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Geometric design of single-lane roundabouts for optimum consistency and operation

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GEOMETRIC DESIGN OF SINGLE-LANE ROUNDABOUTS FOR OPTIMUM CONSISTENCY AND OPERATION

by

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B.Eng.,
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ABSTRACT

The objectives while designing roundabout is design consistency and operational performance. Design consistency affects roundabout safety while operational performance affects its level of service. Along with design consistency, roundabout will be more safe if its geometry forces traffic to enter and circulate at less than specified design speed. Vehicle path radii control speeds at each vehicle path. Vehicle path radii are traditionally obtained from drawing freehand each vehicle paths on proposed roundabout geometry. Existing design approaches for roundabouts use a trial-and-error procedure to choose the design parameters in order to satisfy design standards. With this approach it is quite complicated to satisfy design guidelines and site conditions at the same time. A minor change in geometry can result in significant changes in safety and operational performance. Therefore, many iterations of geometric layout would be required to evaluate safety and operational analysis at given traffic conditions. Designer needs to revise and refine the initial geometric layout to enhance safety and its operational performance. In this thesis, an optimization model is developed that predicts optimum design parameters with multiple objectives: maximum design consistency and minimum average intersection delay. At optimum design parameters, this model also provides vehicle path radii for each path. These vehicle path radii were used to predict operating speed along each path using an existing operating speed prediction model. The optimization model takes site conditions as input and satisfies the two objectives for given traffic and geometric conditions. This is a new approach of optimum design of single-lane roundabouts with four legs intersecting at right angle. The model not only satisfies the two objectives, but also limits the operating speed along each path (left, through, and right), below the specified design speed of roundabout.

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INTRODUCTION

A roundabout is a form of road intersection and control at which traffic streams flow in one direction around a central island with yield control at the entry points, and gives priority to circulating vehicles within the roundabout. Roundabouts first evolved in the mid-1960s when the British reengineered the traffic circle to overcome its limited capacity and related safety problems. The differences between these two circular intersection forms are not readily clear to the typical driver, but the difference in performance is dramatic (Champa 2002). Roundabouts are easily confused with traffic circles because they have the same general physical appearance. However, only the roundabout operates with yield control at each entry to give priority or right-of-way to circulating traffic.

The original traffic circles were designed to give priority to entering vehicles. This facilitated high speed entries and forced circulating traffic to yield which resulted in high crash experience and congestion at relatively low traffic volumes. Modern roundabouts did not exhibit the operational problems or safety experience of the old traffic circles. This has increased the installation of roundabouts in many European countries (France, Germany, Great Britain, etc.) and Australia. They were first appeared in the U.S. around 1990. The main design parameters of modern roundabouts include entry width, inscribed circle diameter, the central island, circulating width, entry radius, flare length, exit radius, and splitter island. Safety, operational, environmental, and economic benefits lead to the installation of roundabouts. A detailed feasible study is required to evaluate these benefits for various alternatives prior to the installation of roundabouts.

The entry capacity of a roundabout is estimated by either theoretical or empirical approach. The theoretical approach (or gap-acceptance theory) is based upon assumptions of driver behavior. Entry capacity models based on gap-acceptance theory are developed at Australian and Danish roundabouts (Troutbeck 1993, Aagaard 1996). Due to the complex relationships between gap-acceptance parameters and geometric elements of roundabout, gap-acceptance theory overestimates the entry capacity when using gap-acceptance parameters measured in strict adherence to the assumed driver behavior (Aagaard 1996, Kimber 1989). In this empirical approach, regression analysis was used in developing entry capacity models for England, Germany, France and Denmark (Aagaard 1996, Kimber 1980). Comparison of the observed capacity data in previous studies indicated that the empirical approach provides reasonable capacity estimate. Besides, the empirical approach makes it possible to investigate how different geometric elements affect the estimated capacity.

Queue length and delay are important aspects of roundabout performance. Queue length indicates the existence of blockage of traffic at roundabout, while delay determines the level of service of roundabout. Empirical or statistical methods and queuing theory methods are used to estimate queues and delays at roundabouts. Most formulas are based on queuing theory, such as Harder's method modified by Harder (Harder 1989) the CETUR (French Government organization responsible for urban transportation guidelines nationwide) method (CETUR 1988) and the Kimber and Hollis or TRRL (Transport and Road Research Laboratory) method (Kimber and Hollis 1979).

The roundabout improves safety by eliminating or altering conflict types as compared to conventional intersection, by reducing speed differentials at consecutive geometric elements, and by forcing drivers to decrease speeds as they proceed into and through the roundabout. Roundabout geometry that allows consistent speeds at each vehicle path results in better safety performance. The radii at which driver negotiates along the vehicle path, control its speed. Each vehicle path (left, through, and right) is traditionally drawn by freehand on the proposed roundabout geometry. The conflict points are entering-circulating for each path and left-turn and through path conflict at the central island with right-turn path. If relative speeds at consecutive negotiation radii of each path and conflict points is less than 20 km/h, the design is considered to be consistent and safer. An iterative process is normally performed to achieve roundabout geometry for consistent design.

Roundabout geometric design involves choosing trade-offs between safety and operational performance. In order to avoid the iterative design process, for optimum safety and operational performance, an optimization model was developed in this research. The objective function of the model is to maximize design consistency and minimize average intersection delay. The model requires as input traffic data and site conditions and directly provides the optimum design. This is a new approach of optimizing geometric design of roundabout. The model was developed for single-lane roundabouts with four legs intersecting at right angles.

1.1 Modern Roundabouts

Design principles of modern roundabouts are quite different from those of traffic circles built in the Unite States in the first half of the 20^{th} century (Jacquemart, 1998). The design of older traffic circles included such inefficient features as yielding to the entering traffic, tangential entries, and huge inner circle island provided for long weaving distances. These circles encountered serious safety and operational problems, including the tendency to lock up at high volumes. In 1966, the British adopted the 'priority-to-the-circle' rule that eliminated the locking up of circles at high volumes, reduced both injury crashes and delays by 40 percent, and increased capacity by 50 percent (Waddell and Edmund, 1997). The British also began designing roundabouts with smaller diameters to eliminate weaving and make drivers concentrate on gap-acceptance only. Besides, deflection of the entering traffic was also found to improve the safety of the roundabouts.

These changes along with other minor adaptations brought about a significant increase in the number of roundabouts in Europe in the 1970's. The modern roundabouts represented a substantial improvement in terms of operation and safety compared with older rotaries and traffic circles (Todd, 1991). The strong interest expressed in modern roundabouts in the United States in recent years is partially due to its success in Europe and Australia, where the modern roundabout has changed the practice of intersection design (Waddell and Edmund, 1997).

1.1.1 Modern Roundabouts vs. Traffic Circles

Since the purpose of this thesis is developing a model for the design and performance evaluation of single-lane roundabouts, it is necessary to distinguish between roundabouts and traffic circles for public understanding. The roundabout is different from traffic circles, in the following features:

- Traffic Control: Yield control is used on all entries of the roundabout, and the circulator roadway has no control. Whereas, some traffic circles use stop control or no control on one or more entries.
- Priority to Circulating Vehicles: In roundabouts, circulating vehicles have the right-of-way. But some traffic circles require circulating traffic to yield to entering traffic.
- Pedestrian Access: Pedestrian access is allowed only across the legs of the roundabout behind the yield line. In some traffic circles pedestrian have access to the central island.
- Parking: In roundabouts, no parking is allowed either within the circulatory roadway or at entries. Whereas, some traffic circle allow parking within the circulatory roadway.
- Direction of Circulation: In roundabouts, all vehicles circulate counter-clockwise and pass to the right of the central island. But in some traffic circles, left-turn vehicles are allowed to pass to the left of the central island.

1.2 Categories of Roundabouts

There are six basic categories of roundabouts based on environment, number of lanes, and size of the roundabouts:

- Mini-roundabouts
- Urban compact roundabouts
- Urban single-lane roundabouts
- Urban double-lane roundabouts

- Rural single-lane roundabouts
- Rural double-lane roundabouts

Multilane rural and urban roundabouts are also possible. The basic geometric elements for these roundabouts are the same as those discussed above. This thesis is confined to single-lane roundabouts, and therefore single-lane rural and urban roundabouts are discussed below.

1.2.1 Urban Single-Lane Roundabouts

These roundabouts have single-lane entry at all legs and one circulatory lane. They have inscribed circle diameter more than urban compact roundabouts. Their design allows slightly higher speeds at the entry, on the circulatory roadway and at the exit. Sometimes low design speed is used for the safety of pedestrians and bicycles. The roundabout design focuses on achieving consistent entering and circulating vehicle speeds. The geometric design includes raised splitter islands and a nonmountable central island with preferably no apron. The recommended maximum entry speed for this type of roundabout is 35 km/h and the inscribed circle diameter ranges from 25-30 m (Robinson et al. 2000).

1.2.2 Rural Single-Lane Roundabouts

Rural highways usually have high design speed, where the average approach speed at these roundabouts ranges from 80 to 100 km/h. Therefore, they require supplementary geometric and traffic control device treatments on approaches to force drivers to slow to a safe speed before entering the roundabout. These roundabouts may have larger inscribed circle diameter than urban roundabouts to allow slightly higher speeds at the entries, on the circulatory roadway, and at the exits, provided that few pedestrians are expected at these intersections. They do not require apron because their larger diameter may accommodate larger vehicles. Supplemental geometric design elements include extended and raised splitter islands, a non-mountable central island, and adequate horizontal deflection.

1.3 Basic Geometric Elements of Single-Lane Roundabouts

For the purpose of design and operational analysis of single-lane roundabouts, it is useful to define a number of basic geometric elements. These elements are discussed in the following sections and are shown in Figure 1.1:

- Approach width: Approach width is the one-way width of the roadway approaching the roundabout. British engineers defined this as the approach half-width. It is typically not more than half of the total width of the roadway.

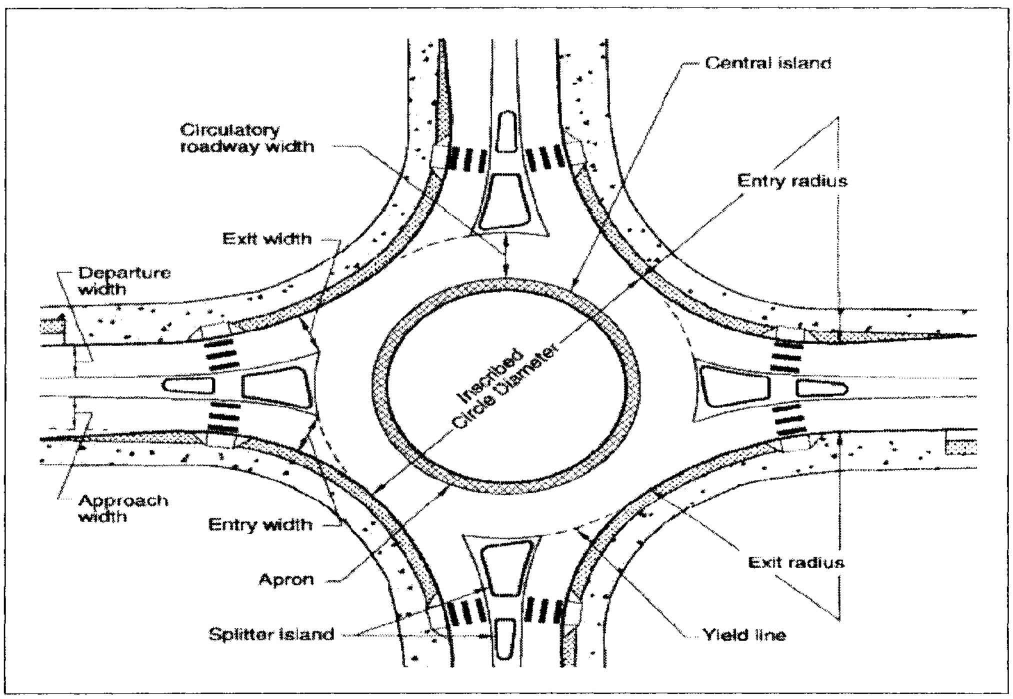


Figure 1.1: Design Elements of a Modern Roundabout (Source: Robinson et al. 2000)

- Departure width: The departure width is the one-way width of the roadway used by departing vehicles from the roundabout. It is typically less than or equal to half of the total width of the roadway.
- Central Island: The central island is the area in the center of a roundabout around which traffic circulates. It can be raised or flushed (for mini-roundabouts) or it can have a raised central island with a mountable or drivable apron surrounding it. The truck apron is generally included in the central island.
- Circulatory Roadway: The circulatory roadway is the curved path around the central island on which circulating vehicles travel in a counterclockwise direction.
- Entry Width: The entry width is measured perpendicularly from the right edge of the entry to the intersection of left edge line and the inscribed circle.
- Exit Width: The exit width is measured perpendicularly from the right curb line of the exit to the intersection of the left edge line and the inscribed circle.
- Entry Radius: The entry radius is the minimum radius of curvature of the right-side curb at the entry.
- Exit Radius: The exit radius is the minimum radius of curvature of the right-side curb at the exit.
- Inscribed Circle Diameter: The inscribed circle diameter is the diameter of the circle that can be inscribed within the outer curb line of the circulating roadway. It is the basic parameter used to define the size of a roundabout.
- Splitter Island: Splitter island is a raised or painted area within a leg of a roundabout used to separate entering traffic from exiting traffic, deflect and slow

entering traffic, and provide storage space for pedestrians crossing the road in two stages.

- Truck Apron: The truck apron is the portion of the roundabout that is drivable and is specifically provided to accommodate the wheel tracking of large vehicles. It is generally constructed with a different material to discourage passenger cars from driving over it.
- Yield Line: The yield line is a broken line marked across the point of entry from an approach into the circulatory roadway and is generally marked along the inscribed circle. Entering vehicles wait on yield line until an acceptable gap is available to enter the circulating flow.

1.4 Roundabout Site Selection

The reason behind the decision of installation of a roundabout at a specific site is either operational improvement, safety enhancement, or both. The environment will be either rural or urban, but the number of lanes of the roundabout is defined on the basis of the expected traffic and capacity requirements. The capacity of the roundabout is a critical parameter, so it should be checked properly in its feasibility study. Traffic volume in the feasibility study is considered in terms of the average daily traffic (ADT) or the average annual daily traffic (AADT). As operational analysis is carried out at the design hour, to obtain the design-hour traffic volume, two factors, "K" and "D" are assumed. K represents the proportion of the AADT assigned to the design hour, whereas D represents the two-way traffic that is assigned to the peak direction. For planning purposes, the values of $K = 0.1$ and $D = 0.58$ are assumed (Robinson et al. 2000).

Two other factors are also taken into account: one is the proportion of traffic on major street and the proportion of left-turn vehicles. These two factors affect the operation significantly. The proportion of traffic on major street is assumed to lie between 0.5 and 0.67, and left-turn vehicles are assumed to range from 0 to 40 percent of the total volume (Robinson et al. 2000). Once the proportion of left turning vehicles and major street traffic are assumed, the number of lanes is determined Figure 1.2. If the 24-hour volume falls below the volumes indicated in Figure 1.2, a roundabout will have no operational problem at any time of the day. For single-lane roundabouts, the daily service volume ranges from 20,000 to 22,000veh/day. Detail capacity analysis is carried out in the final design of the roundabout.

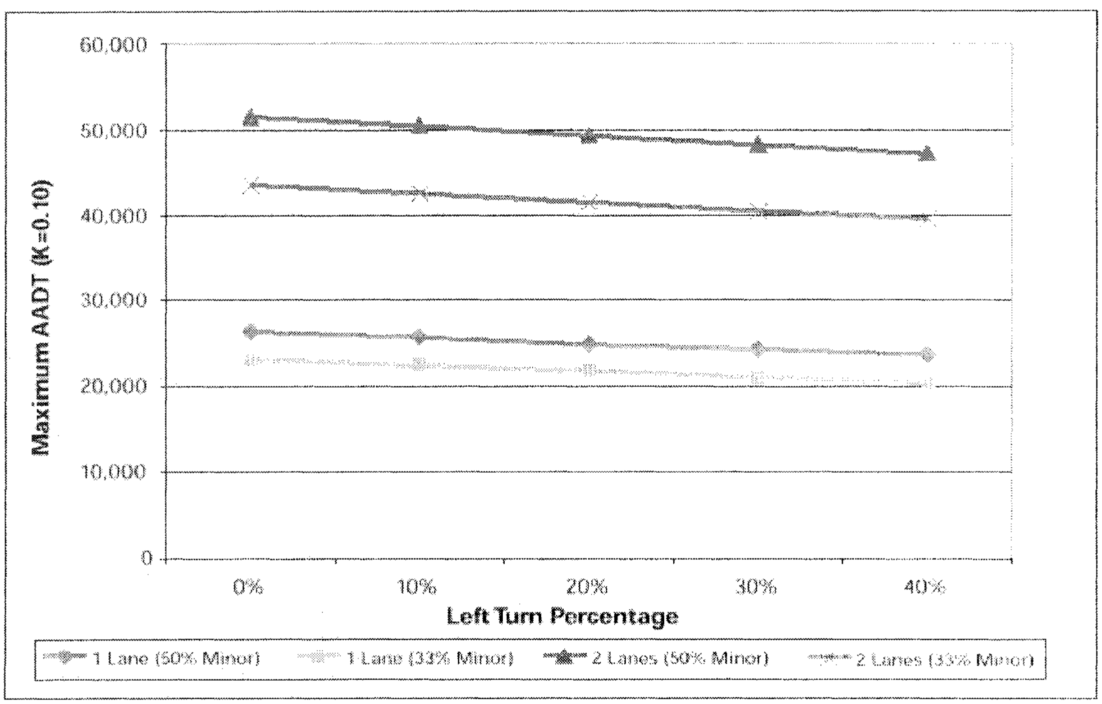


Figure 1.2- Maximum Daily Service Volumes for a Four-Leg Roundabout (Robinson et al. 2000)

When a single-lane or double-lane roundabout is conceded, a feasibility study is carried out for various alternatives prior to the detailed design of roundabout. The aspects for which various alternatives are compared are safety, capacity, operational performance, construction cost, and operational and maintenance cost. The availability of right-of-way is also an important issue when deciding the installation of the roundabout. For the installation of roundabout, the Austroad design guideline has presented the appropriate and inappropriate locations as below (Austroad 1993).

1.4.1 Appropriate Sites for Roundabout

The following situations may lead to the installation of roundabout:

- When STOP or yield signs at the intersections result in unacceptable delays for the minor road traffic, the installation of roundabout would decrease delays to the minor road traffic and increase delays to the major road traffic.
- At intersections, where traffic signals would result in greater delays than a roundabout. It should be noted that in many situations the roundabout may operate with lower delays and better safety, particularly in the off-peak periods, but provide similar capacity to that of traffic signals.
- As roundabouts can operate efficiently with high volumes of left-turn vehicles, the intersections with high proportion of left-turn vehicles can be replaced by roundabouts.
- If one or more legs of an intersection with more than four legs cannot be closed or relocated, or some turns prohibited, roundabout can provide a convenient and effective treatment. Traffic signals may be less efficient due to the large number

of phases required and STOP or Yield signs often do not practically define priorities adequately. This results in high proportion of lost time.

- The roundabout can improve safety and neighborhood management, especially on local roads and to a lesser extend on arterial roads.
- The roundabout can resolve the safety problem, involving crossing or left-turn traffic versus opposing traffic at rural cross intersections. However, if low-volume road traffic is less than 200 vph, consideration could be given to using a staggered T treatment.
- At intersections of arterial roads, where traffic speeds and left turning traffic flows are high, the installation of well-designed roundabout can have advantage over traffic signals in reducing left turn-through traffic accidents and overall delays.
- At T or cross intersections, where the major traffic route turns through a right angle. In these situations, the major movements within the intersection are turning movements that can effectively and safely be accommodated at roundabouts.
- The installation of roundabout can be appropriate when the major road intersects at Y or T intersections because these usually involve a high proportion of left-turn traffic.
- The locations, where traffic growth is expected to be high and future traffic patterns are uncertain or changeable.
- At local road intersections, where it is not desirable to give priority to either road.

1.4.2 Inappropriate Sites for Roundabout

The installation of roundabout may not be appropriate in the following situations:

- The sites where satisfactory geometric design cannot be provided due to insufficient space, unfavorable topography, and unacceptable high cost of construction, including property acquisition and service relocations.
- At the intersection of minor and major roads, the roundabout can result in unacceptable delay to major road traffic.
- When traffic flows are unbalanced with high volumes on one or more approaches, this will result in long delays to some vehicles.
- When pedestrian flow is high, and due to high traffic volume, it is difficult for them to cross either road.
- Where peak period reversible lanes may be required.
- When large and over sized vehicles frequently use the intersection and insufficient space is available for the required geometric layout.
- Where the traffic leaving the roundabout would be interrupted by a downstream traffic control that could result in queuing back into the roundabout.

1.5 Purpose and Scope of Research

The purpose of this study is to develop a new optimization model that will determine the optimum design of roundabout based on design consistency, capacity and operational performance. This model will not only improve design consistency (safety), capacity and operational performance of roundabout, but also eliminate the present iterative, time-consuming design process of roundabouts. Although this model focuses on single-lane roundabout with four legs intersecting at right angle, it presents a new approach for the optimum design of roundabout, in general. Future extension of this model will be for skewed double-lane and multi-lane roundabout. This model along with future extensions will act like a complete software for the optimum design of roundabout.

1.6 Brief Description of Thesis

This thesis is structured in five chapters as follows (Fig. 1.3):

Chapter 1: This chapter presents an introduction to roundabouts and thesis research as a whole. Differentiation between modern roundabouts and old traffic circles along with definitions of design parameters of roundabout are also presented. Guidelines for site selection for roundabout installation and the scope of the thesis research are described briefly.

Chapter 2: This chapter presents the literature review about capacity and operational performance of roundabouts. Gap-acceptance theory and regression analysis, used for capacity analysis of roundabout, described in detail. Operational performance measures include delay, degree of saturation and queue length. The models developed by different researchers for these operational performance measures are presented briefly.

Chapter 3: This chapter presents a literature review for the geometric design of roundabouts. The design principles and complete design process for single-lane roundabouts are presented. Deign guidelines for each geometric design element of single-lane roundabouts are described in detail.

Chapter 4: The literature review of the first three chapters gives sound background to understanding the modeling process presented in chapter 4. An optimization model for the optimum design and operational performance of roundabout is developed.

The Existing methodology for the design of roundabouts is presented briefly. The development of the optimization model is presented in a systematic way so that it can be easily understood by the reader. An application of model is the presented to illustrate the design of single-lane roundabout.

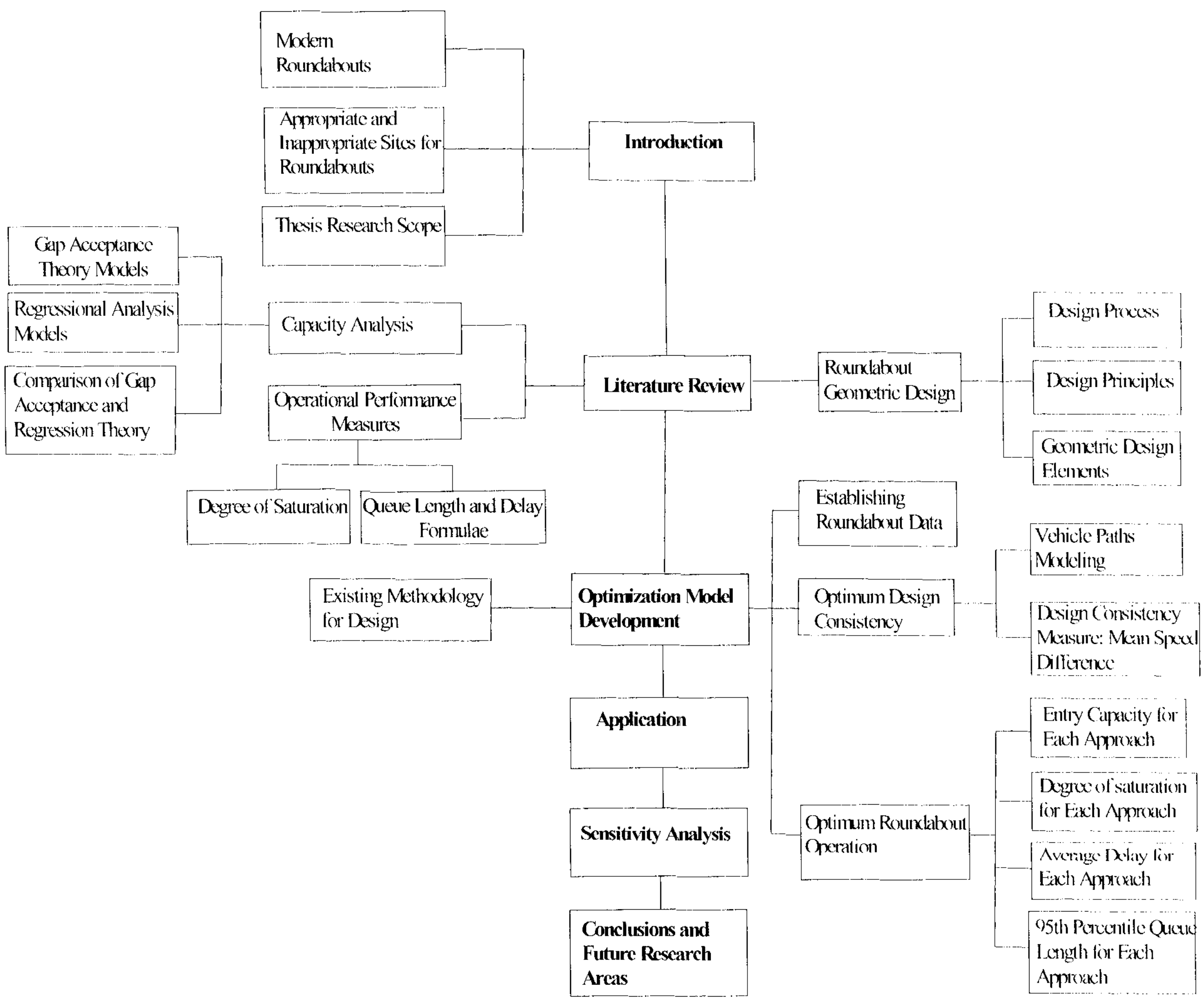


Figure 1.3: Thesis Structure and Research Activities

Chapter 5: This chapter presents conclusions and future areas of research work. The conclusions are related to model features and its applicability. The proposed future research includes extensions of the optimization model.

Chapter 2

CAPACITY AND OPERATIONAL ANALYSIS

2.1 Introduction

The installation of roundabouts is preferred because of its safety and operational benefits over conventional intersections. The designer must design roundabout parameters for given traffic and operational requirements. An operational analysis of roundabout involves estimation of two measures, capacity and level of performance. The Highway Capacity Manual (HCM 1999) defines the capacity of a facility as "the maximum hourly rate at which persons or 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." The level of performance is measured in terms of two measures of effectiveness, queue length and delay. The capacity of the roundabout not only predicts the ability to accommodate various streams of user, but also affects vehicle delay and queue.

In addition to delay, all intersections including roundabouts cause drivers to incur geometric delays when making turns at intersection. A detailed delay analysis also accounts for geometric delay because of slower vehicle paths required to negotiate the roundabout. There are two approaches to calculate entry capacity of the roundabouts. One is the empirical technique and the other is the theoretical (or gap-acceptance) technique. The empirical technique is based on an empirical formula developed based on field measurements at saturated roundabouts. The theoretical technique is based on simplifying assumptions of driver behavior. This chapter presents a literature review of the capacity analysis methods, traffic queues, and delay at the roundabout entries.

2.2 Roundabout Capacity

The main objective of capacity analysis is to evaluate the operational performance of the roundabout. In the early stages of roundabout development, the concept of weaving capacity was adopted, but afterward it was changed in favor of the entry capacity. The capacity of each entry is the maximum number of vehicles that can enter the roundabout in one hour at given traffic and roadway conditions. In modern roundabouts, priority is given to the circulating traffic, and therefore the entry capacity decreases with an increase in the circulating flow when less appropriate gaps are available.

Therefore, the effect of the circulating flow in both gap-acceptance theory and empirical theory is the same. The British and French empirical relationships for capacity analysis depend on roundabout geometric parameters and entry and circulating traffic flows. The analysis allows designers to design roundabout geometric parameters both for operational and safety aspects. The theoretical approach conceptually relates traffic interactions at roundabouts to the availability of gaps in the traffic streams.

2.2.1 Data Requirement

Both the empirical method and gap-acceptance theory require geometric and traffic data for capacity analysis of each entry of the roundabout. The traffic data include the conflicting circulating traffic flow for 15-minute periods for each roundabout entry.

Intersection volume counts for each directional movement are made with an observer noting the number of cars at the intersection over a specified time period.

Volumes are typically expressed in passenger cars per hour (pce/h), for a specified 15-minute period. Usually the analysis period is the morning or evening peak-hour. Other types of vehicles are converted to passenger car equivalents (pce) using the conversion factors given in Table (2.1).

The circulating flow is the sum of the vehicles from different movements passing in front of the adjacent upstream splitter island. Once the entry flow for each movement (left, right, u-turn, and through movements) is known, the conflicting circulating flow for each entry can be calculated from Equation (4.9) presented in chapter 4. Entry flow is simply the sum of left, right, u-turn, and through traffic flows at each entry. The entry flow is used to check the degree of saturation at each entry. The exit flow at each entry is calculated using observed data to verify the provision of single-lane or multi-lane roundabout. Exit flows exceeding 1200 pce/h may indicate the need for a double-lane exit (Robinson et al. 2000).

Table 2.1: Conversion Factors for Passenger Car Equivalents (pce) (Jessen 1968, Harders 1976)

Vehicle Type	Passenger Car Equivalents (pce)
Car	1.0
Single-unit Truck or Bus	1.5
Truck with trailer	2.0
Bicycle or Motorcycle	0.5

The geometric data include entry width, entry angle, approach half width, entry radius, inscribed circle diameter, and average effective flare length. These data are required for entry capacity analysis with the empirical method. The gap-acceptance theory needs only the number of entry lanes, number of circulating lanes, and inscribed circle diameter as geometric data for the capacity analysis of the roundabout. Thus, the geometric data and traffic data may determine the entry capacity of each approach of the roundabout at a given time period.

2.3 Entry Capacity Models

As mentioned previously, the entry capacity can be analyzed with two approaches. The first is a regression analysis or empirical method and the second is the gap-acceptance theory. Most countries adopted capacity formulas based on either one of these two approaches. Details of these approaches are described in the following sections.

2.3.1 United Kingdom Capacity Model

The United Kingdom capacity model is based on regression analysis. . The regression capacity formula is based on Kimber's study. (Kimber 1980). The UK research indicates that the entry capacity is quite sensitive to the approach half width, entry width, and average effective flare length. Whereas the entry radius and entry angle have relatively little effect on capacity, provided that the radius is 20 m or more. The inscribed circle diameter also has a small effect when it is 50 m or less. These parameters are defined in the introduction chapter. As per Kimber's study, the entry capacity of each approach of the roundabout can be determined using the following formula,

$$Q_e = F - f_c Q_c \qquad [2.1]$$

where,

Q_e = Entry capacity (vph)

Q_c = Circulating flow (vph)

F, f_c = Parameters defined by roundabout geometric parameters

For the regression analysis, Kimber used the data collected by Philbrick (1977), Kimber and Semmens (1977), Glen et al. (1978), and Ashworth and Laurence (1977, 1978). The type of data and their range of values used in the regression analysis are as follows:

e = entry width, 3.6-16.5 m

v = Approach half width, 1.9-12.5 m

l'= Effective flare length, 1- ∞ m

S = Sharpness of flare = 1.6 (e-v)/l', 0- 2.9 (decimal)

D = Inscribed circle diameter, 13.5- 171.6 m

Φ = Entry angle, 0- 77 degrees

r = entry radius, 3.4- ∞ m

Kimber found that the effective entry width depends on the approach half width, entry width, and sharpness of flare. The effective entry width, x_2, is given by

$$x_2 = v + \frac{e+v}{1+2S} \qquad [2.2]$$

The intercept of the capacity equation, F, is found using the linear regression of F as a function of x_2.

$$F = 303\, x_2 \qquad [2.3]$$

It is found that the entry capacity is greater on roundabouts with larger inscribed circle diameter, given the same entry flow and other roundabout geometry. Therefore, the slope of the capacity equation, f_c, decreases as the diameter increases. A factor 't_d' was included in the equation for f_c to account for this effect. Kimber obtained the equation for the slope f_c as,

$$f_c=0.210(1+0.2\,x_2)\,t_d \qquad [2.4]$$

where t_d is,

$$t_d= 1+\frac{0.5}{1+\exp\left(\frac{D-60}{10}\right)} \qquad [2.5]$$

Kimber also found that the entry angle and entry radius have little effect on capacity. Therefore, the capacity equation is modified by adding of a correction factor k,

$$Q_e= k\,(F\text{-}f_c\,Q_c) \qquad [2.6]$$

where,

$$k=1\text{-}0.00347(\Phi\text{-}30)-0.978\left(\frac{1}{r}-0.05\right)\frac{0.978}{r} \qquad [2.7]$$

The best angle is found to be 30 degree. Kimber tested for linearity and found that the parabolic function did not significantly improve the predictive ability. He concluded that linear approximation is the best for entry capacity analysis of roundabouts. Equation (2.6) along with other supporting equations is adopted as the UK capacity formula for the roundabouts. Roundabouts fall in two categories: those with inscribed circle diameter of less than 50 m and those with a diameter above 50 m. The British capacity relationship holds for both of these categories of roundabouts. Besides, the UK capacity formula is the same for rural and urban roundabouts.

2.3.2 German Capacity Formulas

Germany investigated both regression and gap-acceptance theory to analyze the entry capacity of the roundabouts. However, the regression method was used instead of the gap-acceptance theory. The following sections describe the German regression and gap-acceptance methods.

2.3.2.1 German Regression Capacity Formula

In contrast to the UK linear regression, German used the exponential regression to describe the entry/circulating flow relationship because of the better agreement with the gap-acceptance capacity formula developed by Siegloch (1973). The German capacity formula is,

$$Qc = A\ exp\left(\frac{-BQc}{10000}\right) \qquad [2.8]$$

where,

Q_c = Conflicting circulating flow, (vph)

Q_e = Entering flow, (vph)

A, B = defined parameters

Table 2.2: Parameters for Calculating Roundabout Capacity (Brilon et al. 1990)

Number of Lanes		Parameters	
Entry	Circulatory Roadway	A	B
1	1	1089	7.42
2-3	1	1200	7.30
2	2	1553	6.69
3	2	2018	6.68

The parameters A and B in Equation (2.8) have been determined separately from measurements by regression calculation for a different number of lanes of entry and circulating roadway. Their values are shown in Table (2.2),

The German capacity results were found to be 0.7-0.8 of the English values. Brilon et al. (1991) explained that this difference is due to different driver behavior. As roundabouts have been installed in England from long time ago, it is assumed that drivers in England are more familiar with this type of intersection control.

Later on, research conducted by the Federal government of Germany showed that linear regression instead of an exponential function has a better agreement of the variance data (Brilon et al. 1997). The new modified capacity formula is,

$$Q_e = C + D\,Q_c \qquad [2.9]$$

where, C and D are parameters that can be obtained from Table 2.3.

Table 2.3: Parameters for Linear Regression (Brilon et al. 1997)

Number of Lanes		Parameters	
Entry	Circulatory Roadway	C	D
1	1	1218	-0.74
½	1/3	1250	-0.53
2	2	1380	-0.5
2	3	1409	-0.42

2.3.2.2 German Gap-acceptance Capacity Formula

Brilon et al. (1997) modified the idea presented by Tanner (1962) and proposed the following formula for estimating the entry capacity of the roundabout.

$$Qc = \left(1 - \frac{\Delta Qc}{n_c}\right)^{n_c} \frac{n_e}{T_0} \exp\left(-Qc\left(t_0 - \Delta\right)\right) \qquad [2.10]$$

where,

Qe = Maximum entry capacity (vph)

Qc= Circulating flow (vph)

n_c = Number of circulating lanes

n_e = Number of entry lanes

$t_0 = T - \frac{T_0}{2}$

T = critical gap (sec)

T_0 = Follow-up time (sec)

Δ = Minimum headway between vehicles in circulating lane (sec)

2.3.3 French Capacity Formulas

France developed two roundabout capacity formulas for urban and rural environments. These capacity formulas are discussed below,

2.3.3.1 French Capacity formula for Urban Roundabouts

In the French capacity formula, the impeding traffic flow is considered to be the most effective flow for capacity analysis instead of the circulating flow, unlike the British and Australian methods. The original capacity formula was developed by CETUR, a government organization responsible for urban transportation guidelines nationwide (CETUR 1988). The impeding flow is calculated in a similar way to the US method for unsignalized intersections. It is the sum of the circulating flow and a proportion of the exit flow at the same branch,

$$Q_g = Q_c + \alpha\, Q_s \qquad [2.11]$$

where,

Q_g = Impeding flow

Q_c = Circulating flow

Q_s = Exiting flow

α = Variable that is the function of the splitter island (0.2 on average)

The impeding flow is adjusted to an equivalent impeding flow when the circulating roadway is at least 8 m wide. The concept behind impeding flow is that entering traffic is hampered to some degree by the exiting traffic because of the uncertainty over whether these vehicles actually exit or not. The French entry capacity formula is based on linear regression. The entry capacity "C" is defined by the following equation:

$$C = 1500 - \frac{5}{6} Q_g \qquad for \ Q_g < 1800 \qquad [2.12]$$

$$C = 0 \qquad for \ Q_g > 1800 \qquad [2.13]$$

With two entry lanes entry, the capacity is increased by 40 percent. The capacity equation represents the straight line expressing the entry capacity as a function of the impeding flow. This capacity is the maximum theoretical capacity; however it requires a reserve capacity for design purposes.

2.3.3.2 French Capacity formula for Rural Roundabouts

The original capacity formula for rural roundabouts was developed by the French national design service for rural highways (SETRA 1988 and 1997). The same capacity formula is followed by the SETRA design guide (SETRA 1996). It is similar to the CETUR capacity formula, but with minor variations. Both CETUR and SETRA capacity formulas are linear equations with the impeding flow as the independent variable. The following SETRA capacity formula is applicable to rural roundabouts with a radius of the central island of 15 m or more.

$$C = (1330 - 0.7\,Qg)\,[1 + 0.1(le - 3.5)] \qquad [2.14]$$

where,

C = Entry capacity (vph)

$Qg = (Qc + \frac{2}{3} Q's)\,[1 - 0.085(la - 8)]$

le = entry width (m)

la = Circulatory roadway width (m)

$Q's = \frac{Qs(15 - li)}{15}$

li = width of splitter island (m)

Q's= 0 for li >15 m

The reserve capacity and its percentage are calculated as,

Reserve Capacity = C – Qe

$$\text{Percentage of Reserve Capacity (\%)} = \frac{C - Qe}{Qe} \; 100$$

where, Qe = Entering flow (vph)

2.3.4 Swiss Capacity Formula

The Institute of Transportation of the Federal Polytechnic School of Lausanne prepared the Swiss Roundabout Guide (Bovy 1996).

The capacity formula is based on linear regression similar to the CETUR French formula, but with a different slope. It also correlates the entry capacity 'Ce' of the roundabout with the impeding flow Qg,

$$Ce = 1500 - \frac{8}{9} Qg \qquad [2.15]$$

$$Qg = b\,Qc + \alpha \; Qs$$

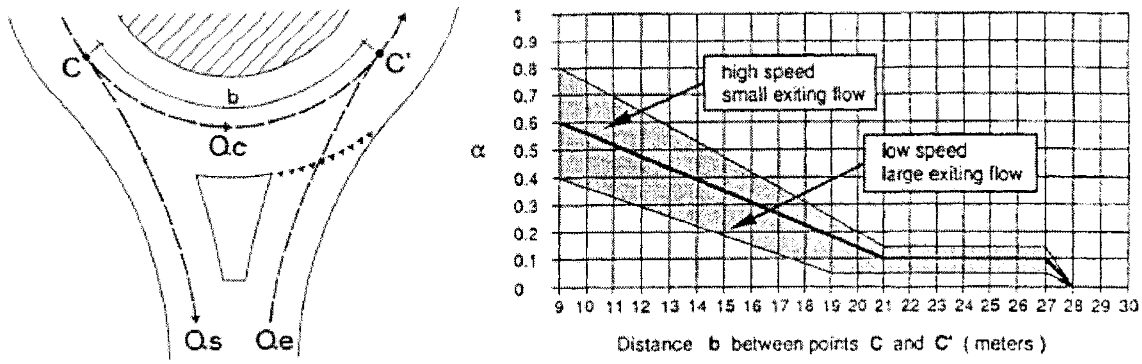
where,

Ce = entry capacity (vph)

Qg = Impeding flow (vph)

Qc = circulating flow (vph)

Qs = Exiting flow (vph)



Determination of α

Figure 2.1: Capacity Factors (Simon 1991)

The coefficient 'α" accounts for the impedance of the entry due to the exiting flow. It is determined by a simulation model as a function of the distance between the conflict points of the exit and entry (Figure 2.1).

2.3.5 Australian Capacity Formula

The Australian capacity formula is based on gap-acceptance theory. This method relates traffic interactions at roundabouts with the availability of gaps in the traffic streams. With gap-acceptance theory, it is easier to adjust gap-acceptance parameters for unusual conditions.

The Australian capacity formula is based on Tanner's capacity formula for intersections. This formula was modified in order to relate the equation to observed data from the field. The modified Tanner's equation is adopted by Australia for the capacity analysis of the roundabouts.

Tanner (1962) analyzed intersection delays of two streams in which the major stream had priority over the minor stream. He assumed that both minor and major stream vehicles arrive randomly, but the major stream vehicle cannot enter the intersection sooner than Δ sec after the preceding major stream vehicle, whereas a Δ is the minimum headway. The minor stream vehicle enters only when there is an acceptable gap available, which is more than T sec (i.e. minimum gap acceptable for entry). If the chosen gap is large enough, minor stream vehicles follow each other through the intersection at intervals of T_0 sec (Follow-up time). Tanner's equation for entering capacity is defined as,

$$q_e = \frac{qc(1-\Delta qc)\exp(qc(T-\Delta))}{1-\exp(-qcT_0)} \qquad [2.16]$$

where,

q_e = entering capacity (veh/sec)

q_c = Circulating flow (veh/sec)

T = critical gap (sec)

T_0 = Follow-up time (sec)

Δ = Minimum headway (sec)

Several studies have been conducted to find the appropriate values of T, T_0, and Δ. Studies indicated that values of T = 3-4 sec, T_0= 2 sec, and Δ = 1 or 2 sec are suitable for the Australian conditions (Troutbeck 1984). For two-lane roundabouts, the values T = 4sec, T_0 = 2sec and Δ = 0 provide good prediction of the entry capacity for circulating flow of 300-2000 pcph (Avent and Taylor 1979).

Avent and Taylor (1979) studied three Brisbane roundabouts to validate the above values and found that proper values should be T = 3.5 sec. and T_0 = 2.0-2.7 sec. They also objected to the Horman and Turnbull's conclusion that the minimum headway on multilane circulation flow was zero. They concluded that T= 2.5 sec, T_0 = 2.1 sec, and Δ = 2.1 and 1.1 for single-lane and two-lane roundabouts respectively. Tanner's assumptions that T and T_0 are constant and the headway distribution of priority stream was random were not realistic (Troutbeck 1988, 1991). Vehicles travel in two ways: either vehicle travel in bunches following too closely or travel in a free manner without interactions with the vehicle ahead. Tanner's equation is modified by Troutbeck (1991) with Cowan's M3 distribution. The modified capacity formula is,

$$Qc = \frac{3600(1-\theta)qc\exp(-\lambda(T-\Delta))}{1-\exp(-\lambda T_0)} \qquad [2.17]$$

where,

Q_c = entering capacity (vph)

q_c = Circulating flow (vps)

Δ = Minimum headway in circulating streams, 1 sec for multilane and 2 sec for single lane.

θ = Proportion of bunched vehicles

λ = Decay parameters = $\frac{(1-\theta)qc}{1-\Delta qc}$

Troutbeck (1990) studied the interaction of traffic streams and their influence on each other. He concluded that entering vehicles are often unsure about circulating vehicles, whether they will exit or travel along their paths. Therefore, entering drivers will give way to all circulating vehicles regardless of one or two circulating lanes. Consequently, drivers exiting at the same leg will have little influence on the entering vehicles. Sometimes circulating vehicles decelerate and give way to entering vehicles, this result in shorter mean follow-up time and critical-gap for entering vehicles. It is also observed that the drivers turning right are expected to use the right-hand lane and drivers turning left expected to use the left-hand lane.

Troutbeck's study introduced the concept of dominant and subdominant streams in multilane roundabouts. The stream with the greatest entry flow is considered to be the dominant stream. In this stream, critical-gap parameters are lower and result in a higher entry-lane capacity. On the other hand, the subdominant stream has larger critical-gap parameters and consequently lower capacity. It is also concluded that there is only one dominant stream at each entry and all other streams are subdominant. If there is only one stream (i.e. single-lane roundabout), it will be a dominant stream (Troutbeck 1990).

Troutbeck developed new models to calculate the critical gap and follow-up time in each lane of the roundabout. The same models are used in the Austroad guideline. The follow-up time in the dominant stream can be computed as,

$$T_{0\,dom} = 3.37 - .000394\,Qc - 0.0208\,Di + 0.000089\,Di^2 - 0.395\,n_e + 0.388\,n_c \qquad [2.18]$$

where,

Qc = Circulating flow (vph)

Di = Inscribed circle diameter (m)

n_e = Number of entry lanes

n_c = Number of circulating lanes

The follow-up time for the subdominant stream, T_{0sub}, depends on the follow-up time of the dominant stream and the ratio of the entry flows of dominant and subdominant streams,

$$T_{0sub} = 2.149 + 0.5135 T_{0\,dom} \frac{Q_{dom}}{Q_{sub}} - 0.8735 \frac{Q_{dom}}{Q_{sub}} Q_{dom} \qquad [2.19]$$

This equation shows that larger follow-up time for the dominant stream will result in larger follow-up time for the subdominant stream, which is quite realistic.

The dominant stream follow-up time also increases with larger variations in the lane entry flows.

Troutbeck also modeled critical gap that is dependent on the follow-up time, the circulating flow, the number of circulating lanes, and the average entry lane width (e_e). The ratio of critical gap to the follow-up time was found to decrease with an increase in circulating flow, the number of circulating lanes, and the average entry-lane width. This condition is applied to all entry lanes of single-lane and multilane roundabouts. The ratio is defined as,

$$\frac{T}{T_0} = 3.6135 - 0.0003137\,Qc - 0.3390\,e_e - 0.2775\,n_c \qquad [2.20]$$

The initial capacity equation developed by Tanner has a limitation because it did not take into account the roundabout geometry. Troutbeck modified this capacity formula and modeled the follow-up time, and critical gap by taking into account the inscribed circle diameter, average entry width, and number of circulating and entry lanes. The Austroad guideline follows the gap-acceptance theory developed by Troutbeck for the capacity analysis of roundabouts.

2.3.6 US Capacity Studies

Flannery and Tapan (1996, 1997) conducted a study to evaluate the operational performance of roundabouts in the US. Data for roundabouts in Maryland and Florida were collected for the study. The authors focused on gap-acceptance method for the capacity analysis. The primary reason for choosing the gap-acceptance approach was the lack of variability in the data. The regression analysis needs a large sample of data from sites ranging from 16 to 35 sites. The data for two gap-acceptance parameters, critical gap, and follow-up time were collected from a wide record. The maximum-likelihood technique was used to determine the critical gap what was found to be 3.89 sec. The authors concluded that the critical gap and follow-up time were lower in three of the four sites, as compared to the values determined using the Austroad's method. The Federal Highway Administration published a comprehensive design guide for roundabouts in 2000. This guideline follows the UK regression method for the capacity analysis of roundabouts.

2.4 Gap-Acceptance vs. Empirical Regression

Roundabout capacity can be calculated using two approaches: gap-acceptance and empirical regression. The gap-acceptance approach is based on driver behavior and is considered to be consistent and homogenous. Many studies have shown that this assumption of consistent driver behavior is not appropriate in every circumstance and may result in wrong capacity prediction. At low traffic, capacity is overestimated and at high traffic capacity is underestimated (Aagaard 1996, Kimber 1989). Gap-acceptance parameters change with driver behavior. The aggressive drivers will accept much smaller gaps than hesitant drivers. If a hesitant driver missing the gap that following driver thinks is acceptable, that might make the following driver more aggressive. However, these characteristics are not fixed and vary from driver to driver. Sometimes entering vehicles do not get suitable gap and 'push' into the circulating stream forcing the circulating vehicles to modify their speeds and path. This is called gap forcing.

It is also common for circulating traffic to deliberately slow down or change its intended path to create space for an entering vehicle, knowing the difficulty for entering vehicles from their experience. The main flaw of the gap-acceptance theory is that it poorly evaluates capacity for at-capacity roundabouts. The Australian capacity formula also attempted to resolve the shortcomings of the gap-acceptance technique. For example, a model was developed to incorporate the variation of critical gap and follow-up time with different volumes of traffic and correlating gap-acceptance parameters with geometric parameters variations. These include the inscribed circle diameter, average entry width, and number of entry and circulating lanes. The main credit goes to Troutbeck's research to improve Australian capacity formula.

The UK regression approach indicates that the relationship between entry capacity and circulating flow is linear, and both the intercept and slope of this relationship can be easily determined from the knowledge of the geometry and the flows of turning movements. This is very important result that defines the extremely complex and interactive actions of individual drivers when they use the roundabout.

The UK regression model also indicates that six geometric parameters play an important role in determining roundabout capacity. This model has proved to be remarkably robust. A vital area in which the empirical method scores over the analytical method is the use of local widening or flaring to enhance capacity. The reliability of the empirical method depends on the sampling and sample size of the data used in model development. While the reliability of the gap-acceptance model depends on the assumptions at which the model is developed. It is also found that the gap-acceptance model is easy for planning purposes, but the empirical method is easy for geometric design purposes. Based on a comparison of these two methods, the UK empirical method was preferred for use in this thesis for developing the optimization model to design single-lane roundabouts.

2.5 Pedestrian and Entry Capacity

If pedestrians are crossing at a marked crosswalk, then they have priority over entering vehicles. This will significantly affect entering capacity. The Federal Highway Administration suggests a reduction factor for entry capacity depending on pedestrian and circulating flows. If the circulating flow and pedestrian flow are known, the reduction factor 'M' for single-lane roundabouts can be determined from Figure 2.2. The Highway Capacity Manual (HCM 1999) provides additional guidance on the capacity of pedestrian crossings.

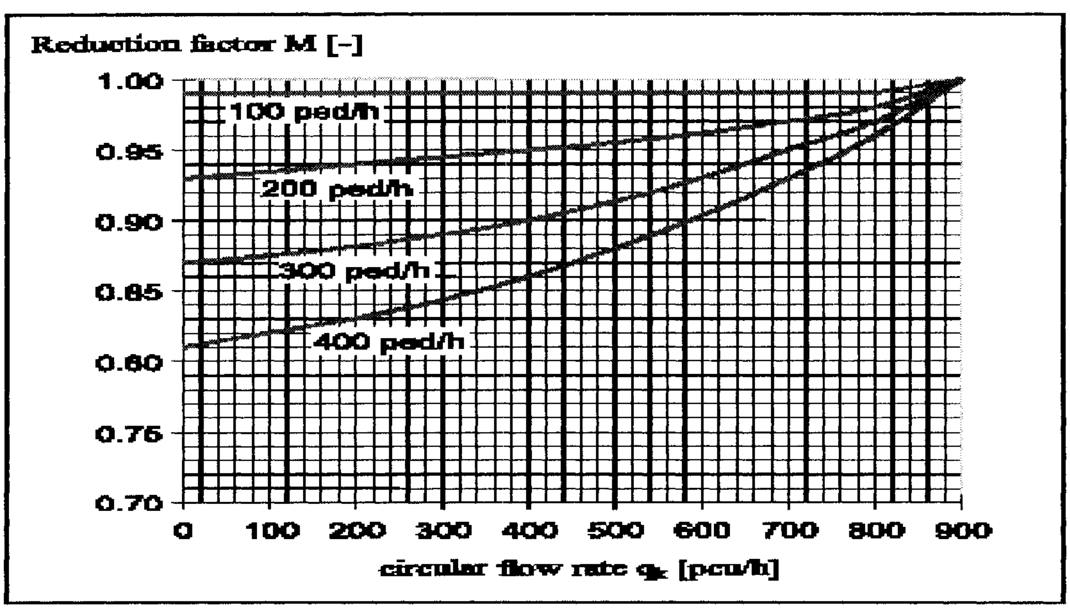


Figure 2.2: Capacity Reduction Factor M for a Single-lane Roundabout

(Brilon et al. 1993)

2.6 Exit Capacity

Normally it is difficult to achieve an exit flow more than 1400 vph on single-lane roundabouts. Under normal urban conditions (tangential alignment, low pedestrians, and bicyclists), the exit lane capacity ranges from 1200 to 1300 vph. Therefore, exit flows exceeding 1200 vph may indicate the need for a double-lane exit (Brilon 1999).

2.7 Performance Analysis

The roundabout is an intersection control device. Three performance measures are used to evaluate the performance of a proposed roundabout design: degree of saturation, delay, and queue length. Each individual measure provides a unique perspective on the quality of operation of the roundabout at given traffic and geometric conditions. If it is possible, designer should estimate all these parameters to obtain the broadest possible evaluation of the performance of a given roundabout design. Capacity is the primary measure before estimating the performance measures of an entry of the roundabout. The literature review of capacity analysis been discussed previously. The following sections provide a perspective view on performance measures.

2.7.1 Degree of Saturation

The level of congestion at each entry is measured by the degree of saturation. Degree of saturation is defined based on the volume/capacity ratio at each entry of the roundabout. The Australian design procedure suggests that the degree of saturation should not be more than 0.85 for satisfactory operation of the roundabout. When it exceeds this limit, roundabout operation deteriorates rapidly. In this case, queues may develop and delay begins to increase exponentially.

2.7.2 Delay

Delay is the most important parameter to measure the performance of a roundabout. Delay to a vehicle is the difference between interrupted (due to control, geometric, traffic, and incidents) and uninterrupted travel times through the roundabout. The Highway Capacity Manual (HCM 1999) identifies delay as the primary measure of effectiveness for intersections.

The delay at entry of a roundabout is the sum of the initial deceleration delay, queue move-up time, stopped delay, acceleration delay, and geometric delay. The first four delays are combined to define a delay term called 'control delay' that is attributed to traffic control measures, either traffic signals or stop signs. Geometric delay is caused by the presence of an intersection such as a roundabout. It occurs because vehicles must reduce their speeds to negotiate the roundabout. While negotiating the roundabout, vehicles decelerate from the approach cruise speed to the approach negotiation speed, travel at that speed, accelerate to an exit negotiation speed, travel the remaining negotiation distance at constant exit negotiation speed, and finally accelerate back to the exit cruise speed. This delay experienced by the drivers while negotiating the roundabout is called geometric delay. The geometric delay is usually used in the cost analysis of roundabouts.

2.7.3 Queue Length

While designing the roundabout, the designer should also consider one of the important performance measures, queue length. Queue length gives an idea about the blockage of traffic at the preceding intersection. If queue length is long enough to block traffic at preceding intersection, then the designer should change the roundabout geometry to improve the operation and reduce queue length. It is also useful for comparing roundabout performance with other types of intersections at the time of planning. A number of queue length formulas are discussed in the following section.

2.8 Queue and Delay Formulas

Researchers presented different formulas for the determination of delay and queue length at the entries of roundabouts. These formulas are developed in different countries, but can be transferred in other countries by proper calibration using local observed data.

2.8.1 Kimber's Formulas

The deterministic state delay formulas are suitable for an oversaturated traffic conditions while steady state formulas are suitable for undersaturated traffic conditions. Kimber and Hollis (1979) developed a delay prediction formula that can be used for both under and oversaturated conditions. The average delay per arriving vehicle is given by,

$$d = 0.5\left(\sqrt{j^2 + k} - k\right) \qquad [2.21]$$

where,

$$j = ti\frac{(1-\rho)}{2} - \frac{L_o + 1}{\mu}$$

$$k = 2\frac{ti}{\mu}$$

$$\rho = \frac{q}{\mu}$$

The average queue length (L) is,

$$L = 0.5\,(\sqrt{A^2 + B} - A \qquad [2.22]$$

where,

$A = (1-\rho)\ \mu\,ti + 1 - L_0$

$B = 4\,(L_0 + \rho\ \mu\,ti)$

The units of measurements are as follows: d is in sec/h, L is in veh, L_0 is the initial queue length in veh, ti is the time interval in sec, and arriving flow rate q and capacity rate μ are in veh/sec. Kimber's formulas are based on probabilistic theory. Probability distributions of different queue lengths as functions of time were determined. Then, the average queue length was calculated and used to compute the average queuing delay. The UK deign guide for roundabouts follows these formulas for queue and delay analysis.

2.8.2 CETUR Formulas

CETUR (CETUR 1988) has proposed formulas for determining the average queue length (L) and delay per arriving vehicle (d) as follows,

$$L = d\,\frac{Qe}{3600} \qquad [2.23]$$

$$d = \frac{(2000 + 2\,Qg)}{Qc - Qe} \qquad [2.24]$$

These formulas can be used for a one-hour time interval, and they can only be applied to undersaturated conditions, this is, entry flow (Qe) is less than entry capacity (Qc). Qg is the impeding flow.

2.8.3 Harder' Formulas

Harder (1989) proposed the following formulas for determining the average queue length (L) and delay per arriving vehicle (d).

$$L = d\,\frac{Qe}{3600} \qquad [2.25]$$

$$d = \frac{3600[1 - \exp(-(Qg\,tg - Qd\,tf)/3600)]}{Qe - Qd} \qquad [2.26]$$

Where tg is the critical gap and tf is the move-up time, and their values are taken as 4.2 sec and 2.2 sec, respectively, for average conditions. These formulas are also used for undersaturated situations and one-hour time intervals.

2.8.4 Akçelic and Troutbeck Formula

Akçelic and Troutbeck (1991) delay formula is based on the Tanner's delay equation with the gap parameters from Avent and Tayler (1979). Initially, Dunne and Buckley rearranged Tanner's delay equation into an easier form as follows,

$$D = \frac{D\min + \eta x}{1 - x} \qquad [2.27]$$

where,

x= degree of saturation in the specified flow period

$$\eta = \frac{\exp(QcT_0) - QcT_0 - 1}{Qc(\exp(QcT_0) - 1)}$$

Dmin is called the Adams delay, which can be calculated from,

$$\text{Dmin} = \exp(Qc(T-\Delta)) - T - \frac{1}{Qc} - \frac{\Delta^2 Qc}{2}$$

Troutbeck (1988) derived new delay formula with dichotomized headway distribution. The new delay formula is,

$$Dmin = \frac{\exp(\lambda(T-\Delta))}{Qc\alpha} - T - \frac{1}{\lambda} - \frac{\lambda\Delta^2 - 2\Delta + 2\Delta\alpha}{2(\Delta\alpha + \alpha)} \qquad [2.28]$$

Tanner (1962) and Troutbeck (1990) assumed a zero queue length at the arrival of the vehicles. Troutbeck (1991) realized this limitation and modified his formula considering the delay due to the presence of queue at the entry lanes. The modified formula for average delay is,

$$D = Dmin + \frac{3600kx}{Qc(1-x)} \qquad [2.29]$$

where,

k = delay parameter given by, ($k = D_{min} Q_c/3600$).

Q_c is the entry capacity (vph), x is the degree of saturation.

All of the above formulas are for steady state condition. Finally, Akçelic and Troutbeck (1991) further researched the model and developed a new time-dependent delay model. The new model is,

$$D = Dmin + 900[Z + \sqrt{Z^2 + \frac{8kx}{QcH}}] \qquad [2.30]$$

H = Flow period (hrs)

x = degree of saturation in specified flow period

Z = x-1

This delay formula is adopted by the Austroads Design Guide. The control delay formula is presented by the Highway Capacity Manual. The formula, based on Akçelic and Troutbeck (1991), is as follows,

$$d = \frac{3600}{C_{mx}} + 900T\left[\frac{V_x}{C_{mx}} - 1 + \sqrt{\left(\frac{V_x}{C_{mx}} - 1\right)^2 + \frac{\frac{3600}{C_{mx}}\left(\frac{V_x}{C_{mx}}\right)}{450T}}\right] \qquad [2.31]$$

where,

d = average control delay (sec/veh)

V_x = volume for movement x, (vph)

$C_{m\,x}$ = Capacity for movement x, (vph)

T = analysis time period (hr), usually a 15 minute (0.25 hr) analysis period is taken.

This analytical model assume that the demand is less than the capacity in the given analysis period. If the demand exceeds the capacity, then Kimber's formula is suggested for the calculation of average delay. Usually roundabouts are designed for the undersaturated conditions with degree of saturation less than 0.85. In this thesis, the delay formula presented in equation [2.31] is used in the developed optimization model.

2.9 Summary

This chapter presents a literature review of the important design aspects, capacity analysis, and operational performance of the roundabouts. The two main methodologies for capacity analysis, gap-acceptance and empirical regression, were discussed. Different countries around the world adopted one of these methodologies for capacity analysis. Each country presented its capacity formulas. The background and development of each capacity prediction formula was discussed in detail. Comparison of gap-acceptance and empirical regression was also presented with logical reasons. Finally, the literature review of two important measures of effectiveness for operational performance, delay, and queue length, is discussed.

Chapter 3

ROUNDABOUT GEOMETRIC DESIGN

3.1 Introduction

Two important aspects of roundabout geometric design are safety and capacity. Roundabout will be safer if speeds at entering, exit, and around the central island are low. This can be achieved by providing horizontal curvature and narrow pavement widths. On the other hand, reducing the widths and radii of entry and circulatory roadways will reduce the entry capacity. Besides capacity and safety, the geometric elements are also governed by the maneuver requirements of design vehicle. Therefore, roundabout geometric design is the process of determining the optimal balance between safety provisions, operational performance, and large vehicle accommodation.

The basic features of roundabouts are uniform for all locations, but the design techniques and parameters are different depending on the speed environment and the desired capacity at individual sites. In rural areas, as speed environments are high and pedestrian and bicyclist movement is low, the design objective is different compared to urban areas where pedestrian and bicyclist safety is the primary objective. The design process for single-lane and multilane roundabout is also different. This chapter describes fundamental design principles for all types of roundabouts and then, presents a literature review of the design guidelines for rural and urban single-lane roundabouts.

3.2 Design Process

Designing roundabout geometry is quite different from other forms of intersections. The roundabout design process involves iterations among geometric layout, operational analysis, and safety evaluation. A minor change in roundabout geometry may result in a significant change in safety and/or operational performance. The designer often needs to revise and refine the initial proposed roundabout design to enhance its capacity and safety. It is quite difficult for the designer to obtain optimum design at first attempt. Each individual component of the roundabout should be compatible to other components to achieve overall performance objectives. Before defining roundabout geometry, three fundamental elements should be determined in the preliminary design stage: the optimal roundabout size, the optimal position, and the optimal alignment and arrangement of approach legs.

3.3 Design Principles

General design principles to define design speed through the fastest vehicle path allowed by roundabout geometry that accommodate design vehicle and speed consistency, are common among all roundabout categories. These principles are discussed in the following sections.

3.3.1 Design Speed

Roundabout speed impacts its safety, and therefore achieving appropriate speeds through the roundabout is the most critical design objective. The speeds should not only be less than proposed design speed of the roundabout, depending on the speed environment, but also relative speeds between conflicting traffic streams should not be large to enhance safety.

Design speed of the roundabout is defined by the speed at the fastest vehicle path allowed by the geometry. Further, speed consistency check is carried out to ensure safety of the roundabout. Studies have shown that increasing the vehicle path curvature decreases the relative speed between entering and circulating vehicles and thus usually results in decreases in the entering-circulating and exiting-circulating vehicle crash rates (Robinson et al. 2000). On the other hand, increasing vehicle path curvature creates greater side friction between adjacent traffic streams at multilane roundabouts and can result in more vehicles cutting across lanes and higher potential for sideswipe crashes (QDMR 1998). Therefore, for each roundabout there is an optimum design speed to minimize crashes. The recommended maximum entry design speeds in the FHWA design guide for roundabouts at various site categories are provided in Table (3.1).

At high approach speeds, it is recommended that vehicle speed must be gradually reduced by means of horizontal reverse curves (Krames et al. 1995). According to Arnt and Troutbeck (1996), accidents can be reduced by introducing three reverse curves shown in Figure (3.1). It is recommended that the change in the 85th percentile speed at successive curves should not be more than 15 km/h. This speed can be estimated from the following formula (Krames et al. 1995).

$$V_{85}=103.66-1.95D \qquad [3.1]$$

where,

V_{85} = 85th percentile speed on the curve (km/h)

D = 1746.82/R = degree of curvature (degrees)

Table 3.1: Recommended Entry Design Speed for Various Roundabouts

(Robinson et al. 2000)

Site Category	Recommended Maximum Entry Design Speed
Mini-Roundabout	25 km/h (15 mph)
Urban Compact	25 km/h (15 mph)
Urban Single Lane	35 km/h (20 mph)
Urban Double Lane	40 km/h (25 mph)
Rural Single Lane	40 km/h (25 mph)
Rural Double Lane	50 km/h (30 mph)

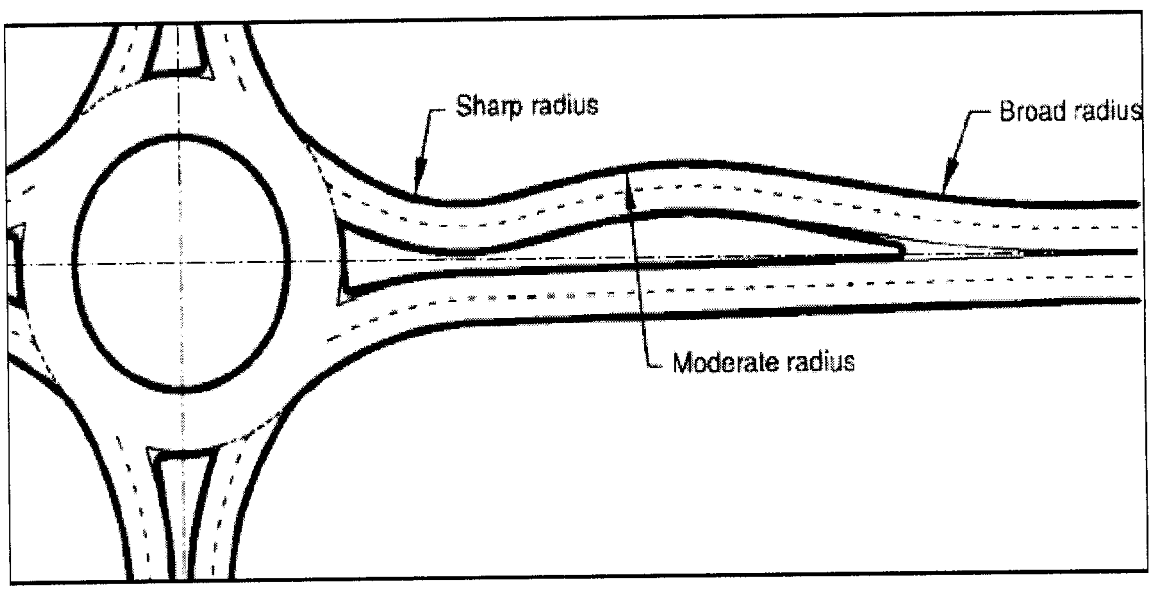


Figure 3.1: Use of Successive Curves on High Speed Approaches (Robinson et al. 2000)

R = curve radius (m)

This model is applicable only to rural areas. Reverse curves should be provided in such a way that they should not obstruct visibility of central island or splitter.

3.3.1.1 Speed and Vehicle Paths

The speed of the roundabout for its proposed geometry is determined by drawing fastest vehicle path allowed by the geometry. The proposed geometry forces drivers to drive on a certain path and depends on driver's behavior. There are three vehicle paths that are analyzed while determining the speed of roundabout: right, through, and left paths. While drawing each vehicle path, it is assumed that there is no traffic except a single vehicle that is allowed to traverse the roundabout freely.

A vehicle is assumed to be 2 m (6 ft) wide and to maintain a minimum clearance of 0.5 m (2 ft) from a roadway centerline or concrete curb, and flush with a painted edge line (QDMR 1998). At entrance and exit, the vehicle is assumed to be flush with painted edge of splitter or curb of splitter. Therefore, the centre line of the vehicle's path is drawn at a distance of 1 m from the painted edge of splitter or curb of splitter, and 1.5 m from the concrete curb or 1.5 m (5 ft) from a roadway centerline in case of multilane roundabouts. The through path is shown in Figure 3.2 as an example to understand the vehicle's paths concept. Usually the fastest possible path is the through movement, but in some cases it may be a right-turn movement (Robinson et al. 2000). This is the usual practice to draw vehicle paths by freehand on the proposed roundabout geometry. The vehicle paths for given roundabout geometry have not been formulated previously.

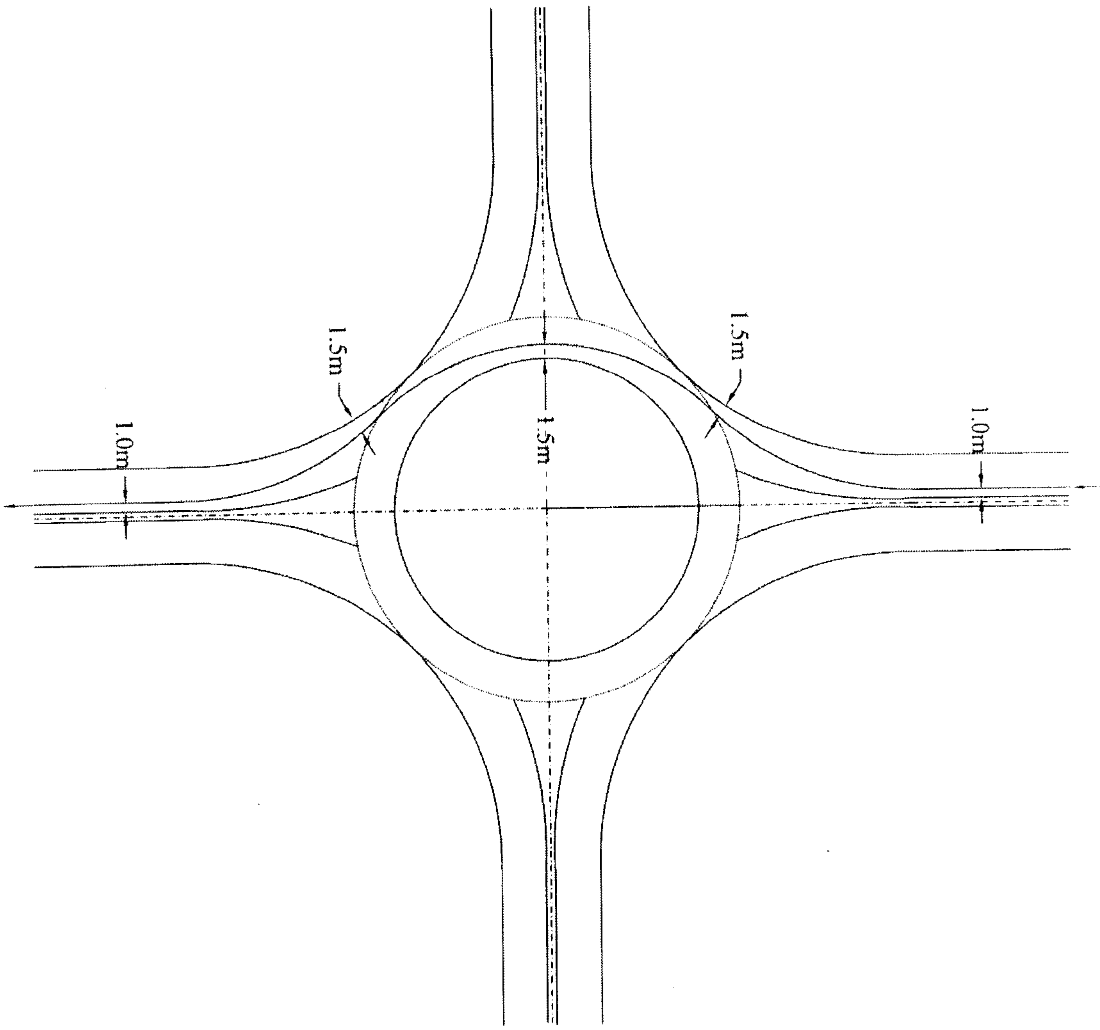


Figure: 3.2- Fastest Through Vehicle Path

The design speed of the roundabout is determined from the smallest radius along the fastest allowable path. The smallest radius usually occurs on the circulatory roadway as the vehicle curves to the left around the central island. It is important that roundabout geometry should be designed such that the entry path radius is not significantly larger than the circulatory path radius. The fastest vehicle path should be drawn for all approaches not only to restrict safe negotiation speed within the speed environment limit, but also to allow the design consistency check.

3.3.1.2 Negotiation Speed

The relationship between safe negotiation speed and horizontal curvature is determined using the AASHTO Green Book (1994) and Austroad (1993) by the following formula,

$$V = \sqrt{127R(e+f)} \quad [3.2]$$

where,

V = Design speed, km/h

R = Radius, m

e = super elevation, m/m

f = side friction factor

The superelevation values are usually assumed to be +0.02 for entry and exit path curves and -0.02 for path curves around the central island. The side friction can be determined according to Figure III-19 of AASHTO (1994). According to AASHTO, the side friction factor varies with vehicle speed. Rahmi Akçelik (2003) developed a relationship which determines the side friction factor at the roundabout depending on the average vehicle mass. This relationship is quite effective for calculating side friction at roundabouts. SIDRA, uses this relationship. The relationship is,

$$Fs=0.30-0.00084\sqrt{\mathrm{Mv}} \quad [3.3]$$

where 'fs" is side friction factor and 'Mv" is average vehicle mass (kg) expected to use the roundabout.

3.3.1.3 Speed Consistency

Speed consistency is also one of the design principles. There are two main objectives of speed consistency:

- The relative speeds between consecutive geometric elements should be minimized
- The relative speeds between conflicting traffic streams should be minimized.

Roundabout geometry produces path radii for each vehicle path. Therefore, each vehicle path (through, left, and right) is drawn for each approach and speed consistency at consecutive path radii along each path and at conflicting path radii from other approaches is checked. This is an iterative process to obtain optimum deign consistency. Figure 3.3 shows five critical path radii. These radii must be checked for all approaches. R1 is the minimum entry path radius on the fastest through path prior to the yield line. R2 is the minimum circulating path radius on the fastest through path around the central island. R3 is the minimum exit path radius on the fastest through path into the exit. R4 is the minimum left-turn path radius around the central island on the fastest left-turn path. R5 is the minimum right-turn path radius on the fastest path of a right-turn vehicle. Roundabout geometry is first laid out and then the vehicle path radii are drawn to check speed consistency. These path radii completely depend on roundabout geometry, but there is no formulation to calculate these radii directly for a given roundabout geometry.

For speed consistency there should be a minimum difference among R1, R2 and R3. These are the series of reverse curves for the through path. It is observed that there are also entry and exit path curves for other two right-turn and left-turn vehicle paths. Therefore, for speed consistency the relative difference among consecutive path radii along right and left-turn path should also be minimized.

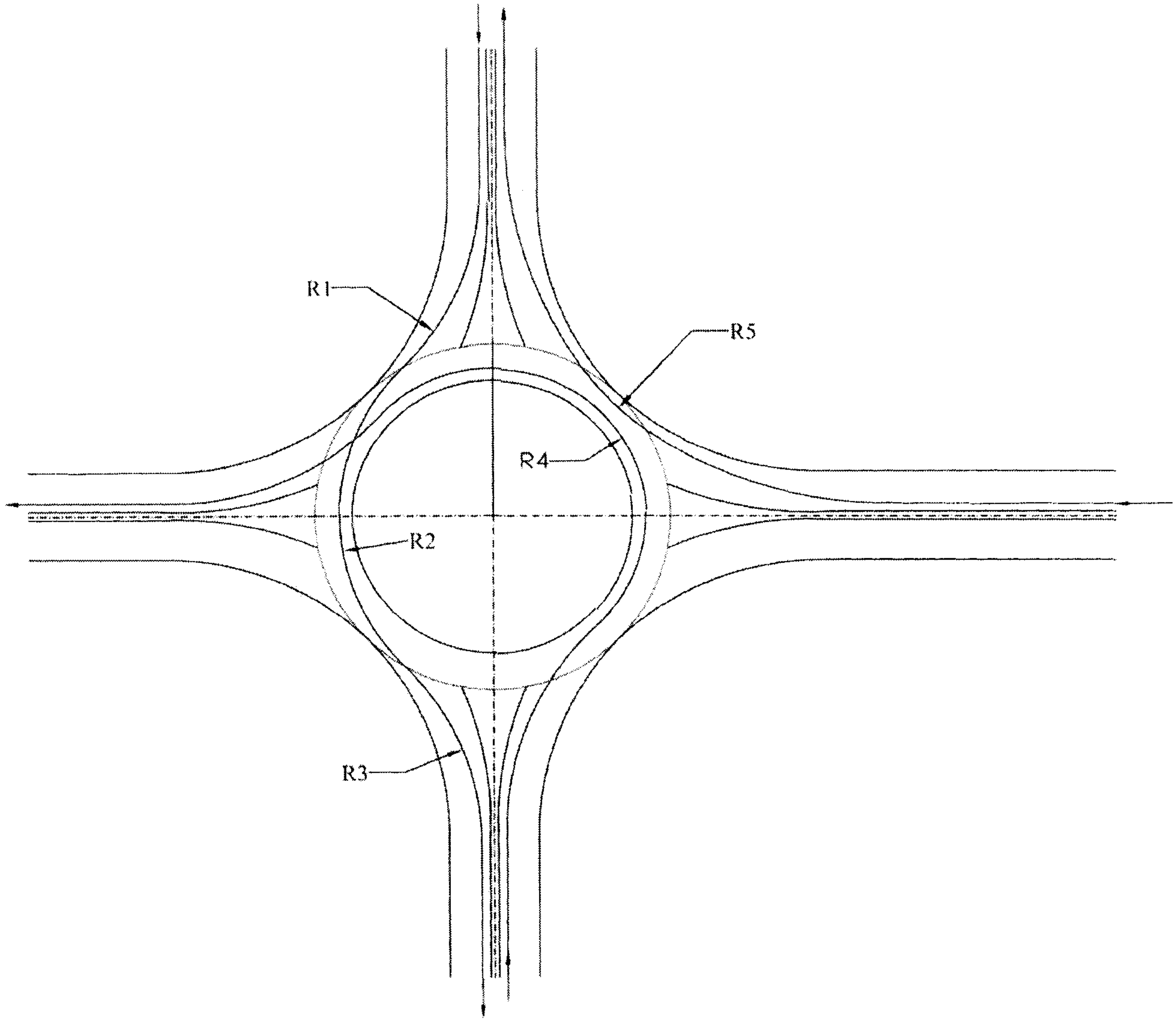


Figure 3.3: Critical Path Radii

To avoid entry-circulating crashes, the relative speed difference between entry and circulating speeds should be minimize at each approach. The other conflicting traffic streams are at R5 and R4 path radii. This conflicting point should also be considered while checking speed consistency. At single-lane roundabouts with pedestrian activity, exit radii should be small (the same or slightly larger than R2) in order to minimize exit speeds (Robinson et al. 2000). For good design, the relative difference in speeds should be less than 20 km/h and preferably less than 10 km/h. Besides checking speed consistency, the speed at each vehicle path radius must be less than the proposed design speed of the selected site of the roundabout for the given speed environment (rural or urban).

3.3.2 Design Vehicle

Another important principle is the accommodation of the largest motorized vehicle likely to use the roundabout. The turning path of this vehicle, termed as the design vehicle, will dictate many of the roundabout dimensions. The design vehicle is decided depending on the approaching roadway types and the surrounding land use characteristics. AASHTO (1994) provides the dimensions and turning path requirements for a variety of common highway vehicles. Larger roundabouts need to accommodate large design vehicles, while maintaining low speeds for passenger vehicles. When site constraints do not allow accommodating large semi-trailer combinations, truck aprons are provided to allow additional traversable area around the central island. Truck aprons provide lower level of operation, and therefore it should only be used when there is no other solution to accommodate the design vehicle. The design vehicle would usually be an AASHTO WB-15 for national highway and state highway systems (Bared 1997).

3.3.3 Non-motorized Design Users

Like the design vehicle, there are also design considerations for non-motorized potential roundabout users like bicyclists, pedestrians, skaters, wheelchair users, strollers, etc.

Table 3.2: Key Dimensions of Non-motorized Design Users (Pein 1996)

User	Dimension (m)	Affected Roundabout Features
Bicycles		
Length	1.8	Splitter island width at crosswalk
Minimum operating width	1.5	Bike lane width
Later clearance at each side	0.6 1.0 to obstructions	Shared bicycle-pedestrian path width
Pedestrians (Walking)		
Width	0.5	Sidewalk width, crosswalk width
Wheelchair		
Minimum width	0.75	Sidewalk width, crosswalk width
Operating width	0.90	Sidewalk width, crosswalk width
Person Pushing stroller		
Length	1.70	Splitter island width at crosswalk
Skaters		
Typical operating width	1.8	Sidewalk width

These users span a wide range of ages and abilities that can have a significant effect on the design of a roundabout. Basic design dimensions for various non-motorized design users are given in Table 3.2.

3.3.4 Alignment of Approaches and Entries

The optimal position of a roundabout is the point of intersection of the centerlines of all approaches. This position usually produces adequate design that allows vehicles to maintain low speeds at entry and exit points. The radial alignment also makes the central island more conspicuous to approaching drivers. If it is not possible to align the inscribed circle centre at the intersection of the approach legs, then it is desirable the centerline passes to the left of the roundabout's center point (offset to the left). This alignment will also allow sufficient curvature at the entry to reduce speed. Care must be taken, however, that the approach offset should not produce an excessively tangential exit especially in urban environments.

The alignment of approaches to be offset on the right side of the roundabout center point is never acceptable. This kind of alignment produces approaches at more tangential angle and reduces the space available to provide sufficient entry curvature. Vehicles will enter the roundabout too fast that can result in loss of control crashes and higher crash rates between entering and circulating vehicles (Robinson et al. 2000). The angles between approaches should be equally spaced and most appropriate angles are 90 degrees for four-leg roundabouts and 72 degrees for five-leg roundabouts. These findings are found in the FHWA Design Guide 2000 and are consistent with findings of the British accident prediction models. The radial alignment of entries is shown in Figure 3.4.

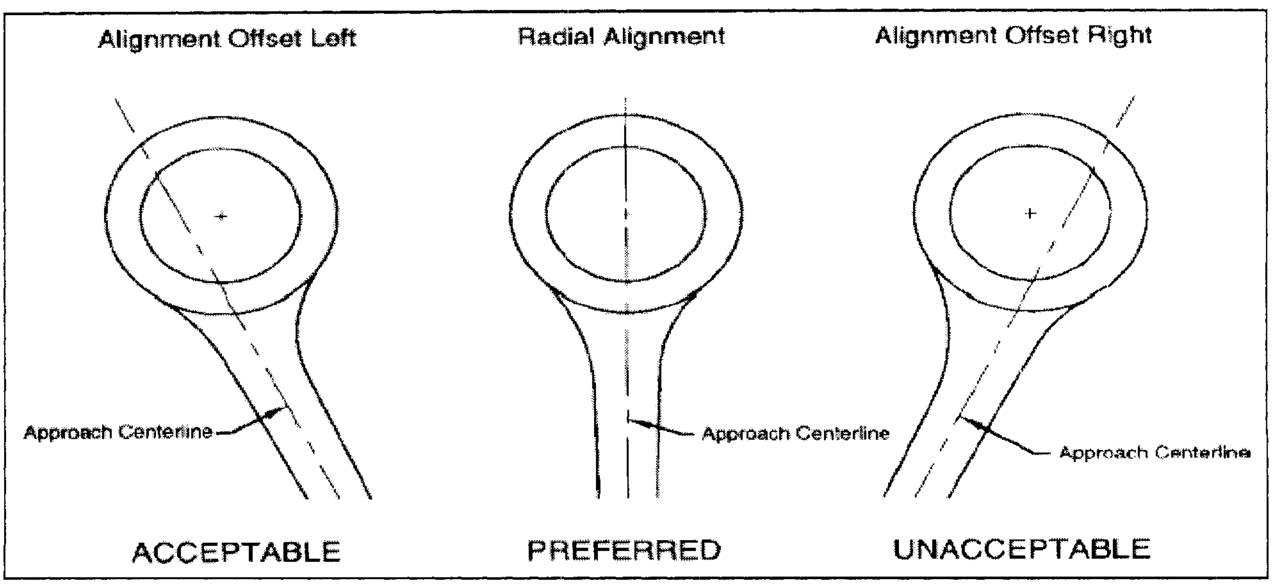


Figure 3.4: Radial Alignment of Entries (Robinson et al. 2000)

3.4 Design Guidelines

The design guidelines used within USA and all over the world for the design of roundabout geometry are:

- Roundabout Design Guidelines by Maryland DOT
- Roundabout Design Guidelines by Ourston & Doctors
- Florida Roundabout Guide by Florida DOT
- Australian guidelines
- British design guidelines
- French design guides
- CETUR Guide for Urban Conditions
- SETRA Guide for Rural Conditions
- Swiss Roundabout Guide
- German guidelines
- Roundabouts: An Information Guide, FHWA (2000)

Each guideline has its own features, but the basic design principles and design process are the same in all guidelines.

3.5 Geometric Design Elements

All geometric features of the roundabout are shown in Figure 1.1. The following sections present a literature review of guidelines for the design of all geometric parameters of the roundabout. These guidelines must be kept in mind while designing each individual element but the interaction of these elements is also very important. All geometric elements should be compatible with each other to achieve safety and operational objectives.

3.5.1 Inscribed Circle Diameter

The inscribed circle diameter is the distance across the circle inscribed by the outer curb (or edge) of the circulatory roadway. It is the sum of the central island diameter (which includes the apron, if present) and twice the circulatory roadway. The inscribed circle diameter depends on a number of design objectives. The designer determines its optimum size by several experiments with different diameters at the given location of roundabout. For the single-lane roundabout, its diameter largely depends on design vehicle. It should be large enough to accommodate the turning requirements of design vehicle. However, the circulatory roadway width, entry and exit widths, entry and exit radii, and entry and exit angles also play a significant role in accommodating the design vehicle and providing deflection. Therefore, appropriate design of these elements may allow selecting a smaller diameter. Thus, it is a challenging task to decide its diameter at a given location. In general, the inscribed circle diameter should be a minimum of 30 m (100 ft) to accommodate a WB-15 (WB-50) design vehicle. Table (3.3) shows the recommended inscribed circle diameter ranges for different categories of roundabout and design vehicle.

Table 3.3: Recommended Inscribed Circle Diameter Ranges (Robinson et al. 2000)

Site Category	**Typical Design Vehicle**	**Inscribed Circle Diameter Range* (m)**
Mini-Roundabout	Single-Unit Truck	13–25
Urban Compact	Single-Unit Truck/Bus	25–30
Urban Single Lane	WB-15 (WB-50)	30–40
Urban Double Lane	WB-15 (WB-50)	45–55
Rural Single Lane	WB-20 (WB-67)	35–40
Rural Double Lane	WB-20 (WB-67)	55–60

* Assumes 90-degree angles between entries and no more than four legs

3.5.2 Entry Width

The roundabout entry capacity of each approach largely depends on its entry width. Capacity is not sensitive to the number of entry lanes. As long as entry width increases regardless of entry lanes, capacity increases. Therefore, the basic sizes of entries and circulatory roadways are generally described in terms of width, not number of lanes. A minimum of 6 m is considered to accommodate multiple traffic streams and it is striped to designate separate lanes (Robinson et al. 2000). The circulatory roadway width is usually not striped to more than one lane even if it can accommodate multiple traffic streams. This can only be done in multilane roundabouts. The entry width requirements for each approach depend on the expected traffic volume on that approach.

Roundabout safety decreases as entry width increases. Therefore, the entry width is determined based on a tradeoff between safety and capacity. The circulatory and entry widths should be decided based on the minimum requirements of capacity and operational analysis. Appropriate entry width range for single lane entrances is 4.3 to 4.9 m (Robinson et al. 2000). However, values greater or less than this range can be used according to site specific conditions and speed requirements for critical vehicle paths.

If the entry width is only a solution to increase the capacity, then the entry width can be increased by two ways.

- Adding a separate lane on the upstream of roundabout
- Increasing entry width gradually with flaring of approaches

Flare lengths should be a minimum of 25 m in urban areas and 40 m in rural areas (Robinson et al. 2000). If shorter than these length are to be used because of site constraints, then advance notice should be provided.

Sometimes roundabout is designed in such a way that it should accommodate projected design traffic, 20 years from the present. In this case, the inscribed circle diameter is designed for projected 20 years traffic requirements, but with larger central island diameter. After 20 years, the central island diameter is reduced and the corresponding entry widths and circulatory widths increased to accommodate capacity requirements of design traffic volume of that year.

3.5.3 Circulatory Roadway

The circulatory roadway width depends on the width of entries and turning requirements of the design vehicle. It should always be at least as wide as the maximum entry width and up to 120 percent of the maximum entry width. It should also remain constant throughout the roundabout (TD 1993). Sometimes turning requirements of the design vehicle may require the circulating roadway width to be so wide that the amount of deflection necessary to slow passenger vehicles is compromised. In this case, a truck apron is provided to accommodate large vehicles. The French and Australian guidelines, recommend a 1 to 2 percent negative cross slope for the circulatory roadway. A cross slope towards the outside of the central island improves visibility and eases surface drainage away from the central island.

3.5.4 Central Island

The central island of a roundabout consists of a raised, often landscaped, nontraversable area, and sometimes a truck apron to traverse large vehicles. It is landscaped for aesthetic reasons to enhance driver recognition of the roundabout upon approaching it. It should always be raised so that it can be easily recognized by the approaching drivers. The mountable area or apron cross slope should be steeper than that of the circulatory roadway (usually is 4 to 5) percent to provide faster drainage of a course surface and to discourage passenger vehicles from driving on it (Robinson et al. 2000).

The recommended central island shape is circular rather than oval to prevent speeding and to provide skewed entry angles. The size of the central island is an important factor to impose deflection on the through vehicle path. Its diameter depends on the inscribed circle diameter, entry width, and circulatory roadway width. Once these parameters are selected, a fastest vehicle through path is drawn to check whether its speed is more than the design speed for a given central island diameter. If it is more, then the central island diameter is increased and other parameters are adjusted. This is also a kind of iterative process to check the adequacy of the central island diameter. In general, roundabouts in rural environments typically need larger central islands than urban roundabouts in order to enhance their visibility and to enable the design of better approach geometry (QDMR 1998).

3.5.5 Entry Curves

The entry curves are the set of one or more curves along the right curb or edge of pavement of the entry roadway leading into the circulatory roadway. It should not be confused with the entry path curve defined by the fastest vehicle path through the geometry, as shown in Figure 3.2. It significantly impacts both capacity and safety. Larger entry radii produce high entry speeds, which improve capacity, but they result in high crash rates between the entering and circulating vehicles. The entry curve should be curvilinearly tangential to the outside edge of the circulatory roadway. In the same way, the projection of the inside edge of the entry roadway should be curvilinearly tangential to the central island.

The primary objectives of the entry radius are to produce the appropriate entry path radius which is not significantly different from the circulating path radius, and that the design speed at entry path curve is adequate. In single-lane roundabouts there is no adjacent traffic stream, and therefore it can easily be decreased and increased to obtain the desired entry path radius. At urban single-lane roundabout it ranges from 10 to 30 m but larger radii can be used provided that they do not produce an excessive entry path curve (Robinson et al. 2000). At local streets, it can be below 10 m if the design vehicle is small. At rural roundabouts, the speed differential is very important. If the speed differential is greater than 20 km/h, it is desirable to adjust approach curves or entry curves to the desirable speed differential.

3.5.6 Exit Curves

Exit curves should be large enough so that the exit path curve is larger than the circulating path radius to minimize the occurrence of congestion. If the exit path radius is smaller than the circulating path radius, vehicles will be traveling too fast to negotiate the exit geometry and may crash into the splitter island or the opposing traffic in the adjacent approach lane.

Like the entry curves, exit curves should also curvilinearly tangential to the outside edge of the circulatory roadway, and the inside edge of the exit roadway should be curvilinearly tangential to the central island. At single-lane roundabouts in urban environments, exit curves should be designed to enforce a curved exit path with a design speed below 40 km/h for maximum safety of pedestrians. It should not be less than 15 m but at locations where pedestrian activity is heavy, it can be less than 15 m provided that there is no large semitrailer traffic. In rural areas where pedestrians are few, exit curves can be designed with large radii to allow vehicles to exit quickly and accelerate back to traveling speed.

3.5.7 Pedestrian Considerations

Design of pedestrian crossing at roundabouts represents a balance among pedestrian convenience, pedestrian safety, and roundabout operations. To minimize out of direction travel, pedestrians require crossing locations be close to the intersections. Crossing location and crossing distance are critical elements for pedestrian safety. Crossing distance should be minimized to reduce pedestrian-vehicle conflicts. Crossings should also be located at a distance equivalent to vehicle length away from the yield line to reduce the chance that vehicles will be queued across the crosswalk. Therefore, crosswalk location also affects vehicle operation. Crossings should also be away from the yield line, but this requires longer splitter island. The Dutch guidelines recommend that the crossing location be augmented with handicapped ramps or colored/patterned concrete, or both (CROW 1993). The pedestrian refuge should have a minimum width of 1.8 m to adequately provide shelter for persons pushing a stroller or walking a bicycle (Robinson et al. 2000).

3.5.8 Splitter Island

A splitter island should be provided on both rural and urban roundabouts, except those having very small diameter that obstructs the visibility of the central island. The purpose of the splitter island is to provide shelter for pedestrians, including wheelchairs, bicycles, and baby strollers and assist in controlling speeds, guiding traffic into the roundabout, physically separating entering and exiting traffic streams, and deterring wrong-way movements. The size of the splitter island is adapted to the central island and inscribed circle dimensions. If the approach speed is very high, the length should be long enough for comfortable deceleration. At least, it should be 15 m long to provide sufficient protection for pedestrians and to alert approaching drivers to the roundabout geometry.

The minimum dimensions of the splitter island of single-lane roundabout are shown in Figure (3.5). A recent study by the Queensland Department of Main Roads found that maximizing the width of the splitter island has a significant effect on reducing entering/circulating vehicle crash rates (QDMR 1998). However, a larger splitter island width requires a larger inscribed circle diameter.

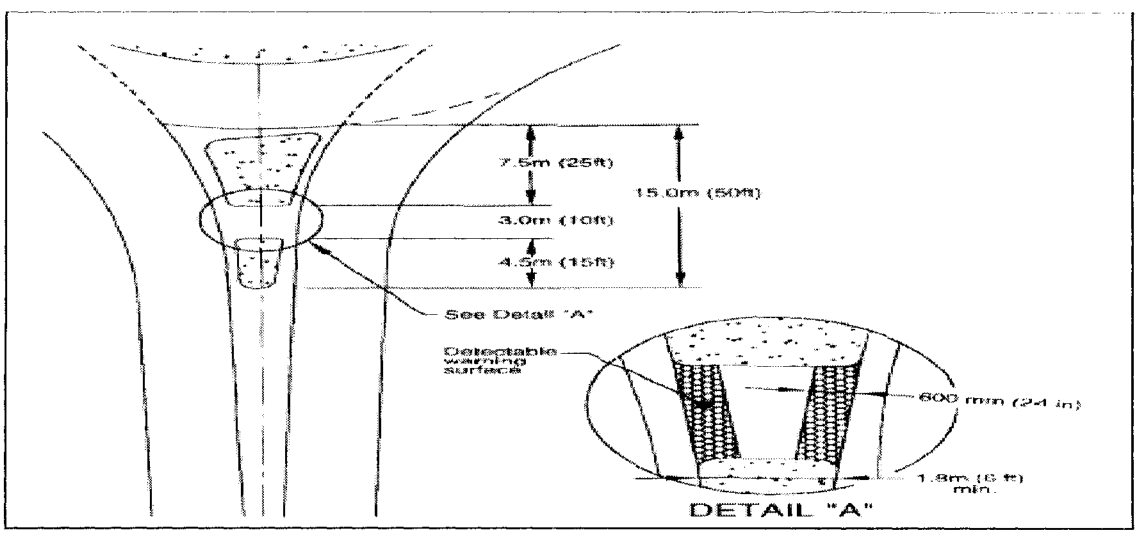


Figure 3.5: Minimum Splitter Island Dimensions (Robinson et al. 2000)

3.5.9 Stopping Sight Distance

Stopping sight distance is the distance along the roadway required by drivers to perceive and react to an object in the roadway and stop the vehicle safely. Stopping sight distance should be provided not only at entering and exiting approaches but also at every point within the roundabout. Visibility of the splitter island, the central island, and the circulating roadway is an important concern in designing the roundabout. The National Cooperative Highway Research Program (NCHRP) Report 400 recommends the following formula to calculate Stopping Sight Distances (Fambro et al 1997).

$$d=0.278(t)(V)+0.03V^2/a \qquad [3.4]$$

where,

d = stopping sight distance, m

t = perception-brake reaction time, assumed to be 2.5 sec

V = initial design speed km/h

a = driver deceleration, assumed to be 3.4 m/s^2

At the roundabout, three critical locations must be checked for stopping sight distance,

- Approach sight distance, see Figure (3.6)
- Sight distance on circulatory roadway, see Figure (3.7)
- Sight distance to crosswalk on exit, see Figure (3.8)

Stopping sight distance is measured using a driver's eye height of 1080 mm and an assumed height of object of 600 mm (Fambro et al 1997).

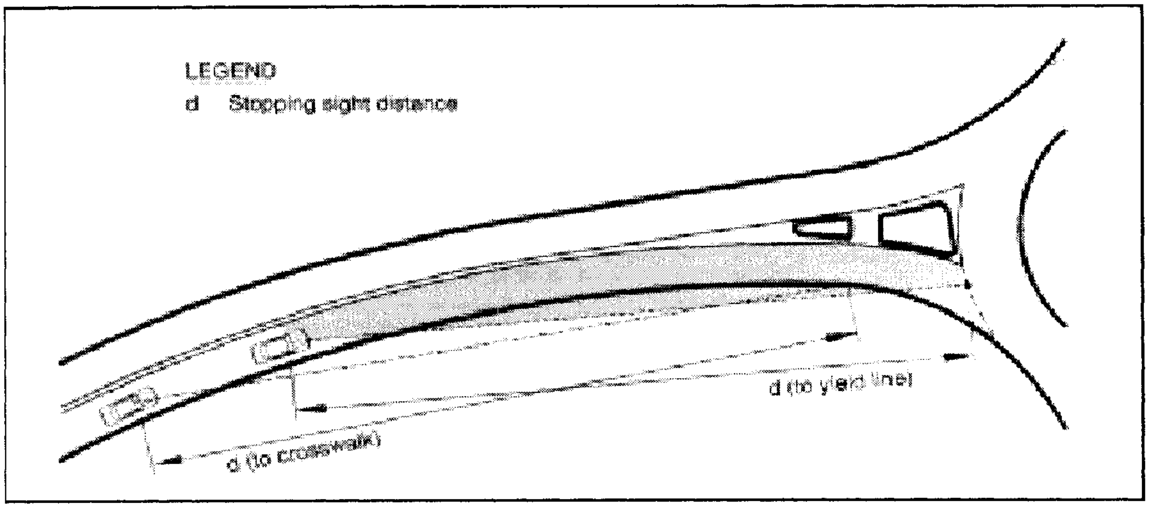


Figure 3.6: Approach Sight Distance (Robinson et al. 2000)

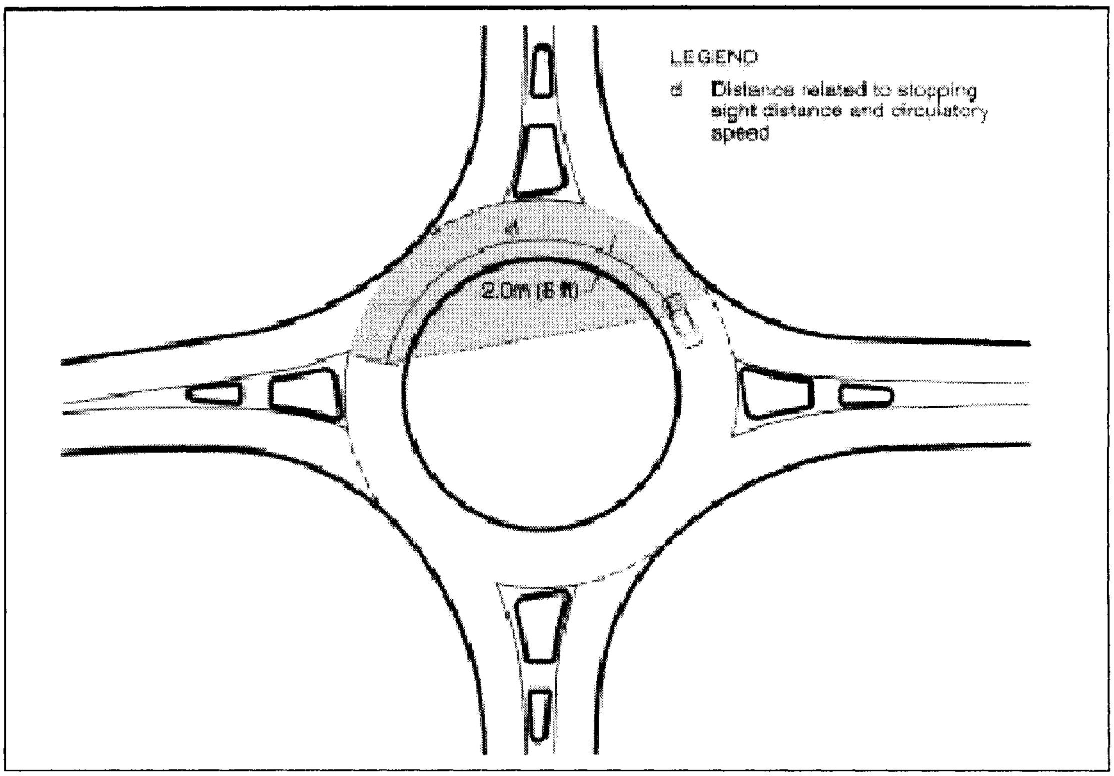


Figure 3.7: Sight Distance on Circulatory Roadway (Robinson et al. 2000)

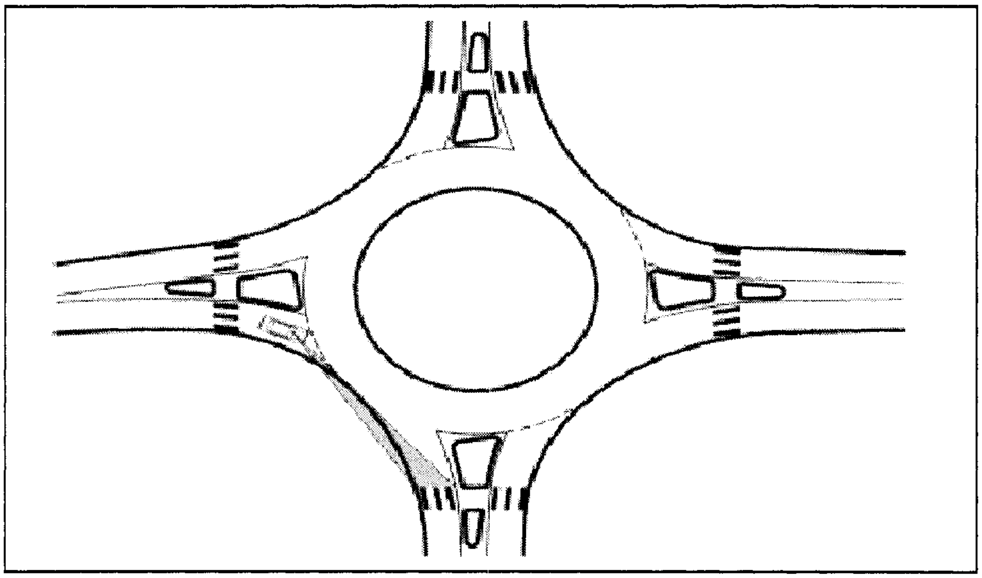


Figure 3.8: Sight Distance on Crosswalk on Exit (Robinson et al. 2000)

3.5.9.1 Intersection Sight Distance

Intersection sight distance (ISD) is the distance required for a driver to perceive and react to the presence of conflicting vehicles at the entry point within the right-of-way. This distance is usually measured by determining a sight triangle. The sight triangle is bound by a length of roadway defining a limit away from the intersection on each of the two conflicting approaches and by a line connecting those two limits. The length of the roadway is measured along the vehicle path.

Intersection sight distance is also measured using driver's eye height of 1080 mm and an assumed height of object of 1080 mm (Fambro et al 1997). Figure 3.9 shows the method of determining the intersection sight distance. The sight triangle has two conflicting approaches; each must be checked independently. The length of each approaching sight limits is calculated, as discussed in the following sections.

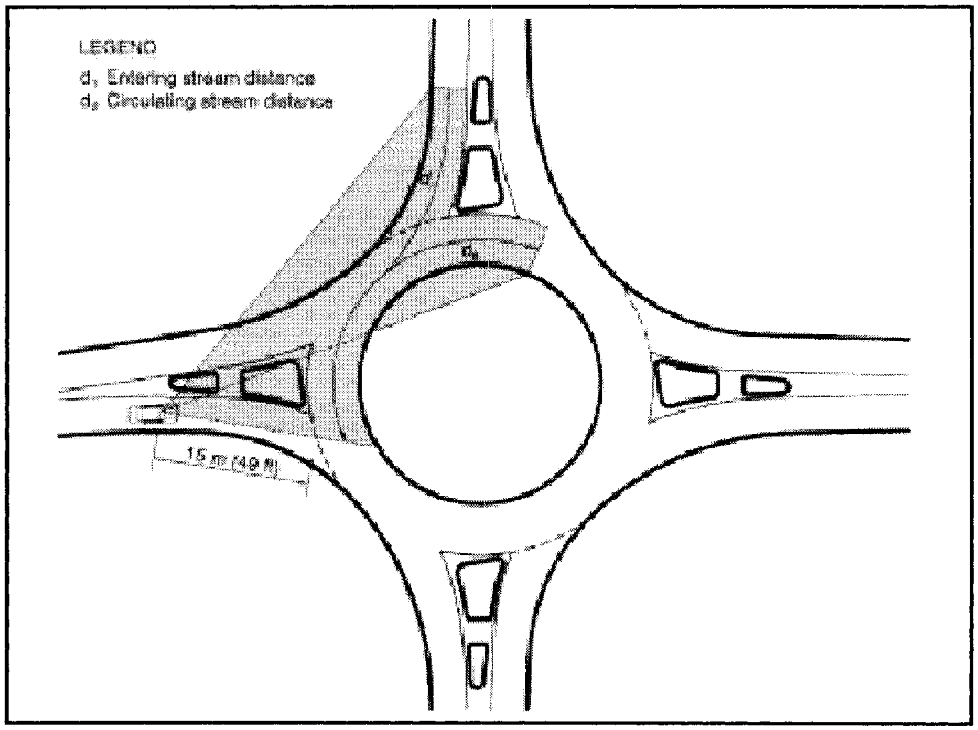


Figure 3.9: Intersection Sight Distance (Robinson et al. 2000)

3.5.9.1.1 Length of approach leg of sight triangle

The length of approach leg of sight triangle should be limited to 15 m (Robinson et al. 2000). This value is consistent with the British and French guidelines. It allows drivers to slow down as they approach and focus on the pedestrian crossing prior to the entry. The British research indicates that excessive ISD increases the frequency of crashes. Therefore, if ISD is more than 15 m then it is advisable that landscaping should be provided to restrict sight distance to the minimum requirements.

3.5.9.1.2 Length of conflicting leg of sight triangle

The approaching vehicle at each entry of the roundabout faces the conflicting vehicles within the circulatory roadway. The length of the conflicting leg is given by,

$$b = 0.278\ (Vmaj)\ (t_c) \qquad [3.5]$$

where,

b = length of the conflicting leg of sight triangle, m

Vmaj = design speed of the conflicting movement, km/h

t_c = critical gap for entering the major road, 6.5 sec

For intersection sight distance, two conflicting traffic streams at each entry are checked: entry stream and circulating stream. Taking the average of the entry path speed at radius R1 and the circulating path speed at radius R2 determines the speed for the entry stream. R1 and R2 are shown in Figure 3.3. The circulating stream is comprised of vehicles that entered the roundabout prior to the immediate upstream entry. This speed is approximated by the speed of left-turn vehicles around the central island (i.e. path with radius R4).

The critical gap for entering is based on the time required for a vehicle to turn right while the conflicting traffic stream vehicle slows down to not less than 70 percent of the initial speed. This phenomenon is based on research on critical gaps at stop-controlled intersections, adjusted for yield-controlled conditions (Hardwood et al 1996). The critical gap value of 6.5 sec used in Equation 3.5 is calculated for passenger cars that are assumed to be the most critical vehicles for ISD calculation. This value also holds true for single-unit and combination truck speeds that are at least 10 and 15 - 20 km/h slower than passenger cars, respectively.

3.6 Vertical Alignment

The design of vertical alignment includes profile, approach grades, superelevation, and drainage. These are discussed in the following sections.

3.6.1 Profiles

The approach roadway and central island profiles combine to make the profile of the roundabout. The development of each profile is an iterative process to tie up the elevations of approach roadway profile and the profile around the central island. Usually each approach roadway profile is designed to the point where it intersects with the central island. Then central island profile is developed so that it passes from all four intersection points of each entry in case of four-leg roundabouts. Each approach roadway profile is readjusted to meet smoothly with the central island profile. The development of roundabout profile is explained in Figures (3.10) - (3.12), which explain sample plan, approach profile, and central island profile, respectively.

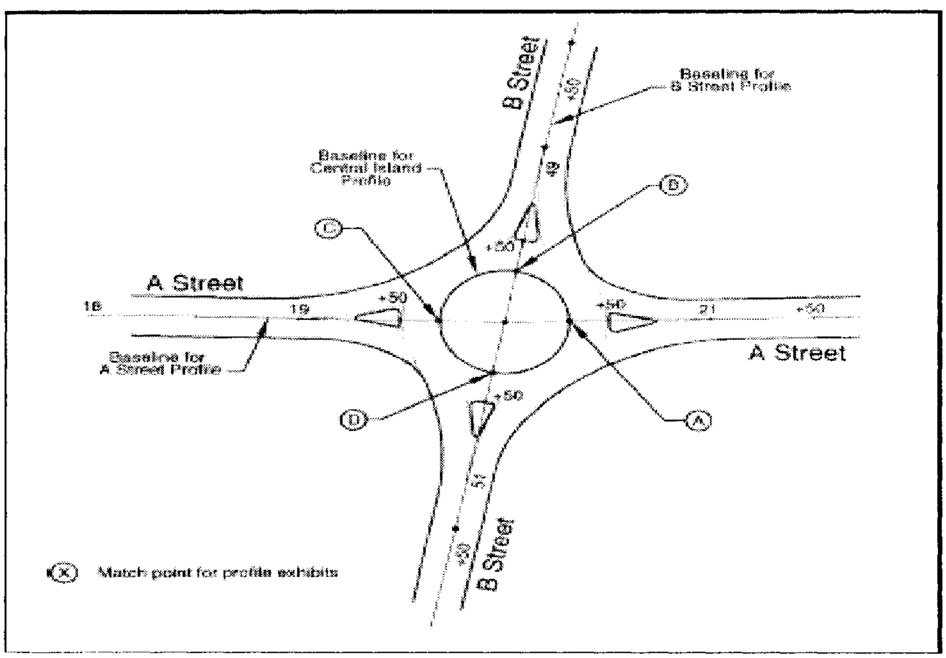


Figure 3.10: Sample Plan View (Robinson et al. 2000)

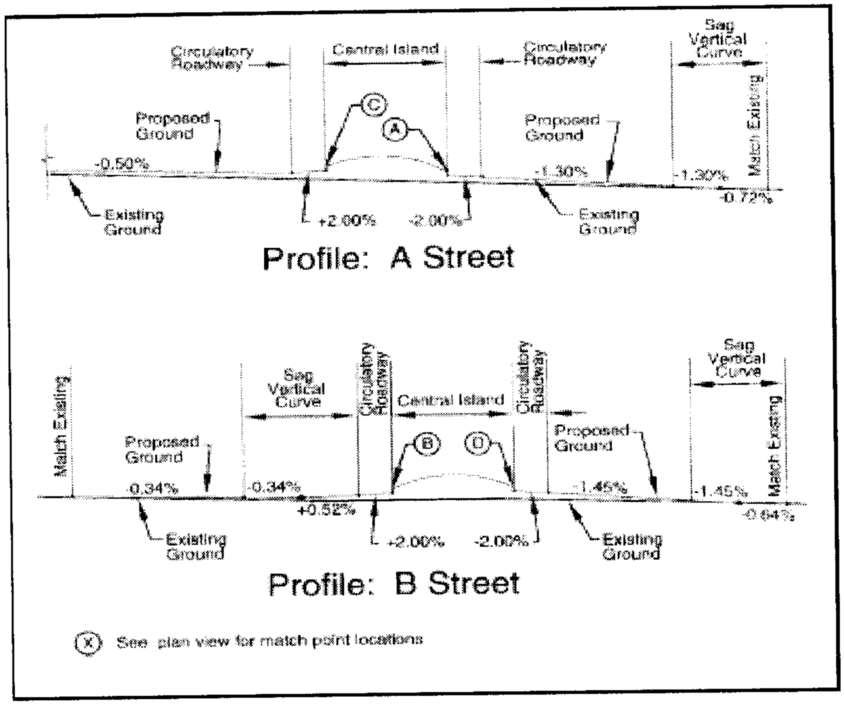


Figure 3.11: Sample Approach Profile (Robinson et al. 2000)

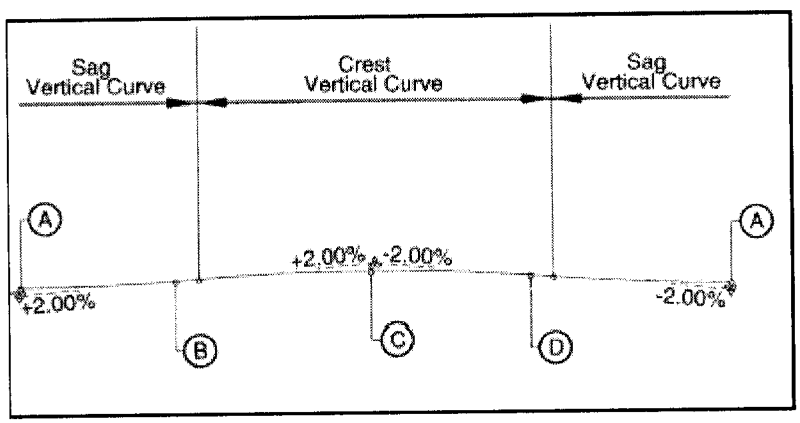


Figure 3.12: Sample Central Island Profile (Robinson et al. 2000)

3.6.2 Superelevation

A negative superelevation of 2 percent is provided around the central island for the circulatory roadway. Providing slope outward on the circulatory roadway is recommended for four main reasons.

- It raises the elevation of the central island and improves its visibility which consequently enhances safety
- It produces lower circulating speeds
- It minimizes breaks in the cross slopes of the entrance and exit lanes
- It helps drain off surface water outside of the roundabout

A positive superelevation of 2 percent is provided for entry and exit curves.

3.6.3 Grades

Generally the designer should avoid to constructing roundabouts at locations where grades through the intersection are more than 4 percent. The installation of roundabouts at locations where grades through the intersection are less than 3 percent is generally not problematic (SETRA 1998). The locations where a constant grade has to be maintained, the circulatory roadway can be constructed on a constant slope plane. In this situation, the cross slope may vary from +3 percent on the high side of the roundabout (i.e. slope towards the central island) to -3 percent on the low side (i.e. slope outward). At constant-grade roundabouts, the central island cross slope will pass through the level at a minimum of two locations.

3.6.4 Drainage

When the circulating roadway slopes away from the central island, inlets are provided on the outer curbline of the roundabout. But constant-grade roundabouts may require inlets along the central island. If the central island is quite large, the designer can consider placing inlets in the central island.

3.7 Signing and Lighting

The concept of roundabout signing is similar to conventional intersections. Signing is usually required for proper regulatory control, advance warning, and directional guidance, which are required to avoid any false sense of driver expectancy. The signs should be placed at the recommended distance for stopping conditions or deceleration to a minimum speed given by the MUTCD (FHWA 1988) and the Standard Highway Signs (FHWA 1979) or local applicable standards.

As geometric design of roundabouts is different from other types of intersections, especially provision of the central island in the middle of intersection, the roundabout should properly be illuminated for approaching drivers to recognize this type of traffic control. Florida, Maryland, and Australian guidelines recommend that good illumination should be provided on the approach nose of the splitter islands, at all conflict areas where traffic is entering the circulating stream and at all places where the traffic streams separate to exit the roundabout. Special consideration should also be given to the lighting of any pedestrian crossing area. The designer should avoid placing columns and other poles on the small splitter islands, the central island directly across from an entry roadway, or the right-hand perimeter just downstream of an entry point. The minimum horizontal illuminance for a mini roundabout without a curbed central island should be 20 lux (Taekratok 1998).

3.8 Landscaping

Landscaping of the roundabout not only enhances aesthetic, but also improves safety. Proper landscaping on the center islands indicates to drivers that they cannot pass across the central island and also discourages pedestrian traffic as well. Landscaping should not interfere with the visibility of signs and sight distance requirements. The slope of the central island should not exceed 6:1 (AASHTO 1989). Landscaping has not only the aesthetic purpose, but also enhances safety of the roundabout. Therefore, landscaping should be part of the original design plans.

3.9 Bicycle Considerations

The reputation of roundabouts in many countries regarding safety of bicyclists is questionable. Usually when bicyclists enter the roundabout, they feel that they are at risk. At large roundabouts and gyratory systems, many cyclists are prepared to alter their routes or get off and walk to avoid hazards (Brown 1995). Therefore, all guidelines recommend some provisions for the geometric design of roundabout to ensure safety of cyclists. The geometric treatments for the safety of cyclists depend on the proportion of cyclists, functional classification of road, and overall traffic management strategies. For safety consideration of cyclists, Maryland recommends the following precautions (SMDT 1995):

- Ensure adequate deflection and speed control on the entry and throughout the roundabout
- Avoid larger than necessary inscribed diameters
- Avoid excessive entry widths
- Ensure that sight lines are not obstructed by landscaping, traffic signs, or poles
- Provide adequate lighting

- Based on the Netherlands Bicycle Facilities Design Manual (CROW 1994), roundabouts are classified into four types according to the design and right-of-way situations as described below.

3.9.1 Roundabout with Mixed Flow

For low-volume bicycle traffic, special lanes for bicycle are not provided. In such types of roundabouts, cyclists usually operate as motorists. But in the Netherlands, the right of way is given to cyclists and motorists cannot pass cyclists until they exit the roundabout. The Dutch guidelines recommend mixed flow on roundabouts that are less than or equal to 5 m wide. (CROW 1994). Cyclists experience more stress and conflicts with additional motors in the case of multilane roundabouts (Austroads 1993).

3.9.2 Roundabout with Bicycle Lane

According to the Dutch guidelines, if there is a narrow roadway that makes it impossible to have a roundabout with mixed traffic flow, a separate bicycle lane within the circulatory roadway should be provided. The priority is given to the cyclists while approaching or leaving the roundabout. However, problems might occur at the exit when motorists cannot see cyclists in the blindspots. The Dutch guidelines also recommend placing a physical separation of 0.50 to 1.00 m wide between bicycle lanes and motorized traffic lanes within the roundabout and at the roundabout entrances and exits. This physical separation prevents motorists from cutting off bicyclists (CROW 1993).

3.9.3 Roundabout with Separate Bicycle Path

UK and Australian studies indicate that accident risk increases as bicyclists circulating within the roundabout (SMDT 1995). Therefore, a separate bicycle lane outside the circulating area is suggested as an alternative. The Dutch guide has two designs for roundabouts with separate bicycle path; bicyclist with right-of-way and motorists with right-of-way (CROW 1993). For bicyclists with right-of-way, bicycle path runs around the complete circumference at equal distance from the motor vehicle roadway at all points, see Figure (3.13). The bicycle path is the integral part of the roundabout in which bicyclists have priority over motor vehicles entering or exiting the roadway.

The Dutch guide recommends that the 5 m distance between the bicycle path and the circulating roadway should be kept small, since more conflicts can occur. This storage area between the roundabout and bicycle crossing allows approaching traffic to have the right-of-way in two stages: first to bicyclists on the path and then to motorized traffic on the roundabout. Cyclists are allowed to travel in only one direction similar to the vehicles traveling in the roundabout. For bicyclists with no right-of-way, roundabout design is similar to the roundabout with separate bicycle path. In this case however, bicycles have no priority and they are required to yield motorized traffic. In addition, the alignment of bicycle path is different since it bends outward instead of inward, see Figure (3.14).

The implementation of these roundabouts depends on many factors, such as volume of cyclists and motor vehicles (including heavy vehicles during the peak and off-peak hours), roundabout dimensions, accidents statistics, and driver experience (Van Mine 1996).

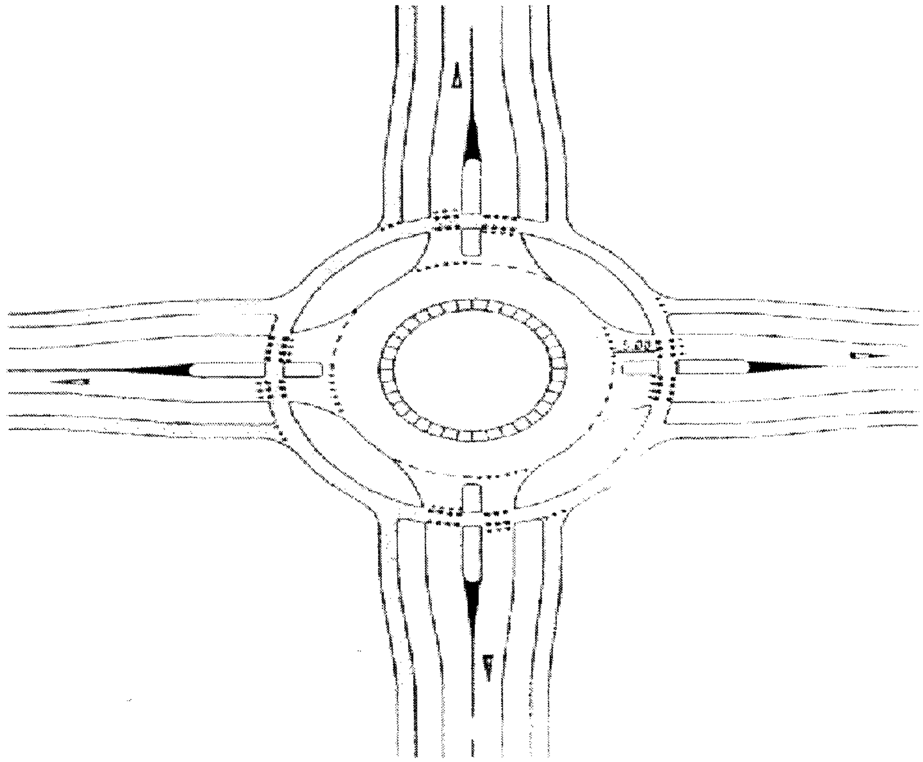


Figure 3.13: Bicyclists have Right-of-Way (CROW 1994)

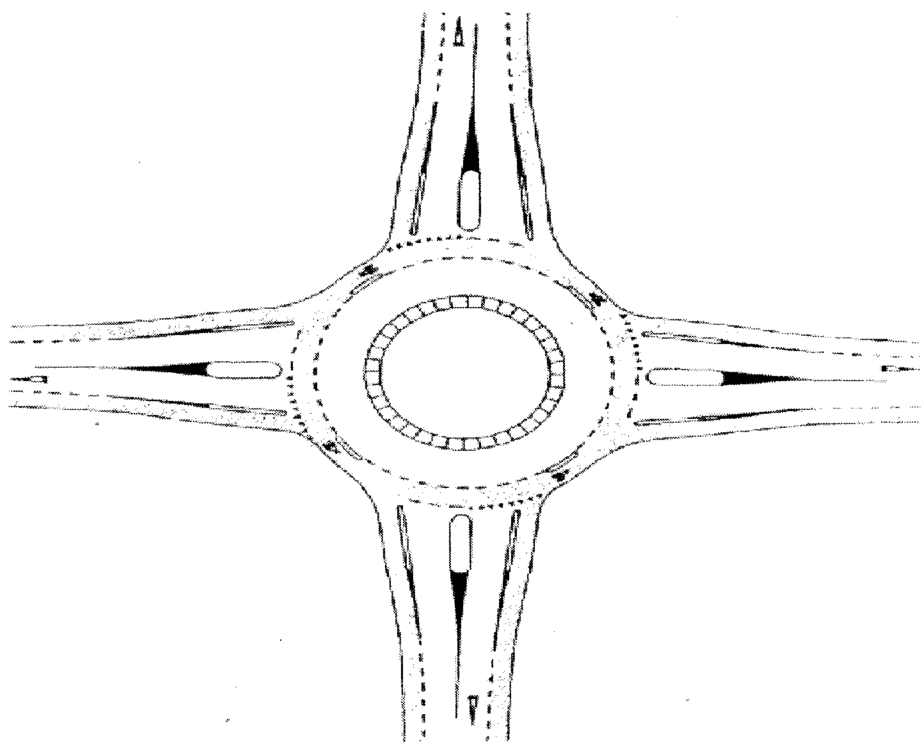


Figure 3.14: Bicyclists have no Right-of-Way (CROW 1994)

3.10 Summary

This chapter has presented the design process and general design principles for the roundabouts. A detailed literature review of the design guidelines for each geometric element of the roundabout is presented. This literature review is quite useful for designing roundabouts for maximum safety and operational performance. It is concluded that the design of roundabout parameters is quite complicated and time consuming because it relies on a trial-and-error procedure. The following chapter presents an optimization model that directly provides the optimum design subject to a wide variety of geometric and operational constraints.

Chapter 4

MODEL DEVELOPMENT AND APPLICATION

4.1 Introduction

Since the beginning of modern roundabouts, the design process has been a complex affair, requiring an iterative process of design, drawing, and evaluation. The development of low-cost high performance computers provides an excellent opportunity to develop better techniques for roundabout design. Optimization is one of the programming techniques used to determine decision variables subject to certain constraints for a given objective function. The decision variables for the roundabout design include entry width, inscribed circle diameter, circulating width, central island diameter, and radii of entry and exit curves. The roundabout design involves constraints relating to site conditions and design standards.

The objective function involves design consistency, which reflects safety, and operational performance in terms of average intersection delay. The delay depends on the degree of saturation while in turn depends on entry capacity and entry flow. Therefore, two measures are included in the objective function (design consistency and average intersection delay) to satisfy the design requirements of roundabouts. The application of the developed model is limited to single-lane roundabouts with four legs intersecting at right angle. This chapter presents the modeling methodology and its application (Easa and Mehmood 2003, Mehmood and Easa 2003).

4.2 Existing Methodology for Roundabout Design

Two methods are used for the design of roundabouts: manual method and computer-aided design. The manual method involves drawing preliminary proposed geometric layout of the roundabout for a specific location and then checking its safety, capacity, and operational performance according to one of the approved guidelines for roundabout design. The computer-aided design involves using proposed geometric data and expected traffic data in one of the roundabout design software and checking the same measures as in the manual method. Both methods involve an iterative process to obtain good design of roundabouts.

Different transportation agencies use different guidelines and softwares for the design of roundabouts. Designers select the geometric parameters that they expect (from experience or reference to current design guidelines) may produce a satisfactory design. Using these parameters and the projected traffic flows, the degree of saturation and delays can be determined by the approved methods of the transportation agency. These methods and guidelines are already discussed in Chapters 2 and 3. Again the parameters are modified as necessary and the process is repeated until a suitable design is achieved. It should be pointed out that a suitable design might not be an optimum design. The optimum design is the best design for given constraints and objective of the design.

4.3 Establishing Roundabout Data

Before the detailed design of roundabout a preliminary study is carried out to determine the feasibility of the roundabout. The feasibility study includes comparisons of the roundabout with other intersection forms. The roundabout is constructed either in urban or rural environment, but its preliminary configuration is defined in terms of the minimum number of lanes at each approach for required capacity. The category of roundabout (single-lane or double-lane) is determined based on the expected traffic flow and the space available at the site. Once the site and category of the roundabout are determined, the approximate design parameters and operational characteristics are defined for the detailed design process. Detailed feasibility is carried out with planning and policy considerations. For the development of optimization model, three types of data are required.

- Approximate Design Parameters Range
- Expected Traffic Data
- Side Friction Factor

4.3.1 Approximate Design Parameters Range

The scope of this research is limited to the development of an optimization model for the design of single-lane roundabout with four legs that intersect at right angle. For the approximation of design parameters range, an aerial photograph of the selected site is recommended (Fig.4.1). The ranges of design parameters can be defined from the photograph using a GIS software, like ArcView.

A fixed roundabout centre is defined that can accommodate the maximum diameter of the inscribed circle, D_{max}. The range of minimum diameter of the inscribed circle, D_{min}, is defined based on the design vehicle. Therefore, the design diameter of the inscribed circle, D, should lie between the minimum and maximum values,

Figure 4.1: Satellite Photograph of Selected Site for the Installation of Roundabout

$$D_{min} \leq D \leq D_{max} \qquad [4.1]$$

The centerline from the fixed center of roundabout is drawn on the same photograph. The maximum entry or exit-width of all four legs, $Emax_j$, can be defined on the photograph based on site conditions. The minimum entry or exit-width, $Emin_j$, is defined based on the minimum requirements for single-lane roundabouts. The constraint for the design entry or exit width, E_j, is then given by

$$Emin_j \leq E_j \leq Emax_j, \qquad j = 1,2,3,4 \qquad [4.2]$$

If flaring is likely to be introduced to improve the entry capacity, the entry width becomes somewhat more than the approach half-width. Otherwise, it is equal to the approach half width. If flaring is to be provided, a range of the flaring length should also be provided based on site conditions. The design flare width is given by

$$E_j = W_j \qquad \textit{(for no flaring)} \qquad [4.3]$$

$$E_j > W_j \qquad (for\ flaring) \qquad [4.4]$$

where, W_j = approach half-width for leg j (m). The constraints for the effective flare length is,

$$lmin_j \leq l_j \leq lmax_j \qquad [4.5]$$

The circulatory width of roundabout, C, depends on the maximum entry width of all four legs, C_1, such that,

$$C_1 = max\{E_j\}, \quad j = 1,2,3,4 \qquad [4.6]$$

$$C_1 \leq C \leq 1.2C_1 \qquad [4.7]$$

The central island radius, R_{CN}, is considered as a variable that depends on the circulatory width and the inscribed circle diameter. That is,

$$D = 2R_{CN} + 2C \qquad [4.8]$$

One of the most important factors in operational performance is queue length. From the satellite image of the proposed intersection for roundabout and other nearby intersections, the maximum queue length that can be accommodated on each leg without blockage of the preceding intersection can be estimated. This maximum queue length can be used as a constraint to that the queue length is less than the maximum values for each leg. So, the maximum available queue length at each leg j (in vehicles), $Lmax_j$, is also an input. The determination of approximate input data ranges of all geometric design parameters from the satellite photograph is illustrated in Figs. 4.2 and 4.3.

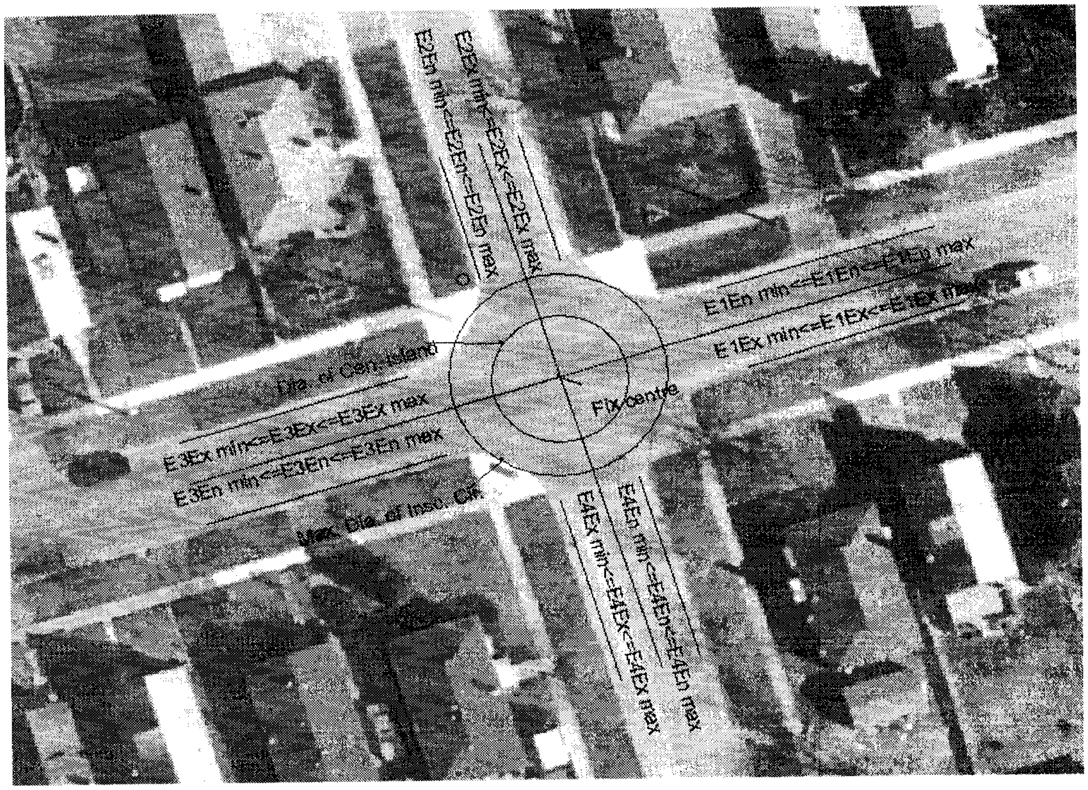


Figure 4.2: Roundabout Geometric Data Ranges from Satellite Image

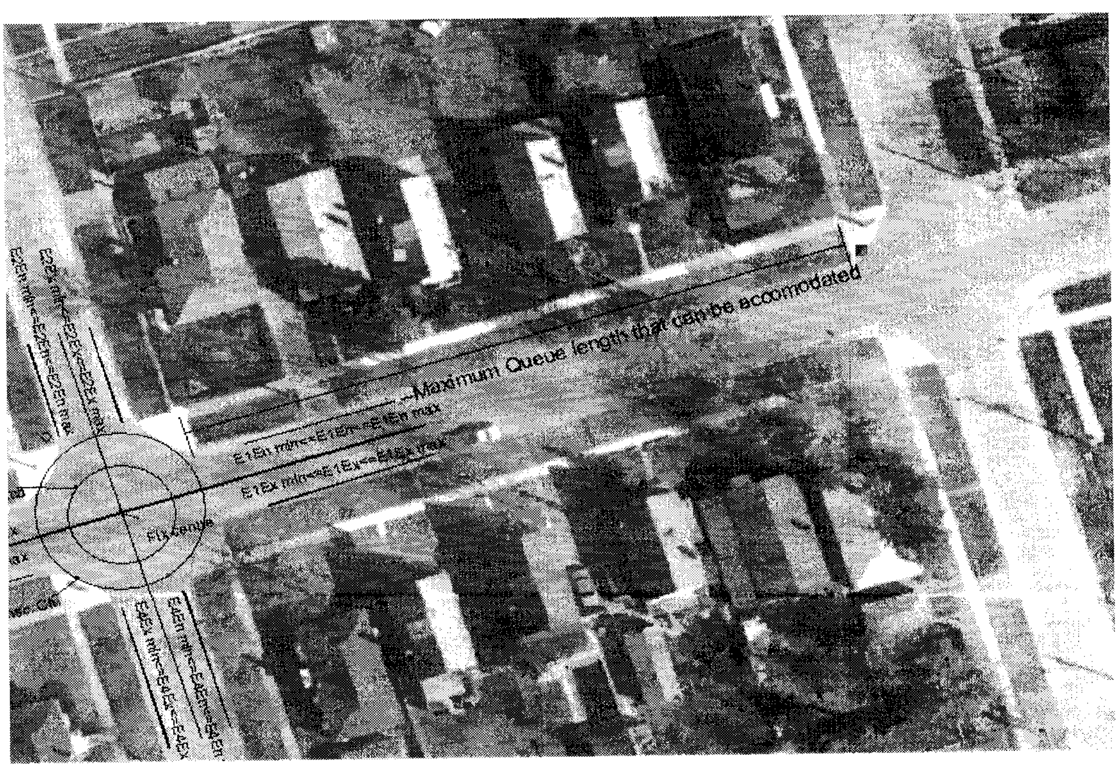


Figure 4.3: Maximum Available Queue Length at Roundabout Entries from Satellite Image

4.3.2 Expected Traffic Data

Traffic data is collected to insure that the proposed design have sufficient capacity and good level of performance in terms of minimum delay and queues. For capacity analysis, the conflicting traffic at each approach is needed. The entry flow (vph) at each approach is required for the comparison of entry capacity and entry flow to ensure that the volume/capacity ratio does not exceed the desired maximum design value. Traffic data for urban roundabout are collected for each directional movement during the morning and evening peak periods. For rural roundabout, the designer should check the design requirements of the agency with the justification of the site. The data collection methods are described in the Manual of Transportation Engineering studies (Robertson et al 1994).

The entry flow is simply the sum of the through, left, and right turn movements on an approach. While circulating flow is the sum of the vehicles from different movements passing in front of the adjacent upstream splitter island. For the design of new roundabout at existing intersection, traffic flow data can simply be measured in the field. Right turns are not included in circulating volumes because they exit before the next entrance. For the layout of the reference geometry of roundabout refer to Fig 4.4. The entry capacity at leg j is affected by the conflicting circulating flow rates (pce/h) given by

$$Qc_j = QeUT_{j+1} + QeUT_{j+2} + QeLT_{j+2} + QeUT_{j+3} + QeLT_{j+3} + QeTH_{j+3}, \quad j = 1, 2, 3, 4 \qquad [4.9]$$

When the subscript of any variable is greater than 4, subtract 4 from it to obtain the appropriate leg number. The entry flow rate (pce/h) for leg j is simply the sum of the through, left-turning, right-turning, and u-turning vehicles at each leg,

$$Qe_j = QeRT_j + QeUT_j + QeLT_j + QeTH_j \,. \qquad j = 1, 2, 3, 4 \qquad [4.10]$$

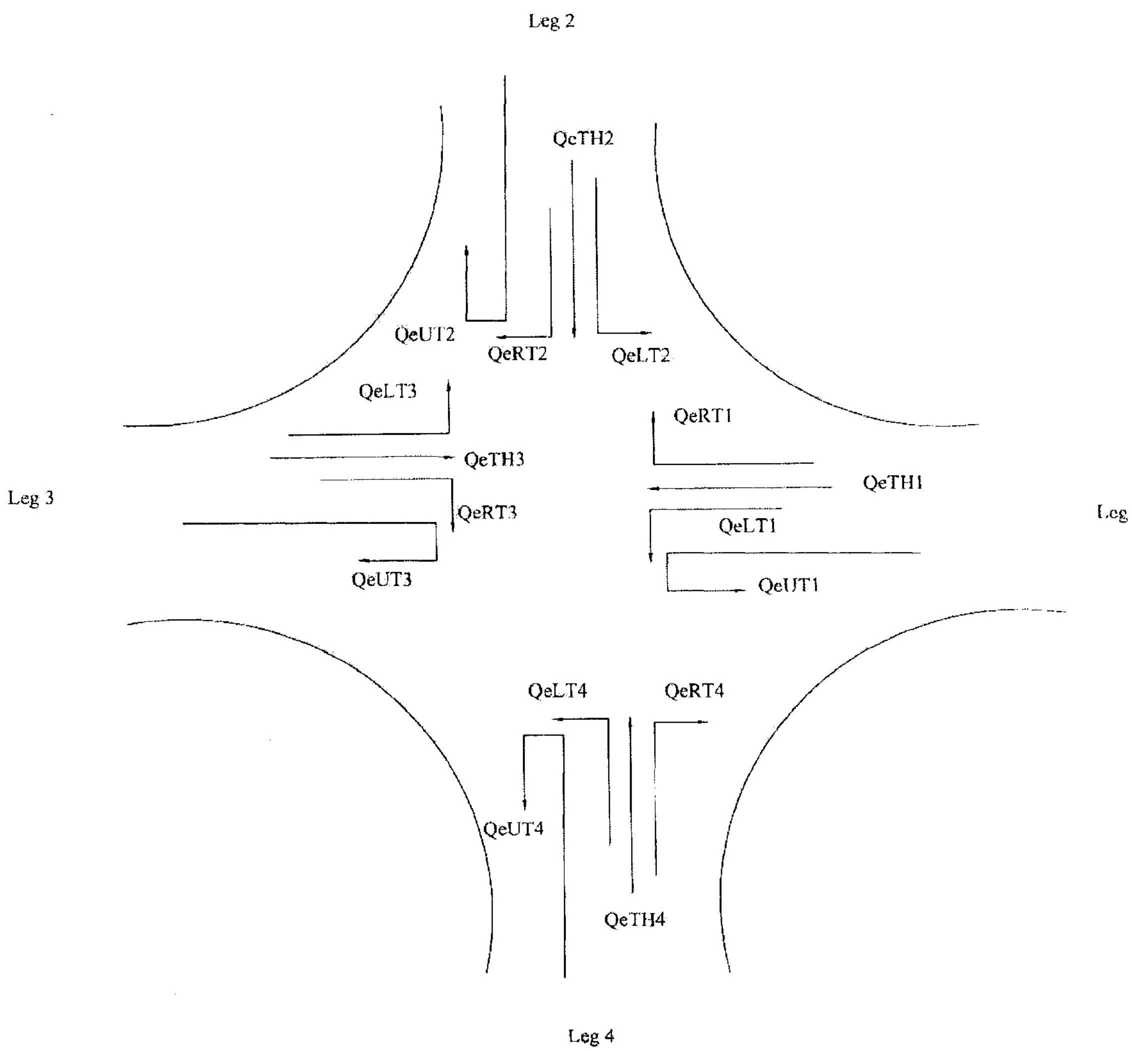


Figure 4.4: Geometry of Roundabout for Traffic Flow

The traffic data for the selected site will be collected and will be used in model as an input. For the purpose of simplicity, the entry flow rate and conflicting circulating flow rate for each leg are generalized, where Qcj = conflicting circulating flow rate for leg j (pce/h) and Qej = entry flow rate at leg j (pce/h). Since the conflicting flow rate (pce/h) and entry flow rate (pce/h) are in passenger car equivalents per hour, all types of traffic is counted, multiplied by the peak-hour factor and then converted into passenger car equivalents using the conversion factors given in Table 2.1.

4.3.3 Side Friction Factors

The side friction factors for light and heavy vehicles are needed for estimating operating speed. The following formulas, developed by Rahmi Akçelik (2003) for SIDRA, one of the popular software for the design of roundabout, are used,

$$fsLV=0.30-0.00084\sqrt{MvLV} \qquad [4.11]$$

$$fsHV=0.30-0.00084\sqrt{MvHV} \qquad [4.12]$$

where fsLV, fsHV = side friction factors for light and heavy vehicles, respectively, and MvLV, MvHV = average vehicle masses for light and heavy vehicles (kg), respectively. The average side friction factor for the combined light and heavy vehicles can be calculated based on the percentage of heavy vehicles as follows,

$$fs = (1 - PHV)\,fsLV + (PHV)\,fsHV \qquad [4.13]$$

where PHV = percentage of heavy vehicles at roundabout (in decimal)

4.4 Modeling Vehicle Paths

The speed of the roundabout is determined by establishing the fastest vehicle path allowed by the proposed geometry of the roundabout. While establishing the vehicle path it is assumed that there is no traffic or lane marking. Therefore, a single vehicle can move freely, traversing through the entry, around the central island, and out through the exit. It is observed that along each vehicle path (through, right, and left-turn) there are three path radii: entry path radius, path radius around the central island, and exit path radius. It is assumed that the vehicle is 2 m wide and will maintain a minimum clearance of 0.5 m from the roadway centerline or concrete curb and flush with painted edge line of splitter (QDMR 1998). Thus the centerline of the vehicle path lies at a distance of 1.5m from the concrete curb and 1.0 m from the painted edge line of the splitter. Through vehicle path is shown in Figure 3.2 as an example to understand the vehicle paths concept. Vehicle path radii for each vehicle path are modeled separately for use in the optimization model.

4.4.1 Fastest Through Movement Radii

The fastest path for the through movement is a series of reverse curves (i.e a curve to the right, followed by a curve to the left, followed by a curve to the right). There are three curves: entry, exit, and around the central island. If there is no central island in the roundabout, this through path will be a straight line rather than series of three curves. The central island radius depends on the inscribed circle diameter and the circulatory roadway width, as described in Equation (4.8). The circulatory roadway width directly depends on the entry width. Therefore, the radii of the reverse curves of the through path depend on central island radius, inscribed circle diameter, and circulatory roadway width.

When a free-hand through path is drawn on different sizes of single-lane roundabouts with four legs at right angle, it is observed that the entry and exit points at yield lines of roundabout are at 30 degree with the centre of the roundabout. For the radius of curve around the central island along through path, the deflection angle, the mid ordinate, and length of long chord are needed. The curve around the central island for through path is located at a distance of 1.5 m from the edge of the central island. Hence, the distance

$\overline{Ltt}$ depends on the radius of the central island, while the distance $\overline{Lt}$ depends on the diameter of the inscribed circle (Figure 4.5). This is,

$$\overline{Ltt} = R_{CN} + 1.5 \qquad [4.14]$$

$$\overline{Lt} = \frac{D}{2}\, Sin\ 30 \qquad [4.15]$$

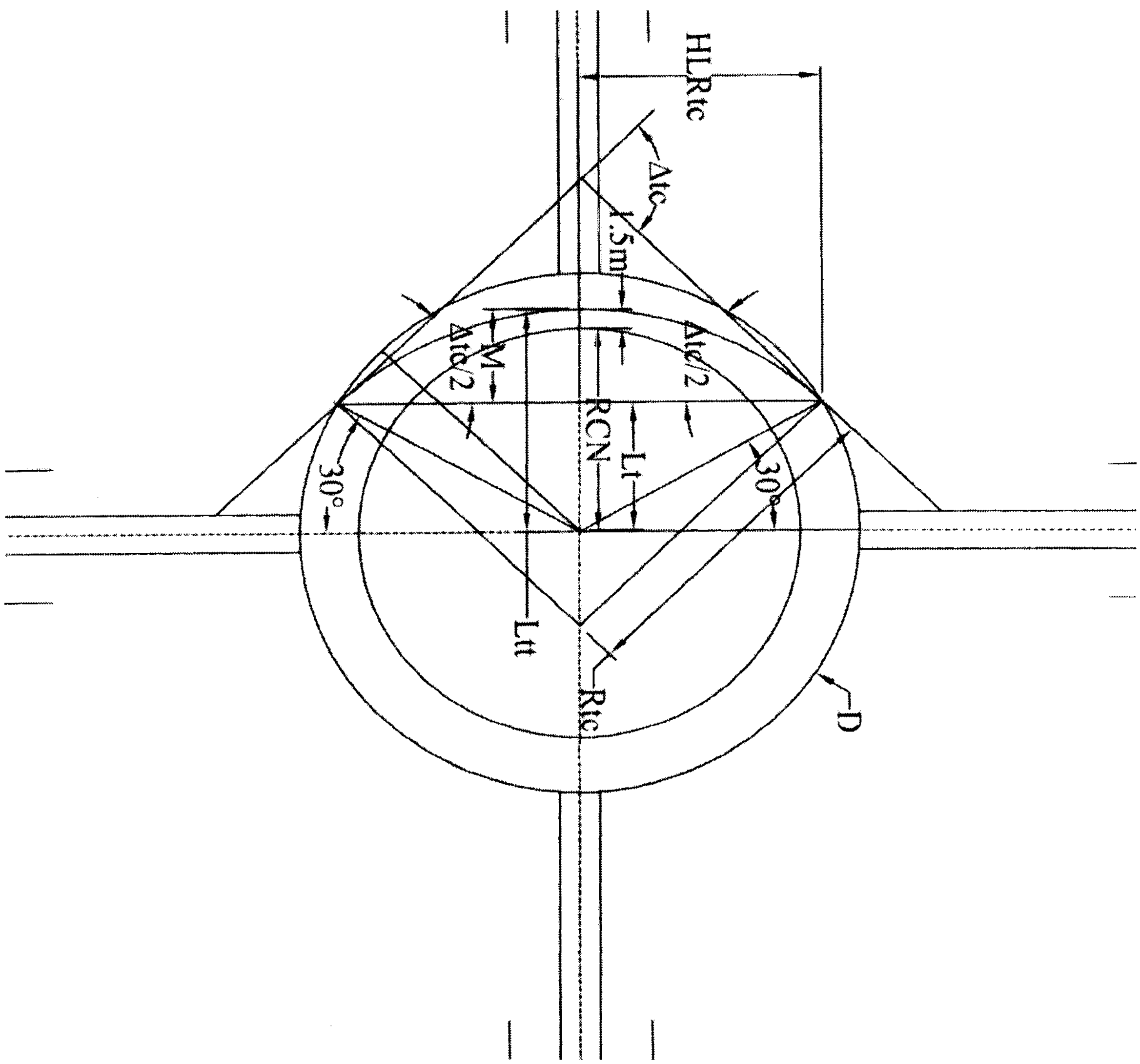


Figure 4.5: Dimensions of Path Curve around the Central Island for Through Vehicle Path

The difference between $\overline{Ltt}$ and $\overline{Lt}$ is the mid ordinate M,

$$M = \overline{Ltt} - \overline{Lt} \qquad [4.16]$$

To keep the mid ordinate in proper position, R_{CN} must be more than Lt. Therefore, a constraint is used to ensure that Lt is less than R_{CN},

$$R_{CN} \geq \overline{Lt} \qquad [4.17]$$

The half length of chord can be calculated as,

$$HLR_{tc} = \frac{D}{2} \; Cos\ 30 \qquad [4.18]$$

The half length of chord and mid ordinate are also given by,

$$\mathrm{HLR}_{\mathrm{tc}} = Rtc \ \mathrm{Sin} \frac{\Delta_{tc}}{2} \qquad [a]$$

$$M = Rtc \left(1 - \mathrm{Cos} \frac{\Delta_{tc}}{2}\right) \qquad [b]$$

As HLR_{tc} and M are known dividing Equations (a) and (b), can provide the value of the deflection angle, Δ_{tc}, which can further be used to determine radius for through vehicle path around the central island, Rtc. That is,

$$\frac{\mathrm{HLR}_{\mathrm{tc}}}{\mathrm{M}} = \frac{\mathrm{Sin} \frac{\Delta_{tc}}{2}}{\left(1 - \mathrm{Cos} \frac{\Delta_{tc}}{2}\right)} \qquad [4.19]$$

$$Rtc = \frac{\mathrm{HLR}_{\mathrm{tc}}}{\mathrm{Sin} \frac{\Delta_{\mathrm{tc}}}{2}} \qquad [4.20]$$

When a vehicle enters the central island or to leaves the central island its position becomes straight and it maintains a distance of 1.0 m from the edge of the painted splitter island as mentioned previously. As the through vehicle path is a series of reverse curves bending towards the right then the left and again the right, the entry and exit path curves for through movement will have the same tangent of path curve around the central island (Figure 4.6). The deflection angle of the entry/exit path curves will be the half deflection angle of the curve around the central island,

$$\Delta_{te} = \frac{\Delta_{tc}}{2} \qquad [4.21]$$

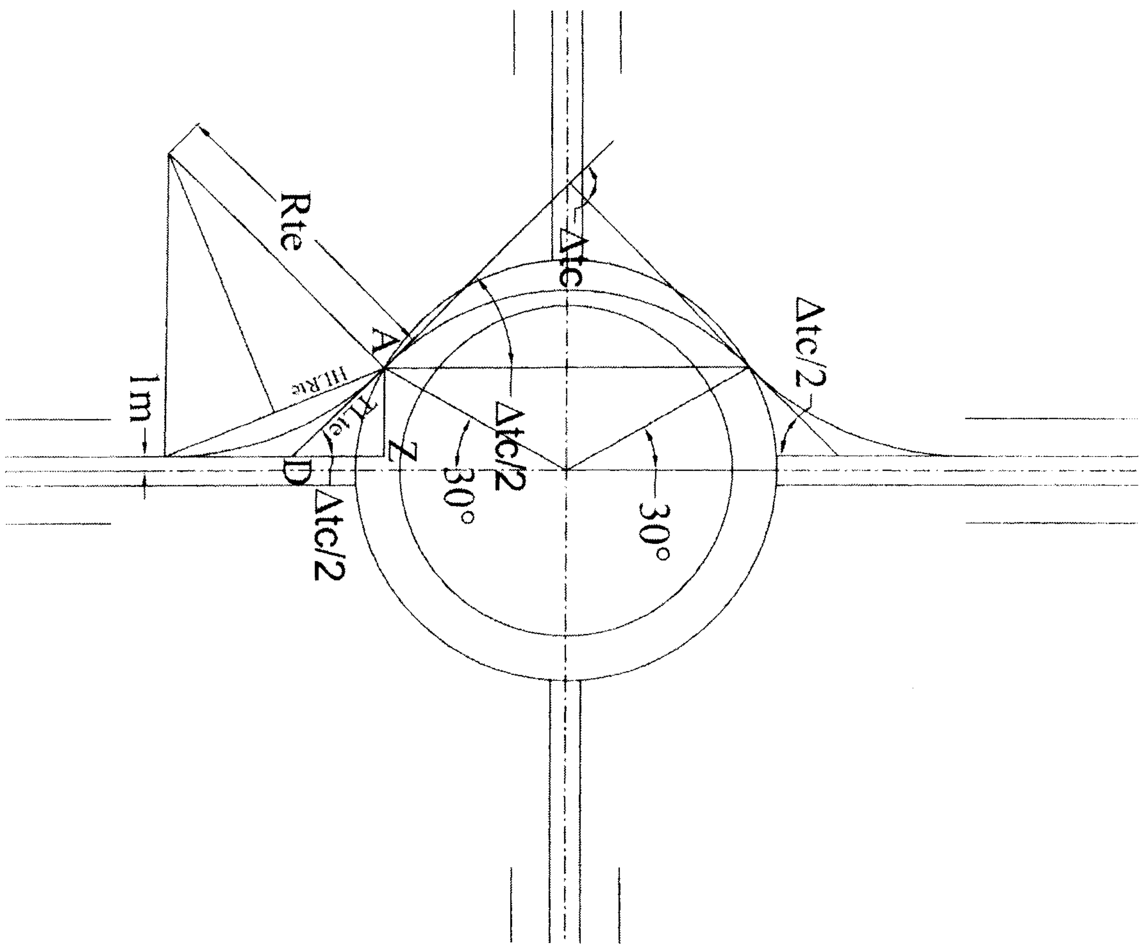


Figure 4.6: Dimensions of Entry/Exit Path Curves for Through Vehicle Path

From Δ AZD, the distances $\overline{AZ}$, $\overline{DZ}$,and $\overline{TL_{te}}$ can be determined as,

$$\overline{AZ} = \frac{D}{2} Sin\ (30)\text{-}1 \qquad [4.22]$$

$$\overline{DZ} = \frac{\overline{AZ}}{\tan \Delta_{te}} \qquad [4.23]$$

$$\overline{TL_{te}} = \sqrt{\overline{DZ}^2 + \overline{AZ}^2} \qquad [4.24]$$

The half length of chord and entry/exit path curve radius for the through path can easily be formulated in terms of tangent length and deflection angle,

$$HLR_{te} = \overline{TL_{te}}\ (Cos \frac{\Delta_{te}}{2}) \qquad [4.25]$$

$$R_{te} = \frac{HLR_{te}}{\sin \frac{\Delta_{te}}{2}} \qquad [4.26]$$

Since all four legs of the roundabout intersect at right angle, the symmetrical geometry of the roundabout results in the same radius of the path curve around the central island and the entry/exit path curve radii for through movement of all approaches.

4.4.2 Fastest Right-Turn Path Radii

The right-turn vehicle path consists of a series of three curves turning in the same direction. One is entry path curve that the diver perceives based on the circulatory width available and the central island diameter of the roundabout. Once the driver enters the roundabout, he/she takes a sharp turn towards the exit lane and then finally turns the vehicle to avoid striking the splitter and goes in a straight position along the splitter, keeping a 1.0 m distance from the splitter. This is the fastest expected right turn path according to the procedure of establishing the fastest right-turn. The radii of the right turn path are shown in Figure 4.7.

Based on trials of drawing right-turn paths by freehand on different sizes of roundabouts, it is observed that the entry and exit points at yield lines are at 30 and 60 degrees from the fixed centre of the roundabout, respectively. Horizontal curve parameters, like mid ordinate, length of chord, and deflection angle, are required to calculate the radius of vehicle path curve within the inscribed circle, R_{rn}, for right-turns.

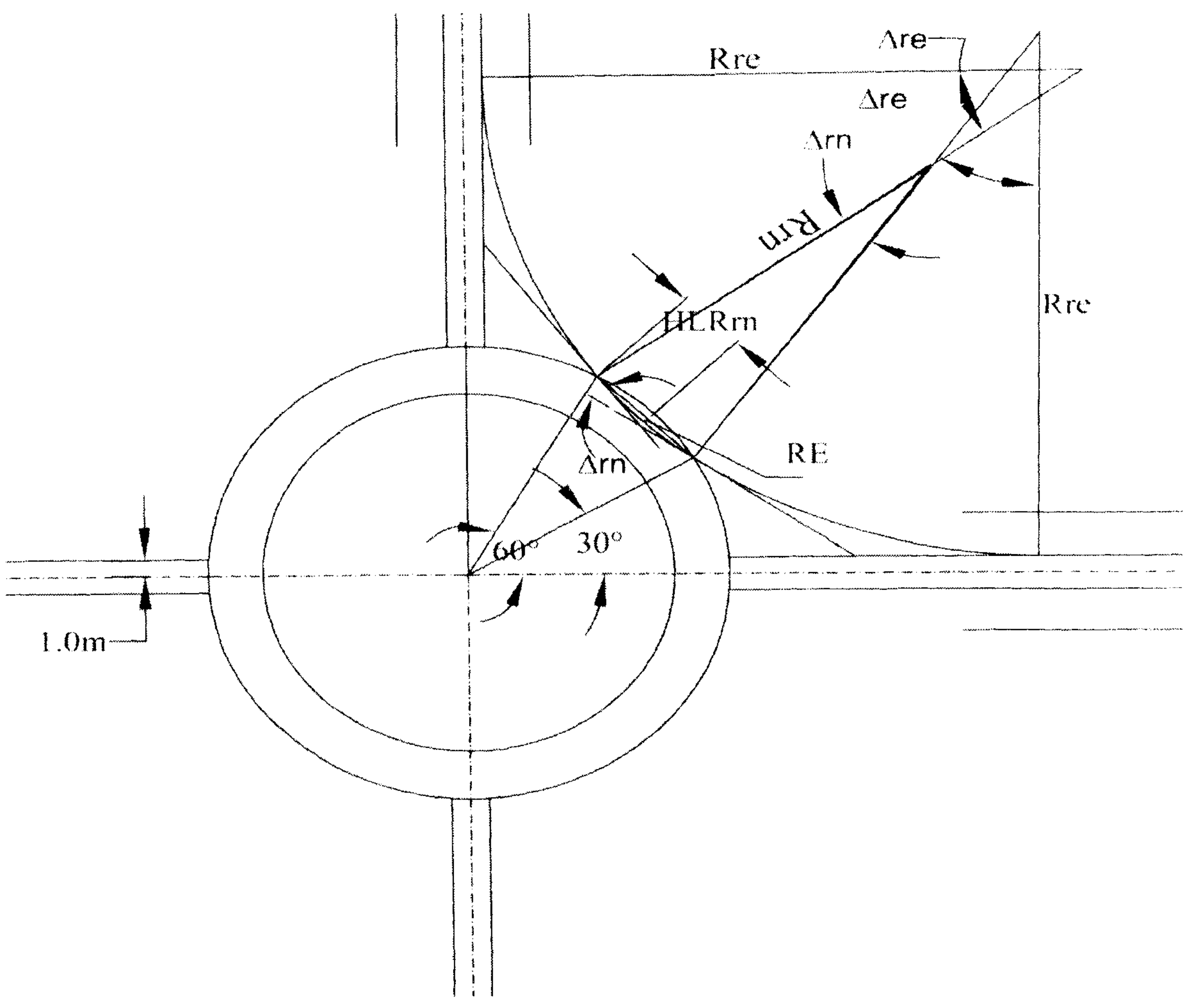


Figure 4.7: Dimensions for Right-Turn Vehicle Path Curve within Inscribed Circle

This radius depends on the inscribed circle diameter and the circulatory roadway width of the roundabout. The positions of the entry and exit points are known with respect to the roundabout centre. Therefore, the length of chord can be calculated with two equations. The length of the chord increases if the inscribed circle diameter increases and vice versa. The half length of chord is given by,

$$HLR_{rn} = \frac{1}{2}\left[\left(\frac{D}{2}(Sin30 - Cos30)\right)^2 + \left(\frac{D}{2}(Cos30 - Sin30)\right)^2\right]^{0.5} \qquad [4.27]$$

The mid ordinate, R_E, is modeled by making a small program to check the sensitivity of different parameters, like the radius of the central island and circulatory roadway width based on observed data for drawing the negotiation radii with freehand for different roundabouts. It is observed that the mid ordinate is quite sensitive to the circulatory roadway width, and the most appropriate relation is,

$$R_E = \frac{1}{10}C \qquad [4.28]$$

This relation also shows that if the circulatory roadway width increases, drivers will have more space to take rounded turn; otherwise drivers will take a sharp turn. The deflection angle can be determined using the half length of chord and mid ordinate, which can be used to determine the radius of vehicle path curve for right-turn within the inscribed circle, R_{rn},

$$\frac{HLR_{rn}}{R_E} = \frac{\sin\frac{\Delta_{rn}}{2}}{\left(1 - \cos\frac{\Delta_{rn}}{2}\right)} \qquad [4.29]$$

$$R_{rn} = \frac{HLR_{rn}}{\sin\frac{\Delta_{rn}}{2}} \qquad [4.30]$$

Drivers observe deflections at the entry and exit points to negotiate the entry/exit path radii for right-turn path. The initial and final positions of vehicle before entering and after exiting are parallel to the splitter and maintain a 1.0 m clearance from the highway centerline for fastest vehicle path. Like through vehicle path, the entry and exit path curves for right-turn path are the same because of the symmetrical geometry of the roundabout. The deflection angle for the entry and exit path curves can be determined by considering the polygon 'BCDE" of four sides (Fig 4.8). For simplicity the absolute value of the deflection angle is used,

$$Abs\,(\Delta_{re}) = 45 - \frac{\Delta_{rn}}{2} \qquad [4.31]$$

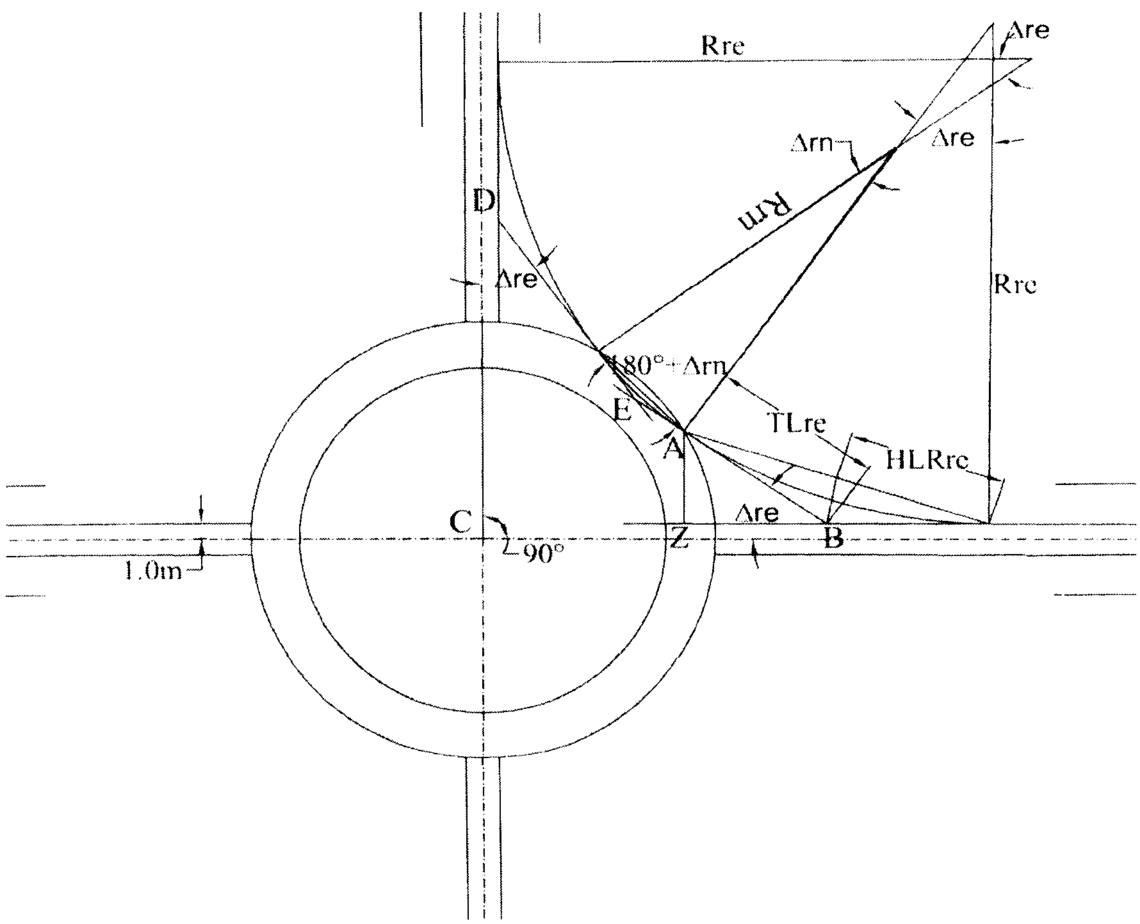


Figure 4.8: Dimensions of Entry/Exit Path Curve for Right-Turn Vehicle Path

The tangent length, $\overline{TL}_{re}$, can be calculated from the right angle triangle ABZ, which can help determine the half length of the chord, HLR_{re}, and the radius of the entry/exit curve for right-turn vehicle path.

$$\overline{AZ} = \frac{D}{2} Sin\ (30)\text{-}1 \qquad [4.32]$$

$$\overline{ZB} = \frac{\overline{AZ}}{\tan\Delta_{re}} \qquad [4.33]$$

$$\overline{TL_{re}} = (ZB^2+AZ^2)^{0.5} \qquad [4.34]$$

$$HLR_{re} = TLre\ (Cos \frac{\Delta_{re}}{2}) \qquad [4.35]$$

$$R_{re} = \frac{HLR_{re}}{\sin\frac{\Delta_{re}}{2}} \qquad [4.36]$$

4.4.3 Fastest Left-Turn Path Radii

The fastest left-turn vehicle path has three turning radii. The left-turn vehicles follow three radii: first a right-turn from its parallel position at a distance of 1.0 m from the painted edge of the splitter to a point in the roundabout to make a safe left-turn, a left-turn around the central island, and finally a right-turn to reach a parallel position with the painted edge of splitter. The drawing of left-turn fastest vehicle path by freehand at different roundabouts, show that the entry and exit point positions are at an angle of 45 degree with respect to the roundabout center. It should be noted that the analysis was done only for right-angled four legs single-lane roundabouts. Because of the symmetrical geometry of the roundabout, the entry and exit path radii are the same. The negotiation radius of left-turn vehicle path around the central island can be determined by adding 1.5 m to the central island radius (Robinson et al. 2000).

$$R_{Lc} = R_{CN} + 1.5 \qquad [4.37]$$

Referring to Fig. 4.9, BC in the right-angle triangle BCD is given by,

$$\overline{BC} = R_{Lc} \, Cos\,(45) - 1 \qquad [4.38]$$

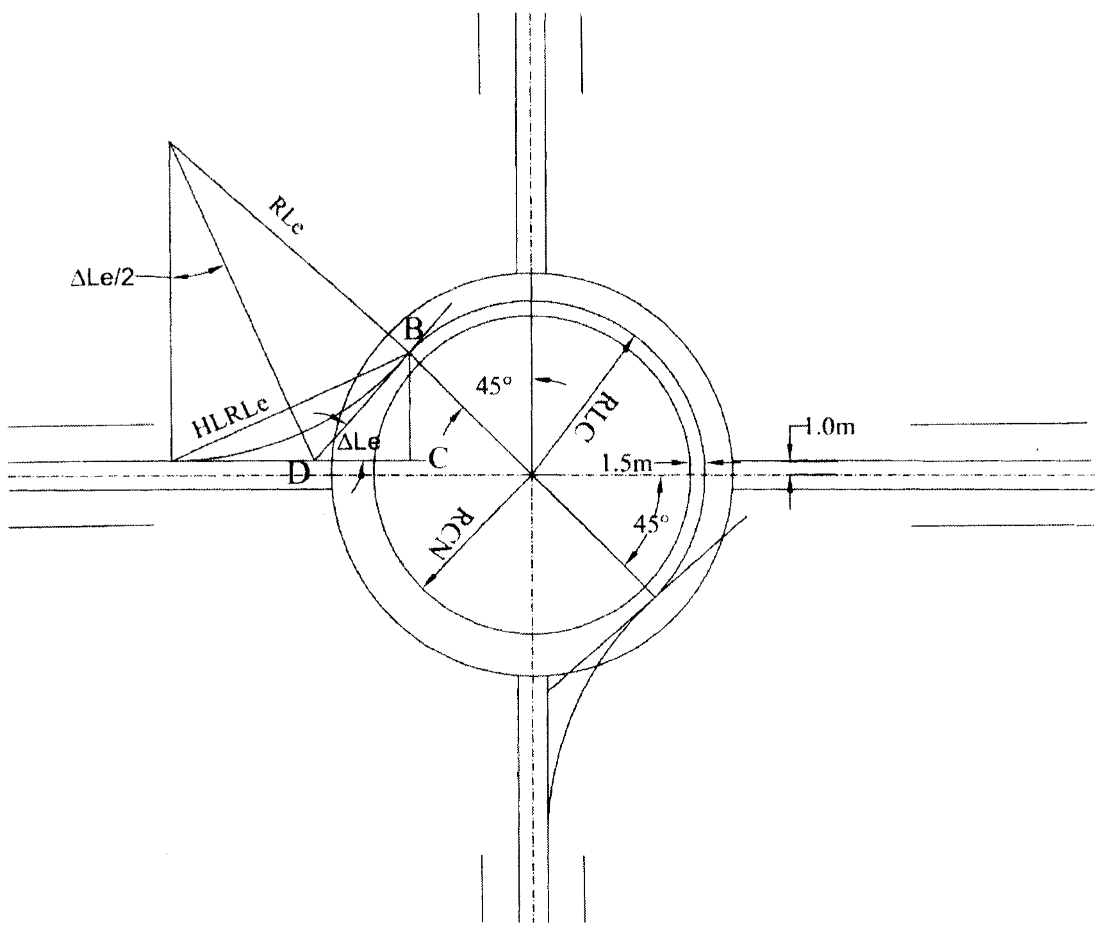


Figure 4.9: Left-Turn Vehicle Path Radii

The analysis was done using observed data taken from drawing the fastest left-turn paths for different circulating widths, central island radii, and inscribed circle diameters. The analysis showed that the base $\overline{CD}$ of the right angle triangle BCD for left-turn entry and exit path radii depends on the central island radius. If the central island radius increases, $\overline{CD}$ increases and vice versa. The best observed relation is found to be,

$$\overline{CD} = 0.6\, R_{CN} \qquad [4.39]$$

Using $\overline{BC}$ and $\overline{CD}$, deflection angle (Δ_{Le}), the half length of chord (HLR_{Le}) and the entry/exit negotiation radius of the left-turn path (R_{Le}) can be determined as,

$$CD = \frac{BC}{\tan \Delta_{Le}} \qquad [4.40]$$

$$HLR_{Le} = TL_{Le}\, Cos \frac{\Delta_{Le}}{2} \qquad [4.41]$$

$$R_{Le} = \frac{HLR_{Le}}{Sin \frac{\Delta_{Le}}{2}} \qquad [4.42]$$

4.5 Optimization Model

The vehicle path radii control roundabout geometry and related design aspects, such as design consistency, capacity and operational performance that depend on the vehicle-path radii from each approach of the roundabout. The design parameters of roundabout allow vehicles to move on certain path radii from each approach. The vehicle path radii that are modeled for through, left-turn and right-turn traffic totally depends on roundabout geometry. These vehicle path radii are used in the optimization model for design consistency, capacity, and operational performance evaluation. The operational performance is measured by the average delay for traffic at each approach of the roundabout. The modeling process of path radii shows that the entry/exit path radii and path radius around the central island for each vehicle path depends on the inscribed circle diameter, circulating width (that indirectly depends on the entry width), and central island radius.

4.5.1 Consistency Measure: Speed Difference

4.5.1.1 Safe Negotiating Speed

The safe negotiating speeds for each radius of vehicle path are determined by the following formula (Austroads 1993, Robinson et al. 2000),

$$V_P=3.6\,[9.81(fs + e_i)R_p]^{0.5} \qquad [4.43]$$

where,

V_P represents V_{tc}, V_{Lc}, V_{rn}, V_{re}, V_{Le}, or V_{te} and R_P represents R_{tc}, R_{Lc}, R_{rn}, R_{re}, R_{Le}, or R_{te}. The superelevation $e_i = 0.02$ for the entry/exit path curves and -0.02 for the path curves around the central island for all paths (through, left, and right)

The side friction factor is already calculated based on given traffic data. Depending on the roundabout size range, type of road and traffic conditions a maximum design speed of roundabout is determined and used as input in the model. For safe operation of roundabout, all vehicle path speeds must be less than the desired maximum design speed V_{max}. Therefore, a constraint is used in the optimization model to ensure that vehicle path speeds are less than the maximum design speed.

$$V_{tc}\ ,\ V_{Lc}\ ,\ V_{rn}\ ,\ V_{rc}\ ,\ V_{Le}\ ,\ V_{te} \leq V_{max} \qquad [4.44]$$

4.5.1.2 Speed Difference

Low relative speeds at the roundabout in terms of design consistency allow drivers more time to react to potential conflicts. This helps reduce crash severity that improves safety performance of the roundabouts. Design consistency also requires low relative speeds at consecutive geometric elements. This helps reduce loss-of-control crashes. Therefore, each vehicle path (through, left, and right) requires design consistency at consecutive vehicle path radii. The design will be good and safer if the relative difference in speeds is less than 20 km/h (12mph). In the optimization model, design consistency of each individual path is considered by minimizing the relative difference of speeds along each vehicle path from all approaches.

The relative difference at each conflict and consecutive point is determined as,

$$V_{te} - V_{tc} + M_i - M_{i+1} = 0 \qquad [4.45]$$

$$V_{rn} - V_{rc} + M_i - M_{i+1} = 0 \qquad [4.46]$$

$$V_{Le} - V_{Lc} + M_i - M_{i+1} = 0 \qquad [4.47]$$

The most conflicting point corresponds to the entry-circulating point. As entry speed and circulating speed are different for each vehicle path, the relative difference in speed is calculated for each entry-conflicting point as,

$$V_{tc} - V_{Le} + M_i - M_{i+1} = 0 \qquad [4.48]$$

$$V_{tc} - V_{re} + M_i - M_{i+1} = 0 \qquad [4.49]$$

$$V_{Lc} - V_{rc} + M_i - M_{i+1} = 0 \qquad [4.50]$$

$$V_{lc} - V_{tc} + M_i - M_{i+1} = 0 \qquad [4.51]$$

There are also two potential circulating conflict speeds: the conflict of right-turn speed inside the roundabout V_{rn} with the left-turn and through circulating speeds around the central island. Therefore, the relative difference of speeds of these conflicts is also calculated as,

$$V_{rn} - V_{lc} + M_i - M_{i+1} = 0 \qquad [4.52]$$

$$V_{rn} - V_{tc} + M_i - M_{i+1} = 0 \qquad [4.53]$$

Since the relative difference may be positive or negative, two variables (M_i, M_{i+1}), one for positive and one for negative, are used in the model. Each relative difference is constrained to be less than the mean speed difference, MD. The objective function of the model minimizes MD, and all differences are constrained to be less than 20 km/h (12mph).

$$M_i, M_{i+1} \leq MA, \quad \text{where, } i = 1,2,\ldots, 17 \qquad [4.54]$$

$$MD = \frac{\sum_{i=1}^{17}(M_i + M_{i+1})}{n}, \quad \text{where, } n = 9 \qquad [4.55]$$

$$\text{Minimize } \{MD\} \qquad [4.56]$$

where MA is the maximum allowable speed difference (20km/h).

4.5.2 Operational Measure: Average Intersection Delay

The operational measure used in the optimization model is the average intersection delay, which depends on the average delay for each intersection approach (entry) to the roundabout. The delay of each entry, in turn, depends on the capacity of that entry. The capacity of each entry is the maximum rate at which vehicles can reasonably be expected to enter the roundabout from an approach during a given time period under given traffic and roadway geometric conditions.

4.5.2.1 Entry Capacity

The entry capacity of roundabout is estimated by theoretical and empirical approaches. The theoretical (gap-acceptance) approach is based on assumptions of driver behavior. The British (Kimber 1980), French (Lough 1988), and German (Stuwe 1992) analytical procedures present empirical relationships for capacity analysis that directly relate capacity to both traffic characteristics and roundabout geometry. Entry capacity models based on gap-acceptance theory are developed for Australian and Danish roundabouts (Troutbeck 1993, Aagaard 1996). Due to the complex relationships between gap-acceptance parameters and geometric elements of the roundabout, gap-acceptance theory overestimates entry capacity when using gap-acceptance parameters measured in strict adherence to assumed driver behavior (Aagaard 1996, Kimber 1989). A vital area in which the empirical method is better than gap-acceptance methods is in dealing with local widening (or flaring). Therefore British empirical relationships were used to determine the entry capacity of the roundabout.

Traffic conditions for capacity are already discussed (section 4.3). According to the British method (Kimber 1980), the most effective roundabout geometric parameters for capacity analysis are the inscribed circle diameter, the entry width, the approach half width, the entry radius, entry angle and the sharpness of the flare. Roundabout capacity can be increased by increasing the entry width by flaring. The sharpness of flare is the rate at which the extra width is developed by providing effective entry flare length.

The entry radius is observed to be the average of the entry path radii (Through, left, and right) with tolerance of 1-2.5 m based on trial analysis of drawing vehicle path radii for different roundabouts (Fig. 4.10). Therefore, the average entry path radius can be determined by taking the average of three entry radii of through, right and left paths.

$$R_{ave} = \frac{R_{re} + R_{te} + R_{Le}}{3} \qquad [4.57]$$

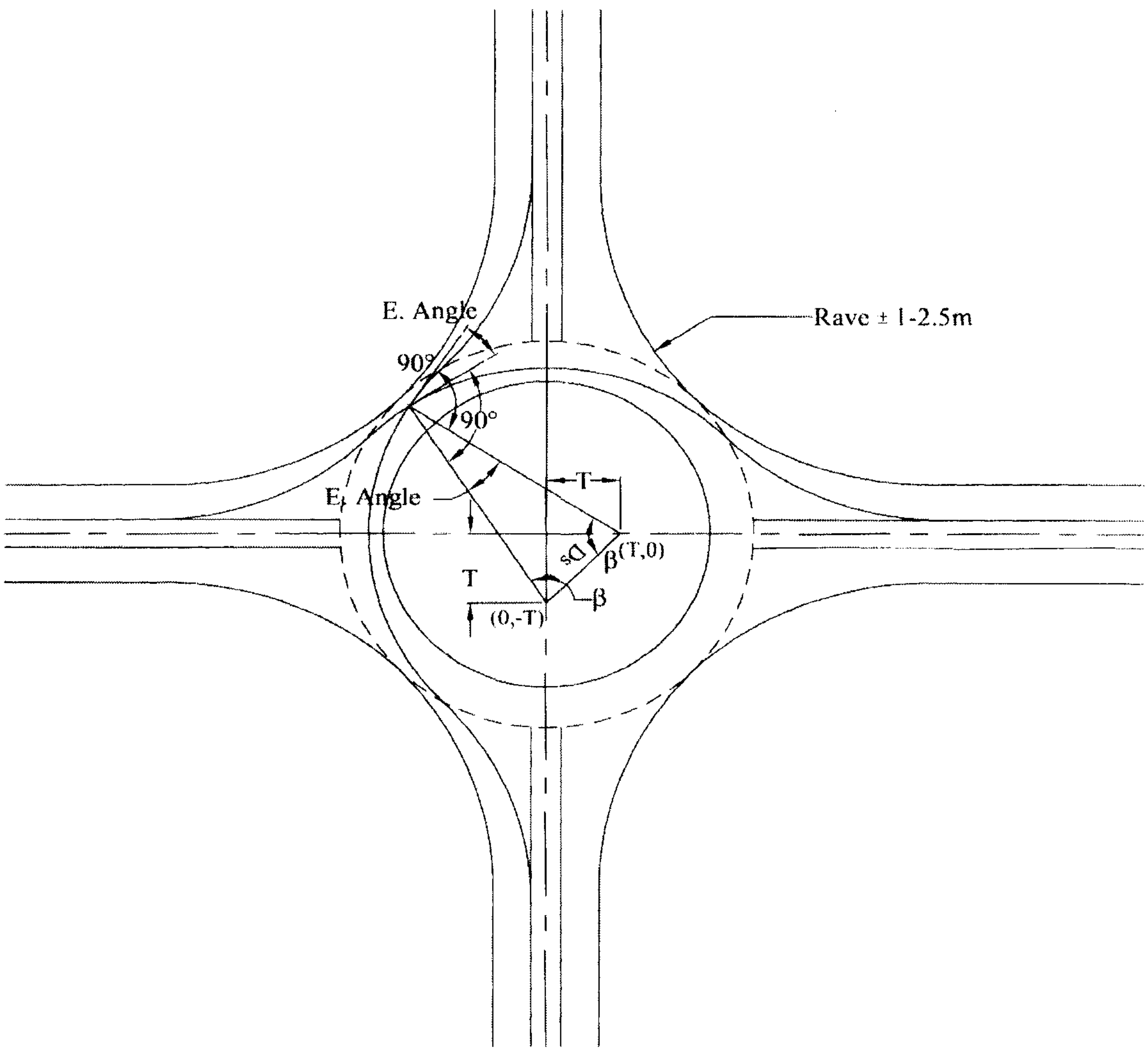


Figure 4.10: Determination of the Entry Angle of the Roundabout

The entry angle is the angle between the tangents drawn at the intersection point of entry and circulating vehicle paths. Two through vehicle paths were drawn to determine the formulation for the entry angle to be use in the optimization model (Fig. 4.10). The distance from the center point of radius of through path curve around the central island to the point of intersection of two through path curves is,

$$T = R_{tc} - R_{CN} - 1.5 \qquad [4.58]$$

The distance between the center points of each curve can be determined as,

$$Ds = [T^2 + T^2]^{0.5} \qquad [4.59]$$

The angle β of Δ ABC can be determined as,

$$Cos\,\beta = \frac{Ds}{2R_{tc}} \qquad [4.60]$$

If β is known, then the entry angle can be determined as,

$$Eagr = 180 - 2\beta \qquad [4.61]$$

As high and low entry angles may result in increased accident potential, it is desirable to equally space the angles between the entries. If possible, the angle shall be between 20 and 60 degrees. Low entry angles force drivers into merging positions in which they must either look over their left shoulders or attempt a true merge using their side mirrors. High entry angles produce excessive entry deflection and can lead to sharp breaking at entries accompanied by rear-end accidents. The best entry angle is 30 degrees (Robinson et al. 2000). A constraint in optimization model was used to control roundabout geometry to limit the entry angle,

$$20 \leq Eagr \leq 60 \qquad [4.62]$$

All angles used in modeling process were shown in degree for simplicity, but these angles must be used in radian for the actual modeling of roundabout design. The entry angle in the optimization model is calculated in radians, but for capacity analysis it should be in degrees. Therefore, the entry angle is converted from radians into degrees in the optimization model by,

$$Eagd = 57.32\ Eagr \qquad [4.63]$$

Following the capacity analysis procedure in Great Britain (Kimber 1980), the entry capacity for each approach is given by,

$$EC_j = k_j\ (F_{ej} - F_{cj}\ Q_{cj}), \qquad j = 1,2,3,4 \qquad [4.64]$$

where F_{cj} is a constant that depends on the geometry of the circle, particularly its outside diameter. It is given by,

$$F_{cj} = 0.210\ Td_j\ (1+0.2X_j) \qquad [4.65]$$

where Td_j and X_j are,

$$Tdj = 1 + \frac{0.5}{1+\exp\left(\frac{D-60}{10}\right)} \qquad [4.66]$$

$$X_j = W_j + \frac{E_j}{1+2S_j} \qquad [4.67]$$

The sharpness of flare for leg j is,

$$S_j = \frac{1.6\left(E_j - W_j\right)}{I_j} \qquad [4.68]$$

then, F_{ej} is given by,

$$F_{ej} = 303\ X_j \qquad [4.69]$$

k_j depends on the entry angle and entry radius,

$$k_j = 1 - 0.00347(Eagd - 30) - 0.978\left(\frac{1}{Rave} - 0.05\right) \qquad [4.70]$$

4.5.2.2 Pedestrian Effect on Capacity

Heavy pedestrian flow significantly affects the entry capacity of each approach. Therefore, it is important for designer to consider pedestrians while deciding roundabout geometry to evaluate the entry capacity. The Federal Highway Administration (Robinson et. al. 2000) suggests in their design guide a reduction factor, M, for capacity analysis of each approach. This reduction factor can be calculated with known circulating flow (pcu/h) and pedestrian flow (ped/h) at each approach (Figure 2.2). In the optimization model the reduction factor is multiplied by the entry capacity of each approach to obtain the effective entry capacity, EEC_j,

$$EEC_j = EC_j\,(M_j)\;,\; j = 1,2,3,4 \qquad [4.71]$$

4.5.2.3 Entry Delay

The volume to capacity ratio is determined as,

$$VC_j = \frac{Qe_j}{EEC_j} \qquad [4.72]$$

The vehicles operating through the roundabout experience two types of delay: geometric delay and control delay. Geometric delay is the time it takes a vehicle to traverse the roundabout from the entry to the exit point (Todd 1979). Control delay is the time that a driver spends in queuing and then waiting for an acceptable gap in the circulating flow while at the front of the queue. The following formula for computing this delay (Akçelic and Troutbeck 1991) used to calculate control delay at each leg of roundabout,

$$De_j = \frac{3600}{EEC_j} + 900TP\left[VC_j - 1 + \sqrt{(VC_j - 1)^2 + \frac{\frac{3600VC_j}{EEC_j}}{450TP}}\right], j = 1,2,3,4 \qquad [4.73]$$

The total delay for all vehicles entering at each leg is calculated as,

$$TDe_j = De_j\, Qe_j\, ,\, j = 1,2,3,4 \qquad [4.74]$$

The average intersection delay is then given by,

$$ATID = \frac{\sum_{j=1}^{4} TDe_j}{\sum_{j=1}^{4} Qe_j} \qquad [4.75]$$

4.5.3 Objective Function

The objective function is defined as to minimize the mean of the speed difference of conflicting and consecutive speeds along each path of the roundabout (design consistency measure) and the average intersection delay (operational measure). That is,

$$\text{Minimize } Z = \lambda\, MD + (1 - \lambda)\, ATID \qquad [4.76]$$

where λ = weighting factor that ranges from 0 to 1. When λ equals 0, the objective function minimizes the average intersection delay. When λ equals 1, the objective function minimizes the mean of speed differences of conflicting and consecutive speeds along each path (or maximizes design consistency). For values of λ between 0 and 1, the objective function minimizes both consistency and operational measures according to the specified value of λ.

4.5.4 Constraints

The queue length at each leg may block traffic at the preceding intersection. Therefore, queue length is also an important operational performance check. The average queue length at each leg of roundabout is useful for comparing roundabout performance with other forms of intersections. Therefore, the average queue length is considered for planning purposes. For design purposes, the 95th percentile queue length (L_j) during the peak-hour time period is used. The FWHA Design Guide (Robinson et al. 2000), presents the following formula for calculating L_j,

$$L_j = \frac{EEC_j}{3600}(900TP)\left[VC_j - 1 + \sqrt{\left(1 - VC_j\right)^2 + \frac{\frac{3600VC_j}{EEC_j}}{150TP}}\right], j = 1,2,3,4 \qquad [4.77]$$

Equation 4.77 only holds for degree of saturation less than 0.85 (unsaturated conditions). If the queue blocks traffic at the preceding intersection, the designer can change roundabout geometry to reduce the degree of saturation and solve the blocking problem. A constraint is used to ensure that L_j is less than the maximum expected queue length based on site conditions to avoid blockage at the preceding intersection,

$$L_j \leq Lmax_j \qquad [4.78]$$

where $Lmax_j$ is the expected maximum queue length for each leg is an input traffic data. To ensure unsaturated conditions for a given roundabout design, a constraint in the optimization model is used to limit the degree of saturation (VC_j) to be less than the desired maximum, VC_{max},

$$VC_j \leq VC_{max} \qquad [4.79]$$

An optimization compiler can be used to run this model. LINGO version 8 is used for the application and analysis of this optimization model to design an actual roundabout. The optimization model consists of Equation 4.1 to 4.79.

The optimization model will provide the optimum design values of the following decision variables: entry widths for each leg, central island diameter, inscribed circle diameter, circulating width, average entry radius of each entry, entry angle, curve path radii for entry/exit and around the central island for each vehicle path (through, left, and right), safe negotiation speed at each curve path radius of each vehicle path, speed differences between consecutive and conflicting speeds, mean speed difference, degree of saturation and capacity of each entry, delay and queue length at each leg and maximum average intersection delay of the entire roundabout.

Although the optimization model provides the average entry radius, it is recommended that it should be drawn in AutoCAD with the help of three point arc command parallel to the path curves just after drawing all parameters given by the model. The tolerance between actual and average entry radius is expected to be 1-2.5 m. Finally, the splitter radius should be drawn parallel to the entry radius. This will complete the roundabout geometry, except the length of splitter. For pedestrian's protection and to alert drivers to the roundabout geometry, the minimum length of splitter should be 15 m (Robinson et al. 2000). Therefore, the length of splitter should be adjusted from 15 m to some maximum value according to site conditions. Roundabout design using the optimization model will be optimum for design consistency and delay.

In summary, the optimization model designs the roundabout for optimum design consistency and operational performance, subject to geometric and traffic constraints.

The user inputs traffic and geometric data ranges. Geometric data ranges include entry width of each approach, inscribed circle diameter, flaring length, and entry angle. The circulatory roadway width is constraint to the maximum entry width decided by the model. The central island diameter depends on the circulatory roadway width and inscribed circle diameter. The model will produce vehicle path radii of each path (left, through and right) based on the entry widths, inscribed circle diameter, circulatory roadway width and central island diameter.

The objective function is comprised of two measures: design consistency and average intersection delay. The design consistency is measured in terms of mean speed difference of consecutive and conflicting speeds. The model performs operational analysis for the average intersection delay and degree of saturation at each approach. In the operational analysis, the model calculates capacity, average delay, queue length, and degree of saturation at each approach. Thus, the model will check multiple objectives (design consistency and average intersection delay), while deciding the design parameters of the roundabout.

4.6 Application

4.6.1 Data Preparation

Roundabout design requires some preliminary study of site selection and then collecting geometric and traffic data. For the application of the optimization model, geometric data ranges are estimated from a satellite image of the proposed site using a GIS software (ArcView). The maximum limit of each parameter is estimated from the image while the minimum limit is defined based on the minimum requirement for the design of single-lane roundabout. The maximum inscribed circle diameter of the selected site is observed to be 40 m. The design vehicle also dictates the selection of the inscribed circle diameter to accommodate the turning path of design vehicle. The selected site was in urban environment. For urban single-lane roundabouts, the typical design vehicle expected to use the facility is WB-15 (WB-50). The minimum inscribed circle diameter for this design vehicle is 30 m (Table 3.3).

The maximum entry widths for approaches 1-4 are found to be 5, 5.5, 5 and 5.9 m respectively. The typical entry width for single-lane entrances is 4.3m (Robinson et. al. 2000). The circulating width depends on the entry width. It should be at least as wide as the maximum entry width and up to 120 percent of the maximum entry width. It should also remain constant throughout the roundabout. The model will decide the maximum entry width and the corresponding circulating width.

The central island affects the deflection of through vehicle's path. Its diameter entirely depends on the inscribed circle diameter and the circulatory roadway width. The model will decide the appropriate central diameter for given circulating width and inscribed circle diameter. The maximum design speed of the selected site is assumed to be 45 km/h. Traffic data, like percentage of heavy vehicles and average vehicle mass of the light and heavy vehicles, are also needed for the calculation of side friction factor.

For capacity and operational performance analysis, the conflicting circulating traffic flow rate, entry flow rate, and desired degree of saturation during peak hour for each leg are also required. As space is available for flaring, flaring is proposed in this application in order to increase the entry width for capacity improvement. The observed maximum flaring length for all legs 1-4 at the site was 40 m. The recommended minimum flaring length in urban areas is 25 m. The approach half width is 4.3 m for all approaches.

To ensure that there is no blockage at each entry, the maximum available queue length at the site from the satellite image was input to the model. The maximum desired average intersection delay is 9 sec. This constraint also improves the results of the optimization model. The design will be good and safe if the speed difference between conflicting and consecutive speeds is less than or equal to 20 km/h. Therefore, for design consistency, the speed difference is limited to 20 km/h. Superelevations for entry/exit path curves and path curves around the central island for each path are used as 0.02 and - 0.02 respectively. Fig. 4.11 shows how geometric data ranges are taken from the image of the site. The input geometric and traffic data ranges for each leg are shown in Table 4.1 and Table 4.2, respectively.

When the optimization model was formulated for given data, a total of 127 variables were generated, out of which 75 were nonlinear and 52 were linear. Total nonzero constraints were 352. LINGO version 8 was used to solve this optimization model for the design of the selected single-lane roundabout. LINGO performs iterations to decide the best decision variables, subject to given constraints and objective function. It takes a few seconds to perform thousands of iterations and provides the optimum solution.

Table: 4.1 Input Geometric Data Ranges

Leg No.	E_j (m)	lj (m)	Eagr (radian)
1	4.3-5	25-40	0.34-1.04
2	4.3-5.5	25-40	0.34-1.04
3	4.3-5	25-40	0.34-1.04
4	4.3-5.9	25-40	0.34-1.04

V_{max} = 45 km/h, MA = 20 km/h, and W_j = 4.3 m for all legs, and D = 30-40 m for the roundabout.

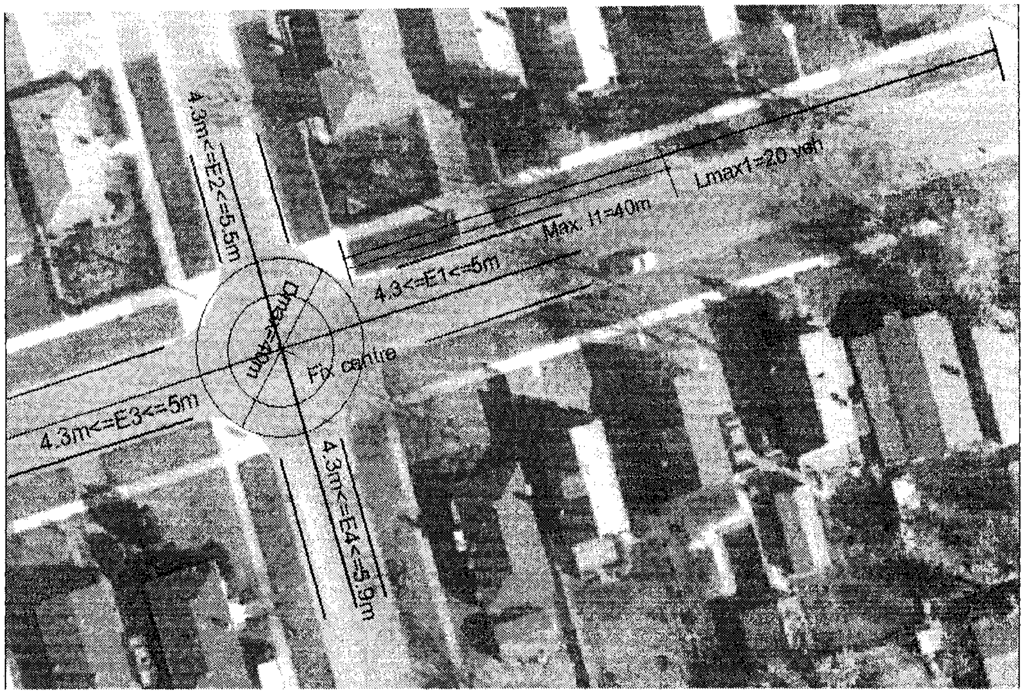


Figure 4.11: Input Geometric Data from Satellite Image

Table: 4.2 Input Traffic Data

Leg No.	Qe_j (pce/h)	Qc_j (pce/h)	PF_j (ped/h)	M_j	$Lmax_j$ (veh)	$Max.VC_j$
1	800	500	100	0.99	20	0.85
2	700	500	80	0.99	15	0.85
3	650	600	70	0.99	22	0.85
4	600	400	90	0.99	10	0.85

For all legs, PHV = 5 %, MvLV = 1400 kg, MvHV = 11,000 kg, Maximum ATID = 9 sec

4.6.2 Results of Optimization Model

The optimization model results vary with given geometric/traffic conditions and design requirements. The design requirements include design consistency and roundabout delay. As far as requirement for design consistency is enhanced, the operation of roundabout is affected. Therefore, a sensitivity analysis is required to find a balance between the optimum design for both design consistency and delay.

4.6.3 Sensitivity Analysis for Final Design

The multiple objective function of optimization model contains two measures; design consistency and delay. Both are important in the design of the roundabout. But in some situations, it is observed that a little compromise on design consistency can significantly improve the operation of the roundabout and vice versa. For good design, the speed difference of conflicting and consecutive speeds along each path is limited to 20 km/h. For good operation, the average intersection delay is limited to 7-9 sec. The sensitivity analysis constitutes increasing the maximum allowable speed difference (MA) gradually and decreasing the maximum allowable average roundabout delay (Max. ATID) gradually for the equal weight of design consistency and average roundabout delay (λ = 0.5). The results are compared and a best design is decided based on safety and operational performance requirements of the roundabout.

A sensitivity analysis was carried out to obtain the best design for the given input data (Tables 4.1 and 4.2). Two parameters Max. ATID and MA were changed gradually to compare the results of alternative design consistency and operational measures for the best design of roundabout. Table 4.3 presents different tested values of the parameters and their relative objectives ('ATID" and 'MD"). Tables 4.4 and 4.5 present the operational and geometric parameters obtained by the optimization model for each tested value. It should be pointed out that this sensitivity analysis is quite different from the manual iterative process because, it provides the optimum design for each design requirement.

Table 4.3: Test Values for Optimization Model and Objective Function Results

Option No	MA (km/h)	Max. ATID (sec)	λ	Weight for MD	Weight for ATID	V_{max} (km/h)	ATID (sec)	MD (km/h)
1	20	9	0.5	0.5	0.5	45	8.28	10.34
2	21	8	0.5	0.5	0.5	45	7.19	10.62
3	22	7	0.5	0.5	0.5	45	7	10.71
4	20	-	1	1	0	45	-	9.26
5	-	7	0	0	1	45	6.80	-

Table 4.4: Optimum Geometric Design Parameters for Test Values

Option No.	E_j (m)				D (m)	R_{CN} (m)	C (m)
	E_1	E_2	E_3	E_4			
1	4.65	4.65	4.65	4.65	40	15.35	4.65
2	4.94	4.94	4.94	4.94	40	15.05	4.94
3	5	5.04	5	5.04	40	14.95	5.04
4	4.3	4.3	4.3	4.3	30	10.70	4.3
5	5	5.39	5	5.39	40	14.61	5.39

Table 4.5: Optimum Operational Performance Measures for Test Values

Opt. No	De_j (sec/veh)				EECj (pce/h)				VCj				Lj (veh)			
	De_1	De_2	De_3	De_4	EEC_1	EEC_2	EEC_3	EEC_4	VC_1	VC_2	VC_3	VC_4	L_1	L_2	L_3	L_4
1	10.23	8.05	8.24	6	1139	1139	1079	1195	0.7	0.61	0.60	0.5	6.17	4.42	4.21	2.89
2	8.66	7.03	7.21	5.41	1205	1205	1143	1261	0.66	0.58	0.56	0.47	5.35	3.91	3.72	2.63
3	8.4	6.7	7.07	5.24	1215	1225	1153	1283	0.65	0.57	0.56	0.46	5.24	3.77	3.66	2.55
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	7.9	5.98	7.23	4.77	1235	1296	1180	1351	0.62	0.53	0.5	0.44	5	3.36	3.4	2.33

The first analysis was done for equal weights of design consistency and delay at a specified design speed of 45 km/h, MA = 20 km/h, and Max.ATID = 9 sec. Although design consistency was good (MD = 10.34 km/h), the operational performance was not good with respect to the average intersection delay of 8.28 sec. In order to improve the operation, the allowable maximum average roundabout delay (Max.ATID) was constraint to 8 sec but at the other hand the design consistency was compromised with an increase of maximum allowable speed difference, MD, to 21 km/h. The average delay dropped from 8.28 sec to 7.19 sec but the design consistency measure was slightly decreased with increasing the mean speed difference from 10.34 km/h to 10.62 km/h.

Another sensitivity analysis was done for the MA of 22 km/h and the Max.ATID of 7 sec to further improve the operation. The design consistency measure (MD) was increased to 10.71 km/h but operational performance measure (ATID) dropped to 7 sec. The average delay, degree of saturation, and 95th percentile queue length at each approach was decreased; while each entry capacity is also improved significantly. A little compromise in the speed difference significantly improved the operation of the roundabout.

After comparing operational performance measures of all sensitivity results, option 3 is considered to be the best optimum design of roundabout for the both design consistency and operational performance. The graphical comparison of operational performance measures for each approach of option 1 and 3 is presented in Figs. 4.12-4.15. When geometric parameters for option 1 and 3 are compared, the entry widths, inscribed circle diameter, and circulating width of option 3 are more than those of option 1. The maximum entry widths, circulating width and inscribed circle diameter are also useful to accommodate future traffic growth. Therefore, the comparison of geometric and operational performance parameters showed that the optimum design of option 3 is the best design of the single-lane roundabout considered in this application.

The last two tests were carried out, to see the individual behavior of the model for the design consistency and the operational performance, as a single objective of the model. Option 4 corresponds to $\lambda = 1$ and the option 5 corresponds to $\lambda = 0$. For the $\lambda = 1, 0$ means the model will design the roundabout only for the design consistency and the operation performance, respectively. The comparison of the geometric design parameters of option 4 and option 5 shows that the model chooses smaller circulating width, inscribed circle diameter, and entry widths to minimize not only the speeds but also the speed difference to improve design consistency and safety. For the operational performance measure, the model chooses larger entry widths, circulating width, and inscribed circle diameter to improve the operation. This proves the design philosophy of the roundabout.

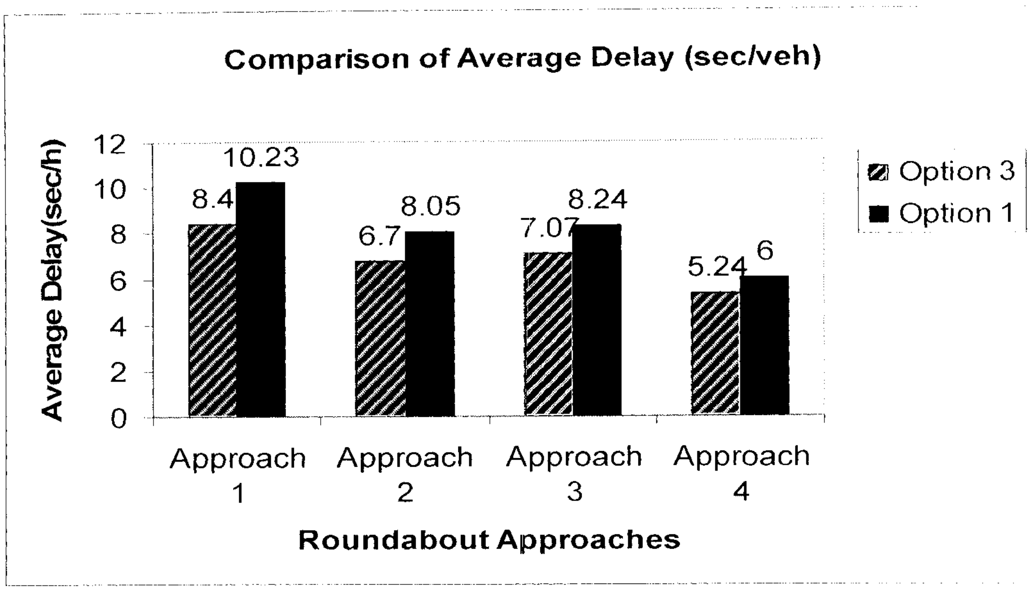


Figure 4.12: Comparison of Average Delay (sec/veh)

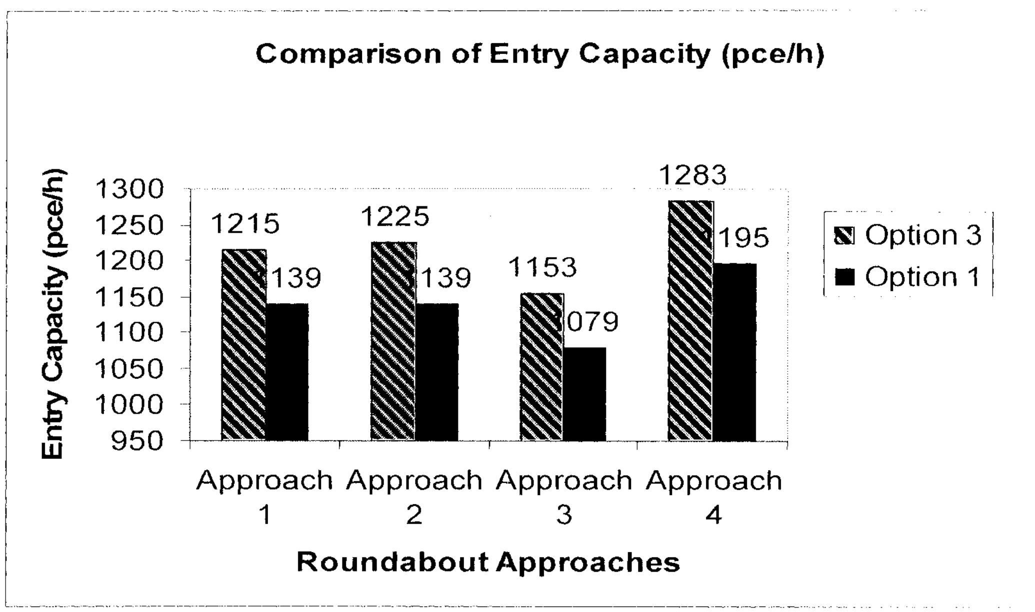


Figure 4.13: Comparison of Entry Capacity (pce/h)

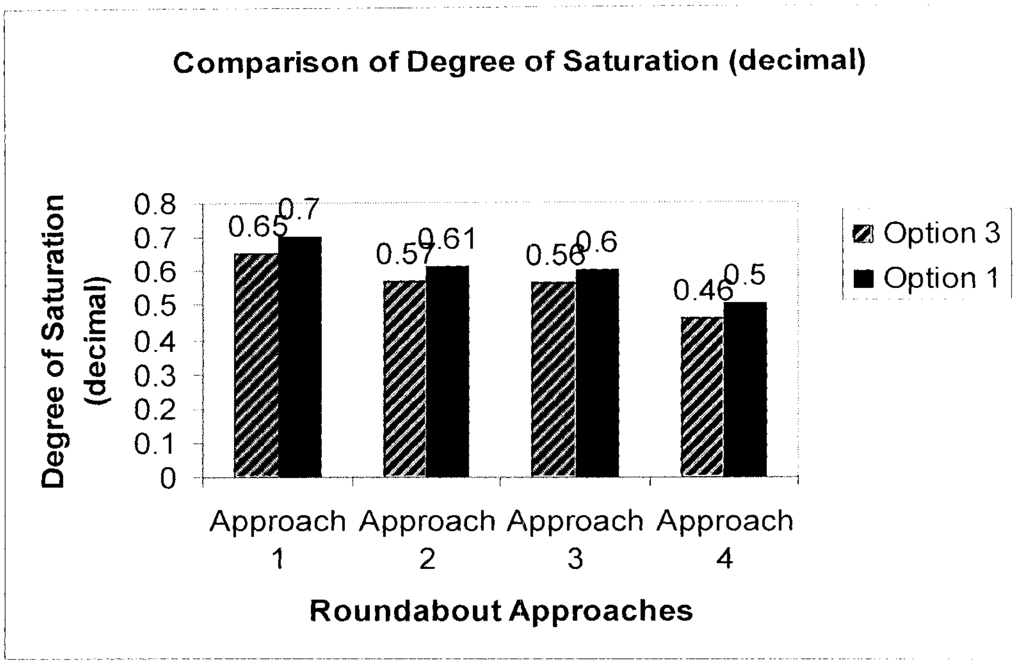


Figure 4.14: Comparison of Degree of Saturation (decimal)

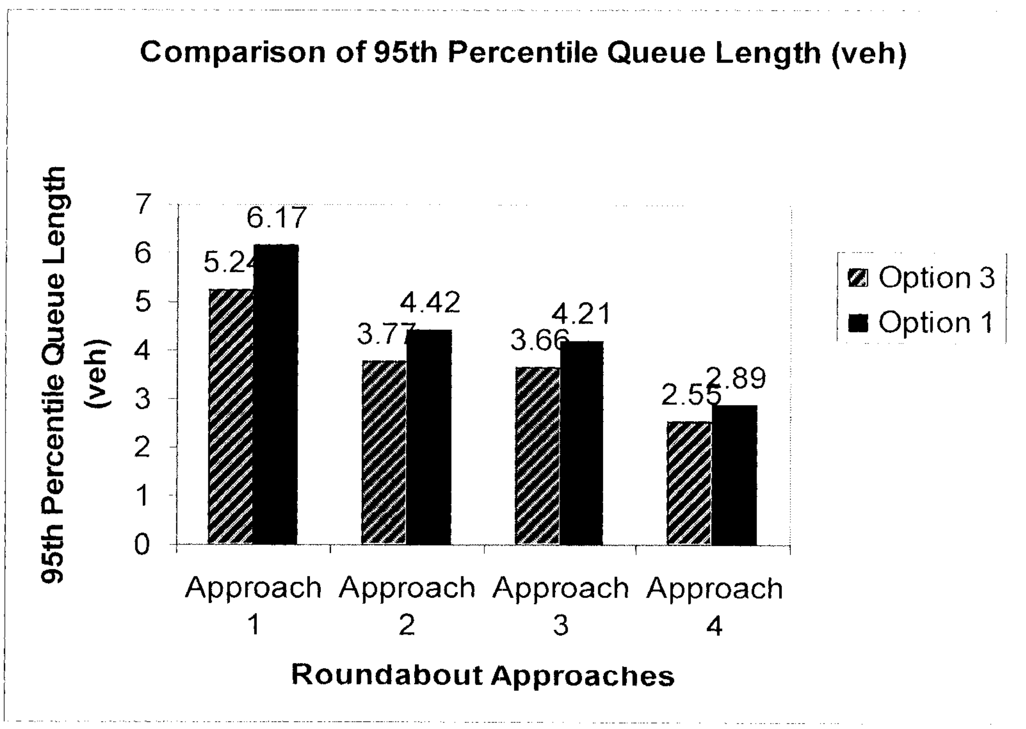


Figure 4.15: Comparison of 95th Percentile Queue Length (veh)

The vehicle path radii for each vehicle path (right, through, and left) are drawn in Fig. 4.16. The approach half width is 4.3 m, but the entry widths are 5 m, 5.04 m, 5 m, and 5.04 m of approaches 1-4 respectively, that result from the flaring of each approach. The inner entry curves (splitter curves) and outer entry curves are drawn parallel to the entry path curves while flaring is introduced from the point perpendicular to the intersection of inner entry curve and circulatory roadway to given approach half width (Fig. 4.17). The exit width is either taken equivalent to the circulating width or the entry width at the upstream approach, whichever is greater. The circulating width (5.04 m) is taken as the exit width for all legs as shown in Fig. 4.17.

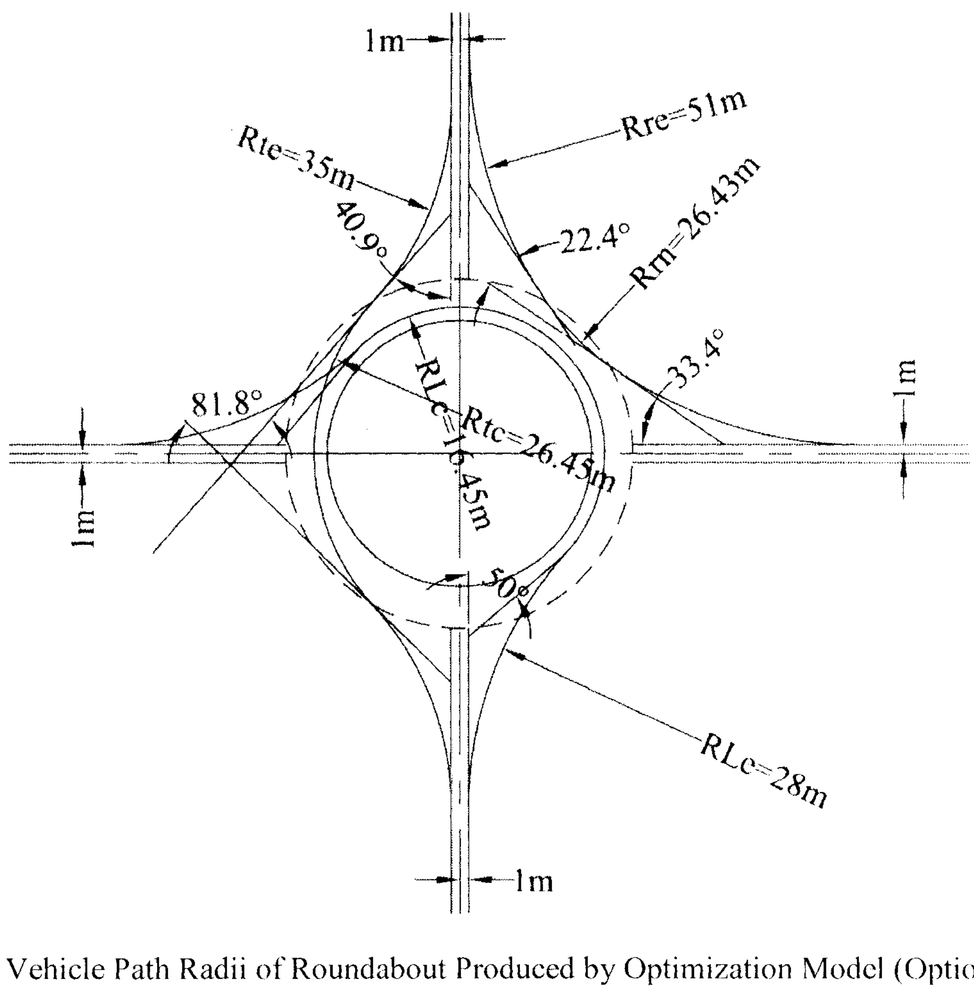


Figure 4.16: Vehicle Path Radii of Roundabout Produced by Optimization Model (Option 3)

As mentioned previously the actual entry radius, when drawn parallel to the entry path radii, varies by 1-2.5 m from the average entry radius (R_{ave}) as shown in Figs 4.16 and 4.17. The speed at each vehicle path is shown in Fig. 4.18. It is clear that the speed difference at the conflicting points and at consecutive points along each path is less than 22 km/h. The final optimum design parameters of single-lane roundabout for given data are shown in Fig. 4.19. This optimum design not only satisfies design consistency, but also operational performance.

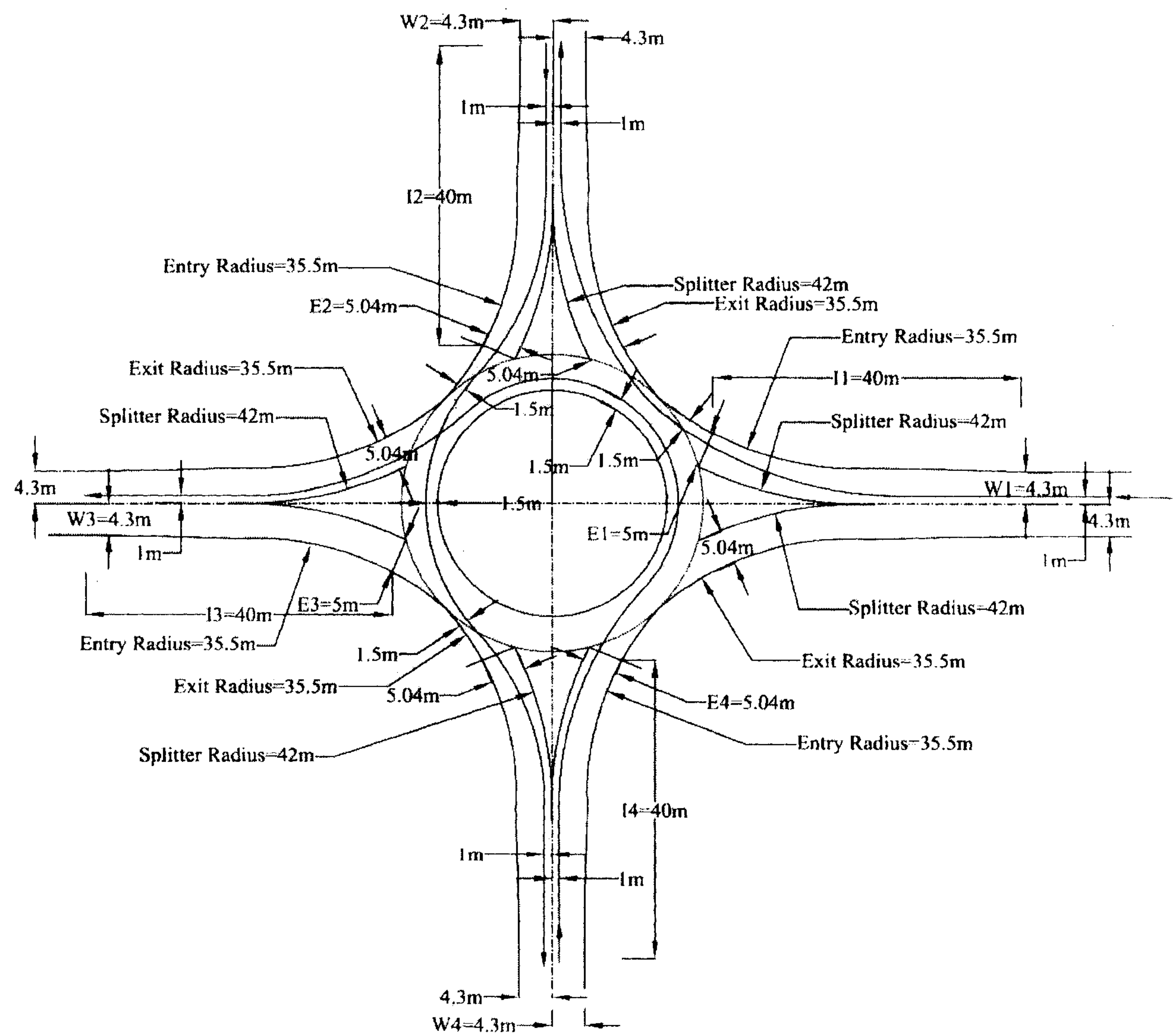


Figure 4.17: Entry/Exit Curves and Splitter Curves Produced by Optimization Model (Option 3)

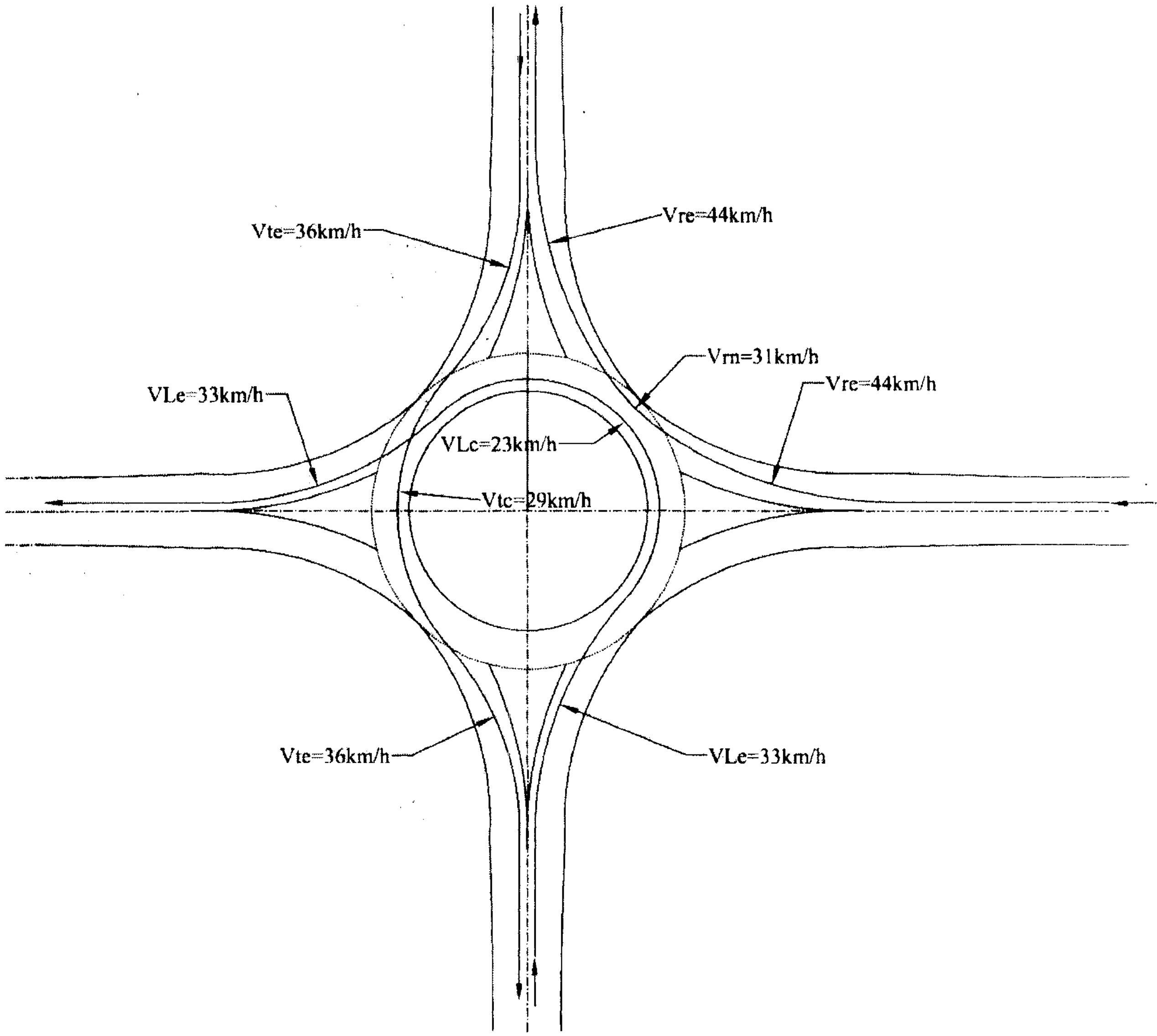


Figure 4.18: Vehicle Path Speeds Produced by Optimization Model (Option 3)

4.8 Summary

This chapter has presented existing design methodology, the complete modeling process of optimization model, and its application. The modeling process constitutes vehicle path modeling, design consistency measure, operational performance measure, and their integration. For application of the optimization model, input traffic and geometric data ranges for a proposed site were used to design a single-lane roundabout. A sensitivity analysis was also carried out to compare alternative optimum designs and select the best design of roundabout.

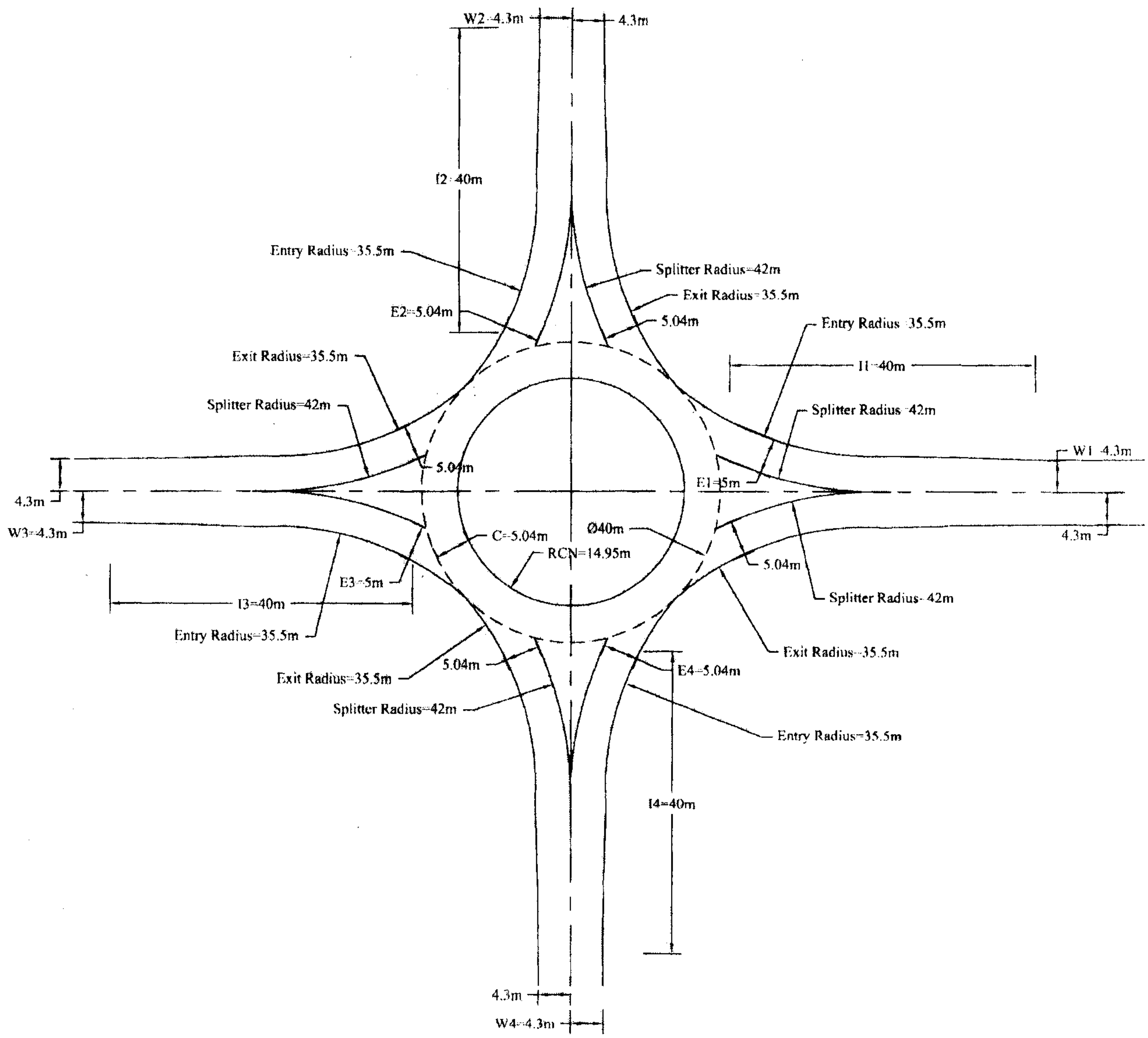


Figure 4.19: Final Optimum Design Parameters of Roundabout (Option 3)

Chapter 5

CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

Based on this research, the following conclusions are made:

1. Roundabout design is one of the most complicated designs in highway design. Its design is a tradeoff between capacity/delay and safety. Roundabout geometry impacts safety and operational performance in different ways. The optimization model developed in this study can be used to design roundabouts based on safety and operational performance. The user only needs to input the required traffic and geometric data of the selected site of roundabout. The mathematical programming used in this model is designed in such a way that all design parameters work together to find the optimum design. The value of one parameter cannot be changed without affecting the value of other parameters. The model decides the best design using given geometric and traffic data ranges. This is a valuable achievement in the design of roundabouts.
2. Roundabout geometry controls vehicle paths (right, left, and through). Traditionally, these vehicle paths are drawn by freehand on the proposed roundabout geometry. Vehicle path radii determine the speed along each vehicle path. Also, the designer needs to draw vehicle paths for the proposed roundabout geometry to check design consistency. In this study, vehicle path radii along each path are modeled in such a way that they not only depend on each other, but also on roundabout geometry. These vehicle path radii were used in the optimization model for automated design

consistency check. This eliminates the manual iterative process for design consistency check. The design consistency in the model is measured in terms of the difference between the speeds at each consecutive path radius and conflicting path radii. The speed difference in the model can be limited to the required consistency level. The relative speed difference at the roundabout is one of the important causes of vehicle accidents. The automated design consistency in the optimization model is a new approach that will help improve roundabout design.

3. The developed model provides details on queue length, average delay, and capacity at each approach of the roundabout, corresponding to the optimum solution. The pedestrian's effect on capacity is also taken into account. The significant parameters that effect capacity are entry width, entry radius, flare length, and entry angle. Out of these four parameters, entry angle, entry radius and entry width, also affect on vehicle paths at the same time. The model decides the optimum values of these parameters that satisfy design consistency and delay requirement. The delay depends on the degree of saturation. The average delay and queue length also depend on the degree of saturation. As the model minimizes average intersection delay, this will not only reduce the degree of saturation, but also balance the capacity of each leg. The model also considers the targeted average delay and queue length at each approach of roundabout. Thus, the model performs design consistency, operational performance, and geometric design simultaneously.
4. The sensitivity analysis of the optimization model helps compare alternative optimum designs for different weighing factors of the objective function. This analysis also has proven that the model is sensitive to roundabout geometry in the expected way. When

the weight of the operational performance measure is increased, the model produces larger entry widths, inscribed circle diameter, and circulating widths to improve the operation, while vehicle path speeds and their relative difference are increased. This is an indication of model validity.

5. Establishing geometric data ranges of roundabout from satellite images of the proposed site and expected traffic data from field to input to the model for optimum design is an innovative approach of roundabout design. If the same philosophy of design is applied to an existing single-lane roundabout, the model can help optimize the existing design subject to specified constraints.

5.2 Future Areas of Research

The proposed areas of future research for the extension of the optimization model are as follows:

1. Future extension of the model will be for skewed, double-lane and multi-lane roundabouts. This model along with future extensions will provide a complete software for the optimum design of roundabouts.
2. Geometric delays and environmental impact can be integrated in the model for cost analysis to compare roundabouts with other alternative intersection controls. Besides, bicycle, future projected traffic, and sight distance consideration can be taken into account in the design. This might require development of some new models to be used in the optimization model.
3. Safety models for different types of accidents at roundabouts are developed by different researchers. Although the developed optimization model takes into account

safety in terms of design consistency, these safety models can be integrated in the optimization model as an additional safety measure. This would require future research to differentiate between design consistency and safety models in terms of their effectiveness as safety measures for roundabouts.

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APPENDIX

NOTATION

ATID = Average intersection delay (sec)

C = Design circulatory width (m)

C_1 = Maximum entry width out of all four legs of roundabout (m)

D_{min} = Minimum diameter of Inscribed Circle available at site (m)

D_{max} = Maximum diameter of Inscribed Circle available at site (m)

D = Design diameter of Inscribed Circle of roundabout (m)

De_j = Average delay at leg j (sec/veh)

Ds = Distance between centre points of radius of through path curve at the central island from opposite legs (m)

$Emin_j$ = Minimum entry width of leg j of roundabout available at site (m)

$Emax_j$ = Maximum entry width of leg j of roundabout available at site (m)

E_j = Design entry width of leg j of roundabout (m)

EE_{max} = Expected maximum entry width based on design inscribed circle diameter (m)

Eagr = Entry angle (radian)

Eagd = Entry angle (degrees)

EC_j = Entry capacity at leg j (pce/h)

EEC_j = Effective entry capacity because of pedestrians at leg j (pce/h)

HLR_{tc} = Half long chord of through path curve at the central island (m)

HLR_{rn} = Half long chord of right-turn path curve within inscribed circle (m)

HLR_{rc} = Half long chord of right-turn path curve at entry/exit (m)

HLR_{tc} = Half long chord of through path curve at entry/exit (m)

HLR_{Lc} = Half long chord of left-turn path curve at entry/exit (m)

l_j = Effective flare length for leg j (m)

$lmin_j$ = Minimum available effective flare length for leg j (m)

$lmax_j$ = Maximum available effective flare length for leg j (m)

L_j = 95^{th} Percentile queue length at leg j (veh)

L_{tt} = Perpendicular distance from point of curvature of through path curve at the central island to centre of Roundabout (m)

L_t = Perpendicular distance from point of intersection of L_{tt} and long chord of through path curve at the central island to centre of Roundabout (m)

M_i = Difference between successive speeds and conflicting path speeds of roundabout (km/h)

M_{i+1} = Difference between successive speeds and conflicting path speeds of Roundabout (km/h)

M = Mid-ordinate of through path curve at the central island (m)

M_j = Reduction factor for entry capacity at leg j (0-1)

MA = Maximum allowable speed difference (km/h)

Max.ATID = Maximum allowable average intersection delay (sec)

Max. VC_j = Maximum allowable degree of saturation at leg j (in decimal)

MD = Mean speed difference (km/h)

MvLV = Average vehicle mass for light vehicles (kg)

MvHV = Average vehicle mass for heavy vehicles (kg)

PF_j = Pedestrian flow (ped/h)

PHV = Percentage of heavy vehicles at roundabout (in decimal)

Qc_j = Conflicting circulating flow at leg j (pce/h)

Qe_j = Entry flow rate at leg j (pce/h)

R_{ave} = Average entry radius for all legs (m)

R_{CN} = Design radius of the central island of roundabout (m)

R_E = Mid-ordinate of right-turn path curve within inscribed circle (m)

R_{Le} = Radius of left-turn path curve at entry/exit (m)

R_{Lc} = Radius of left-turn path curve at the central island (m)

R_P = Curve path radius (m)

R_{re} = Radius of right-turn path curve at entry/exit (m)

R_{te} = Radius of through path curve at entry/exit (m)

R_{rn} = Radius of right-turn path curve within inscribed circle (m)

Rtc = Radius of through path curve at the central island (m)

S_j = Sharpness of flare of leg j (m/m)

T = Distance between centre point of radius of through path curve at the central island and centre of roundabout (m)

TDe_j = Total delay at leg j (sec)

$TLre$ = Distance from PI to PC of right-turn path curve at entry/exit (m)

TL_{Le} = Distance from PI to PC of left-turn path curve at entry/exit (m)

TL_{te} = Distance from PI to PC of through path curve at entry/exit (m)

TP = Analysis time period, hr (TP = 0.25 hr for a 15-minute period)

V_{te} = Operating Speed at of through path curve at entry/exit (km/h)

V_{Lc} = Operating Speed at left-turn path curve at the central island (km/h)

V_P = Operating Speed at curve path radius (km/h)

V_{Le} = Operating Speed at left-turn path curve at entry/exit (km/h)

V_{re} = Operating Speed at right-turn path curve at entry/exit (km/h)

V_{rn} = Operating Speed at right-turn path curve within inscribed circle (km/h)

V_{max} = Maximum design speed of roundabout (km/h)

V_{tc} = Operating speed of through path curve at the central island (km/h)

VC_j = Degree of saturation at leg j (decimal)

W_j = Approach half width for leg j (m)

Δ_{re} = Deflection angle of right-turn path curve at entry/exit (radian)

Δ_{Le} = Deflection angle of left-turn path curve at entry/exit (radian)

Δ_{te} = Deflection angle of through path curve at entry/exit (radian)

Δ_{rn} = Deflection angle of right-turn path curve within inscribed circle (radian)

Δ_{tc} = Deflection angle of through path curve at the central island (radian)

β = Angle between radius of through path curve at central island and Ds (radian)

λ = Weight for average intersection delay and design consistency in objective function (0-1)