ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

CAPACITY ANALYSIS ON MULTI-LANE ROUNDABOUTS: AN EVALUATION WITH HCM2010 CAPACITY MODEL

M.Sc. THESIS

Melike ERSOY

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ÇOK ŞERİTLİ DÖNER KAVŞAKLARIN KAPASİTE ANALİZLERİ: HCM 2010 ÜZERİNE BİR DEĞERLENDİRME

YÜKSEK LİSANS TEZİ

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Tez Danışmanı: Doç. Dr. Hilmi Berk ÇELİKOĞLU

Haziran 2012

Melike Ersoy, a **M.Sc.** student of ITU **Institute of Science and Technology** student ID 501081413, successfully defended the thesis entitled "**CAPACITY ANALYSIS ON MULTI-LANE ROUNDABOUTS: AN EVALUATION WITH HCM 2010 CAPACITY MODEL"**, which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assoc. Prof. Hilmi Berk Çelikoğlu** ....
İstanbul Technical University

Jury Members : **Prof. Dr. Ergun GEDİZLİOĞLU** ....
İstanbul Technical University

Assoc. Prof. Serhan TANYEL ....
Dokuz Eylül University

Date of Submission : 04-05-2012

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To my beloved Dad,

FOREWORD

I would like to express my gratitude to people who supported me in the completion of this Thesis. In addition to my believes in being patient and hard working, this assignment gave me strong analytical abilities.

I would like to thank my advisor, Assoc.Prof. Hilmi Berk ÇELİKOĞLU for all his advice and continuous support throughout my thesis work.

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June 2012 Melike ERSOY

(Civil Engineer)

TABLE OF CONTENTS

Page

ABBREVIATIONS

AASHTO **:**American Association of State Highway and Transportation Officials'

FHWA **:** Federal Highway Administration

HCM **:** Highway Capacity Manual

HDM **:** Highway Design Manual

KGM **:**Turkish General Directorate of Highways (Karayolları Genel Müdürlüğü)

LOS **:** Level of Service

TRL **:** Transport Research Laboratory

TRRL **:** Transport and Road Research Laboratory

LIST OF TABLES

LIST OF FIGURES

Page

CAPACITY ANALYSIS ON MULTI-LANE ROUNDABOUTS: AN EVALUATION WITH HCM 2010 CAPACITY MODEL

SUMMARY

In this study, widely accepted capacity estimation models are investigated for applicability of two roundabouts in Turkey and results are compared with the new methodology of HCM 2010. Methods are evaluated sourcing local data obtained from roundabouts. The Transport Research Laboratory formula for regression and Australian formula for gap acceptance method are considered in comparison with HCM 2010. Calibrated models for gap acceptance and HCM 2010 are also included into study.

Additionally, the sensitivity of HCM 2010 capacity estimates to variations in follow up headways and critical gap are analyzed. Critical gap and follow up time parameters are alternated between maximum and minimum headway intervals within the sensitivity analysis.

As a result, it is seen that gap acceptance and regression models generally gave higher capacity estimation values than HCM2010 default value formulation. Especially for high circulating volumes gap acceptance methodology is found to be more applicable than HCM2010 default value estimations and regression analysis. It is also seen that, lower capacity estimate of HCM2010 under high traffic volume could be regenerated by using calibrated formulations.

ÇOK ŞERİTLİ DÖNEL KAVŞAKLARIN KAPASİTE ANALİZLERİ: HCM 2010 ÜZERİNE BİR DEĞERLENDİRME

ÖZET

Ülkemizde yük ve yolcu taşımacılığı büyük oranda karayolu ulaşımı ile sağlanmaktadır. Nüfus artışı beraberinde trafiğe çıkan araç sayısını da arttırmış olup, talebin en yoğun olduğu kent içi trafiği üzerinde olumsuz etkiler yaratmıştır. Olumsuz etkilerin en başında trafik kazaları ve yetersiz yol kapasiteleri gelmektedir. Doğru tasarım ve düzenlemeler altında, güvenlik ve kapasite üzerinde iyileştirici etkileri olan modern dönel kavşak uygulamaları, Avrupa ve Amerika'dan sonra Türkiye'de de kent içi trafik yönetiminde, öncelik kontrollü ve sinyalize kavşak tasarımlarına alternatif olarak kullanılmaya başlanmıştır.

Dönel kavşakları, trafik çemberi, öncelik kontrollü ve sinyalize kavşak tiplerinden ayıran en önemli özellik girişte yol verme ve trafik akışında defleksiyon hareketleridir. Yaklaşım yolundan kavşağa giriş yapacak araçların kavşakta bulunan dönen akım içerisindeki araçlara yol vermesi gerekliliği ve merkez adanın konumu ile kontrol edilen aracın kavşağı geçiş hızının düşürülmesi dönel kavşaklarda güvenliği arttıran en önemli unsurlardır. Yaklaşım kolunda ki aracın hızının düşürülmesi sayesinde hem araç araca olabilecek hem de araç yaya arasında olabilecek kazaların olasılığı azaltılır.

Yolun belirli bir şeridinden veya kesiminden birim zamanda geçebilecek maksimum araç sayısı olarak tanımlanan yol kapasitesi, kavşaklarda yaklaşım kollarından kavşağa girebilecek birim zamanda ki maksimum araç sayısı olarak çalışılmıştır. Dönel kavşaklarda kapasitenin belirlenmesinde araç boyutları ve araçların bir noktadan geçiş süreleri büyük önem arz etmektedir. Kavşakların geometrik tasarımlarında, sürücülerin kavşağa güvenli giriş yapabilmesi ve diğer sürücülerle yayaların hareketlerini gözlemleyebilmeleri için projelendirme esnasında kavşağa ait bir takım geometrik özellikler göz önünde bulundurulur. Orta ada çapı, giriş ve çıkış şeritleri, dönüş şeridi ve sayısı, yaklaşım genişliği, giriş genişliği ve giriş şeridi sayısı, ayırıcı ada, proje tip aracı ve hızı göz önünde bulundurulması gereken geometrik tasarım elemanlarıdır. Yaklaşım kolunun geometrik özellikleri ve kavşak giriş şerit sayısı ve genişliği taşıtların kavşağa giriş hızlarını doğrudan etkiler. Orta ada yarıçapının boyutları taşıt güzergâhını etkilediğinden dönene akım içerisindeki araçların seyahat hızlarını belirleyici rol oynar. Orta ada yarıçapı arttıkça seyahat hızı artar. Ana akım içerisinde ki ağır araç oranı arttıkça, kavşağa giriş çapı ve dairesel görüş uzunluğu azaldıkça kavşak kapasitesi azalır.

Güvenlik ve kapasite üzerindeki olumlu etkileri sebebiyle dönel kavşaklar birçok ülkede mercek altına alınmış ve performans analizleri yapılmıştır. Analiz yöntemleri ülkeden ülkeye parametreler ve uygulama alanları bazında farklılıklar göstermektedir. Almanya ve İsviçre'de dönel kavşakların giriş kapasitelerinin tahmini için kullanılan Brilon&Bovy formülü kavşaktaki dönüş şeridi sayısını ve yaklaşım kollarındaki giriş şeridi sayısını göz önünde bulundururken İngiliz

yönteminde dönel kavşağın detaylı geometrik özellikleri giriş kapasitesini belirlemede etkin parametreler olarak değerlendirilir. Geometrik özellikler ve şerit sayılarına ilaveten sürücü davranış özellikleri, kritik takip aralığı ve kavşağa giriş için kritik boşluk kabulleri de Fransa, Amerika ve Almanya da kavşağın giriş kapasitesini analiz etmek için geliştirilen formüllerde göz önünde bulundurulmuştur.

Kapasite analiz modelleri için kritik aralık kabulü ve regresyon analizi olmak üzere iki esas yöntemden bahsetmek mümkündür. Regresyon analizi gözlemler sonucunda elde edilmiş veri grupları üzerine kurulan kavşağın geometrik özellikleri ile bağıntılı lineer yahut üstel formüler içerir. Kritik aralık kabul yönteminin esası ise yaklaşım kolundan gelen aracın kavşağa giriş yapabilmesi için zaman cinsinden kritik boşluğa sahip olması gerektiğidir.

Amerikan karayolları standardı The Highway Capacity Manual (HCM) 2010, Amerika'da incelenen birçok kavşaktan elde edilen veriler ışığında, kritik aralık kabul yöntemi ve regresyon analizi yöntemlerinin ikisini de bünyesinde barındıran yeni bir yöntem geliştirmiştir. HCM 2010 kapasiteyi sağ ve sol şeritler olmak üzere şerit bazında incelemiş ayrıca formülü dönüş şerit sayısı ve giriş şerit sayısı birden fazla dönel kavşaklar içinde tanımlamıştır.

Bu çalışmada, Amerika'da ve Avrupa'da birçok ülke tarafından kabul görmüş çok şeritli dönel kavşak kapasite hesap yöntemlerinin Türkiye'de uygulanabilirliği, yeni HCM 2010 yöntemiyle karşılaştırılmıştır. Yöntemlerden elde edilen sonuçlar İzmir'de bulunan Montrö ve Lozan dönel kavşaklarından toplanan verilerin ışığında değerlendirilmiştir. Her iki kavşakta da bir yaklaşım kolu incelenmiş olup, yaklaşımlarda ki giriş şerit sayısı iki, dönen akım şerit sayısı üçtür. Veriler kavşak yakınlarına yerleştirilmiş kameralar sayesinde toplanmış 1'er dakikalık Montrö kavşağı için 45 dakika ve Lozan kavşağı için 46 dakika olan gruplar halinde ele alınmıştır.

Karşılaştırma için regresyon analiz yöntemini temsilen İngiliz modeli içerisindeki TRL formülü kullanılmış olup kavşak geometrilerine bağlı parametreler belirleyici unsur olmuştur. Kritik aralık kabulü yöntemini temsilen Avusturya Hesap Yöntemi seçilmiş olup kavşak giriş kapasitesi baskın ve baskın olmayan iki şerit bazında hesaplanarak toplam kapasite elde edilmiştir. Bunlara ek olarak, sınırlı öncelik ve ters öncelik koşullarının göz önünde bulundurulduğu kalibre edilmiş kritik aralık yöntemi ve HCM 2010 da yerel uygulamalar için öngörülen kalibre edilmiş formüller ile hesaplamalar yapılmış ve HCM nin olağan değerleriyle karşılaştırılmıştır.

HCM 2010'un daha detaylı incelenmesi adına, formülasyonda kullanılan kritik aralık ve takip aralığı değerleri üzerinde hassasiyet analizleri yapılmıştır. Hassasiyet analizlerinde, kritik aralık ve takip aralığı değerleri maksimum ve minimum sınırlarlar içerisinde değişken tutulmuş ve hesaplanan giriş kapasitesinin davranışı incelenmiştir.

Çalışmanın sonucunda elde edilen veriler, kritik aralık kabul yöntemi ve regresyon yönteminin HCM 2010 olağan değerlerine kıyasla genellikle daha yüksek sonuçlar verdiğini göstermiştir. Yöntemler arasında yapılan regresyon analizleri sonucu, özellikle yüksek dönen akımlarımlar altında kritik aralık kabul yönteminin HCM 2010 yönteminden daha uygun sonuçlar verdiği gözlemlenmiştir. Ancak HCM 2010 da yerel uygulamalar için kalibrasyon yapılmasını sağlayan formülasyon sonucunda elde edilen veriler, olağan formülasyonun verdiği düşük kapasite tahminlerini daha uygun değerlere yükseltmiştir

Kritik aralık ve takip aralığı parametrelerinin HCM 2010 modeli üzerinde ki hassasiyet analizleri sonucunda modelin kritik takip aralığı değerine daha duyarlı olduğu görülmüştür. Daha küçük takip aralığı ve kritik aralık kabulleri yapıldığında daha yüksek kapasite değerlerine ulaşılmıştır.

İncelenen analiz yöntemlerinden gözlenen verilere daha yakın sonuçlar elde edilebilmesi için ters öncelik ve sınırlı öncelik koşullarının da hesaplamalarda göz önünde bulundurulması ve formüllerin yerel sürücü davranışlarına göre kalibre edilmesi gerekmektedir. Ayrıca incelenen modellerde çıkış şeritlerinin giriş kapasitesi üzerindeki etkileri göz ardı edilmiş kavşakların birer kolu çalışmada incelenmiştir. Daha gerçekçi kapasite tahminleri elde etmek adına dönel kavşaklar tüm kollarıyla bir sistem halinde incelenebilir.

1. INTRODUCTION

1.1 Motivation

In recent years, modern roundabouts have become one of the frequently preferred intersection types. Deflection on trajectory of approaching vehicles and yielding the right of way to the circulating traffic by these vehicles are the fundamental characteristics that differentiate roundabouts from other intersection types and increase the level of safety in such a conflict area. A well designed roundabout should meet the overall conflicting demand and suffice to safe movement of all vehicle types those are defined in user category.

As success of roundabouts has spread out from Europe to USA, different capacity and performance analysis methods have evolved. The Highway Capacity Manual (HCM) 2010 brings forward a new methodology for evaluating roundabout performance. The new method in HCM2010 presents a lane based capacity model with the combination of a simple lane based regression and gap acceptance models for both single and double lane roundabouts.

In this study, in the purpose of investigating the performance of new HCM2010 method, capacity estimations with the incorporation of HCM2010 method are evaluated sourcing local data obtained from several roundabouts in Izmir, Turkey.

1.2 Scope of the Thesis

The performance evaluation of new HCM2010 method is sought in comparison to some common capacity analysis approaches. Parameter based sensitivity analysis on calculations with the new HCM formula and a comparative evaluation of the new methodology with two most common capacity analysis methods, i.e., the method of critical gap acceptance and the method of regression analysis, are performed.

Maximum and minimum headway intervals of follow up time and critical gap parameters are alternated within the sensitivity analysis. The Transport Research Laboratory formula for regression and Australian formula for gap acceptance method are considered in comparison. Relative comparisons of predictions on capacity by HCM2010 method, regression analysis and gap acceptance method are presented considering field data obtained by observations at two roundabouts in Izmir, Turkey.

The computations carried out within the study enable researchers to assess the appropriateness of the HCM2010 method in capacity estimation/reconstruction procedures, especially in terms of flow-rates at roundabout entrances. The sensitivity of capacity estimates to variations in follow up headways and critical gap are analyzed.

1.3 Thesis Organization

The organization of this Master thesis started with Chapter 2 Modern Roundabouts and Geometric Design. Primary characteristics and parameters of modern roundabouts are explained under Principles in Roundabout Design and Geometric Design Elements of Roundabouts titles. In Chapter 3 Capacity and Operational Performance of Multi-lane Roundabouts are presented. Definition of basic stream parameters, literature review on two main capacity estimation models, regression and gap acceptance, and presentation of entry capacity estimation methods used by different countries are made.

In Chapter 4, the capacity estimation methods used in evaluations those were introduced in Chapter 3 are sourced. Capacity estimations of models are tested for compliance with the observed data collected from two roundabouts and comparison of each method with HCM 2010 model are made. Discussions on conducted capacity analysis are also presented in the following title.

In Chapter 5 a reflection of what has been achieved during this study is given with an overview of future research and suggestions.

2. MODERN ROUNDABOUTS AND GEOMETRIC DESIGN

A modern roundabout is a type of intersection design that controls and diverts traffic flow around a central island. Roundabouts are differentiated from other traffic circles in traffic control, pedestrian access, parking and direction of circulation features.

The primary characteristic of a modern roundabout include "yield at the entry" rule to all entering approaches which requires entering traffic to give way or yield to vehicles within the circulatory roadway. According to this rule approaching vehicles must wait for a gap in the circulating flow before entering the circle therefore circular traffic is preserved against congestion. Turkish General Directorate of Highways also defines yield at the entry rule for roundabouts in Highway Traffic Code 2918 with Article 57, (KGM, 1983). Yield at the entry and roundabout approach signs are shown in the Figures 2.1 and Figure 2.2 respectively.

Figure 2.1 : Yield at the entry sign.

Figure 2.2 : Roundabout approach sign in Turkey.

Contrary to some large traffic circles, modern roundabouts do not provide straight paths for transit passes with high speeds. Location of the central island controls the entry speed of vehicles with manner of deflection move shown in Figure 2.3 (SweROAD, 2000).

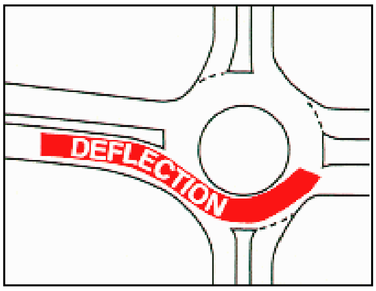

Figure 2.3 : Deflection Move (SweROAD,2000).

In addition to "yield at the entry" and deflection movement there are several characteristics those differ roundabouts from other intersection types. In contrast to some traffic circles, pedestrian are not allowed to cross the circle and access the central islands. Parking and stopping are also not allowed within the roundabout or at entries.

2.1 Roundabout Geometric Design

In this chapter, principles in roundabout design are presented under design speed, design vehicle, non-motorized design users, alignment of approaches and entries titles. Additionally, inscribed circle diameter, entry width, circulatory roadway, central island, entry curves, exit curves, issues relevant to pedestrians, splitter island, stopping sight distance are defined under geometric design elements of roundabouts title.

2.1.1 Principles in roundabout design

A well designed roundabout ensures safety for all types of vehicles those defined in user category. Layout of the roundabout reduces vehicle speed and keeps circulating vehicles in low speed through the roundabout. Available sight distances for entering vehicles are also obtained from roundabout geometry to observe vehicles in conflicting flow and movements of non-motorized users.

Before defining detailed roundabout geometry, three fundamental elements must be determined in the preliminary design stage: The optimal roundabout size, position, alignment and arrangement of approach leg (FHWA, 2000). Design parameters those used to determine size, position and layout are defined in the following parts in the following; design speed, design vehicle, non-motorized design users, alignment of approaches and entries titles.

2.1.1.1 Design speed

Considering the safety aspects, the most critical design objective is achieving appropriate vehicular speeds through 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 (FHWA, 2000). However, at multilane roundabouts, increasing vehicle path curvature creates greater side friction between adjacent traffic streams and can result in more vehicles crossing across lanes and higher potential for sideswipe crashes.

Recommended maximum entry design speeds from US Department of Transportation (2001), for roundabouts at various intersection site categories are shown in the Table 2.1.

Table 2.1 : Entry Design Speeds of Roundabouts (AASHTO, 2001).

SITE CATEGORY	***ENTRY DESIGN SPEED***
Mini-Roundabout	25 km/h
Urban Compact	25 km/h
Urban Single Lane	35 km/h
Urban Double Lane	40 km/h
Rural Single Lane	40 km/h
Rural Double Lane	50 km/h

The fastest path allowed by the geometry determines the speed of a roundabout. Generally, fastest path is the smoothest, least-curved path that can be followed by a single vehicles allowing passes through the entry, around the central island then exit ignoring all lane markings. Usually the fastest possible path is the through movement, but in some cases it may be a right turn movement shown in Figure 2.4 (AASHTO, 2001).

The design speed of the roundabout is assigned by the smallest radius along the fastest allowable path. The smallest radius usually occurs on the circulatory roadway as the vehicle turnes to the left around the central island as shown in Figure 2.4.

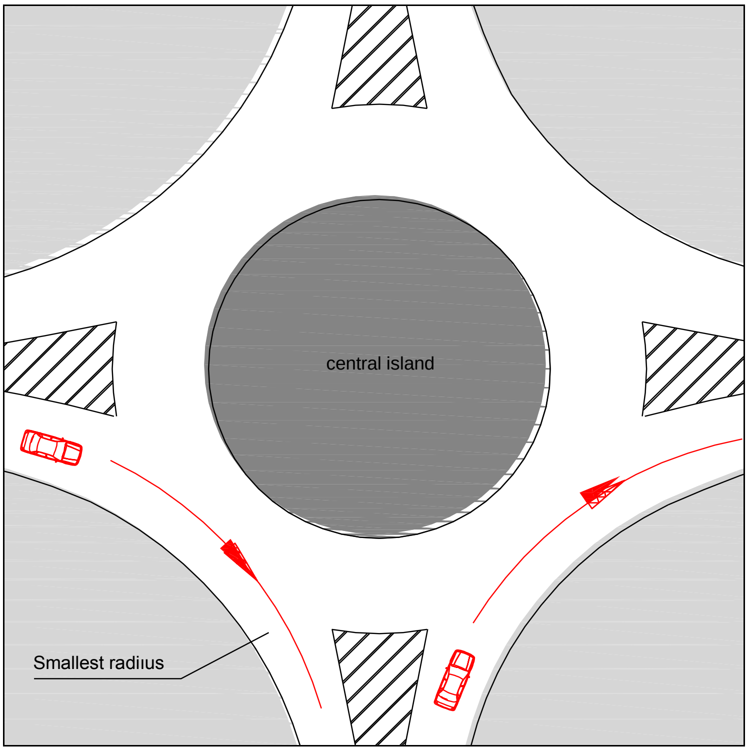

Figure 2.4 : Smallest Radius.

The relationship between travel speed and horizontal curvature is given with Equation **2.1**. by American Association of State Highway and Transportation Officials' (AASHTO, 2001).

$$V = \sqrt{127 \cdot R \cdot (e + f)} \qquad \textbf{(2.1)}$$

Where; 'V' is design speed in km/h, 'R' is radius in m, 'e' is upper elevation and 'f' is side friction factor. Super elevation values are taken as +0.02 for entry and exit curves; -0.02 for curves around the central island in general.

Values for side friction factor can be determined in accordance with the AASHTO relation for curves at intersections as given in Figure 2.5.

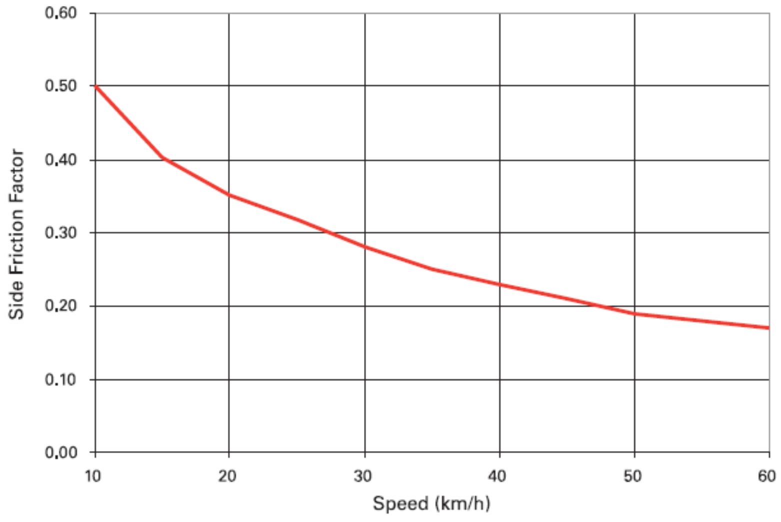

Figure 2.5 : Side Friction Factor (AASHTO, 2001).

2.1.1.2 Design vehicle

Roundabout geometry should give accessibility both for the type of vehicles normally use the roundabout and special vehicles. The smallest turning path layout should accommodate with the longest design vehicle defined for the roundabout user vehicle category. Basic Swedish design vehicles are shown in Figure 2.6 and Figure 2.7.

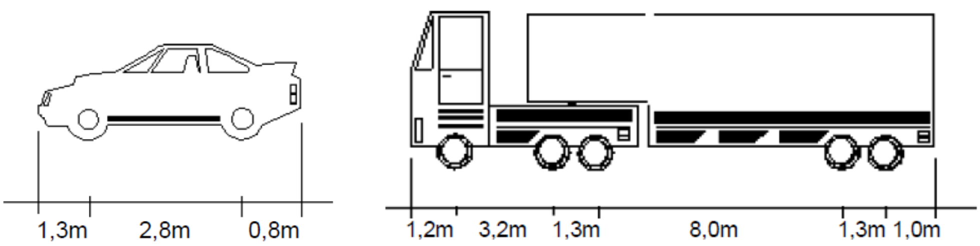

Figure 2.6 : Passenger car, 5m, and Semi trailer, 16m (SNRA, 1994).

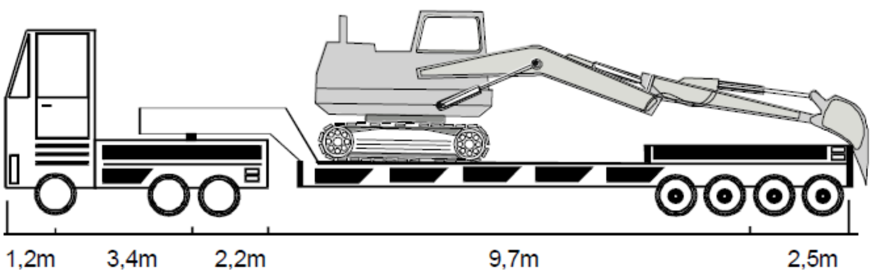

Figure 2.7 : Special Trailer, Total length 19 m (SNRA, 1994).

In Turkey design vehicles are defined for 9 categories according to maximum allowable lengths shown in Table 2.2 (Karayolları Trafik Yönetmeliği, 1997).

Table 2.2: Maximum Length for Design Vehicles (Trafik Yönetmeliği, 1997).

MAXIMUM LENGTH (m)	
Vehicles except buses	12
Trailer	12
2 Axle Buses	13,50
Buses with more than 2 Axle	15
Semi-Trailers	16,50
Articulated Buses	18,75
Trailer-Busses	18,75
Trailer-Trucks	18,75
Vehicle Combinations with Two Trailers	22

The AASHTO A Policy on Geometric Design of Highways and Streets defines 19 design vehicle dimensions and turning path requirements. Design vehicle dimensions in AASHTO, 2001, are shown in Table 2.2. WB-15 (WB-50) vehicles are the largest vehicles in collectors and arterials. Larger trucks, such as WB-20 (WB-67) vehicles generally chosen in freeways or highway systems and smaller design vehicles are usually chosen for local street intersections.

Table 2.3 : Design Vehicle Dimensions (AASHTO, 2001)

		OVERALL DIMENSION		
Design Vehicle Type	***Symbol***	***Height***	***Width***	***Length***
Passenger Car	P	1,3	2,1	5,8
Single Unit Truck	SU	3,4-4,1	2,4	9,2
Busses				
Inter-city Bus (Motor Coaches)	BUS-12	3,7	2,6	12,2
	BUS-14	3,7	2,6	13,7
City Transit Bus	CITY-BUS	3,2	2,6	12,2
Conventional School Bus	S-BUS 11	3,2	2,4	10,9
Large School Bus	S-BUS12	3,2	2,4	12,2
Trucks				
Intermediate Semitrailer	WB-12	4,1	2,4	13,9
Intermediate Semitrailer	WB-15	4,1	2,6	16,8
Interstate Semitrailer	WB-19	4,1	2,6	20,9
Interstate Semitrailer	WB-20	4,1	2,6	22,4
“Double-Bottom”-Semitrailer/Trailer	WB-20D	4,1	2,6	22,4
Triple-Semitrailer/Trailers	WB-30T	4,1	2,6	32
Tumpike Double-Semitrailer/Trailer	WB-33D	4,1	2,6	34,8
Recreational Vehicles				
Motor Home	MH	3,7	2,4	9,2
Car and Camper Trailer	P/T	3,1	2,4	14,8
Car and Boat Trailer	P/B	-	2,4	12,8
Motor Home and Boat Trailer	MH/B	3,7	2,4	16,2
Farm Tractor	TR	3,1	2,4-3,1	4,9

2.1.1.3 Non-motorized design users

The design criteria of non- motorized potential roundabout users (pedestrians, bicyclists wheelchair users etc.) should be considered during the development of the geometric elements of a roundabout design. The basic design dimensions defined by the US department of Transportation for various design users are given in Table 2.3 (FHWA, 2000).

Table 2.4 : Non motorized User Design Dimensions (FHWA, 2000).

USER		***DIMENSION***	***AFFECTED ROUNDABOUT FEATURES***
Bicycles	Length Minimum operating width Lateral clearance on each side	1.8 m 1.5 m 0.6 m	Splitter island width at crosswalk Bike lane width Shared bicycle-pedestrian path width
Pedestrian	Width	0.5m	Sidewalk width, crosswalk width
Wheelchair	Minimum width Operating width	0.75 m 0.90 m	Sidewalk width, crosswalk width Sidewalk width, crosswalk width

2.1.1.4 Alignment of approaches and entries

In order to maintain vehicles pass in slow speeds through both entrance and exit, the centerlines of all approaching legs are preferred to pass through the center of the inscribed diameter. Figure 2.7 shows both preferred and not preferred alignment.

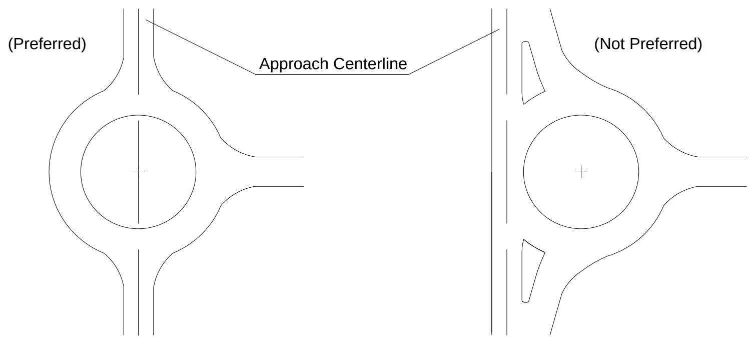

Figure 2.8 : Approach Centerline Alignments (Seim, 1991).

However, approach centerlines aligned through inscribed diameter center, radial alignment, are preferred alignments offset to the left of the roundabout center are also acceptable. In contrast to left offset, alignments offset to the right of the inscribed circle center should be avoided unless other geometric features cannot be applied. An offset to the left is preferred for high speed approaches (FHWA, 2000).

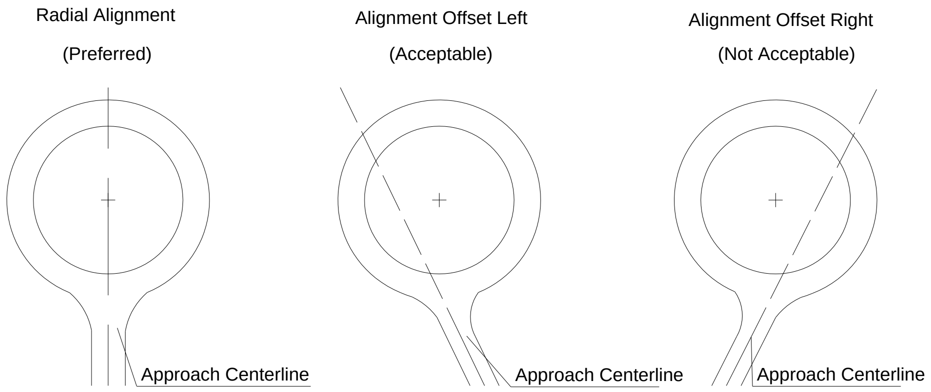

Figure 2.9 : Radial Alignment of Entries (FHWA, 2000).

The right offset alignment brings the approach in at a more tangential angle and reduces the opportunity to provide sufficient entry curvature. In consequence of right offset alignment vehicles are able to enter the roundabout too fast, resulting in more loss-of control crashes and higher crash rates between entering and circulating vehicles (FHWA, 2000).

2.1.2 Geometric design elements of roundabouts

Geometric design elements have significant importance on operational performance and safety objectives of a roundabout. In addition to individual importance of each element, the interaction between each component should be studied for a well designed layout. Geometric design elements detailed in the following topics are; Inscribed circle diameter, entry width, circulatory roadway, central island, entry curves, exit curves, splitter island and stopping sight distance. Some of the elements are shown in Figure 2.10.

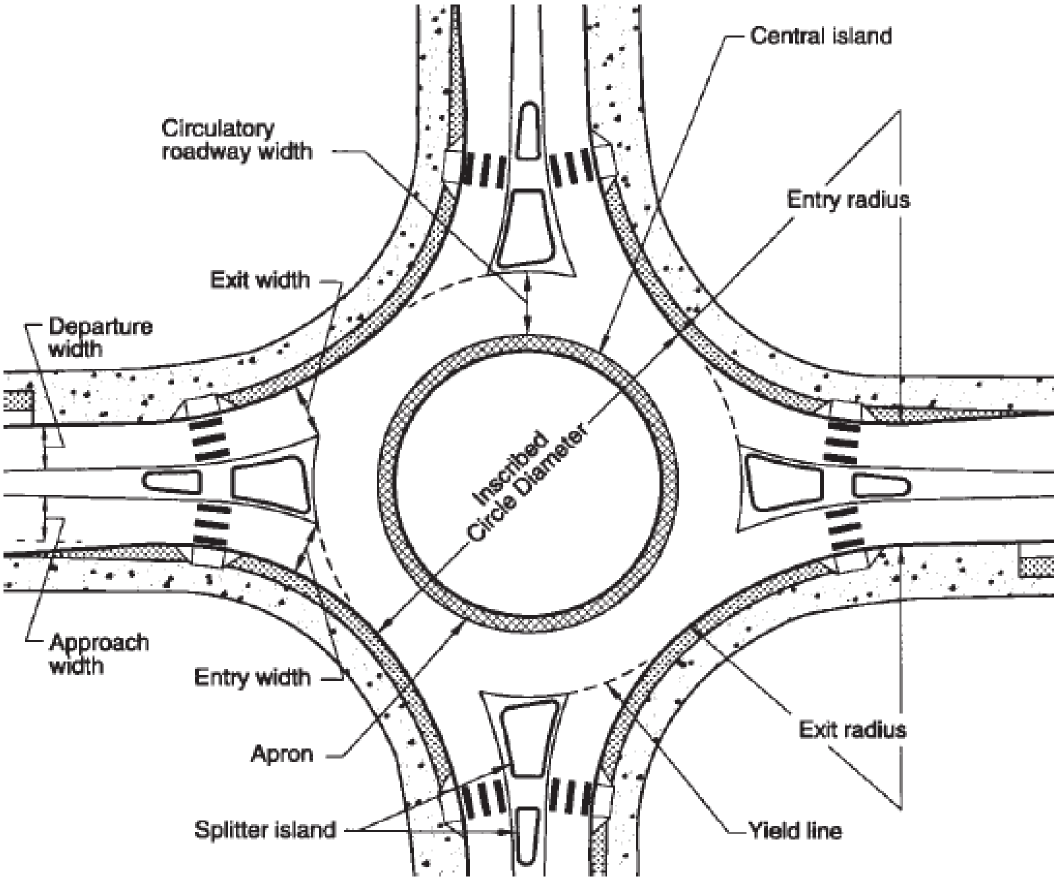

Figure 2.10 : Geometric Design Elements of a Roundabout (FHWA, 2000).

2.1.2.1 Inscribed circle diameter

The inscribed circle diameter is the distance across the circle inscribed by the edge of the circulatory roadway (FHWA, 2000). As shown in Figure 2.9, it consists of central island diameter and the circulatory roadway.

In Table 2.4, recommended inscribed circle diameter ranges by FHWA according to AASHTO design vehicles are given. It is assumed that angles between entries are 90-degree and max. approaching leg number is four.

Table 2.2 : Inscribed Circle Diameters.

ROUNDABOUT TYPE	DESIGN VEHICLE	INSCRIBED CIRCLE DIAMETER RANGE
Mini-Roundabout	Single-Unit Truck	13–25m
Urban Compact	Single-Unit Truck/Bus	25–30m
Urban Single Lane	WB-15 (WB-50)	30–40m
Urban Double Lane	WB-15 (WB-50)	45–55m
Rural Single Lane	WB-20 (WB-67)	35–40m
Rural Double Lane	WB-20 (WB-67)	55–60m

2.1.2.2 Entry width

Entry width is the most important geometric factor effecting roundabout's capacity. As shown in the Figure 2.9, it can be measured from the point where the yield line intersects the left edge of the traveled-way to the right edge of the traveled way, along a line perpendicular to the right curb line (FHWA, 2000). The width of each entry should be designed in order to overcome traffic demand and maintain lower entering vehicle speeds.

2.1.2.3 Circulatory roadway

Circulatory roadway width is determined according to maximum entry width and design vehicle turning requirements. Lane widths should be at least as wide as the entry width and accommodate longest design vehicles to make the left turn movement.

Design stage parameters of circulatory roadways change with the lane number. At single lane roundabouts design vehicle turning requirement is the key determinant. In addition to single lane roundabouts, one, two, or three vehicles, depending on the number of lanes at the widest entry is considered as determinant at multi-lane and double-lane roundabouts.

2.1.2.4 Central island

Central island geometry depends on the width of the circulatory roadway and the inscribed diameter. Island should be raised by a curb with constant radius circular shape to generate constant speeds around the roundabout.

Above all operational issues, central island enables deflection movements of entering vehicles. Island diameter should be large enough for deflection movement and ensure the design speed limitations in the allowable fastest path (FHWA, 2000).

2.1.2.5 Entry and exit curves

Entry and exit curves are adjusted according to approaching roads alignment. Primary operational functions of curves are; lowering approaching vehicle speeds for entry and enabling circulating vehicles to leave the roundabout safely in minimum time interval for exit. For those purposes curvatures of entry and exit could be adjusted by reducing or increasing each curb radius.

Larger entry radius reduces the amount of deflection move at the entry which can result higher crash rates. In contrast to safety aspects, larger entry radius has positive impact on capacity and operational issues. Appropriate entry radius should face with the traffic demand with design speed at the fastest vehicular path.

Considering the safety of vehicles those leave the roundabout, exit curves should have equal or larger radius than the circulating flow radius. On the other hand, it should be small enough to maintain low speeds at the downstream pedestrian crossing.

2.1.2.6 Issues relevant to pedestrians

Locations of pedestrian crossing should be considered both pedestrian safety and roundabout operational side of view. In addition to location, crossing distance also an important parameter. Long crossing distance could increase delay for both pedestrians and vehicles passing through. Therefore, reducing the crossing distance could be useful to minimize pedestrian vehicle accidents. Crossing should be located at a distance from the yield line with a refuge in the splitter island at street grade (AASHTO, 2001).

According to studies modern roundabouts are found out to be safer than the conventional signalized intersections. The study suggests that lower speeds and fewer conflict points of roundabouts are primary contributors to the safety (Stone et al., 2002).

2.1.2.7 Splitter Island

Splitter islands initiates incoming vehicle's deflection from the approaching leg and guide vehicles into the circulating road. Islands prevent wrong way movement by creating physical barriers against vehicles wishing to transverse the roundabout (Russell et al., 2000). In addition to traffic arrangement feature, splitter islands provide pedestrian refuge between incoming and exiting lanes. According to English Highway Design Manual (2003) the length of the splitter island should be measured along the approach at least 15m long to provide sufficient protection for pedestrians. Figure 2.11 shows an example of a splitter island.

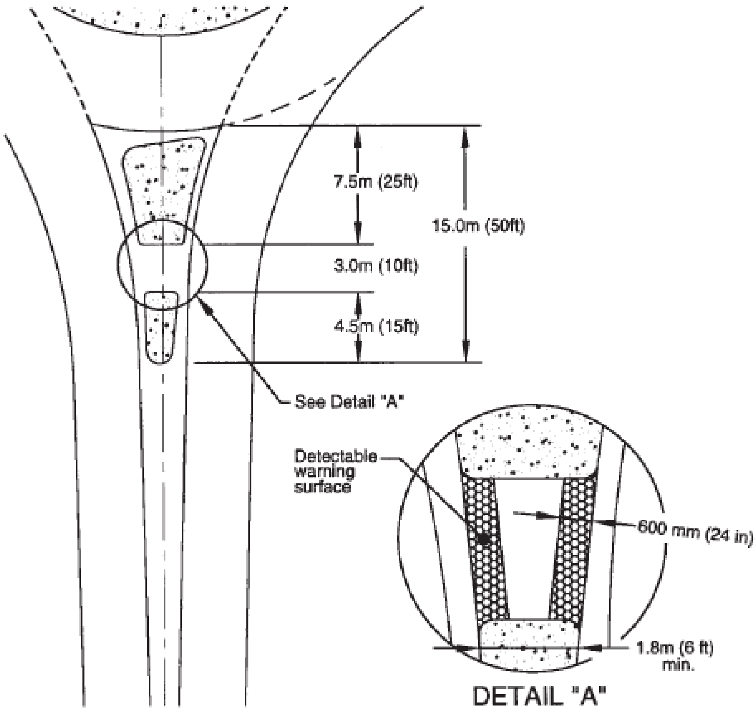

Figure 2.11 : Detailed Splitter Island (FHWA, 2000).

2.1.2.8 Sight distance

Sight distance is one of the most important criteria for safety aspect of roundabouts. All approaches should be placed to confer stopping sight distance for the design speed of the highway (English HDM, 2003).

In order to provide adequate sight distance, approach alignments, splitter island, central island and circulating lane should be well designed to give drivers a good line of sight (Tanyel, 2001).

Another important criteria for appropriate sight distance is that, drivers at the yield line should have clear view of approaching traffic entering the roundabout from an approach immediately to the left. At least a distance representing the travel time equal to the critical gap (Roundabout Design Guideline, 1995)

3. CAPACITY AND OPERATIONAL ISSUES OF ROUNDABOUTS

3.1 Roundabout Capacity Analysis

Most of the European countries and US formed their own capacity formulas according to their needs and highway standards. The consideration parameter in each formula changes with different methodologies. Two main methodologies, regression analysis and gap acceptance theory are accepted. Basic parameters used in formulations and United Kingdom capacity model, German, French, Swiss, Australian capacity formulas, US capacity studies and capacity studies in Turkey are presented under this chapter.

3.1.1 Roundabout capacity and level of service

The Highway Capacity Manual 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." Therefore capacity of a roundabout can be defined as total entering approach capacities.

While capacity is a specific measure that can be defined and estimated, level of service (LOS) is a qualitative measure that "characterizes operational conditions within a traffic stream and their perception by motorists and passengers". HCM uses the average control delay per vehicle (overall delay with geometric delay) as the LOS measure for signalized and unsignalized intersections (1997).

In addition to delay, performance measures such as queue length, proportion queued, effective stop rate and queue clearance time are also related to capacity. It is possible to define the degree of saturation which is the demand/capacity ratio for expressing the relationship between capacity and performance measures.

3.1.2 Circulating stream parameters

Definitions of headways in circulating stream such gap, lag, follow-up and critical headways, the intra-bunch headway, Δ, and proportion of free vehicles, α, the "λ" parameter and merging conditions are made in this chapter.

3.1.2.1 Headway

Headway is defined as the interval between successive vehicles in a traffic lane as they pass a point on the highway in terms of time. It is measured in seconds, from front bumper to front bumper of vehicles.

3.1.2.2 Gap and lag

Gap is the headway between two consecutive vehicles passing the same reference point in the circulating stream. If an entering vehicle on the approaching leg arrives at the yield bar after the gap has already started, the remainder of the gap is called lag. Gap and lag are shown in Figure 3.5 below.

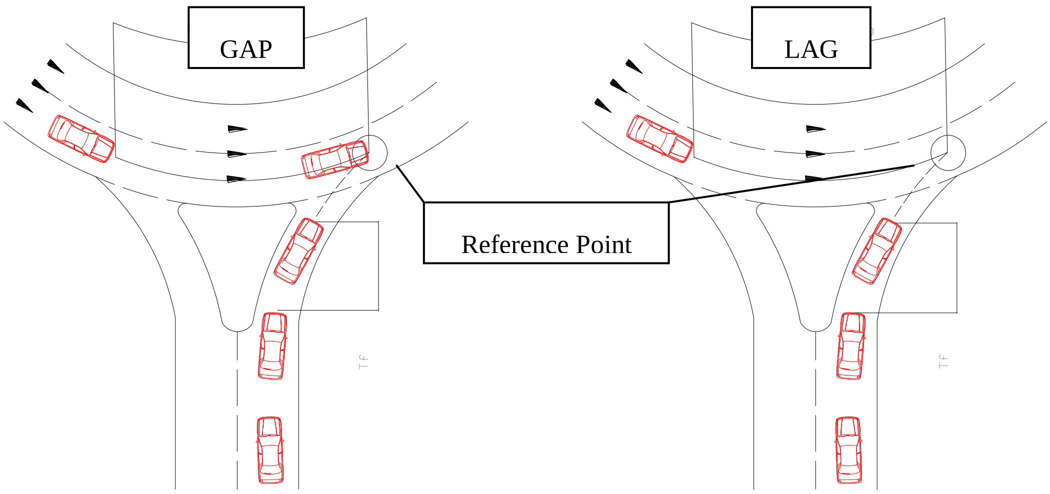

Figure 3.1 : Gap and Lag.

3.1.2.3 Critical and follow-up headways

The minimum gap in terms of time that is acceptable to the entering stream driver to enter the roundabout, is called critical headway (critical gap), T_c . The traditional gap acceptance method assumes that the drivers of the approach lane accept any gap greater or equal to the critical gap and reject any gap smaller than the critical gap

(Troutbeck and Kako, 1999). Accepted and rejected headway percentages and headways are illustrated in Figure 3.6 where 4 seconds is regarded as critical gap.

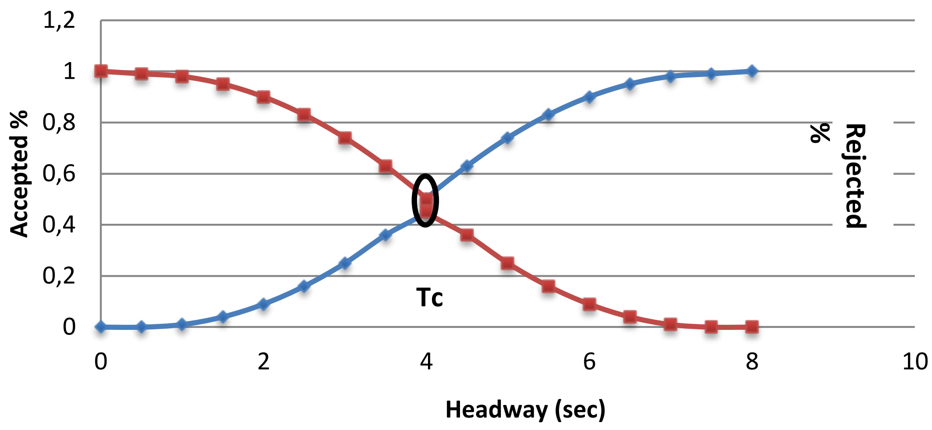

Figure 3.2 : Critical Gap.

Follow-up time, T_f, is the additional time required after the critical gap for following vehicles to enter the roundabout. Every driver can accept different gaps. It is possible to encounter such circumstances that a critical gap much longer than accepted by a driver could be rejected by another one (Gedizlioğlu, 1979).

Critical gap and follow up headways depend on either geometric parameters of the roundabout and driver behaviors.

3.1.2.4 The Intra-bunch headway and proportion of free vehicles

In gap acceptance methodology the intra-bunch headway, Δ, and proportion of free vehicles, α, parameters have significant importance on determination of circulating stream headway distribution. It is seen that different definitions exist for each type of formulation on capacity estimates. Troutbeck (1997) assumed that it is possible to consider vehicles following each other with a headway of greater than 4 secs as free vehicles, vehicles following each other with a headway equal or smaller than 2 secs as bunched vehicles, however it is difficult to decide between 2 and 4 secs.

The intra-bunch headway, Δ, is the minimum headway in the circulating stream and assumed to be equal for all the vehicles in the bunch (Akçelik, 2003). It is possible to estimate other parameters by remaining intra-bunch headway constant (Tanyel, 2001). The intra-bunch headways for roundabout circulating streams according to Akçelik (2003) are given in Equation **3.23**;

$$\Delta = \begin{cases} 2.0 \text{ sec, single lane circulating flow} \\ 1.0 \text{ sec, two lane circulating flow} \\ 0.8 \text{ sec, for circulating flow more than two lanes} \end{cases} \quad \textbf{(3.23)}$$

The proportion of free vehicles identifies the unbunched vehicles with randomly distributed headways (Akçelik, 2003). According to Troutbeck (1997), the most common problem occurs from determination of the headway that defines vehicles whether free vehicles or group of vehicles travelling together as a platoon.

At first, Tanner (1962) estimated the proportion of free vehicles in the circulating stream with Equation **3.24**.

$$\propto = 1 - \Delta \cdot \; Q_c \quad \textbf{(3.24)}$$

In AustRoads (1993) , Akçelik modified Tanner's formula as given in Equation **3.25**.

$$\propto = 0.75 \;\cdot (1 - \Delta \cdot \; Q_c) \quad \textbf{(3.25)}$$

In aaSIDRA, Akçelik brought forward the following Equation **3.26**, which is also used in the calculation of α value in the following chapters of the thesis.

$$\propto = \frac{(1 - \;\Delta \cdot Q_c)}{(\,1 - (1 - k_d) \cdot \Delta \cdot Q_c)} \quad \textbf{(3.26)}$$

Where k_d is the bunching delay parameter which is a constant and equal to 2.2 for roundabouts (Akçelik, 2003).

3.1.2.5 The " λ " parameter

Various "λ " parameter definitions exist in gap acceptance methodology. In 1991, Troutbeck expressed λ as a decay constant, Akcelik and Chung(1994) defined λ as a model parameter. Hagring (1998) stated λ as the intensity of the exponential part of a distribution and Luttinen called λ scale parameter. λ can be foundby using the following equation:

$$\lambda \;=\; \frac{\alpha \cdot \mathrm{Q_c}}{1 - \;\Delta \cdot \mathrm{Q_c}} \quad \textbf{(3.27)}$$

Where α is the proportion of free vehicles, Q_c is the circulating flow and Δ is the intra-bunch headway.

3.1.2.6 Merging conditions

Hagring defines gap forcing as a situation that vehicles entering the circulating flow use so small gaps that vehicles in the circulating flow are forced to give way and have to decelerate or completely stop (1998). In addition to gap forcing it is also possible to define limited priority and reverse priority as merging systems those can occur under over saturated conditions.

At high levels of both entering and conflicting flow HCM defined limited priority as a condition which circulating traffic adjusts its headways to allow entering vehicles to enter and reverse priority as a condition which entering traffic forces circulating traffic to yield (HCM, 2010).

3.1.3 Literature review on capacity estimation

Hypothecal backgrounds of regression model and gap acceptance model are explained under this section.

3.1.3.1 Regression models

Regression method uses linear or exponential equations fitted to data obtained from field studies. Equations are based on traffic volumes at one minute intervals observed during periods of oversaturation. Driver behaviors and geometric components of the roundabout create variation in data. General capacity formula of regression method is shown with Equation **3.28**.

$$Q_e = F - f_c \cdot Q_c \tag{3.28}$$

Where Q_e is the entry capacity in veh/h, Q_c is the circulating flow in veh/h.

F and f_c are parameters related to geometry and traffic flow.

In order to obtain a linear regression equation, a constant queue of vehicles waiting for a suitable gap to enter the roundabout at least for 30 min. period (Tanyel and Yayla, 2010). Transportation Research Laboratory (TRL) method defined by Kimber (1980) is a representative model of regression analysis.

3.1.3.2 Gap acceptance models

Critical gap generates the main principle of the gap acceptance method. It is assumed that the drivers of the approaching lane can enter the circulating lane if only they could find a gap in terms of time, T, which is equal or greater than critical gap (Hagring, 1996).

General capacity formula of gap acceptance method is shown below with Equation **3.29**.

$$q_e = q_c \cdot \int_0^\infty f(t) \cdot g(t) \cdot dt \qquad \textbf{(3.29)}$$

Where q_e is the entry capacity in veh/sec, q_c is the circulating stream volume in veh/sec, *f(t)* is the density function for the distribution of gaps in the circulating stream and *g(t)* is the function of number of entering stream vehicles those can enter into the circulating stream in the time gap sized "t" (Troutbeck and Brilon, 1995).

f(t) can be defined by several simple distributions depend on the variation of driver behaviors. Negative exponential, shifted negative exponential, Gamma, Erlang, log-Person Type 3 or lognormal distribution are the examples of simple distribution where it is also possible to use mixed distributions such as the hyper-exponential, Hyperlang, Cowan M3, M4 and semi-Poisson (Cowan, 1975; Troutbeck and Brilon, 1995).

The capacity of an entry stream can be evaluated with gap acceptance method by making the following assumptions (Troutbeck and Brilon, 1995);

- Constant T_c and T_f values
- Exponential distribution for priority stream gaps
- Constant traffic volumes for each traffic stream.

Some scientists found gap acceptance theory difficult to apply for multilane roundabouts with multilane entries. They stated that in some cases, move-up times were greater or equal to the critical gap and it was difficult to define the correct circulating streams (Stuwe, 1991; Kimber, 1980).

3.2 Entry Capacity Models

For a given volume of circulating vehicles, capacity of each entry under prevailing traffic and geometric conditions is defined as the maximum number of vehicles that can reasonably enter the roundabout within 1 hour. The entry/circulating (Q_e / Q_c) flow ratio is also useful to express the entry capacity relation of the roundabout with circulation flow. As we can see from the ratio, it is possible to say that the entry capacity and circulating flow are inverse proportioned to each other. Drivers coming from the entering leg need gap inside the circulating flow that is large enough to enter the roundabout. Under this circumstance the entry capacity decreases if the circulating flow increases.

In Germany and Switzerland Brilon &Bovy formulations consider the number of circle lanes and leg lanes. In UK detailed roundabout geometry is taken into account. In addition to geometric aspects, the users' behaviors, psycho-technical times, *Tc*, critical gap, and follow-up time, T_f, are also used by France, Germany and US in improved capacity formulations. Consideration parameters of different capacity models are shown in Table 3.1.

Table 3.1 : Consideration parameters of capacity formulations.

	METHODOLOGY	
CONSIDERATION PARAMETERS	***Regression analysis***	***Gap acceptance theory***
the number of circle lanes and leg lanes	Germany (Brilon and Bovy, 1997) Switzerland	
detailed roundabout geometry	UK (TRRL)	
geometric aspects, the users' behaviors, psycho-technical times Tc, critical gap, and follow-up time Tf	US (HCM), Girabase (France)	Australian, Germany (Brilon et al.,2001)

The units of capacity and passenger car equivalencies used in formulas in following titles expressed as; entering flows, Q_e, entry capacities in passenger car unities, pcu/h ; 1 truck, bus=1.5 pcu ; 1 truck + trailer = 2.0 pcu ; 1 motorcycle= 0.5 pcu and 1 bicycle= 0.5 pcu.

3.2.1 United Kingdom Capacity Model

The British Design Manual describes standards for geometric design of roundabouts regarding traffic operation and safety. “The Linear Capacity formula” defining relationship between capacity and entry flow is proceed by R. M. Kimber (1980). Transport and Road Research Laboratory (TRRL) expresses the capacity of a roundabout as a function of the leg and geometric features of the circulating flow in the circle, Q_c, in front of the entry. The relevant entry capacity formula is shown in following Equation **3.1** in a linear form.

$$Q_e = k \cdot (F - f_c \cdot Q_c) \tag{3.1}$$

Where:

$$F = 303 \cdot x_2 \tag{3.1a}$$

$$f_c = 0{,}210 \cdot t_D \cdot (1 + 0{,}2 \cdot x_2) \tag{3.1b}$$

$$k = 1 - 0{,}00347 - (\Phi - 30) - 0{,}978 \cdot (\frac{1}{\mathrm{r}} - 0{,}05) \tag{3.1c}$$

$$t_D = 1 + 1/(2 \cdot \left[1 + \exp\left(\frac{D - 60}{10}\right)\right]) \tag{3.1d}$$

$$x_2 = v + (\frac{e - v}{1 + 2 \cdot S}) \tag{3.1e}$$

$$S = 1{,}6 \cdot \frac{e - v}{l'} = (\mathrm{e} - \mathrm{v})/l \tag{3.1f}$$

In this formula roundabout geometric elements are used as input and the disturbing flow (*Qd*) is directly expressed by circulating flow Q_c. Following Table 3.2 shows the geometric parameters and their symbols used in the formulas.

Table 3.2 : Geometric parameters used by the TRRL formula.

PARAMETER	*DESCRIPTION*	*RANGE VALUES*
e	Entry width	3.6–16.5 m
v	Lane width	1.9- 12.5 m
e′	Previous entry width	3.6–15.0 m
v′	Previous lane width	2.9–12.5 m
U	Circle width	4.9–22.7 m
ℓ, ℓ'	Flare mean length	1–∞m
S	Sharpness of the flare	0–2–9
r	Entry bend radius	3.4–∞m
Φ	Entry angle	0–77◦
D = Dext	Inscribed circle diameter	13.5–171.6 m
W	Exchange section width	7.0–26.0 m
L	Exchange section length	9.0–86.0 m

Geometric elements showed in the table above are also showed in the Figure 3.1 taken from the original work of Kimber (1980) on *The Traffic Capacity of Roundabouts* .

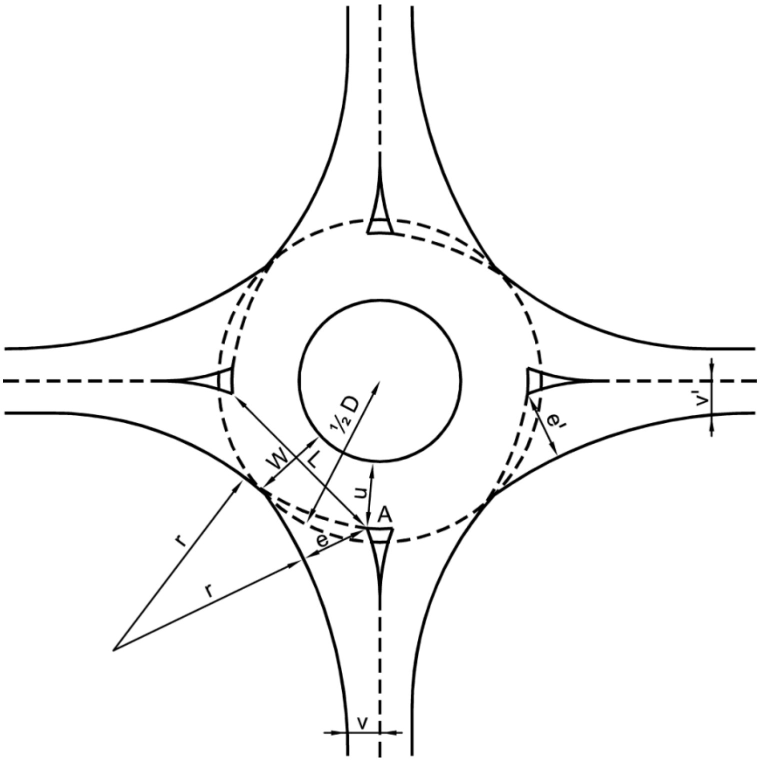

Figure 3.3 : Geometric elements used in the TRRL formula (Brilon, 1991).

- The width of the entry (e) is determined along the perpendicular line traced from point A to the external edge
- The width of the entry lane (v) must be determined upstream of the leg widening next to the entry along the perpendicular line traced from the axis of the roadway to the external edge.
- The width of the circulatory roadway (u) represents the distance between the splitter island at legs (point A) and the central island.
- The entry radius (r) is the smallest bend radius of the external edge next to the entry.
- The width of the weaving section (W) is the shortest distance between the central island and the external edge in the stretch between an entry and the following exit
- The weaving section (L) is defined as the shortest distance between the splitter islands at the legs of two successive entries.
- The mean length of the flare can be determined using either of the two parameters ℓ or ℓ'. Figure 3.2 shows the geometric constructions for their determination. The perpendicular straight line to ½(e-v),the parallel curved

line at the same point. The latter gave the longer length as 1.6 times of the first one.

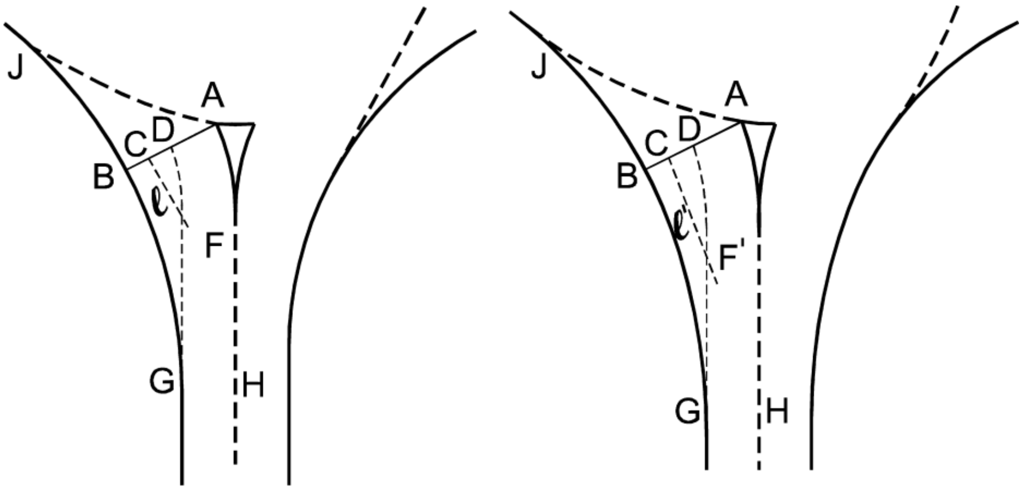

Figure 3.4 : Geometric construction for the determination of ℓ and ℓ' (Brilon, 1991).

- The entry angle (Φ), which represents the conflicting angle between the entering flows and the circulating flows, must be determined according to the straight forward indications shown in Figure 3.3.

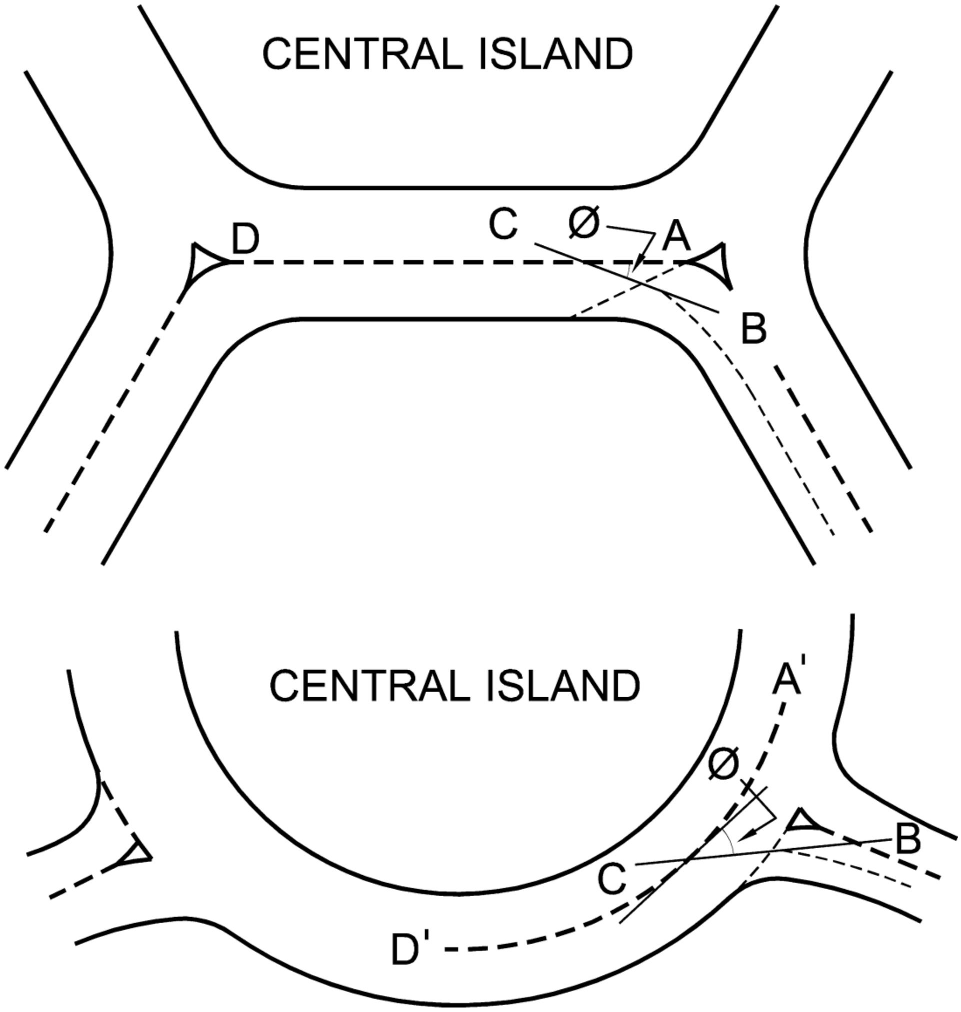

Figure 3.5 : Geometric construction for the determination of the entry angle(Kiber,1980).

3.2.2 German Capacity Formulas

In Germany both of the methodologies linear regression and gap acceptance theory were studied. Previously, capacity was expressed with a simple linear formulation developed by Brilon, Bondzio & Wu in Equation **3.2**.

$$Q_e = A - B \cdot Q_c \text{ (pcu/h)} \qquad \textbf{(3.2)}$$

Where, Q_e is capacity and Q_c is circulating flow in front of the entry. A and B are parameters of linear regression depend on the numbers of entry and circle lanes given in Table 3.3.

Table 3.3 : A and B Values.

CIRCLE LANE NUMBER	*ENTRY LANE NUMBER*	*A*	*B*	*SAMPLE SIZE*
3	*2*	1409	0.42	295
2	*2*	1380	0.50	4574
2	*3*	1250	0.53	879
1	*1*	1218	0.74	1504

Afterwards, Brilon and Wu (1997) modified capacity formula in light of gap acceptance theory as a function of user's behaviors with Equation **3.3**.

$$Q_e = 3600 \cdot \left(1 - \frac{\Delta \cdot Q_c / 3600}{n_c}\right)^{n_c} \cdot \frac{n_e}{T_f} \cdot \exp\left[-\mathrm{Qc}/3600 \cdot \left(\mathrm{T_c} - \frac{\mathrm{T_f}}{2} -\right)\right] \quad \textbf{(3.3)}$$

Where Q_c is circulating flow in front of the entry (pcu/h), n_c is circle lane number, n_e is entry lane number, T_c is critical headway, T_f is follow-up headway, Δ *is* minimum headway between the vehicles circulating in the circle.

3.2.3 French Capacity Formulas

The GIRABASE procedure (France) determines the entry capacity (pcu/h) by using exponential regression methodology with following capacity formula given in Equation **3.4**.

$$Q_e = A \cdot e^{-CB \cdot Qd} \quad \textbf{(3.4)}$$

Where;

$$A = \frac{3600}{T_f} \cdot \left(\frac{Le}{3.5}\right)^{0.8} \quad \textbf{(3.4a)}$$

T_f is follow-up time which is 2.05 secs, *Le* is width of the entry in proximity to the roundabout, determined perpendicularly to the entry direction (m) and *CB* is a coefficient that is 3.525 for urban areas and 3.625 for rural areas.

Formulation uses geometric parameters and pre-fixed follow-up time value. The disturbing flow is expressed by a linear combination of the circulating flow with the exiting flow in Equation **3.5**.

$$Q_d = Q_u \cdot k_a \cdot \left(1 - \frac{Q_u}{Q_c + Q_u}\right) + Q_{ci} \cdot k_{ti} + Q_{ce} \cdot k_{te} \quad \textbf{(3.5)}$$

Where, Q_d is disturbing flow in front of the entry (pcu/h), Q_u is exiting flow (pcu/h), Q_c is circulating flow in front of the entry (pcu/h)and equal to sum of Q_{ci},, traffic rate on the inner circle lane (pcu/h) and, Q_{ce} , traffic rate Q_c on the outer circle lane (close to the entry) (pcu/h).

For $L_i < L_{imax}$;

$$k_a = \frac{R_i}{Ri+LA} - \frac{L_i}{L_{imax}} \quad \textbf{(3.5a)}$$

For other cases;

$$k_a = 0 \quad \textbf{(3.5b)}$$

R_i is central island radius (m), LA is circle width (m) and L_i is splitter island width at legs (m) are shown in Equation **3.6**.

$$L_{imax} = 4{,}55 \cdot \sqrt{R_i + \frac{LA}{2}} \quad \textbf{(3.6)}$$

$$k_{ti} = \min \left\{ \frac{160}{LA \cdot (R_i+LA)} \ ; 1\right\} \qquad k_{te} = \min \left\{ 1 - \frac{(LA-8)}{LA} \cdot \left(\frac{R_i}{R_i+LA}\right)^2 ; 1\right\} \quad \textbf{(3.6a;3.6b)}$$

Figure 3.4 and Table 3.4 below show the traffic flows and the geometric elements of the roundabout and range values of them respectively those used in formulation.

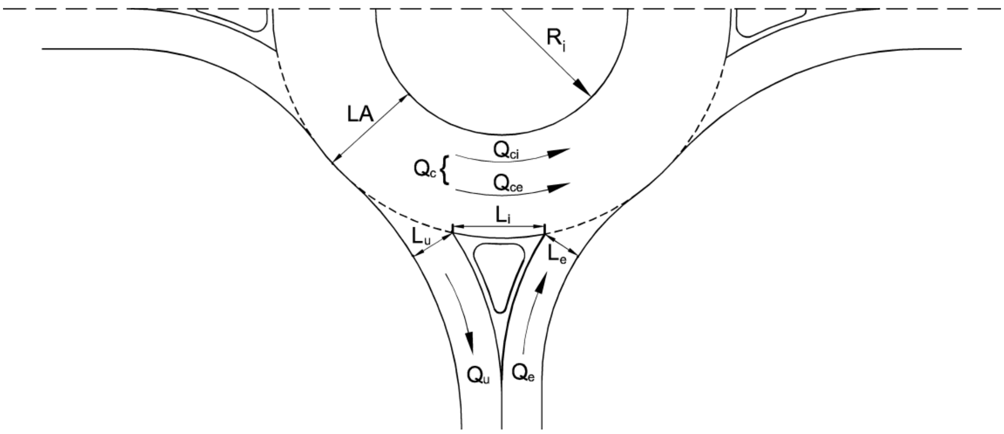

Figure 3.6 : Traffic Flows and Geometric Elements.

Table 3.4 : Range values of geometric elements.

PARAMETER	***DESCRIPTION***	***RANGE VALUES***
$\boldsymbol{L_e}$	Entry width	3–11 m
$\boldsymbol{L_i}$	Splitter Island width	0–70 m
$\boldsymbol{L_u}$	Exit width	3.5–10.5 m
$\boldsymbol{LA}$	Circle width	4.5–17.5 m
$\boldsymbol{R_i}$	Central island radius	3.5–87.5 m

CERTU formulation took over GIRABASE in urban French roundabouts capacity evaluation. CERTU expresses the entry capacity with a simpler linear formulation with Equation 3.7.

$$Q_e = 1500 - \frac{5}{6} Q_d \tag{3.7}$$

Where;

$$Q_d = a \cdot Q_c + b \cdot Q_u \tag{3.7a}$$

Varies a and b change according to central island radius and splitter island width respectively shown in Table 3.5.

Table 3.5 : "a" and "b" values.

	a		**B**
Ri<15m	0.9	**Li >15**	0
Ri>30m	0.7	**Li=0**	0.3

3.2.4 Swiss Capacity Formulas

The Swiss standards based on regression method define the entry capacity Q_e as the maximum inflow of an entry depend on the conflicting flow Q_g with Equation **3.8**.

$$Q_e = K\,[1500 - (8/9) \cdot Q_d] \tag{3.8}$$

Where; K depends on the number of entry lanes. 1, 1.4-1,6 or 2 for single lane, double-lane and multi-lane respectively. Q_d is disturbing flow with Equation **3.9**

$$Q_d = \propto \cdot \; Q_u \; + \; \beta \; Q_c \qquad \textbf{(3.9)}$$

Where, Q_u is exiting traffic stream and Q_c is circulating traffic in front of the exit. Following Figure 3.5 is useful to explain the relevant geometric parameters those effect α and β varies.

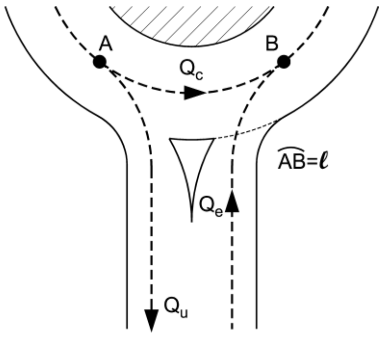

Figure 3.7 : Geometric Parameter.

- α, decreases with ℓ until ℓ > 28m and β , depends on the circulatory lane number.

3.2.5 Australian Capacity Formulas

AUSTROADS, 1993 is the basic design guide for roundabouts. Akçelik and Troutbeck summarized Australian model in 1991 on the basis of gap acceptance methodology. Recent formulations are expressed in Akçelik et al. (1998) and integrated to SIDRA Software. Australian studies examined multilane roundabouts capacity for each entry lane those could differ in capacity. The lane with the higher capacity named dominant stream and other lanes called sub-dominant stream. Australian entry capacity formula build by Akçelik et al. (1980) is given given with Equation **3.10** below.

$$Q_{emax} = \max\{f_{od}Q_g, Q_m\} \qquad \textbf{(3.10)}$$

Where;

$$Q_g = \frac{3600}{T_f}\left(1 - \Delta\frac{q_c}{3600} + 0{,}5T_f \cdot \alpha\frac{q_c}{3600}\right) exp\left(-\lambda(T_c - \Delta_c)\right) \qquad \textbf{(3.10a)}$$

$$Q_m = \min\{Q_e, 60\, n_m\} \qquad \textbf{(3.10b)}$$

$$f_{od} = 1 - f_{qc}\left(p_{qd}p_{cd}\right) \qquad \textbf{(3.10c)}$$

Q_e is the capacity of the entry lane in veh/h, Q_g is minimum capacity estimate using the gap acceptance method in veh/h, Q_m is minimum capacity in veh/h, q_c is total circulating flow rate flow in pcu/h, n_m is minimum number of vehicles can enter the circulating stream under heavy flow conditions in veh/min, f_{od} is origin destination adjustment factor, f_{qc} is calibration parameter, p_{cd} and p_{qd} are proportion of the total roundabout circulating flow that originated from the dominant lane and proportion of queued vehicles on the dominant approaching lane respectively. n_c is number of circulating flow lanes, Δ_c is minimum intra-bunch headway in circulating stream which is 2.0 s for n_c=1 and 1.2s for n_c=2 and λ is arrival headway distribution factor. f_{od} equations according to circulating lane number are given in the Table 3.6 below.

Table 3.6 : f_{od} Equations.

	SINGLE-LANE CIRCULATING FLOW	***MULTI-LANE CIRCULATING FLOW***	***IN CASE***
$\boldsymbol{f_{qc}}$	0,04+0,00015q_c	0,04+0,00015q_c	$q_c < 600$
	$0{,}0007q_c - 0{,}29$		$600 \leq q_c \leq 1200$
		$0{,}00035q_c - 0{,}08$	$600 \leq q_c \leq 1800$
	55		$q_c > 1200$
		55	$q_c > 1800$

T_f and T_c are follow-up headway and critical gap. Follow-up headways are calculated for dominant and subdominant lane with following Equation **3.11** and Equation **3.12** by Troutbeck (1997).

$$T_{fdom} = 3{,}37 - 0{,}0208D_i + 0{,}889 \cdot 10^{-4} D_i^2 - 0{,}395n_e + 0{,}388n_c - 0{,}000394q_c \qquad \textbf{(3.11)}$$

$$T_{fsub} = 2{,}149 + \left(0{,}5135T_{fdom} - 0{,}8735\right) r_{ds} \qquad \textbf{(3.12)}$$

Where, D_i is inscribed circle diameter in m, n_e is the number of entry lanes and r_{ds} is ratio of dominant to subdominant $\frac{q_d}{q_s}$ flow rate. The critical gap is calculated for dominant and subdominant lane with following Equation **3.13** and **3.14**.

$$T_c = (3{,}6135 - 3{,}137 \cdot 10^{-4} q_c - 0{,}339w_L - 0{,}2775n_c)T_f \quad for\ q_c \leq 1200 \qquad \textbf{(3.13)}$$

$$T_c = (3{,}2371 - 0{,}339w_L - 0{,}2775n_c)T_f \qquad for\ q_c > 1200 \qquad \textbf{(3.14)}$$

Where w_L is the average entry lane width in m.

3.2.6 US capacity studies

In HCM 2000 only entry capacity of roundabouts those have one lane in the circle and one lane at the entries were defines as following Equation **3.15**.

$$Q_e = \frac{Q_c\ e^{-Q_c T_c/3600}}{1 - e^{-Q_c T_f/3600}} \text{(pcu/h)} \qquad \textbf{(3.15)}$$

Where, Q_e is capacity of the roundabout and maximum entry capacity (pcu/h), Q_c is conflicting circulating traffic (pcu/h), T_c is critical time (sec) and T_f is follow-up time (sec).

The relationship between entry capacity and circulating flow was defined between upper and lower-bounds of critical gap and follow–up time given in Table 3.7.

Table 3.7 : Upper and Lower Bounds for Critical Gap and Follow-Up Time (HCM,2000).

	CRITICAL GAP (sec)	***FOLLOW-UP TIME (sec)***
Upper bound	4.1	2.6
Lower bound	4.6	3.1

3.2.7 Turkey Capacity Studies

In Turkey, Turkish General Directorate of Highways (Karayolları Genel Müdürlüğü, KGM) uses roundabout design principles depending mostly on Federal Highway Administration's (FHWA) studies (Arıkan Öztürk et al., 2007). Various studies were made in Turkey investigating the availability of different theories (Tanyel et al., 2007; Tanyel and Yayla, 2010).

In 2010 S.Tanyel and Yayla suggested an empirical formulation for capacity estimate of roundabouts using regression analysis according to observations made on four intersections in İzmir, (*A discussion on the Capacity of Rotary Intersections*, 2010). Suggested formulation shown in the Equation **3.17** and also used in this study for calculation of gap acceptance model.

$$Q_e = 921 - 0{,}64\, Q_c + 145\, w_e \qquad \textbf{(3.17)}$$

Where; w_e is the entry width of the approaching lane.

3.2.8 Explicit considerations on HCM2010 method

Highway Capacity Manual 2010 fifth edition developed new methodologies for evaluating roundabout performance. The 2010 Highway Capacity Manual defines capacity as: "the maximum sustainable hourly flow rate at which persons or vehicles can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions." In difference to 2000 edition, multilane roundabouts with up to two entry lanes and one bypass lane per approach were considered in capacity estimates.

Methodology was based on the database of U.S. roundabouts conducted by National Cooperative Highway Research Program Project 3-65.

New method of HCM 2010 presents a lane based capacity model with combination of a simple lane based regression and gap acceptance models for both single and double lane roundabouts (HCM, 2010). Akçelik describes new capacity model as a nonlinear empirical (regression) model with a theoretical basis in gap acceptance (Akçelik, 2011).

As mentioned in capacity concept title of the manual, several merging conditions were not taken into account during the capacity estimates. Exiting flow confliction on circulating flow, priority and limited reversal behaviors and capacity constrain under over capacity conditions are not included in capacity models.

HCM 2010 defined a lane based capacity formulation that covers both regression and gap acceptance theory as expressed in Equation **3.18**;

$$Q_e = f_{HVe} \cdot f_p \cdot f_A \cdot A \cdot e^{-(B/f_B)Q_c'} \qquad \textbf{(3.18)}$$

Where, f_{HVe} is heavy vehicle factor for entry lane capacity, f_p is pedestrian factor for the effect of pedestrians crossing in front of entry lanes. f_A and f_B are adjustment factors for parameter A and B respectively where, $f_A = f_B$means T_c/T_s is kept unchanged. Q_c' is circulating flow rate in front of the entry (adjusted for heavy vehicles) in pcu/h.

f_{HVe} can be calculated by Equation **3.19**;

$$f_{HVe} = \frac{1}{1+P_T(E_T-1)} \text{ in case } E_T > 1 \qquad \textbf{(3.19)}$$

Where E_T is the passenger car equivalent of a heavy vehicle for gap acceptance theory in pcu/veh and P_T is the proportion of heavy vehicles in the entry lane.

Adjusted Q_c' can be determined by Equation **3.20**;

$$Q_c' = \frac{Q_c}{f_{HVc}} \qquad \textbf{(3.20)}$$

Where Q_c' is the adjusted circulating flow rate in pcu/h, Q_c is the circulating flow rate in veh/h and f_{HVc} is heavy vehicle factor. It is possible to calculate f_{HVc} with Equation 3.19 by adjusting P_T to circulating lane ratios.

Under the light of Equation 3.14 HCM defines default values shown in the Table 3.8 and Table 3.9 for capacity models according to observations made at US roundabouts in 2003 (HCM, 2010).

Table 3.8 : Single-lane Parameters (HCM, 2010).

Single lane circulating stream (n_c=1)	T_f	T_c	T_o	T_f/T_c	***A***	***B***
Single lane entry	3.19	5.19	3.60	0.615	1130	0.00100
Multilane entry	3.19	5.19	3.60	0.615	1130	0.00100

Table 3.9 : Multi-lane Parameters (HCM, 2010).

Multilane circulating stream ($n_c > 1$)		T_f	T_c	T_o	T_f/T_c	***A***	***B***
Single-lane entry		3.19	4.11	2.52	0.776	1130	0.00070
Multilane entry	***Dominant lane (right)***	3.19	4.11	2.52	0.776	1130	0.00070
	Subdominant lane (left)	3.19	4.29	2.70	0.744	1130	0.00075

In addition to generalized formulas, it is possible to calibrate equation with local parameters. *A* and *B* parameters could be adjusted according to follow up time and critical headway with Equation 3.21 an 3.22.

$$A = 3600/T_f \tag{3.21}$$

$$B = \frac{T_o}{3600} = (T_c - 0{,}5 \cdot T_f)/3600 \tag{3.22}$$

Where T_o is the parameter that relates critical gap and follow up time parameters in s unit, T_f is follow-up headway and T_c is critical gap headway.

4. CAPACITY ANALYSIS WITH HCM 2010 METHOD

4.1 Data and Geometry

Geometries of roundabouts those are investigated for calculations and observed data specialties are given in this section of the study.

4.1.1 Roundabout geometries

Data for the evaluation of HCM 2010 capacity model is obtained from Tanyel's studies on Montrö and Lozan roundabouts in 2001 (Tanyel, 2001). Both intersections are located in Central İzmir. Geometric features of the Lozan and Montrö roundabouts are given in Table 4.1.

Table 4.1 : Geometric Features of Lozan and Montrö Roundabouts.

GEOMETRIC FEATURES	MONTRÖ	LOZAN
Inscribed Circle Diameter (Di)	65 m	67 m
Entry lane number (n_e)	2	2
Entry lane width (w_e)	3 m	3 m
Exit lane number (n_u)	-	2
Exit lane width (n_u)	-	3 m
Splitter Island width (w_{si})	-	9 m
Circulatory Lane number (n_c)	3	3
Circulatory Roadway width (w_c)	20 m	20 m
Entry angle (ϕ)	46	54

The schematic presentation of Lozan and Montrö Roundabouts are given in the Figure 4.1 and Figure 4.2 respectively. On Lozan Roundabout, Alsancak approaching leg shown in the Figure 4.1 with number 3, is observed. There are two entering and two exiting lanes on Alsancak approaching leg splitted with a 7 m refuge and approach lane widths are 3,00m.

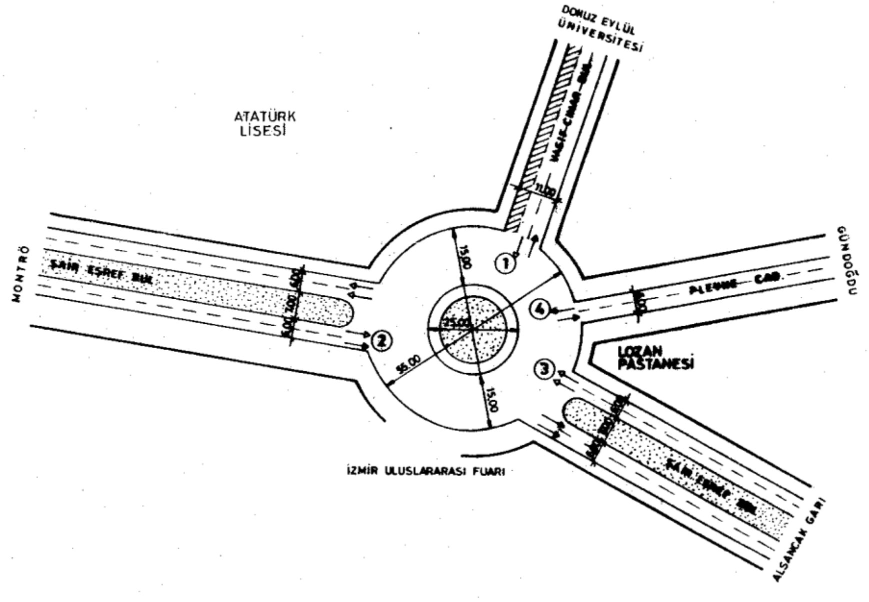

Figure 4.1 : Lozan Roundabout (Tanyel, 2001).

On Montrö Roundabout, Cumhuriyet approaching leg shown in Figure 4.2 with number 5, is observed. There are two entering lanes on Cumhuriyet approach leg with 3,00m width.

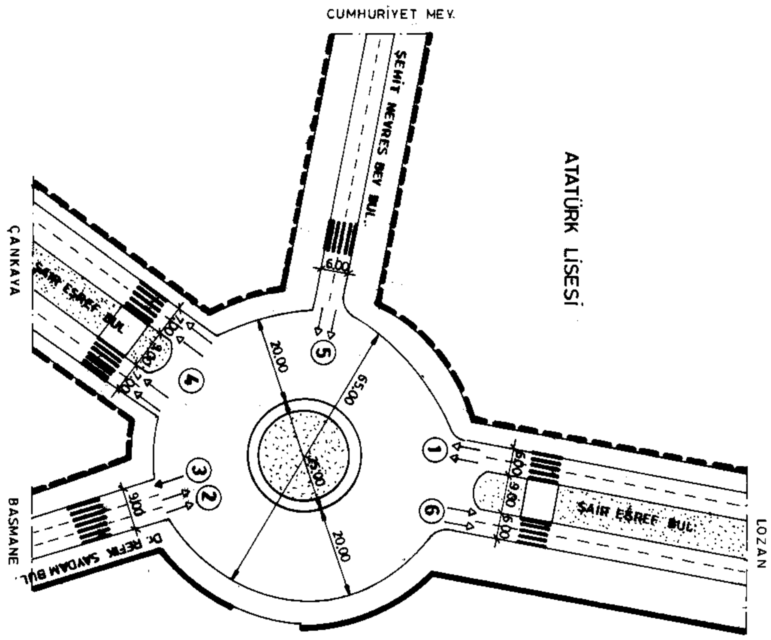

Figure 4.2 : Montrö Roundabout (Tanyel, 2001).

4.1.2 Test data

Test Data used in the evolutions are maintained from observations made by Tanyel (2001) using video cameras located at a high building near the roundabouts. According to Troutbeck (1998), the best way to determine the capacity of a roundabout is the direct measurement of the maximum incoming vehicle number from approaching lanes with observations. In order to obtain such kind of data there should be a constant queue of vehicles waiting on the approaching leg for 30 minutes long. Under this circumstances, data of 1 min and 5 min periods are adequate for capacity estimates (Troutbeck,1998). Data collected from the observations of Lozan and Montrö were consist of 1 min periods those are 46 min and 45 min groups respectively.

According to recordings made at mornings and evenings peak hours; circulatory flow rate in veh/h and veh/ min, number of entering vehicles in veh/h and veh/min, circulatory roadway headways in sec, follow-up times in sec and critical gap headways in sec data are obtained.

For sensitivity analysis roundabout capacity model in HCM 2010 generalized with an exponential function as indicated by Equation **4.1**.

$$C_{pce} = A \cdot e^{(-B \cdot Qc)} \tag{4.1}$$

Where A and B are obtained by Equation **4.2** and Equation **4.3** respectively.

$$A = \frac{3600}{T_f} \tag{4.2}$$

$$B = \frac{T_c - (T_F/2)}{3600} \tag{4.3}$$

Where; C_{pce} is lane capacity, adjusted for heavy vehicles (pc/h), Q_c is circulating flow (pc/h), T_c is critical gap (sec) and T_f is follow up time (sec).

4.2 Applied methods

HCM 2010, gap acceptance and regression models used in calculations are given in this section of the study

4.2.1 HCM 2010 Method

Default values defined for multilane roundabouts in HCM 2010 are considered for evaluations those shown in Figure 3.9 in previous chapter. Equation **4.4** and Equation **4.5** are obtained by default values for left and right lane capacities respectively.

$$Qe = 1130 \,.\, e^{(-0{,}00075 \cdot Q_c)} \text{(Left)} \tag{4.4}$$

$$Qe = 1130 \,.\, e^{(-0{,}0007 \cdot Q_c)} \text{(Right)} \tag{4.5}$$

4.2.2 Regression model

As mentioned in the previous chapters, TRL method is the representative capacity analysis method for regression models, therefore it is chosen for comparison of HCM 2010 with a regression model. TRL entry capacity formula, Equation **3.1** is used for Lozan and Montrö Roundabouts.

$$Q_e = k \cdot (F - f_c \cdot Q_c) \tag{3.1}$$

Parameters of Equation 3.1 are explained in detail in the third chapter. Geometric features of the roundabouts used in regression model are given in Table 4.2.

Table 4.2 : Geometric features.

	D_i (m)	***w_e (m)***	***F_e (deg)***	***nc***	***ne***	***w_a (m)***	***L_f (m)***	***r_e (m)***
Lozan	25,00	8,00	54,0	3,0	2,0	3,61	15,00	9,00
Montrö	25,00	7,00	46,0	3,0	2,0	3,00	10,00	13,00

4.2.3 Gap acceptance model

For evaluation of capacity according to gap acceptance method, Troutbeck's T_c and T_f formulations for dominant and sub dominant lanes are calculated for each data group according to roundabout geometries (Troutbeck, 1997). Exiting flow effect on the capacity is neglected. Mean values of evaluated critical headway and follow up headways for each roundabout are shown in Table 4.4.

Table 4.3 : Mean $\boldsymbol{T_c}$ and $\boldsymbol{T_f}$ values.

ROUNDABOUT	$\boldsymbol{T_{f\,dom}}$ ***(s)***	$\boldsymbol{T_{f\,sub}}$ ***(s)***	$\boldsymbol{T_{dom}}$ ***(s)***	$\boldsymbol{T_{sub}}$ ***(s)***
Lozan	2,492	2,626	3,049	3,210
Montrö	2,273	2,494	2,848	3,120

Intra bunch headway, Δ, is calculated for roundabouts considering multilane stream with Akçelik's formulation (1998) given in Equation **4.6**.

$$\Delta_2' = \Delta_1 - (\Delta_1 - \Delta_2)\,\rho^{0,4} \tag{4.6}$$

Where; Δ_2' is the adjusted intra-bunch headway for a given contributing stream considering lane 1 and 2 together, Δ_1 is intra-bunch headway for single-lane stream which is 2 secs. Δ_2 for two-lane stream with equal lane flows which is 1,2 secs and ρ is the ratio of the second highest lane flow rate to the highest lane flow rate.

Different equations exist to define the proportion of free vehicles, α. Equation **4.7** by Akçelik is used to determine the proportion of free vehicles (2003).

$$\propto = \frac{(1 - \Delta q_c)}{(1 - (1 - k_d)\Delta q_c)} \tag{4.7}$$

Arrival headway distribution factor, λ, is calculated using Equation **4.8** where λ is defined as a decay constant.

$$\lambda = \frac{\propto \cdot\, q_c}{(1 - \Delta \cdot q_c)} \tag{4.8}$$

Entry capacity is calculated using Akçelik's formulation defined in SIDRA as basic gap acceptance capacity model for dominant and subdominant lanes given in Equation **4.9** (1998).

$$Q_g = \frac{3600}{T_f}\left(1 - \Delta\frac{q_c}{3600} + 0{,}5T_f \cdot \alpha\frac{q_c}{3600}\right) exp\big(-\lambda(T_c - \Delta_c)\big) \tag{4.9}$$

Total predicted capacity values were determined by summation of dominant and subdominant lane capacities.

4.2.4 Calibrated models

HCM 2010's calibrated formulation for multilane roundabouts is also considered using Equation **3.21** and Equation **3.22**. Where critical headway for right lane is taken as 4.4 secs, left lane is taken as 4.7 secs and follow-up headway for right lane is taken as 2.2 secs, left lane is taken as 2.2 secs (HCM, 2010).

Alternative models are investigated those can define the observed values. Tanyel and Yayla's empirical formulation given in Equation **3.17** for roundabout capacity is calculated for comparison.

Gap acceptance model evaluated from Akçelik's formulation is also calibrated according to limited priority using Troutbeck's constant "*C*" for merge conditions given in Equation **4.10**.

$$C = \frac{1 - e^{-\lambda T_f}}{\left[1 - e^{-\lambda(T_c - T_f - \Delta)} - \lambda(T_c - T_f - \Delta)e^{-\lambda(T_c - T_f - \Delta)}\right]} \text{ for } T_f + \Delta > T_c > \Delta \qquad \textbf{(4.10)}$$

4.3 Numerical Implementations

4.3.1 Comparative evaluation of regression model with HCM2010 method

Regression formula calculated according to geometric characteristics of each roundabout. Figure 4.3 and Figure 4.4 show observed field data with $Q_{eobserved}$, the results of regression analysis with Q_{ecal} and predicted results of HCM 2010 with HCM 2010 for Lozan and Montrö roundabouts respectively.

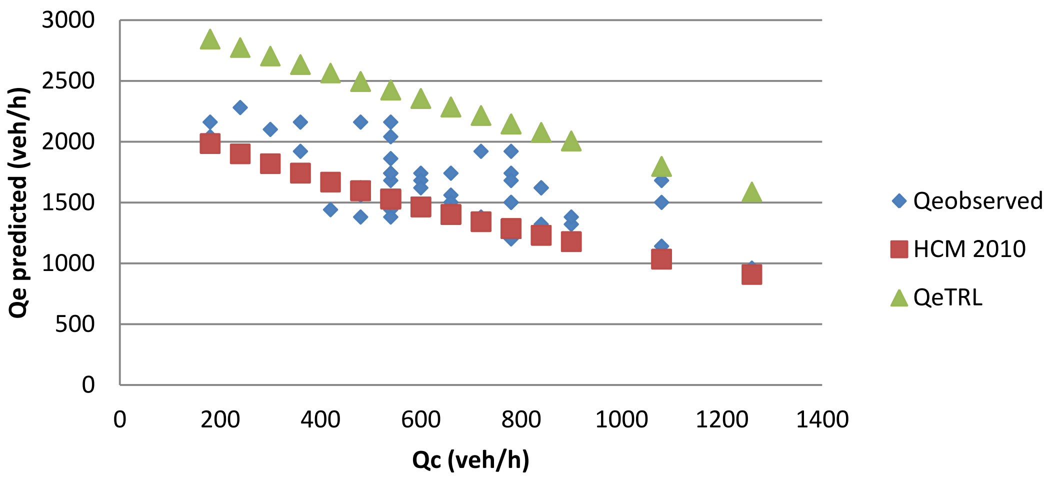

Figure 4.3 : Lozan Entry Capacity Estimates.

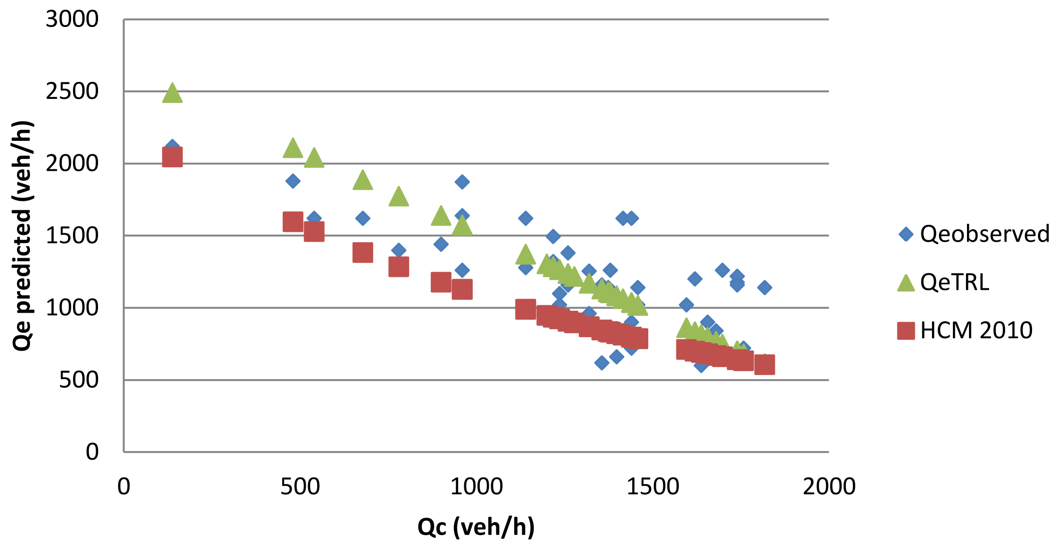

Figure 4.4 : Montrö Entry Capacity Estimates.

A linear regression is done between Q_e observed values and estimated values of regression analysis and HCM 2010 values shown in the Figure 4.5. Correlation coefficients are $r^2 = 0{,}596$ and $r^2 = 0{,}6513$ for TRL and HCM2010 respectively. The linear relation between observed values and predicted entry capacities are given in Equation **4.11** and **4.12** for TRL and HCM 2010 respectively.

$$Q_{epredicted} = 1{,}2635\, Q_{eobs} - 55{,}011 \quad \textbf{(4.11)}$$

$$Q_{epredicted} = 0{,}7486\, Q_{eobs} + 105{,}59 \quad \textbf{(4.12)}$$

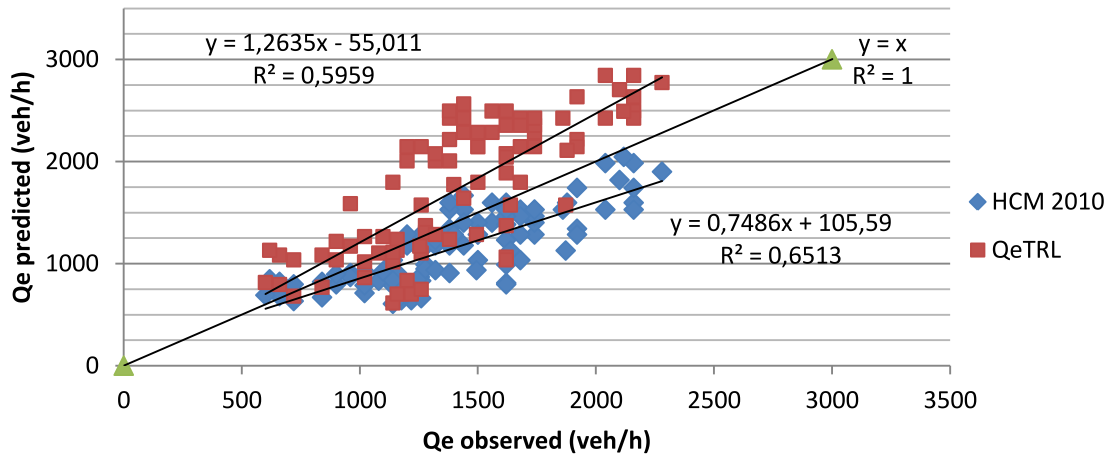

Figure 4.5 : Linear regression between $\boldsymbol{Q_e}$ observed values and estimated values of regression analysis.

As can be seen from the figures, HCM 2010 generally gives lower capacity estimates than regression analysis. Especially in low circulating flow, in Lozan, HCM 2010 gave more accurate results in comparison with linear regression. Under higher circulating flow conditions, in Montrö, HCM 2010 model derived slightly under the observed conditions where the scatter of the TRL model estimates define more appropriate Q_e values.

4.3.2 Comparative evaluation of gap acceptance model with HCM2010 method

Gap acceptance method and HCM 2010 results for Lozan and Montrö roundabouts are shown in the Figure 4.6 and Figure 4.7 respectively. Collected field data shown with Q_e observed.

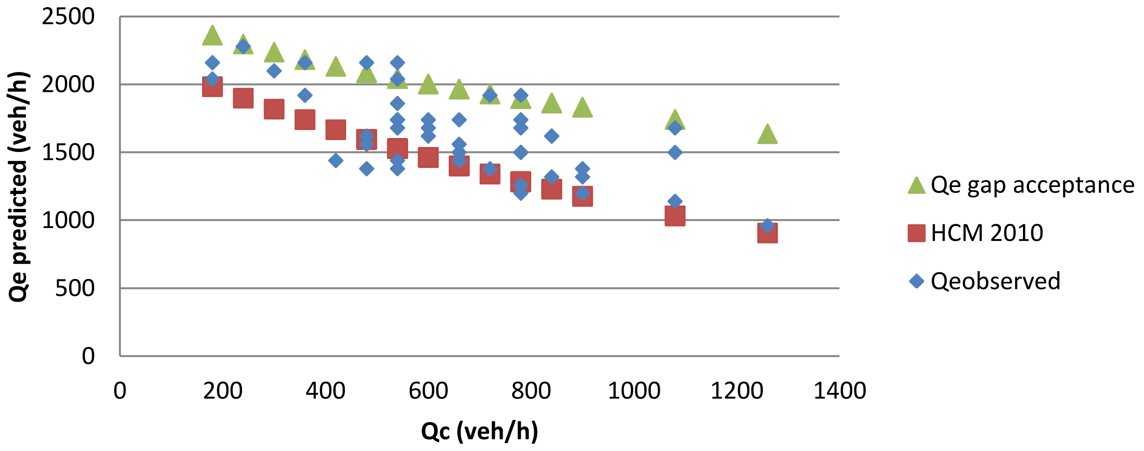

Figure 4.6 : Comparison of capacity models for Lozan.

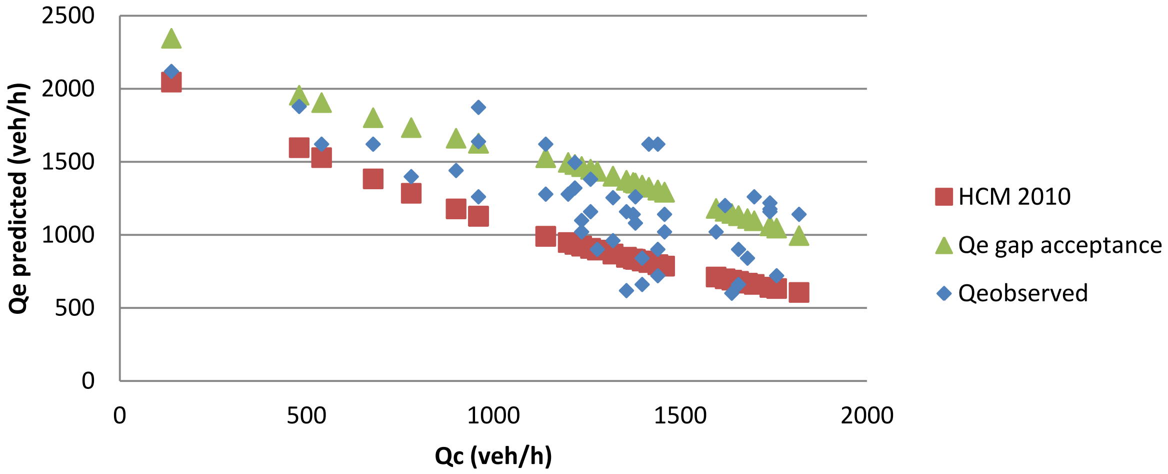

Figure 4.7 : Comparison of capacity models for Montrö.

A linear regression is done between Q_e observed values and estimated values of gap acceptance. Correlation coefficients are $r^2 = 0{,}6154$ and $r^2 = 0{,}6513$ for Gap Acceptance and HCM 2010 respectively. The linear relation between observed values and predicted entry capacities are given in Equation **4.13** and **4.14** for Gap acceptance and HCM 2010 respectively.

$$Q_{epredicted} = 0{,}7236\ Q_{eobs} + 662{,}02 \quad \textbf{(4.13)}$$

$$Q_{epredicted} = 0{,}7486\ Q_{eobs} + 105{,}59 \quad \textbf{(4.14)}$$

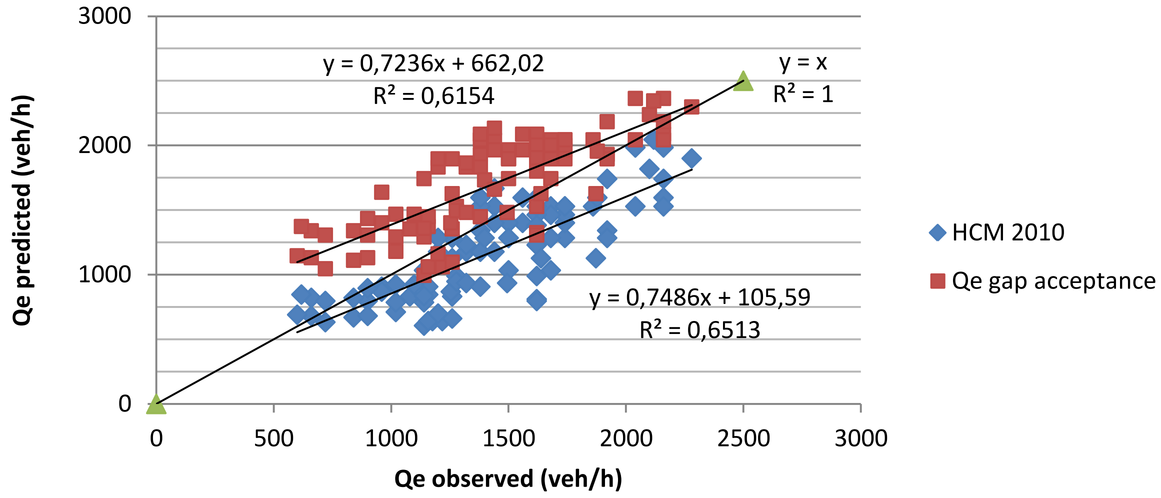

Figure 4.8 : Linear regression between $\boldsymbol{Q_e}$ observed values and estimated values of gap acceptance model.

As it can be seen from the figures, HCM 2010 generally gives lower capacity estimates than gap acceptance analysis. In low circulating flow HCM 2010 gave more accurate results in comparison with gap acceptance. Under higher circulating flow conditions HCM 2010 model derived slightly under the observed conditions.

4.3.3 Comparative evaluation of calibrated models with HCM2010 method

Entry capacity estimations of HCM 2010 calibrated formulation and default values are presented in Figure 4.9. It is seen from Figure 4.9 calibrated model gave higher capacity estimations than default value where circulating flow is approximately 1500 veh/h.

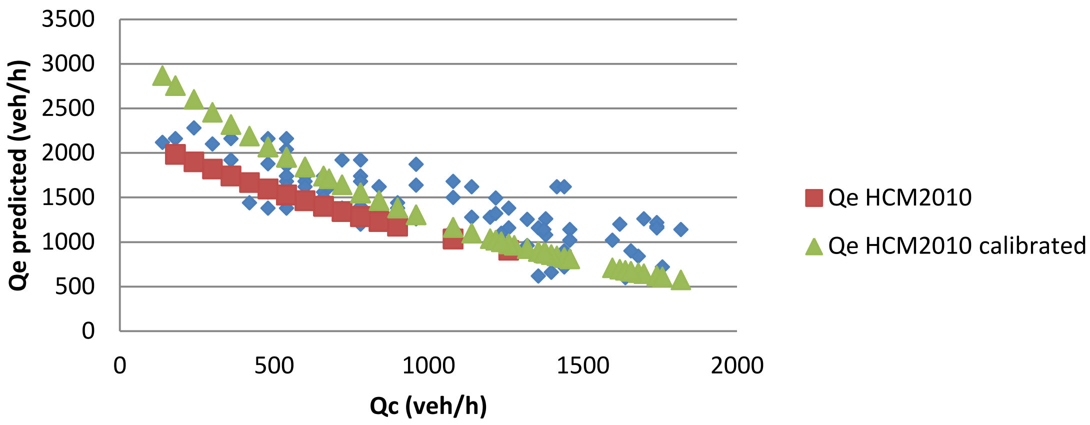

Figure 4.9 : Comparison of HCM 2010 default and calibrated values.

Linear regression is done between HCM 2010 default values and calibrated model. Correlation coefficients are $r^2 = 0{,}6494$ and $r^2 = 0{,}6513$ for calibrated model and HCM2010 respectively. The linear relation between observed values and predicted entry capacities are given in Equation **4.15** and **4.16** for calibrated model and HCM 2010 respectively.

$$Q_{epredicted} = 1{,}1694\ Q_{eobs} - 262{,}72 \quad \textbf{(4.15)}$$

$$Q_{epredicted} = 0{,}7486\ Q_{eobs} + 105{,}59 \quad \textbf{(4.16)}$$

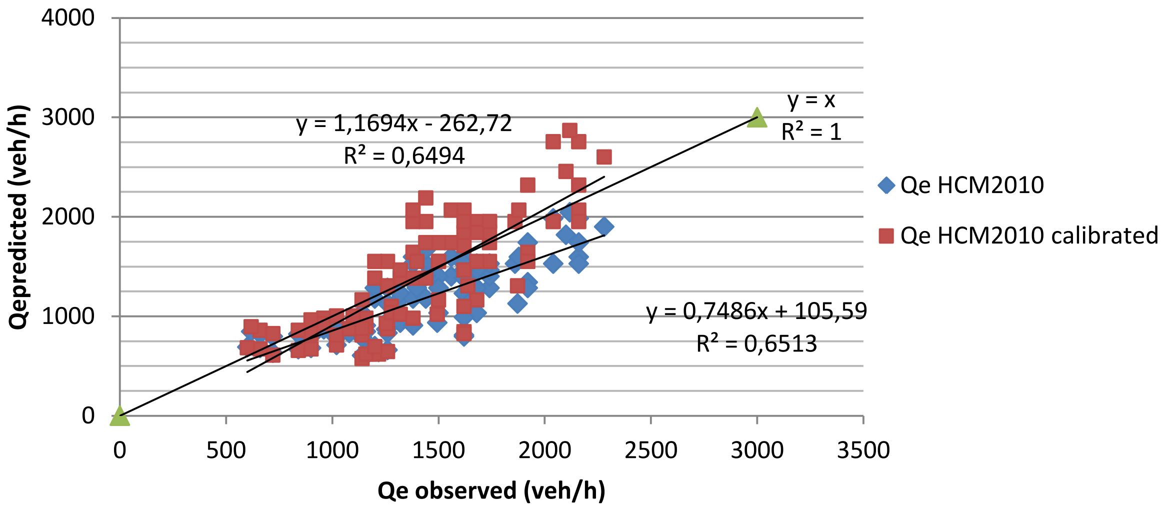

Figure 4.10 : Linear regression between $\boldsymbol{Q_e}$ observed values and estimated values of Calibrated model.

A linear regression is done between estimated values of Tanyel-Yayla's empirical formulation and HCM 2010 values shown in Figure 4.11. Correlation coefficients are

r^2 = 0,6151 and r^2 = 0,6513 respectively. The linear relation between observed values and predicted entry capacities are given in Equation **4.17** and **4.18** for calibrated model and HCM 2010.

$$Q_{epredicted} = 0{,}6756\ Q_{eobs} + 420{,}76 \quad \textbf{(4.17)}$$

$$Q_{epredicted} = 0{,}7486\ Q_{eobs} + 105{,}59 \quad \textbf{(4.18)}$$

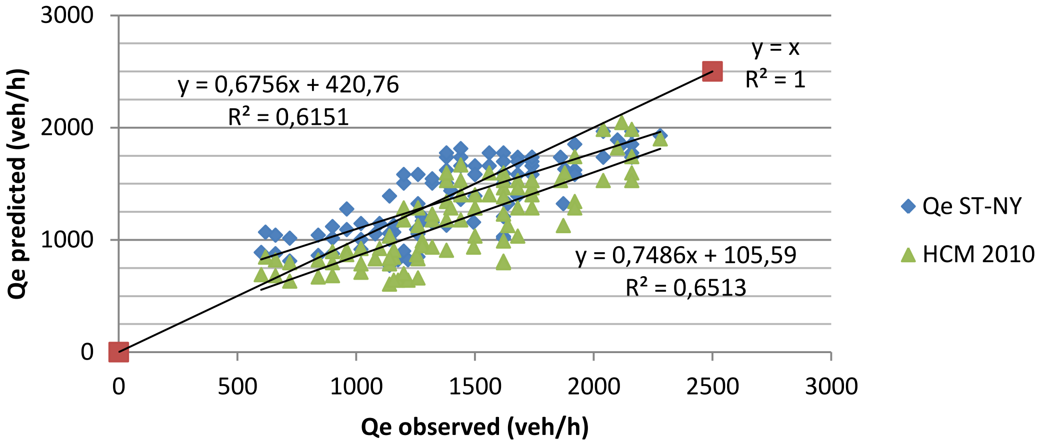

Figure 4.11 : Linear regression between $\boldsymbol{Q_e}$ observed values and estimated values of ST-NY model.

It is seen that HCM 2010 gave more accurate results than Tanyel and Yayla formulation. In order to obtain smaller correlation constants, both methodologies should be considered under reverse priority conditions. Akçelik's formulation calibrated according to limited priority and HCM 2010 results are presented in Figure 4.12. Where correlation coefficient of Akçelik's calibrated model is r^2= 0,6347 with linear formulation in Equation **4.19.**

$$Q_{epredicted} = 0{,}746\ Q_{eobs} + 601{,}72 \quad \textbf{(4.19)}$$

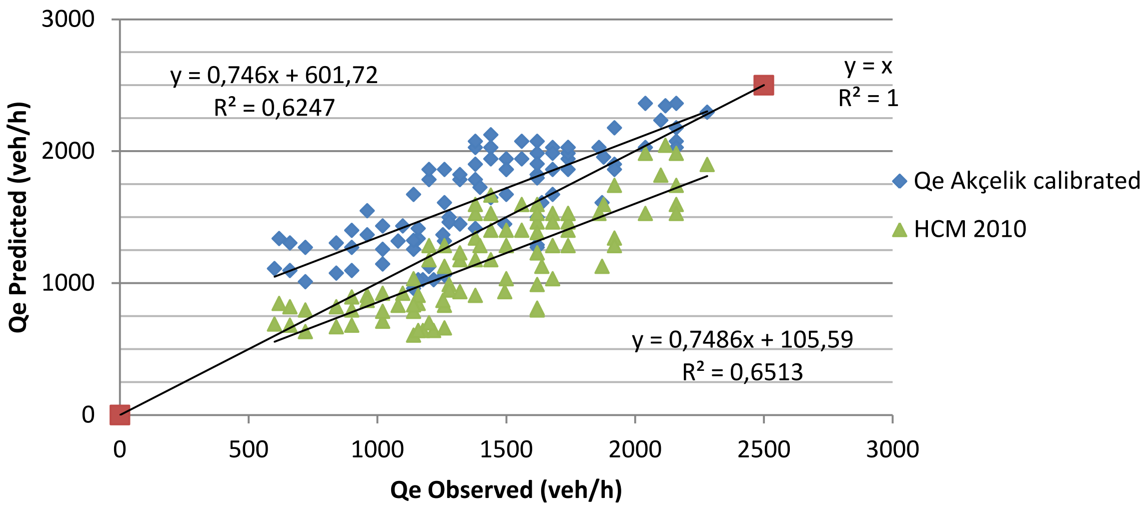

Figure 4.12 : Linear regression between Q_e observed values and estimated values of Akçelik's Calibrated model.

In Figure 4.13 HCM 2010, Tanyel -Yayla empirical formulation and HCM 2010 calibrated formulation entry capacity estimates are shown.

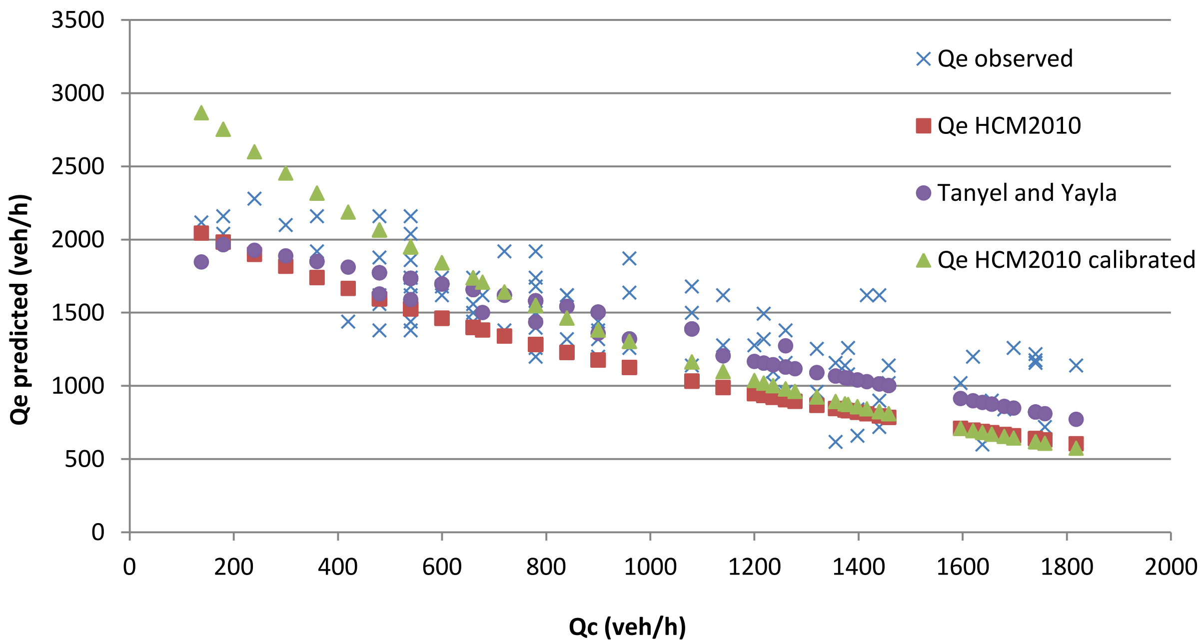

Figure 4.13 : Comparison of HCM 2010 with other models.

4.3.4 Sensitivity analysis on HCM 2010

Besides HCM 2010 default values seem to give lower capacity estimates than gap acceptance and regression methods, it should not be forgotten that it is also possible to calibrate HCM formulation with Equation **3.21** and Equation **3.22** .

The potential impact of T_c and T_f in capacity estimate is examined by varying the two main parameters between minimum and maximum limits under different circulating flows as given in Table 4.3.

Table 4.4 : Minimum and Maximum values of $\boldsymbol{T_f}$ and Tc parameters for roundabouts (Akçelik,1998).

	MINIMUM(sec)	***MAXIMUM(sec)***
Follow-time (Tf)	1.2	4.0
Critical Gap (Tc)	2.2	8.0

Circulating flow values are fictitious those range such 1 veh/h to 1600 veh/h with 100 veh/h intervals. Minimum and maximum values of $T_f$and T_c parameters for roundabouts are used (Akçelik,1998). Change of capacity estimate with parameter T_f and Tc are shown in Figure 4.14 and Figure 4.15 respectively.

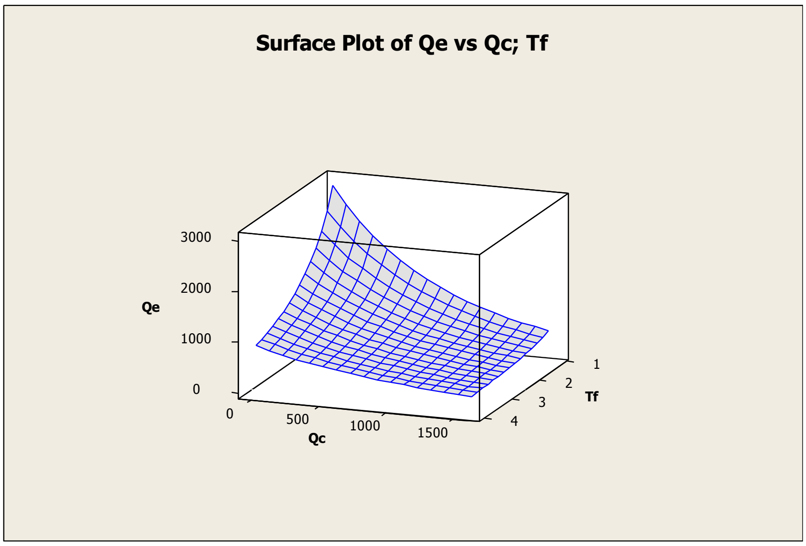

Figure 4.14 Change of capacity estimate with parameter $\boldsymbol{T_f}$.

As can be seen from above figures, HCM 2010 calibrated formulation estimates higher capacity for entry if smaller critical gap and follow up values are accepted by drivers.

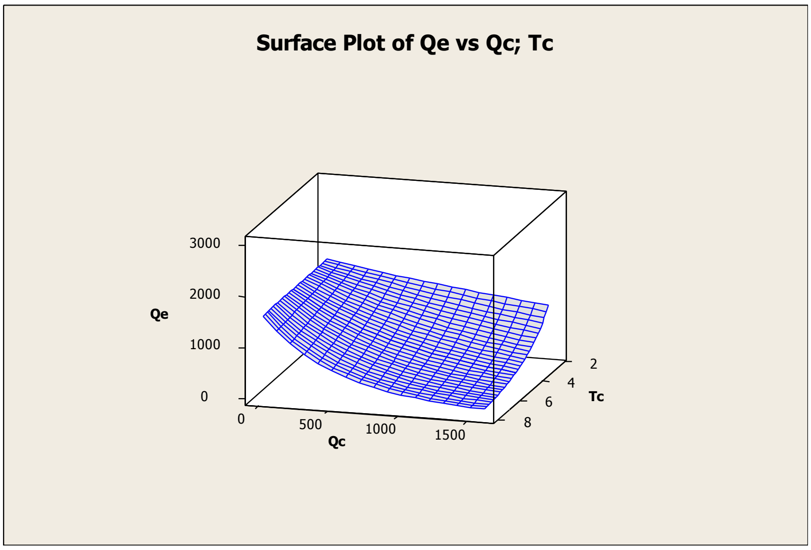

Figure 4.15 : Change of capacity estimate with parameter Tc.

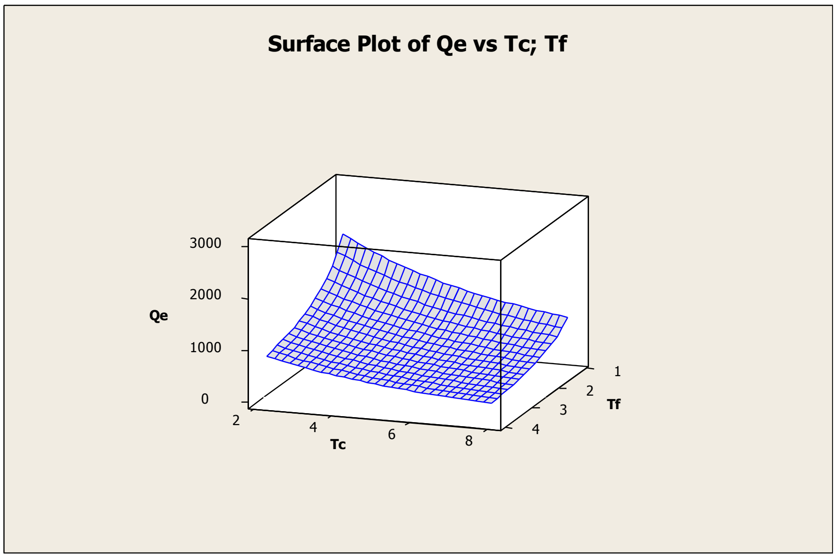

Figure 4.16 : Change of capacity estimate with parameter Tc and $\boldsymbol{T_f}$.

Scatter of entry capacity data make sharper increases when lower follow up times are accepted by drivers. It is also possible to say from Figure 4.16 that, entry capacity estimate is more sensitive to changes on follow-up parameter than critical gap.

4.4 Discussion on Conducted Capacity Analysis

Based on the findings of this study, it is possible to say that HCM 2010 default values remains incapable to define entry capacities because of the gap forcing and priority reversal conditions exist on investigated roundabouts. In order to avoid over-design as a result of lower capacity estimates, driver behaviors and merging conditions should be defined inside HCM 2010 formulations.

All capacity models examined in this study, considered entry capacity for one approach of a multi-lane roundabout. Taking all approaches of the roundabout as a whole for capacity estimation can give more realistic results. Under this circumstance, neglected exiting flow effects on entering approaches could also be considered.

The TRL analysis performed in the study gave higher capacity estimations, especially for Lozan roundabout. Inadequate geometric features of the roundabout can be regarded as a cause of regression models failure. Gap acceptance models gave more accurate results than regression models. In order to achieve better results by varying critical headway and follow-up values for more observation data groups.

For more adequate correlation coefficients on studied models, reversal priority and gap forcing conditions should be considered during the evaluations. It is also useful to mention that increasing number of observed data for different approaches could regenerate scatter of predicted capacity estimate.

5. CONCLUSIONS AND SUGGESTIONS

In this study, data obtained from one approaching leg of two roundabouts in Izmir are studied in order to make comparison between HCM 2010 default values and a regression model, and gap acceptance model, calibrated models and an empirical formulation.

Gap acceptance and regression models generally resulted in higher values than HCM 2010 default value formulation. Especially for high circulating volumes gap acceptance methodology is found to be more accurate than HCM 2010 default value estimations and regression analysis. Lower capacity estimate of HCM 2010 under high traffic volume is regenerated by using calibrated formulations. On the other hand HCM 2010 gave better capacity estimations than empirical formulations defined by Tanyel and Yayla (2010). Results obtained are valid for sample roundabouts because of site specific characteristics. Within the calibrated model it is possible to obtain specialized results for different site conditions using T_c and T_f values.

In this study the obtained data groups are limite**d**. To achieve better results the number of examples should be increased and a detailed research should be done on the effect of driver behaviors for capacity estimation.

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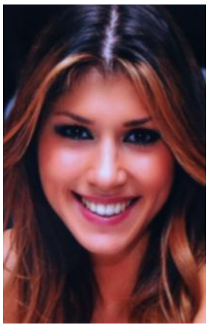

Dikilitas Mah. Tuğrul sok. Arifbey
Apt. No:4 Daire:15 Besiktas / Istanbul
+90 532 520 25 73 ers.melike@gmail.com

MELİKE ERSOY

Personal Information

Date of Birth/ Place	: 07.02.1987 / ISTANBUL
Nation	: Republic of Turkey
Driving License	: Type B

Education

2008-2012 ***Istanbul Technical University***
Institute of Science and Technology
Master of Science inTransportation Engineering

2010-2011 ***University of Trento***
Engineering Faculty
Master of Science in Road Engineering

2004-2008 ***Istanbul Technical University***
Faculty of Civil Engineering,
Bachelor of Science in Civil Engineering

2001-2004 ***Kabatas Erkek Lisesi***

Internships

2007 Sept ***Koray Construction and Engineering Co***.,
Putzmeister Concrete Pumps Factory Construction (Technical Office)
Çerkezköy-Tekirdağ

2006 Aug. ***Bahadır Construction Company***,
Putzmeister Concrete Pumps Factory Construction (pre-construction facilities)
Çerkezköy-Tekirdağ

Work Experience

2011-2012 ***Invistone Financial Solutions***
Financial Reporting and Analysis
Analyst

2008-2010 ***IHI (Ishikawajima-Harima Heavy Industry – IHI Corporation)***
The Seismic Reinforcement Project for Large Scale Bridges in Istanbul
Planning Engineer, Quality and Safety Engineer
Karayolları 17. Bölge Kontrollük Şantiyesi Sarıyer-İst

2008Aug. – Oct ***ERS Road Construction Company***,
(KIPTAS,Housing Development Administiration of Turkey)
Ground stabilization and road construction
Site Engineer

Computer Skills

Computer and Operating Systems – Windows XP and Vista
Application Packages – MS Office (Advanced)
Others – Autocad (Advanced) , Primavera (Basic), MS Project (Basic)

Languages

Turkish – Native
English – Fluently written and spoken
Italian – Basic

Extra-curricular Activities

American Society of Civil Engineers (student member)
ITU MHK Balkan'07 Technical Trip (Bulgaria, Romania, Albania , Serbia, Macedonia)
Kabataş Erkek Lisesi Alumni Association

References

- Rufat Ibrahimov, CFA, Partner
  Invistone Financial Solutions
  rufatibrahimov@invistone.com

- Hiroshi YATSUO Construction Manager
  IHI Corporation
  Karayolları 17. Bölge Kontrollük Şantiyesi
  34470 Sarıyer/ İstanbul
  Tel. : +90 212 229 60 39
  h_yatsuo@ihitr.com

- Doç. Dr. Hilmi Berk ÇELİKOĞLU Academician of Istanbul Technical University
  Civil Engineering Faculty
  TR-80626 Maslak /Istanbul
  Tel. : +90 212 285 37 98
  celikoglu@itu.edu.tr