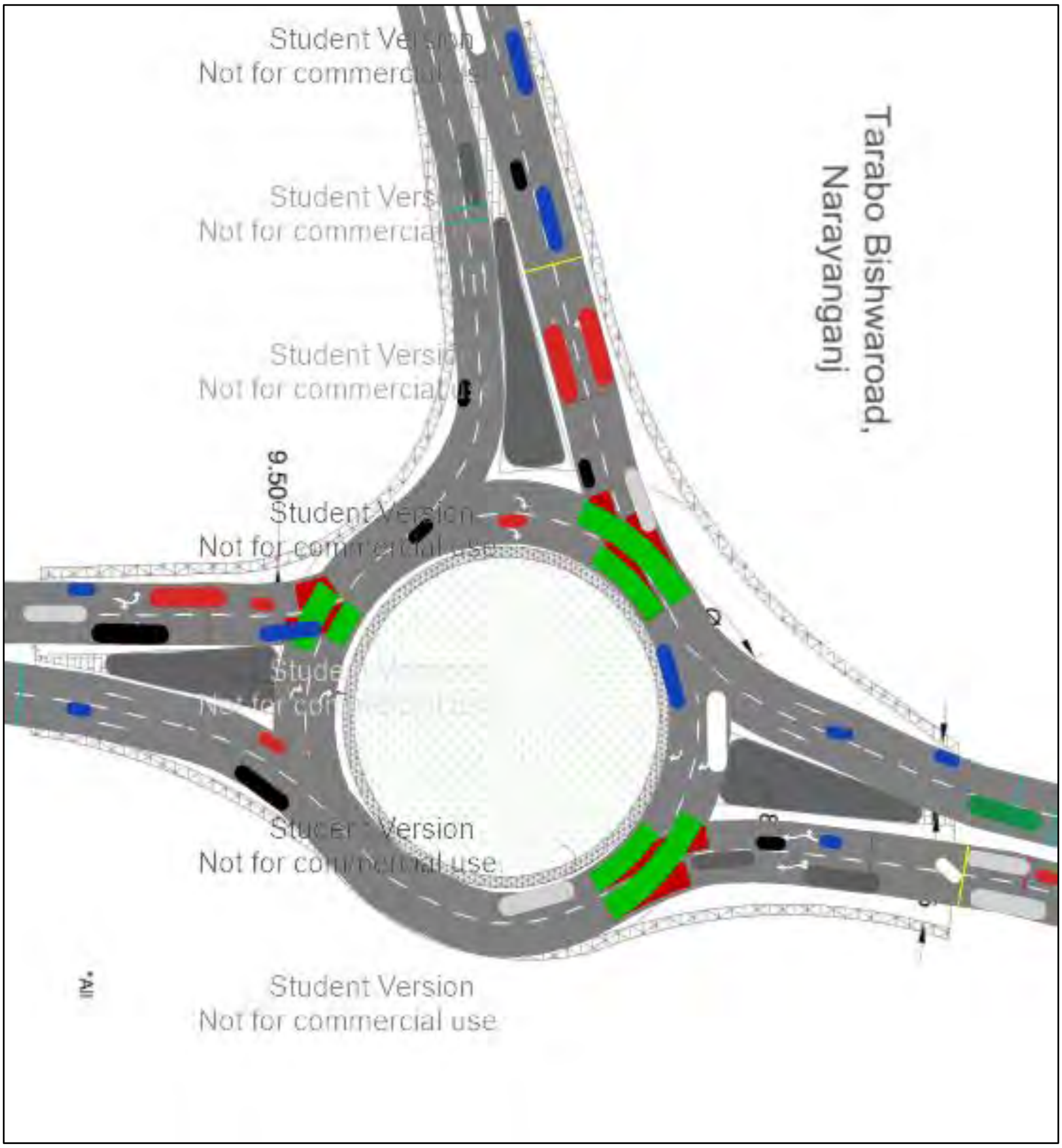

Figure 6.1 2D Simulation screenshot of roundabout R1 in VISSIM

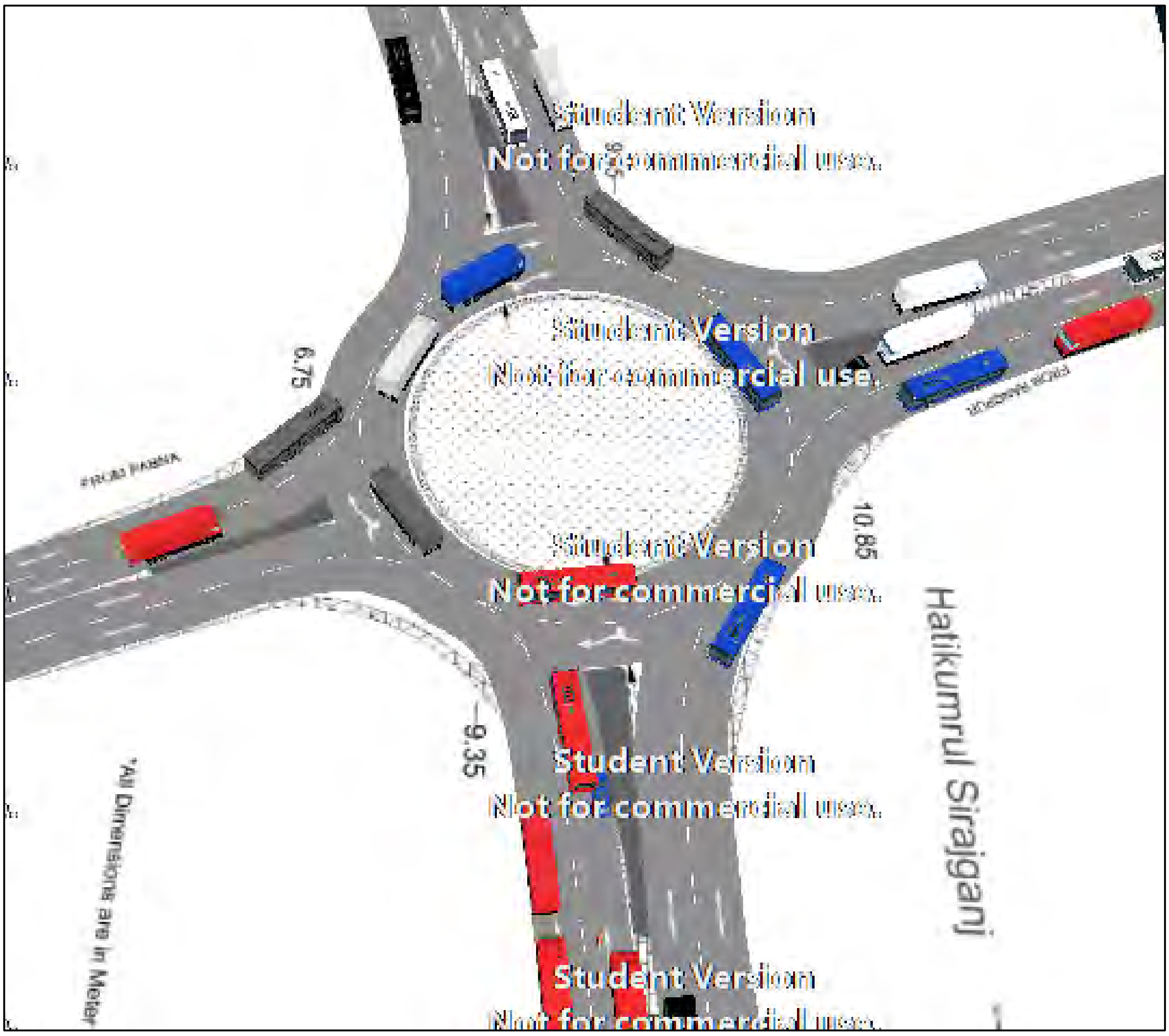

Figure 6.2 3D Simulation screenshot of roundabout R3 in VISSIM

The calibrated VISSIM model was edited with different geometric and traffic flow conditions and simulated for 600sec. The calibrated simulated entry capacity of roundabouts was compared with the developed empirical capacity shown in the Table 6.4. From the table is observed that the difference of simulated and empirical model capacity is significantly low.

Table 6.4 Observed, empirical and VISSIM model capacity

Roundabout Name	Entry Name	Observed Capacity (pcu/h)	Empirical Model Capacity (pcu/h)	VISSIM Model Capacity (pcu/h)
R1	EN1	1085	1112	1108
	EN2	1190	1151	1245
R2	EN3	1654	1782	1568
	EN4	1519	1546	1407

Contd. Table 6.4

Roundabout Name	Entry Name	Observed Capacity (pcu/h)	Empirical Model Capacity (pcu/h)	VISSIM Model Capacity (pcu/h)
R3	EN5	1307	1273	1466
	EN6	1334	1331	1161
	EN7	1572	1630	1599
	EN8	693	555	810
R4	EN9	1492	1268	1544
	EN10	1121	1117	1098
R5	EN11	1193	1178	1161
	EN12	1468	1484	1431
R6	EN13	1565	1410	1490
	EN14	1348	1262	1305

From the Figure 6.3 it is found that the observed , empirical and VISSIM model capacities are very close to each other. However, the developed microscopic simulation VISSIM capacity model has justified the developed empirical model in different geometric configuration of roundabouts as well as different traffic flow scenario.

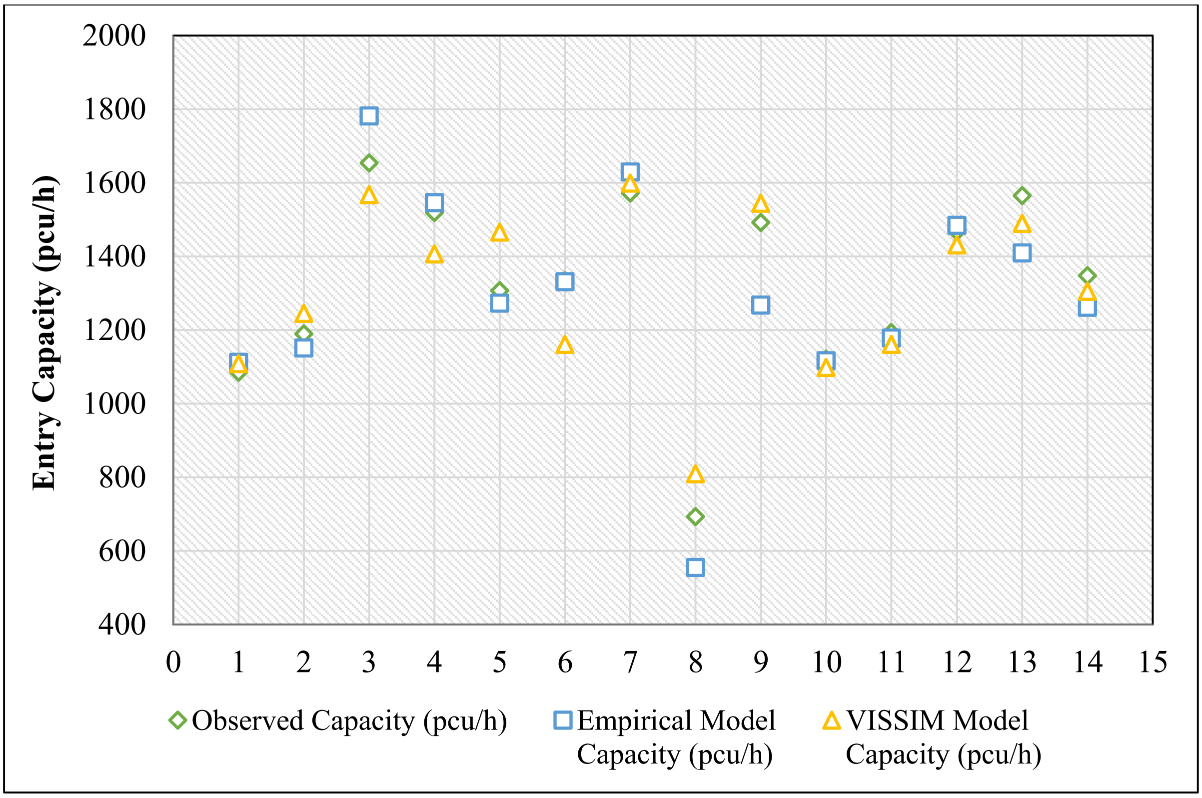

Figure 6.3 Observed and developed model capacity of roundabouts

6.2 Comparison among Different Capacity Estimation Model

In order to find out the entry capacity estimation model that is best fitting to the observed values, a comparison among different entry capacity estimation models has been graphically represented in Figure 6.4. It can be observed from the figure that entry flow decreases with increase in circulating flow for every model. Moreover, it is found that HCM 2016 model always underestimates the entry capacity, German model and TRRL model underestimates or overestimates the entry capacity for varying circulating flow, and IRC model always overestimates the entry capacity of a roundabout compared to the observed entry capacity but the developed entry capacity estimation model gives better estimation of entry capacity.

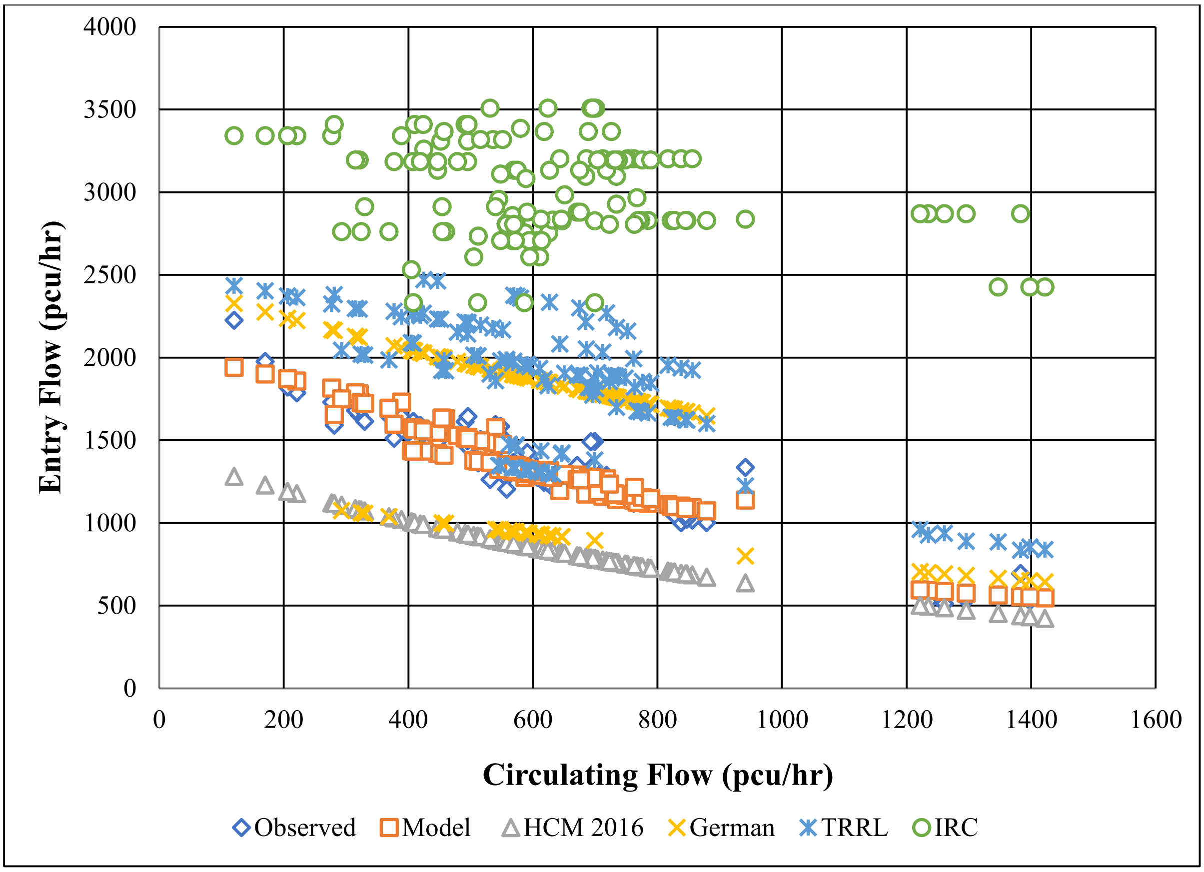

Figure 6.4 Comparison of different models in estimating entry capacity of roundabouts

Based on the hypothesis that the observed capacity values are significantly different from the capacity values estimated using different models, multiple paired two-tailed t-tests have been performed, the results of the analysis are presented in the Table 6.5.

Table 6.5 Results of multiple paired two-tailed t-tests

	Observed Values	Regression Model	HCM 2016 Model	German Model	TRRL Model	IRC Model
Mean (pcu/h)	1314.4688	1312.8438	927.6779	1601.4555	1853.9541	3006.6722
Variance $(pcu/h)^2$	81728.760	78636.830	9372.7100	222863.28	163423.020	85285.7900
No. of Observations	123	123	123	123	123	123
t-Statistics		0.2461	21.9309***	-7.6566***	-21.0249***	-55.1567***

Note: *** $p< 0.001$, ** $p< 0.01$, * $p< 0.05$

The results of t-tests presented in Table 4 reveal that the entry capacity of a roundabout estimated using HCM 2016 model, German model, TRRL model, and IRC model differs significantly from the observed capacity values but the estimation using the developed regression model does not differ significantly from the observed values. Hence, the developed regression model is statistically better in estimating entry capacity of roundabouts. Besides, the established entry capacity estimation models (i.e., HCM 2016 model, German model, TRRL model, and IRC model) are found to be underestimating or estimating the entry capacity which cohorts with the results of Arroju et al. (2015) whereas the developed empirical entry capacity estimation model provides better estimation based on easily measurable parameters, so, it is justified to use the empirical model to estimate entry capacity of rural highway roundabouts.

6.3 Nomograph for Estimation and Prediction of Roundabout Capacity

As an aid for the practitioners in estimating or predicting entry capacity of a roundabout, a graphical tool in the form of a nomograph has been developed using Pynomo software (Glasser and Doerfler, 2019) which is presented in Figure 6.5. Using geometric parameters (i.e., diameter of the central island, distance between entry and the nearest exit, entry width, and circulating road width), and traffic flow parameter (i.e., circulating flow of a roundabout), the entry capacity can be estimated from the nomograph. Further, similar to the results found in Polus and Shmueli (1997), it has been found that an exponential relationship exists between the entry capacity and circulating flow of roundabout which can expressed as $y = 3227.600 \times \exp(-0.001x)$ having a R^2 value of 0.866. While designing a new roundabout, the entry flow can be estimated based on the growth of future traffic demand, and the circulating flow can be estimated using the regression equation. For a developing country, land acquisition is a challenge for constructing new road networks, hence it will be helpful for the policymakers as well as the practitioners to know the area of land required to accommodate the traffic demand at a roundabout. If the number of lanes at the entry and exit are fixed, the width of entry and exit lane as well as the distance between the entry and the nearest exit can be estimated, therefore, the nomograph presented in Figure 6.5 can be efficiently used to determine the required diameter of the central island of a proposed roundabout based on a forecasted traffic volume. This graphical tool can be used as a handy design tool for the practitioners, designers, and engineers which will help policymakers to make better decisions in an efficient manner.

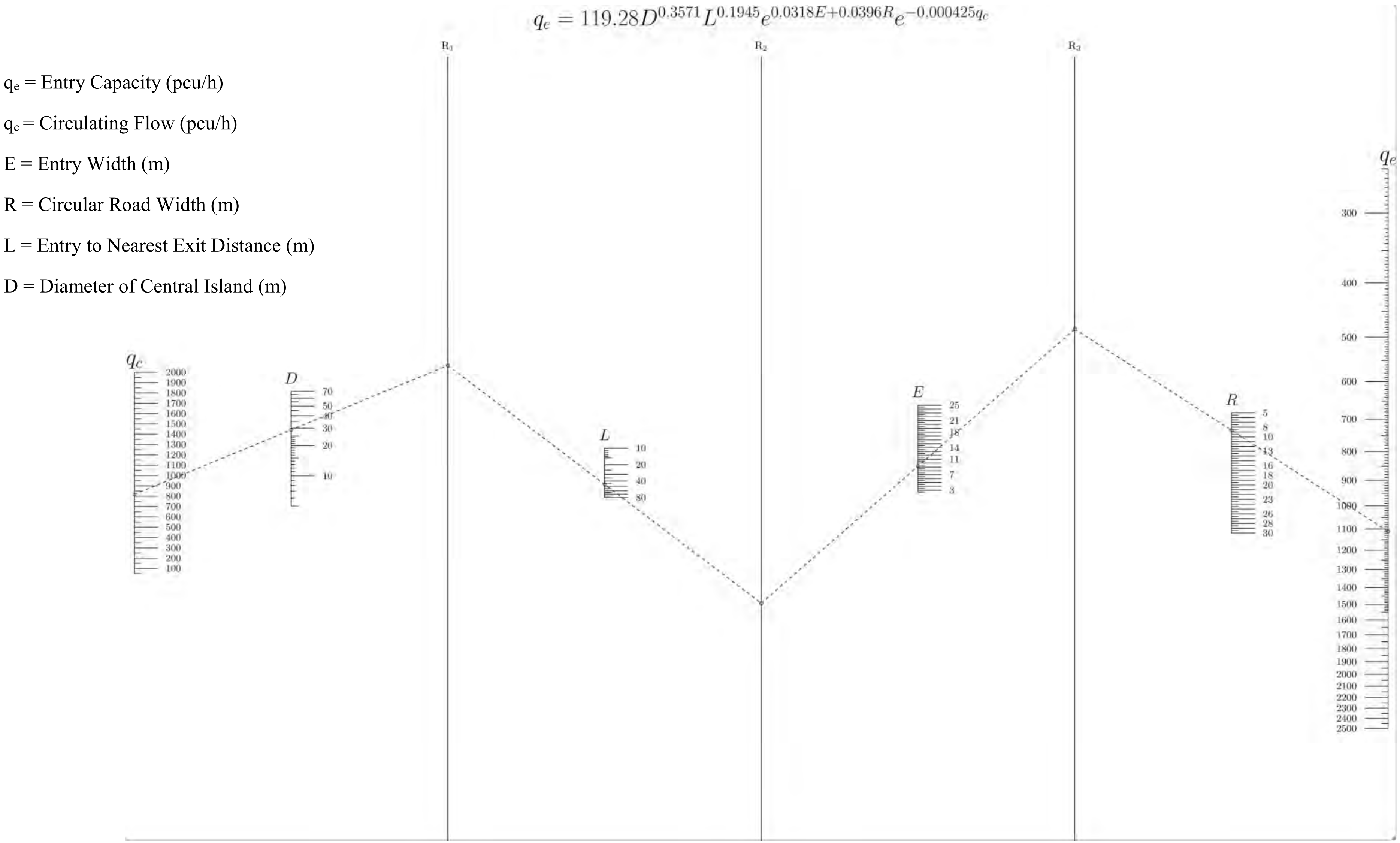

Figure 6.5 Nomograph for estimating and predicting entry capacity of a roundabout

CHAPTER 7

CONCLUSIONS

7.1 Summary

This study aimed to develop an empirical capacity estimation model for roundabouts on rural highways and also a graphical tool to aid the practitioners. The primary focus was to help designing better roundabouts utilizing the existing land area. The research can be broadly categorized into four major phases. The first phase was to conduct an extensive literature review which helped to identify the knowledge gap in terms of factors, variables, and traffic compositions that affect capacity. Another major gap was identified while doing the literature review was the lack of handy graphical tools for estimating and predicting roundabout capacity. This gap is reflected in inputs among existing roundabouts capacity models and in the models' methodological foundations. Practitioners and decision-makers face challenges while designing a new roundabout especially in developing countries like Bangladesh.

The second phase demonstrated that the identified gap resulted in limitations on the accuracy of existing roundabout capacity models. Thus, new empirical models for entry capacity based on traffic flow and geometric parameters were developed. It was shown that the developed model was better at explaining the variation in capacities than existing models, which illustrate the potential gains in accuracy if the appropriate explanatory variables were to be included in the model. This phase also identified the importance of one variable (entry-exit distance), which was not previously been included in many existing empirical capacity models, such as, TRL and German capacity model. The empirical models also answered the questions over how this variable affected entry capacity, given the effects shown by the developed models and other empirical works appeared to be in contrast with those found in previous research based on analytical and simulation approaches.

The third phase of this study investigated the accuracy of the developed model and the effects of the geometric variables using microscopic simulation. The VISSIM model was coded for the selected sites and a detailed calibration was performed. For the selected six roundabouts, it was found that the relationship between the dependent and independent variables could be expressed through a piecewise linear and nonlinear relationship. The VISSIM model was applied in different geometric and traffic compositions and entry capacity was extracted for the selected legs of roundabouts. The simulated capacity and empirical model capacity were statistically indifferent. Thus, it was observed that the developed empirical model accurately predicts the capacity of roundabouts.

The fourth and final phase of this research was to develop a graphical tool for estimating roundabout capacity for designing a new roundabout. A nomograph was developed from the empirical capacity model. The programming language Python-based software Numpy was used for developing nomograph. Further, the accuracy of the nomograph was investigated. The investigation was conducted by comparing nomograph estimated capacity with field observed capacity. This tool will help traffic and transportation engineers while designing roundabouts as well as evaluating the capacity of the roundabouts.

7.2 Key Findings

There has been extensive research on empirical capacity model of modern roundabouts. Despite this, there remains a gap in existing empirical models with respect to the effect of heavy vehicles on roundabout entry capacity. The study has considered the effect of heavy vehicles and found that the presence of heavy vehicles at roundabout has a negative impact on capacity. As the percentage of heavy vehicles increases, the rate of entering vehicles decrease.

In the developed empirical model, circular road widths and central island diameters were found to be more useful predictor variables compared to others used in the established models (e.g., flare length, entry radius, and entry angle). A negative exponential relationship was found between entry capacity and circular flow. The entry width and entry to the nearest exit distance of roundabouts were found to have a positive linear relationship with entry capacity.

From the sensitivity analysis of the developed model, it was found that 1% increment in circulating flow resulted in 0.09% decrease of the entry capacity. Likewise, 1% increment of circular road widths caused 1.92% increment of the entry capacity. Whereas, 1% increment of entry road widths, central island diameters, and entry to nearest exit distances resulted in increment of capacity by 0.05%, 1.2%, and 0.45%, respectively.

Results of multiple paired two-tailed t-tests for regression model, HCM 2016 model, German model, TRRL model and IRC model were found to be 0.2461, -7.6566, -21.0249 and -55.1567 respectively. The results reveal that the entry capacity of a roundabout estimated using HCM 2016 model, German model, TRRL model, and IRC model differs significantly from the observed capacity values but the estimation using the developed regression model does not differ significantly from the observed values. Hence, the developed regression model is statistically better in estimating entry capacity of roundabouts.

Capacity curves were developed of selected entry for each independent variable and the RMS values of these curves were found higher than the capacity curves developed by utilizing existing models. The R^2 value of the entry and circulating flow curve was found 0.9068. Similarly, the R^2 value of capacity curve for entry flows vs entry widths, entry flows vs circular road widths, entry flows vs central island diameters, and entry flows vs entry to nearest exit distances were found to be 0.8645, 0.7425, 0.6104, and 0.7543 respectively.

The developed nomograph performed well with the shortlisted explanatory variables. The estimated capacity from the nomograph replicated the observed field capacity. This graphical tool has created a benchmark for estimating and predicting roundabout capacity.

The developed VISSIM microscopic simulation model realistically represented the effects of traffic and geometric field condition of roundabouts. The changed values of look ahead distance (max. 250 m and min. 30 m), standstill distance (1.5 sec.), gap time distribution (5 sec.), waiting time before diffusion (600 sec), min. clearance (1 m), distance standing (0.1m), and distance driving (1.5 m) were perfectly replicated the field capacity of roundabouts. As the VISSIM microscopic simulation model capacity and the developed model capacity was indifferent, it proved the robustness of the developed empirical capacity model.

7.3 Limitation of the study

The limitations on resources restricted the scope of the research to developing empirical capacity model considering traffic flow parameter (circulating flow) and geometric parameters (entry-exit distance, central island diameter, entry width, and circular road width) effecting entry capacities. However, the empirical models showed that more variables significantly affect capacity, which is also worth further investigation. Linearity by default was assumed for geometric variables and nonlinearity for circulating flow but there could be other nonlinear forms that could better explain their impacts on capacity.

The empirical model was developed considering six roundabouts of rural highway. Hence, the data collection sites selected for the research were relatively small. The total hour's video recording period for data extraction for developing the model could be extended. The development of the entry capacity model considering only circulating traffic flow, exiting traffic flow of roundabout is not considered. However, literature has shown the significant effect of exiting flow on entry flow. The geometric parameters i.e., entry radius, entry angle, flare length, etc. have not been considered in developing the model. It is noted that this study was limited to examining entry capacities, which are typically achieved in unflared entries or lanes. However, many roundabouts have flared entries, and the flaring effects discussed in section 4.2.3 can considerably limit the entry flows.

The developed model can only estimate the entry capacity of the non-lane-based roundabout. Lane by lane entry capacity is not estimated by the model. The variation of saturation traffic flow and degree of saturation with time, days, and month was not considered in this research. Also, the delay time of traffic was not considered. The microscopic simulation approach that was adopted to estimate the capacity in VISSIM is basically based on the car-following model, gap acceptance theory, and continuous smooth traffic flow condition. Hence, the traffic flow is constant, traffic composition is predefined and local traffic impact is not coded but in real field condition the traffic flow is discontinuous, various traffic composition and local traffic impact is very common at the intersection. For these reasons, the capacity estimation of the simulation model may not be perfectly representative.

Although, sufficient data has been utilized in this study for developing the nomograph and empirical models, for wider application roundabout design calls for more data to validate their applicability. Notwithstanding these caveats, the research presented in this thesis has addressed the research objectives in section 1.2 which were aimed at developing an empirical capacity model along with a graphical tool for highway roundabout in Bangladesh. Thus predicting accurate capacity and better roundabout design. In particular, given the relatively limited resources available, this research has focused on developing a better understanding of traffic and geometric significant variables which effect the prediction of roundabout entry capacity, and demonstrated how their inclusion could result in developing capacity models and nomograph.

7.4 Scope for Future Research

This research is clearly an important step towards developing an empirical capacity model for rural highway roundabouts in Bangladesh. For further development, the empirical models, nomograph and the findings from this research could form the foundations of capacity models for engineering application. Before the models can be used in general practice, further research into the following areas are recommended.

The empirical model developed to estimate the roundabout entry capacity is based on circulating traffic flow and geometric parameters of two national highways of Bangladesh, which is assumed to be similar to other highways. For extending and validating the empirical models through a geographically wide database and more capacity flow and geometric configuration measurements is needed. This is particularly important to assess the ability of the models to be in design and the capacity evaluation of roundabouts.

Having a better model of, say, the effects of flare length on capacity, could provide useful improvements in the accuracy of the developed models, and improve their transferability. This will necessarily involve increased empirical data collection (possibly with larger saturated time intervals for reduced variability in capacity flow data points), or human factors research based on naturalistic driving or improved driving simulators.

The capacity of roundabouts depends on traffic flow parameters and geometric configuration. In the present study, the selected roundabouts having three and four legs, and are located in rural areas. Capacity also gets affected by pedestrian movements, stopping vehicles near the intersection, and local vehicles (NMV). All these factors need to be studied and develop a new model taking into consideration the maximum possible variables. Also, evaluating the applicability of the developed capacity models to mini-roundabouts, very large roundabouts, and compact roundabouts for urban and semi-urban areas.

Developing improved data collection systems for vehicle kinematic and interaction behavior at roundabouts, which may include recording positions, distances, speeds, and accelerations through video image recognition, wireless sensors (e.g. Bluetooth), embedded detectors, or other methods. These could then be used to efficiently quantify flows, headways, queue lengths, delays, origin-destination patterns, and other more detailed aspects of traffic behavior, allowing them to be investigated as explanatory variables for entry capacity. The resulting additional empirical data would also enable a step-change in the future development of capacity modeling.

Modeling the effects of upstream and downstream link capacity on roundabout entry capacity. In urban areas or severely congested highway links, spilling back of queues on the exit links can have a major impact on entry capacity, and could become a more significant problem with long-term traffic growth.

REFERENCES

Aagaard, P. (1996). Recent research into capacity in danish roundabout. *74th Annual Meeting of the Transportation Research Board.* Washington, D.C.: Transportation Research Board.

AASHTO. (2011). *A policy on geometric design of highways and streets. 6th ed.* Washington D.C: American Association of State Highway and Transportation Officials.

Acelik, R., Chung, and Besley. (1998). *Roundabouts: Capacity and performance analysis.* Vrmont South, Victoria: ARRB Transport Research.

Akcelik, R. (2003). Speed-flow and bunching relationships for uninterrupted flows. *Conference of Australian Institute of Transport Research (CAITR 2003).* Adelaide: University of South Australia.

Akcelik, R. (2011c). Some common and differing aspects of alternative models for roundabout capacity and performance estimation. *3rd International Conference on Roundabouts.* Carmel: Transportation Research Board.

Akcelik, R., and Associates Pty Ltd, A. (2013). *SIDRA Intersection (Version 6.0).* [Software] Akcelik and Associates Pty Ltd.

Akcelik, R., Chung, E., and Besley, M. (1997). Analysis of roundabout performance by modeling approach-flow interactions. *Third International Symposium on Intersections without Traffic Signals* (pp. 15-25). Portland, Oregon: University of Idaho.

Akcelik, R., and Besley, M. (2004). Differences between the AUSTROADS roundabout guide and aasidra roundabout analysis method. *26th Conference of Australian Institutes of Transport Research (CAITR 2004).* Melbourne: Australian Institutes of Transport Research.

Akcelik, R. (2003). Speed-flow and bunching relationships for uninterrupted flows. *25th Conference of Australian Institute of Transport Research (CAITR 2003).* Australia, Adelaide: University of South.

Akcelik, R. (2007). A Review of gap-acceptance capacity models. *29th Conference of Australian Institutes of Transport Research (CAITR).* Adelaide: University of South Australia.

Akcelik, R. (2011a). An assessment of the highway capacity manual 2010 roundabout capacity model. *3rd International Conference on Roundabouts.* Carmel, Indiana, U.S.A.

Akelik, R. (2011b). *ROUNDABOUTS - Comments on the SIDRA INTERSECTION model and the UK TRL linear regression model.* Retrieved from Akcelik and Associates. Available: http://www.sidrasolutions.com/Cms_Data/Contents/SIDRA/Folders/Resouces/Articles/Articles/~contents/MU5245V62B5CFVAX/SIDRA_and_UK_Roundabout_Models.pdf.

Akcelik, R., Chung, E., and Besley, M. (1998). *Roundabouts Capacity and Performance Analysis.* Vermont South, Victoria: ARRB Transport Research.

Akelik, R., and Chung. (1994). Traffic performance models for unsignalised intersections and fixed-time signals. *Australian Road Research Board*, pp. 21-50.

Al Masaeid, H. R., and Faddah, M. Z. (1997). Capacity of roundaabouts in Jordan. *Transportation Research Record*, 1572, pp. 76-85.

Alexander, J., Braham., P., and Black, I. (2002). Factor influencing the probability of an incident at a junction: Result from an interactive driving simulator. *Accident Analysis and Prevention*, 34 (6) pp. 779-792.

Alphaned, F, Noelle, U, Guichet, and Brilon. (1991). Evolution of design rules for urban roundabouts in France. In: Brilon, W., ed. Intersections without Traffic Signals II. *Springer-Verlag*, pp. 126-140.

Arshi, A.N., Alhajyaseen, W.K.M., Nakamura, H., and Zhang, X., (2018). A comparative study on the operational performance of four-leg intersections by control type.

Arroju, R., Gaddam, H.K., Vanumu, L.D., and Rao, K.R., (2015). Comparative evaluation of roundabout capacities under heterogeneous traffic conditions. J. Mod. Transport., 23 (4), 310-324.

Ashworth, R., and Bottom, C. (1977). Some observations of driver gap-acceptance behaviour at priority intersection. *Traffic Engineering and Control*, 18 (12), pp. 517-569.

Austroads, A. (2009). *Guide to road design.* Sydney, Australia: Austroads.

Bared, J. G., and Afshar, A. M. (2009). Using Simulation to plan capacity models by lane for two- and three-lane roundabouts. *Transportation Research Record*, 2096, pp. 8-15.

Barnard, S.R., Hall, R.D., and Macdonald, M. (1995). *Roundabout capacity studies.* of southampton: Report to the Transport Research Laboratory; Transportation Research Group; University of Southampton. [Unpublished].

Berthelon, C., and Mestre, D. (1993). Curvilinear approach to an intersection and visual detection of a collision. Human Factors. *The Journal of the Human Factors and Ergonomics Society*, 35 (3), pp. 521-534.

Berthelon, C., Mestre, D., Pottier, A., and Pons, R. (1998). Is visual antricipation of collision during self-motion related to perceptual style. *Acta Psychologica*, 44, pp. 1-16.

Board, T. R. (2007). *National Cooperative Highway Research Program (NCHRP) Report 572: Roundabouts in the United States.* Washington: Transportation Research Board of the National Academies.

Brilon, W., M, G., and B., S. (1991). Toward a new german guideline for capacity of unsignalized intersections. *Transportation Research Board*, pp. 168-174.

Brilon, W. (2005). Roundabouts: A state of the art in Germany. *National Roundabout Conference.* Colorado: Vail.

Brilon, W. (2014). *Roundabouts: A state of the art in germany.* Washington: Transportation Research Board.

Brilon, W., (2016). Safety of roundabouts: an international overview. In: Transportation Research Board Annual Meeting: Compendium of Papers, Washington, D.C.

Brilon, W. (1988). Recent developments in calculation methods for unsignalized intersections in West Germany. *pringer-Verlag*, pp. 111-153.

Brilon and Stuwe. (1993). Capacity and design of traffic circles in germany. *Transportation Research Record*, 1398, pp. 61-67.

Brilon, W., Koenig, R., and Troutbek, R. (1999). Useful estimation procedures for critical gaps. *Transportation Research Part A*, 33 (3-4), pp. 161-186.

Brilon, W., WU, N., and Bondzio, L. (1997). Unsignalized intersections in Germany. *Third International Symposium on Intersections without Traffic Signals* (pp. 61-70). Portland Oregon: University of Idaho.

Brrilon, W. (2011). Studies on roundabouts in Germany lessons learned. *3rd International TRB Roundabout Conference.* Indiana: 3rd International TRB Roundabout Conference.

Burtenshaw, G. (2012). *JUNCTIONS 8 user guide, application guide 67.* Crowthorne: TRL Limited.

Certu, C. (2006). *Girabase Version 4.0.* Lyon: Certu.

Chard, B. (1997). ARCADY Health Warning – Account for unequal lane usage or risk damaging public purse! Traffic Engineering and Control, 38 (3), pp.122-132.

Chevallier, E., and Leclercq, L. (2009a). Microscopic merging models reproduce the observed priority sharing ratio in congestion. *Transportation Research Part C 17 (3).*, 328-336.

Chevallier, E., and Leclercq, L. (2009b). Microscopic dual-regime model for single lane roundabouts. *Journal of Transportation Engineering, 135 (6)*, 386-394.

Chin, H. (1985). SIMRO: A model to simulate traffic at roundabout. *Traffic Engineering and Control,26(3)*, 109-113.

Chin, H. C. (1985). (1985). SIMRO: A model to simulate traffic at roundabouts. *Traffic Engineering and Control 26 (3)*, 109-113.

Chung, E., Young, W., and Akcelik, R. (1992). Comparison of roundabout capacity and delay estimates from analytical and simulation models. *16th ARRB Conference* (pp. 369-385). Perth: ARRB.

Chung.E, Y. A. (1992). Comparison of roundabout capacity and delay estimates from analytical and simulation modesls. *16th ARRB Conference. Vol. 16*, pp. 369-385. Perth: ARRB.

Cicu, F., Illotta, P. F., Bared, J., and Iserbrands, H. (2011). *VISSIM calibration of roundabouts traffic performance.* Wasington, D. C.: Transportation Research Board.

Cooper, D. F., Storr, P., and Wennell, .(1977). Traffic studies at T-Junction: The Effect of Speed on Gap Acceptance and Conflict rate. *Traffic Engineering and Control*, 18 (3), pp. 110-112.

Cooper, P. J., and Zheng, Y. (2002). Turning gap acceptance decision-marking: The impact of driver distraction . *Journal of Safety Research*, 33 (3), pp. 321-335.

Cowan, R. C. (1975). Useful headway models. *Transportation Research*, 9 (3), pp. 371-375.

Dahl, J., and Lee, C., (2012). Empirical estimation of capacity for roundabouts using adjusted gap- acceptance parameters for trucks. Transportation Research Record, 2312(1), 34-45.

De Aragao, P., Blance, P., and Veuve, L. (1991). *Guide Suisse Des Giratoires.*

De Baan, D. (2012). *Aantal 'Gespotee' Turbotones. [Online}*. Retrieved from http://www.dirkdebaan.nl/locaties.html

DOT, Department for Transport., (2007). *TD 16/07 geometric design of roundabout.* London: Department for Transport.

DOT, Department of Transport. (1981). *TA 23/81 junctions and accesses:Determination of size of roundabouts and major/minor junctions.* London: Department of Transport.

Dougherty, M. (1995). A review of neural networks applied to transport. *Transportation Research Part C: Emerging Technologies, 3 (4)*, 247-260.

Duong, D. S., Hellinga, B. R., and Guido, G. P. (2011). Calibration of a microscopic traffic simulation platform: A roundabout case study. *3rd International TRB Roundabout Conference.* Carmel, Indiana.

Evesham, H.A. (1986). Origins and development of nomography. AnnHistComput.;8(4):324–333.

Faddah, M. Z. (1996). Capacity of roundabout entries. In M. Z. Faddah, *Capacity of roundabout entries: M.S Thesis.* Irbid, Jordan: Department of Civil Engineering, Jordan University of Science and Technology.

FHWA, Federal Highway Administration., (2000). *Roundabouts: An informational guide.* U.S. Department of Transportation.

Fitzpatrick C, Abrams D, Tang Y, and Knodler, M (2013) A spatial and temporal analysis of driver gap acceptance behavior at modern roundabouts. J Transp Res Board 2388, PP. 14–20.

Flannery, A., Kharoufeh, J. P., Gautam, N. and Elefteriadou, L. (2005). Queuing delay models for single-lane roundabouts. Civil Engineering and Environmental Systems, 22 (3), pp. 133-150. doi: 10.1080/10286600500279949.

Fortuijn, L. G. (2009b). Turbo roundabouts: Estimation of capacity. *Transportation Research Record*, 2130, ppp. 83-92.

Geometric Design Standards Manual (Revised), (2005). Roads and Highways Division, Ministry of Communications, Government of the People's Republic of Bangladesh.

Glasser, L., and Doerfler, R. (2019). A brief introduction to nomography: graphical representation of mathematical relationships. International Journal of Mathematical Education in Science and Technology, 50(8), 1273-1284.

Glen, M. G., Sumner, S. L., and Kimber, R. M. (1978). *SR436 The capacity of offside priority roundabout entries.* Crowthorne: Transport and Road.

Godavarthy, R., Russell, E.R., (2015). Integrating roundabouts with freight roadway networks. Smart Grid Renew. Energy 6, pp. 293–302.

Godavarthy, R.P., Russel, E., and Landman, D., (2016). Using vehicle simulations to understand strategies for accommodating oversize, overweight vehicles at roundabouts. Transportation Research Part A, 87, pp. 41-50.

Grossmann, M. (1988). KNOSIMO A practicable simulation model for unsignalized intersections. *In W. Brilon (Ed.), Intersections without traffic signals: Proceedings of an International Workship* (pp. 263-273). Bochum: Springer-Verlag.

Guichet, B. (1997). Roundabouts in France: Development, Safety, Design, and Capacity. *Third International* (pp. 100-105). Portland, Oregon, U.S.A: University of Idaho.

Guichet, B. (1997). Roundabouts in France: Development, safety, design, and capacity. (pp. 100-105). Oregon: U.S.A.: University of Idaho.

Haddiuzzam, M., Haque, N., Rahman, Hossain, F., S., S., M.R.K, and Qui, T. (2017). Pixel-based heterogeneous traffic measurement considering shadow and illumination variation. *SIViP*,11 (7), pp. 1245-1252.

Hagring. (2000). Effects of OD flows on roundabout entry capacity. *Transportation Research Board*, pp. 434-445.

Hagring, O. (1996). The use of the Cowan M3 distribution for modelling roundabout flow. *Traffic Engineering and Control, 37 (5)*, pp. 328-332.

Hagring, O. (2000b). Estimation of critical gaps in two major strams. *Transportation Research Part B: Methodological, 34 (4)*, pp. 293-313. doi:10.1016/S0191-2615 (99)00026-0.

Hagring, O. (2001). Derivation of capacity equation for roundabout entry with mixed circulating and exixting flows. *Transportation Research Record, 1776,* pp. 91-99. doi: 10.3141/1776-12.

Hancock, P., Carid, J. K., S., S., and Vercruyssen, M. (1991). Factors influencing driver's left turn decision. *Proceedings of the Human Factors Society 35th Annual Meeting*, (pp. 1139-1143). San Francisco, California.

HCM. (2016). Highway Capacity Manua1 2016. Transportation Research Board, Nationa1 Research Counci1.

Hewitt, R. H. (1983). Measuring critical gap. *Transportation Science, 17 (1)*, pp. 87-109.

Hossain, M. (1999). Capacity Estimation of Traffic Circles Under Mixed Traffic Conditions Using Micro-Simulation Technique. *Trannsportation Research Part A Policy and Practice*, pp. 47-61.

Hummer, J., Milazzo, J., Schroeder, B., and Salamati, K. (2014). Potential for metering to help roundabouts manage peak period demands in the United States. *Transportation Research Record, 2402*, pp. 56-66. doi:10.3141/2402-07.

Irani, L., Kay, B., Sang, A., and Katesmark, S. (1993). ROBOSIGN: Computer-aided design for roundabout. *Traffic Engineering and Control*, 34 (4), pp. 185-193.

Istoka Otkovic, I., Tollazzi, T., and Sraml, M. (2011). Calibration of microsimulation traffic model using neural network approach. *Expert Systems with Applications, 40 (15)*, pp. 5965-5974. doi:10.1016/j.eswa.2013.05.003.

Karlafits, M., and Vlahoginni, E. (2011). Statistical methods versus neural networks in transportation research: Differences, Similarities and Some Insights. *Transportation Research Part C*, 19 (3), pp. 387-399.

Keen, S., Sargeant, S., and MA, T. (2008). Micro-simulation of a roundabout - A reality test. *National Roundabout Conference* (p. National Roundabout Conference). Kansas City, MO, U. S. A.: Transportation Research Board.

Kimber. (1980). *LR942 The traffic capacity of roundabouts.* Crowthorne: Transport and Road Research Laboratory.

Kimber, R. M. (1980). *the traffic capacity of roundabouts.* London: Transportation and Road Research Laboratory.

Kimber, R. M. (1989). Gap-acceptance and empiricism in capacity prediction. *Transportation Science*, 23 (2), pp. 100-111.

Kimber, R. M., and Coombe, R. D. (1980). *The traffic capacity of major/minor priority junctions.* Crowthorne: Transport and Road Research Laboratory.

Kimber, R. M., and Semmens, M. (1977). SR334 A track experiment on the entry capacities of offside priority roundabouts. *Transport and Road Research Laboratory*.

Kimber, R., and Hollis, E. (1979). *LR909 Traffic queues and delays at road junctions.* Crowthorne: Transport and Road Research Laboratory.

Kittleson and Associates. (2020) Modern Roundabouts: The Web Site http://roundabouts.kittelson.com/Roundabouts [accessed on March 2020].

Krogcheepers, and Roebuck. (2000). Unbalanced traffic volumes at roundabouts. *Fourth International Symposium on Highway Capacity* (pp. 446-458). Maui, Hawaii: Transportation Research Board.

Krogscheepers, J. C. (1999). *Simulation of traffic at roundabouts.* Institute of Transportation Engineers. Las Vegas : 69th Annual Meeting of the Institute of Transportation Engineers.

Krogscheepers, J. C., and Roebuck, C. (1999). *Simulation of traffic at roundabouts.* Las Vegas, Nevada: Institute of Transportation Engineers.

Krogscheepers, J. C., and Roebuck, C. S. (2000). Unbalanced traffic volumes at roundabouts. *Fourth International Symposium on Highway Capacity* (pp. 446-458). Maui, Hawaii: Transportation Research Board.

Kutner, M. H., Neter, J., Nachtsheim, C. J. and Li, W. (2005). Applied linearstatistical models. 5th International ed. New York: McGraw-Hill.

Leemann, M., and Santel, G. (2009). Two-lane roundabouts. *9th Swiss Transport Research Conference*, (pp. 9-11). Ascona.

Li, Z., Deamico, M., Chitturi, M. V., Bill, A. R., and Noyce, D. A. (2013). Calibration of vissim roundabout model: A Critical Gap and Follow-up Headway Approach. *Transportation Research Board 92nd Annual Meeting.* Washington, D. C.; U. S.A.: Transportation Research Board.

Lindenmann, H. P. (2006). Capacity of small roundabouts with two-lane entries. *Transportation Research Record, 1988,* pp.119-126. doi: 10.3141/1988-17.

Linse, L. (2010). Capcal for small roundabouts-Current status and improvements. Master of Science in Communication and Transport Engineering, Linköpings Universitet.

Louah, G. (1988). Recent French studies on capacity and waiting times at rural unsignalized Intersections. *In W. Brilon (Ed.), Intersections without traffic signals: Proceedings of an international workshop* (pp. 248-262). Bochum: Springer-Verlag.

Louah, G. (1992). Panorama critique des modeles français de capacité des carrefours giratoires [Critical overview of French capacity models forroundabout intersections]. *Centre d'Etudes des Transports Urbains*, pp. 213-228.

Louveton, N., Montagne, G., Berthelon, C., and Montagne, G. (2012a). Intersection crossing considered as intercepting a moving traffic gap: Effects of task and environmental constraints. *Acta Psychologica*, 141 (3), pp. 287-294.

Louvton, N., Montagne, G., Berthelon, C., and Boostsma, R. J. (2012b). Intercepting a moving traffic gap while avoiding collision with lead and trail vehicles. *Human Movement Science*, 31 (6), pp. 1500-1516.

Luttinen, R. T. (1999). Properties of Cowan's M3 headway distribution. *Transportation Research Record, 1678,* pp. 189-196. doi: 10.3141/1678-23.

Macdonald, M., Hounsell, N., and Kimber, R. (1984). *SR810 Geometric delay at non-signalised intersections.* Crowthorne: Transport and Road Research Laboratory.

Mahesh, S., Ahmad, A., and Rastogi, R., (2016). An approach for the estimation of entry flows on roundabouts. Transportation Research Procedia, 17, pp. 52-62.

Mandavalli, S., Rys, M.J., and Russell, E.R., (2008). Environmental impact of modern roundabouts. Int. J. Ind. Ergon. 38, pp. 135–142.

Marlow, M., and Maycock, G. (1982). *SR724 The effect of zebra crossings on junction entry capacities.* Crowthorn: Transport and Road Research Laboratory.

Marstrand, E. (1988). The capacity of large roundabouts. *Highways and Transportation*, pp. 9-12.

Mathew, S., Dhamaniya, A., Arkatkar, S., and Joshi, G. (2017). Roundabout capacity in heyerogeneous traffic condition: Modification of HCM equation and calibration. *Transportation Research Procedia*, pp. 985-992.

Mauro, R., and Guerrieri, M. (2013). Right-turn bypass lanes at roundabouts. *Modern Applied Science, 7 (1)*, pp. 1-12. doi: 10.5539/mas.v7n1p1.

Mereszczak, Y., Dixon, M., Kyte, M., Rodegerdts, L. and Blogg, M. (2006). Including exiting vehicles in capacity estimation at single-lane U.S roundabouts. Transportation Research Record, 1988, pp. 23-30. doi: 10.3141/1988-05.

Mohamad A, S. (2015). *Capacity models for multilane roundabouts and their evaluation using microscopic simulations.* United Arab Emirates University.

Mohamed, A.I.Z., Ci, Y., and Tan, Y., (2020). A novel methodology for estimating the capacity and level of service for the new mega elliptical roundabout intersection. Journal of Advanced Transportation, Volume 2020.

NCHRP, N. C. (2010). *Rounadabouts: An informational guide, Second Edition.* Washington, D. C.: Transportation Research Board.

Ozuysal, M., Calishanelli, S., Tanyel, S., and Baran, T. (2009). Capacity prediction for traffic circles: applicability of ANN. *Transport, 162 (TR4)*, pp. 195-206.

Paramics Microsimulations, P. (2011a). *S-Paramics 2011 reference manual.* Edinburgh: SIAS Limited.

Paramics Microsimulation, P. (2011b). *S-Paramics (Parallel microscopic traffic simulator) (Version 2011.1).* [Software] SIAS Limited.

Park, B., and Qi, H. M. (2005). Development and evaluation of a procedure for the calibration of simulation models. *Transportation Research Record: Journal of the Transportation Research Board, 1934*, pp. 208-217.

Peterson, R. W., Lewis, S. J., Fugal, K. J., and Lancaster, R. D. (2008). Modeling rouabouts: lessons learned in Idaho. *National Roundabout Conference.* Kansas City, MO, U.S.A.: Transportation Research Board.

Pollatschek, M. A., Polus, A., and Livenh. (2002). A decesion model for gap acceptance and capacity at intersections. *Transportation Research Part B: Methological*, 36 (7), pp. 649-663.

Polus, A., and Lazar, S. (1999). Entry capacity at roundabouts and impact of waiting times. *Road and Transport Research*, 8 (3), pp. 43-54.

Polus, A., and Lizar, S. S. (2003). Critical gap as a function of waiting time in determining roundabout capacity. *Journal of Transportation Engineering, 129 (5),* pp. 504-509. doi: 10.1061/(ASCE)0733-947X(2003)129:5(504).

Polus, A., and Shmueli, S. (1997). Analysis and evaluation of the capacity of roundabouts. *Transportation Research Record, 1572*, pp. 99-104.

Polus, A., Lazar, S. S., and Livneh, M. (2003). Critical gap as a function of waiting time in determining roundabout capacity. *Journal of Transportation Engineering*, 129 (5), pp. 504-509.

Polus, A., Shiftan, Y., and Shmueli-Lazar, S. (2005). Evaluation of the waiting time effect on critical gaps at roundabouts by a logit model. *European Journal of Transport and Infrastructure Research*, 5 (1), pp. 1-12.

PTV Group, P. (2021). *PTV Vissim 2021 user manual.* Karlsruhe: PTV AG.

Rasheed, S. (2010). Survey of Canadian roundabout. Institute of Transportation Engineers (ITE).

Rodegerdts, L. B. (2006). *National Cooperative Highway Research Program (NCHRP) Web-Only Document 94: Appendixes to NCHRP Report 572: Roundabouts in the United States.* Washington D.C: Transportation Research Board of the National Academies.

Rodegerdts, L., Bansen, J., Tiesler, C., Knudsen, J., Myers, E., Johnson, M., Moule, M., Persaud, B., Lyon, C., Hallmark, S., Isebrands, H., Crown, R.B., Guichet, B., and O'Brien, A., (2010). Roundabouts: An Informational Guide – Second Edition. NCHRP Report 672, Transportation Research Board of the National Academics, Washington, D.C.

Rodel Software Ltd, R. (2012). RODEL (Version v1-Win).

Russell, E.R., Luttrell, G.,and Rys, M., (2002). Roundabout studies in Kansas. In: Proceedings of the Fourth Transportation Specialty Conference of the Canadian Society for Civil Engineering, Canada.

Russell, E.R., Mandavilli, S., and Rys, M., (2005). Operational performance of kansas roundabouts: Phase II. Report No: K-TRAN: KSU-02-4, Kansas Department of Transportation.

Savoy Computing Services Ltd, S. (2010). *Autotrack junctions.* [Software] Savoy Computing Services Ltd. Retrieved from Savoy Computing Services Ltd.

Savoy Computing Services Ltd., S. (2012). *Time saving by using a bim workflow in roundabout design.* Retrieved from http://savoycomputing.files.wordpress.com/2013/03/bimworkflowsavings.pdf.

Semmens, M. C. (1980). *LR941 PICADY: A computer program to model capacities, queues and delays at major/minor junctions.* Crowthorne:: Transport and Road Research Laboratory.

Semmens, M. C. (1982). *SR721 The capacity of some grade-separated roundabout entries.* Crowthorne: Transport and Road Research Laboratory.

Semmens, M. C. (1985). *RR36 PICADY2: An enhanced program to model apacities, queues and delays at major/minor priority junctions.* Crowthorne: Transport and Road Research Laboratory.

Semmens, M. C. (1988). *RR142 The Capacity of entries to very large roundabouts.* Crowthorne: Transport and Road Research Laboratory.

Simon, M. J. (1991). Roundabouts in Switzerland: Recent experiences, capacity, Swiss roundabout guide. *Springer-Verlag*, pp. 41-52.

Stuwe, B. (1991). Capacity and safety of roundabouts – German results. *Springer-Verlag*, pp. 1-12.

Suh, W., Barry, C., Schmitt, L., Anderson, J., Rodgers, M. O. and Hunter, M. (2015). Impact of including exiting vehicles in single-lane roundabout capacity model. Transportation Research Board 94th Annual Meeting, 2015, Washington, D.C.: Transportation Research Board.

Tan, J. -A. (1991). A microscopic simulation model of roundabout entry operations. *Springer-Verlag*, pp. 159-176.

Tan, J.-a. (1991). A microscopic simulation model of roundabout entry operations. *In W. Brilon (Ed.), Intersections without traffic signals II: Proceedings of an international workshop* (pp. 159-176). Bochum: Springer-Verlag.

Tanyel, J. C., and Yayla, N. (2003). A Discussion on the parameters of Cowan M3 didtribution for Turkey. *Transportation Research Part A*, pp. 129-143.

Tanyel, S., and Yayla, N. (2003). A discussion on the parameters of Cowan M3 distribution for Turkey. *ransportation Research Part A : Policy and Practice, 37 (2),* pp. 129-143. doi: 10.1016/S0965-8564(02)00009-5.

Tenekeci, G., and Montgomery, F. and. (2010). Roundabout capacity in adverse weather and light conditions. *roceedings of the ICE - Transport, 163 (TRI)*, 29-39.

Teply, S., Abou-Henaidy, M. I., and Hunt, J. (1997). Gap acceptance behaviour: aggregated and logit perspectives. *Traffic Engineering and Control*, pp. 474-482.

Transoft Solutions Inc, T. (2012). *TORUS Roundabouts (Version 4.0).* [Software] Transoft Solution Inc.

TRB, Transportation Research Board. (1985). *Special report 209.* Highway Capacity Manual (HCM) Washington, D.C: Transportation Research Board.

TRB, Transportation Research Board, T. (2000). *Highway Capacity Manual 2000.* Washington, D.C., 2000: Transportation Research Board.

TRB, Transportation Research Board, T. (2010). *Highway Capacity Manual 2010.* Washingtton, D.C., 2010: TRB, National Research Council.

TRB, Transportation Research Board, T.(2000). *HCM.* Washington, D.C.: Transportation Research Board.

TRB, Transportation Research Board, T.(2000). *Roundabouts: An Informational Guide.* FHWA.

TRB, Transportation Research Board, T. (2010a). *HCM 2010.* Washington: Transportation Research Board.

TRB, Transportation Research Board, T. (2010b). *National Cooperative Highway Research Program (NCHRP) Report 672 Roundabout An Informational Guide. 2nd ed.* Washinton D.C: Transportation Research Board of the National Academies.

TRL Software, J. (2012). Junctions 8. *[Software] TRL Software.*

TRL Software, T. (2012). *Junctions 8. [Software].* TRL Software.

Troubeck, R. J. (1998). Background for HCM section on analysis of performance of roundabouts. *Transportation Research Record, 1646*, pp. 54-62.

Troutbeck, R. J. (1989). *SR45 Evaluating the performance of a roundabout.* Victoria: Australian Road Research Board.

Troutbeck, R. J. (1990). Traffic interactions at roundabouts. *15th ARRB Conference* (pp. 17-42). Darwin, Australia: Australian Road Research Board.

Troutbeck, R. J. (1991). Recent Australian unsignalised intersection research. *Springer-Verlag*, pp. 238-257.

Troutbeck, R. J. (1993). Effect of heavy vehicles at Australian traffic circles and unsignalized intersections. *Transportation Research Record*, pp. 54-60.

Troutbeck, R. J., and Kako, S. (1999). Limited priority merge at unsignalized intersections. *Transportation Research Part A*, 33 (3-4), pp. 291-304.

TSS-Transport Simulation Systems, T. (2011). *Aimsum (Advanced interactive microscopic simulator for urban and non-urban networks).* [Software] Transport Simulation Systems.

Tudge, R. (1988). INSECT-The calibration and validation of an intersection simulation model. *In W. Brilon (Ed.), Intersections without traffic signals: Proceedings of an international workshop* (pp. 214-235). Bochum: Springer-Verlag.

Tupper, S. M., Knodler, M. A., Fitzpatrick, C., and Hurwitz, D. S. (2013). Estimating critical gap - A comparison of methodologies using a robust, real-world data set. *Transportation Research Board 92nd Annual Meeting*. Washington, D.C., U.S.A.: Transportation Research Board.

Vaiana, R. G., and Iuele, T. (2012). Simulation of observed traffic conditions on roundabouts by dedicated software. *Procedia - Social and Behavioral Science, 53 (0)*, pp. 741-753. doi: 10.3141/2265-26.

Vaiana, R., and Gallelli, V. (2011). *The calibration of traffic microscopic simulation model: kinematical approach to the through movement on roundabout.* Washington, D. C.: Transportation Research Board.

Valdez, M., Cheu, R. L., and Duran, C. (2011). Operation of modern roundabout with unbalanced approach volumes. *Transportation Research Record, 2265*, pp. 234-243. doi: 10.3141/2265-26.

Vasconcelos, L., and Seco, A. S. (2014a). Hybrid calibration of microscopic simulation models. *computer-based modelling and optimization in transportation. Springer International Publishing*, pp. 307-320.

Vasconcelos, L., Silva, A., Seco, A., Fernandes, P., and Coelho, M. (2014b). Turboroundabouts: multicriterion assessment of intersection capacity, safety, and emissions. *Transportation Research Record: Journal of the Transportation Research Board, 2402*, pp. 8-37. doi: 10.3141/2402-04.

Wanger, I., and E., W. (2014). *Using IBM(R) SPSS(R) Statistics for research methods and Social science statistics.* Sage Publications.

Wei, H., and Grenard, J. L. (2012). Calibration and Validation of highway capacity manual 2010 capacity model for single-lane roundabouts. *Transportation Research Record, 2286*, pp. 105-110. doi: 10.3141/2286-12.

Weinert, A. (2000). Estimation of critical gaps and follow-up times at rural unsignalized intersections in Germany. *Transportation Research Circular E-018: 4th International Symposium on Highway Capacity* (pp. 409-421). Maui, Hawaii: Transportation Research Board.

Wennell, J., and Cooper, D. (1981). Vehicle and driver effects on junction gap acceptance. *Traffic Engineering and Control*, 22 (12), pp. 628-632.

WU. (2012). Equilibrium of probabilities for estimating distribution function of critical gaps at unsignalized intersections. *Transportation Research Record*, 2286, pp. 49-55.

WU, N. (1999). Capacity of shared-short lanes at unsignalized intersections. *Transportation Research Part A*,33 (3-4), pp. 255-274.

Xu, F., and Tian, Z. Z. (2008). Driver behavior and gap-acceptance characteristics at roundabouts in California. *Transportation Research Record, 2071,* pp. 17-124. doi: 10.3141/2071-14.

Yan, X., Radwan, E., and Guo, D. (2007). Effects of major-road vehicle speed and driver age and genter on left-turn gap acceptance. *Accident Analysis and Prevention*, pp. 843-852.

Zheng, D., Chitturi, M. V., Bill, A. R. and Noyce, D. A. (2012). Critical gaps and follow-up headways at congested roundabouts. Transportation Research Board 91st Annual Meeting, 22-26 January 2012, Washington, D.C., U.S.A.: Transportation Research Board.

Appendix A-1: Traffic Data Collection Form

ROADS AND HIGHWAYS DEPARTMENT **TRAFFIC COUNT TALLY SHEET** Sheet :.........of.........

Name of Road :..Road No. : ....Direction From : ....To : ....

Station Name :...Station Number :...

Date:............./..................../.....................
DD MM YY

Enumerator : ....Supervisor : ....

HOURS COUNTED	MOTORISED										NON-MOTORISED		
	1	2	3	4	5	6	7	8	9	10	11	12	13
	Heavy Truck	**Medium Truck**	**Small Truck**	**Large Bus**	**Mini Bus**	**Microbus**	**Utility**	**Car**	**Auto Rickshaw**	**Motor Cycle**	**Bicycle**	**Cycle Rickshaw**	**Animal/Push Cart**
: to :													
: to :													
: to :													
: to :													

Form MCC/01

ROADS AND HIGHWAYS DEPARTMENT **DAILY TRAFFIC SUMMARY SHEET**

Road Name: .... **Road Number:** …………………. **Station Name:** .... **Station Ref:** .... **Zone:** .... **Circle:** ....

Date: ..../.........../............. **Directions of count** **To:** .... **Hours Counted** **From:** ....:.... Hours **To:** ....:.... Hours

(DD/MM/YY) **From:** .... **Supervisor:** ....

	1 Heavy Truck		2 Medium Truck		3 Small Truck		4 Large Bus		5 Medium Bus		6 Micro Bus		7 Utility		8 Car		9 Auto-Rickshaw		10 Motor Cycle		11 Bicycle		12 Cycle-Rickshaw		13 Cart		Total Motor	Total Non-M	Grand Total
Time	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From			
00:00-01:00																													
01:00-02:00																													
02:00-03:00																													
03:00-04:00																													
04:00-05:00																													
05:00-06:00																													
06:00-07:00																													
07:00-08:00																													
08:00-09:00																													
09:00-10:00																													
10:00-11:00																													
11:00-12:00																													
12:00-13:00																													
13:00-14:00																													
14:00-15:00																													
15:00-16:00																													
16:00-17:00																													
17:00-18:00																													
18:00-19:00																													
19:00-20:00																													
20:00-21:00																													
21:00-22:00																													
22:00-23:00																													
23:00-24:00																													
Tot. One Way																													
Tot. Two Way																													

Date completed: ………./………./………. By:……………………………………………
(DD/MM/YY) (Signature)

Note to Traffic Count Supervisors: Do not fill in grey shaded areas unless requested to.

FORM MCC/02

TRAFFIC COUNT TALLY SHEET Sheet: ….. . Of ……….

Name of Road: ………………………………. Direction: From ……………………… To ……………..........

Enumerator: ……………………………… Supervisor: ………………………… Date: …………………..

Vehicles	Hour Counted: ……. …….to ……………	Hour Counted: ……….. …to ……………..
Heavy Truck		
Medium Truck		
Small truck		
Utility (Pick up, Covert Van Leguna)		
Large Bus		
Mini Bus		
Microbus		
Car/Taxi		
CNG		
Auto/Tempo		
Motor Cycle		
Bicycle		
Rickshaw/Van		

TRAFFIC COUNT TALLY SHEET Sheet: ….. . Of ……….

Name of Road: ………………………………. Direction: From ……………………… To …………….............

Enumerator: ……………………………… Supervisor: …………………………. Date: …………………..

Vehicles	**Hour Counted: ……….. to …………..**	**Hour Counted: ……….. ..to ………………**
Heavy Truck		
Medium Truck		
Small truck		
Utility (Pick up, Leguna & Covert Van)		
Auto/Tempo		
Bicycle		
Rickshaw/Vah		

TRAFFIC COUNT TALLY SHEET Sheet: ….. . Of ……….

Name of Road: ………………………………. Direction: From ……………………… To ……………...........

Enumerator: ……………………………… Supervisor: …………………………. Date: …………………..

Vehicles	**Hour Counted: ……. to …………**	**Hour Counted: ……….. to ……………**
Large Bus		
Mini Bus		
Microbus		
Car/Taxi		
CNG		
Motor Cycle		

Appendix A-2: Geometric Data

S/L	Roundabout	Highway Name	Entry Name	Flow Direction	Entry width (m)	Circular Road Width (m)	Dia. Of Central Island (m)	Entry/Exit Distance (m)
1	Bangabandhu Bridge East	Dhaka-Rangpur	EN1	From Dhaka	9.21	8.64	28.79	45.89
			EN2	From Rangpur	9.21	8.64	28.79	45.89
2	Bangabandhu Bridge West	Dhaka-Rangpur	EN3	From Dhaka	11.05	10.71	33.77	63.6
		Dhaka-Rangpur	EN4	From Rangpur	9.85	9.91	33.77	58.56
3	Hatikumrul	Dhaka-Rangpur	EN5	From Dhaka	9.35	9.27	31.51	40.66
		Dhaka-Rangpur	EN6	From Rajshahi	9.45	9.57	33.51	40.88
		Dhaka-Rangpur	EN7	From Rangpur	10.85	10.5	33.51	59.73
		Dhaka-Rangpur	EN8	From Pabna	6.75	6.5	20.25	19.72
4	Bishwaroad Tarabo	Dhaka-Sylhet	EN9	From Dhaka	9.5	9.25	30.28	53.57
		Dhaka-Sylhet	EN10	From Sylhet	8.09	8.5	30.28	49.49
5	Panchdona	Dhaka-Sylhet	EN11	From Dhaka	8.95	8.83	31.71	42.65
		Dhaka-Sylhet	EN12	From Sylhet	10.15	10.12	31.71	58.42
6	Shaheprotab Bus Stand	Dhaka-Sylhet	EN13	From Dhaka	9.43	10.56	29.41	44.54
		Dhaka-Sylhet	EN14	From Sylhet	9.31	10.4	29.41	42.48

Appendix A-3: Traffic Data

S/L	Roundabout	Highway Name	Entry Name	Flow Direction	Entry Flow (PCU/h)	Circulating Flow (PCU/h)
1	Bangabandhu Bridge East	Dhaka-Ragnpur	EN1	From Dhaka	1085	817
					1002	838
					1120	762
					1192	712
					1017	856
					1275	643
					1228	686
					1172	752
			EN2	From Rangpur	1190	734
					1202	685
					1239	675
					1367	569
					1431	447
					1282	627
					1287	718
					1350	575
					1486	425
					1327	580
2	Bangabandhu Bridge West	Dhaka-Rangpur	EN3	From Dhaka	1654	321
					1680	315
					1643	389
					1730	277
					1786	221
					1822	206
					1976	170
					2225	120
		Dhaka-Rangpur	EN4	From Rangpur	1519	452
					1460	495
					1523	407
					1493	447
					1589	419
					1512	377
					1497	495
					1532	479
		Dhaka-Rangpur	EN5	From Dhaka	1307	587
					1289	625
					1359	567
					1276	607
					1303	594
					1320	572
					1366	548
					1292	614
					1214	632
					1325	545

S/L	Roundabout	Highway Name	Entry Name	Flow Direction	Entry Flow (PCU/h)	Circulating Flow (PCU/h)
3	Hatikumrul				1343	589
		Dhaka-Rangpur	EN6	From Rajshahi	1334	573
					1271	647
					1331	562
					1287	699
					1324	573
					1249	646
					1337	941
					1297	613
		Dhaka-Rangpur	EN7	From Rangpur	1572	460
					1645	369
					1597	454
					1692	324
					1742	293
					1615	330
					1567	454
					1596	540
		Dhaka-Rangpur	EN8	From Pabna	525	1235
					536	1296
					693	1383
					574	1222
					512	1261
					596	1422
					565	1347
					530	1398
	Bishwaroad Tarabo	Dhaka-Sylhet	EN9	From Dhaka	1522	405
					1492	699
					1615	408
					1347	586
					1382	511
					1294	611
					1384	595
					1390	505
					1363	512
					1316	567
					1274	651
					1584	548
		Dhaka-Sylhet	EN10	From Sylhet	1096	822
					1121	785
					1128	773
					1022	847
					1126	769
					1048	827
					1046	845
					1001	879

S/L	Roundabout	Highway Name	Entry Name	Flow Direction	Entry Flow (PCU/h)	Circulating Flow (PCU/h)
4					1146	767
					1176	734
5	Panchdona, Narsingdi	Dhaka-Sylhet	EN11	From Dhaka	1193	726
					1143	748
					1146	737
					1130	776
					1174	729
					1192	704
					1141	789
					1182	732
		Dhaka-Sylhet	EN12	From Sylhet	1468	536
					1516	551
					1504	516
					1612	491
					1487	410
					1541	424
					1643	496
					1592	281
6	Shaheprotab Bus Stand, Narsingdi	Dhaka-Sylhet	EN13	From Dhaka	1242	689
					1245	618
					1565	457
					1490	693
					1310	701
					1242	624
					1344	696
					1263	531
		Dhaka-Sylhet	EN14	From Sylhet	1348	671
					1425	591
					1249	676
					1160	763
					1274	557
					1187	723
					1205	558
					1320	569

Appendix A-4: Nomograph

$$q_e = 119.28 D^{0.3571} L^{0.1945} e^{0.0318E + 0.0396R} e^{-0.000425 q_c}$$

qe = Entry Capacity (pcu/h)
qc = Circulating Flow (pcu/h)
E = Entry Width (m)
R = Circular Road Width (m)
L = Entry to Nearest Exit Distance (m)
D = Diameter of Central Island (m)