Thesis 237

Evaluation of right turn on red at signalized intersections with VISSIM

- A pilot study for a more mobile Lund

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Keywords:
Signalized intersection, RTOR, microscopic simulation, vissim, delay, traffic safety.

Abstract:
This thesis evaluates the contribution to the efficiency of the transportation system, using microscopic simulation, with right turn on red (RTOR) at signal controlled intersections allowing the movement. The purpose is to measure the time savings in reduced delays in the transport network. Furthermore, to evaluate whether RTOR movement is a positive, safe and a good way to reduce not only the delays but also the emissions from traffic and the increased air pollution which occurs as a result of the increasing population and travel demand around the world. Additional purposes have been to study the traffic safety and how it relates to vehicles, bicycles, and pedestrians; fuel consumption, and emissions with current oil prices. The advantages and disadvantages of right turn on red are usually the delay savings and accident risks, respectively. The most common RTOR-related accidents and accident data are therefore analyzed. The data used was collected in field studies, at 10 various intersections in Phoenix, Arizona (USA) and at the intersection of Malmövägen and Ringvägen in Lund (Sweden). VISSIM was used to build and run a microscopic simulation model for both the AM peak-hour and the PM peak-hour, with and without a RTOR movement. The conclusion is that RTOR is beneficial for the intersections in Phoenix and would also be beneficial at the intersection in Lund. An additional conclusion is that the fuel savings are approximately 3 percent for the AM peak-hour and slightly less than 1 percent for the PM peak-hour.

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Summary

Title: Evaluation of right-turn on red at signalized intersections with VISSIM - A pilot study for a more mobile Lund.

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With increasing traffic environmental problems such as congestion and queuing are arising. Human behavior and lifestyle of today's people has changed over time and requires new amount of energy to perform various activities. Traffic congestion in urban areas is an important topic since it influences many major parts of our infrastructure. Heavy congestion can result in large delay times for important transportations which in a wider sense, can affect the economic growth. For businesses, it decreases productivity and increases labor costs. Also, from the drivers point, congestion leads to higher speed fluctuations and frequent stops which increases the fuel consumption and consequently result in higher emissions.

This thesis looks at how right-turn on red (RTOR) legislation would affect the efficiency and the delay at four-legged signal controlled intersections in Sweden compared to the intersections in Phoenix, Arizona (USA). Since the intersections in Sweden, especially Lund, have generally higher pedestrian and bicycle volumes compared to the intersections in Phoenix, a concern was raised about the performance of RTOR. Furthermore, it was not sure whether RTOR would be applicable to Lund´s transportation system due to these many cyclists and pedestrians.

The purpose of this thesis is to study the efficiency of right turn on red (RTOR) in Lund, Sweden, which will be done by first studying the RTOR in Phoenix (USA) and then trying to apply it to similar conditions in Lund. The key question is whether the legislation of right turn on red is a positive and effective way to reduce delays in the transport network with regards to what it means for the accident risks?

An additional purpose is to study the traffic safety and how it relates to vehicles, bicycles, and pedestrians; fuel consumption, and emissions.

The method used in the thesis consists of three major parts: a literature study, data collection and data analysis. This is to cover the necessary information needed to understand and complete this thesis. The literature study was carried out through the thesis with focus on subjects such as signalized intersections, current legislations in the U.S. and in Sweden, classical measures and definitions such as delay, level of service, gap acceptance and also the theory behind micro simulation and the software VISSIM.

The data collection contains field studies, model building and data processing. In the data analysis all results were compared and different hypotheses were tested.

The signalized intersection consists of legs which are all controlled by signals and who pass through three successive periods repeated in a cyclic way - the green period, the amber period and the red period. Some of the factors that influence the use of a RTOR movement are the demands for right-turn movements, sight distance at the intersection approach, degree of saturation of conflicting through movements and conflicts with pedestrians and bicycles. The RTOR movement can be blocked if the number of pedestrians and bicyclists crossing perpendicularly to the vehicle is too large. The possibility to find a gap for the RTOR movement will become harder to execute during the red phase.

A microscopic simulation model describes the system entities with its activities and interactions at high level of detail and makes it possible to follow individual vehicles through the network. The selected simulation software VISSIM uses a discrete, stochastic, microscopic time-step and behavior based simulation model. VISSIM considers a physical and physiological aspect of the driver and is a car-following logic which uses dynamic speeds. Stochastic distributions of speed and spacing thresholds reproduce individual driver behavior characteristics.

Ten signalized intersections with a permitted RTOR located in the Phoenix urban area were selected as the basis for this thesis. The intersection of Malmövägen and Ringvägen in Lund was chosen as the study object in Sweden since it is one of the most saturated intersections in Lund and makes a rather fair comparison to the chosen American intersections.

The results showed that RTOR is beneficial for the intersections in Phoenix and would also be beneficial at the intersection of Malmövägen and Ringvägen in Lund. It is an effective way to reduce the delay, especially the right-turn delay at signalized intersections. The benefits with RTOR would be greater in Lund than for the observed intersections in Phoenix. The results also indicate that the storage length plays an important role to a certain point, but the delay is most likely more affected by the possibility of finding sufficient gaps.

By doing on-site field visits of every intersection in Phoenix it could be confirmed that almost no vehicles come to a complete stop but rather a rolling stop or yielding maneuver where RTOR applied. This is a key factor that affects the acceleration and delay. The acceleration and stopping maneuver are significant factors on how effective RTOR will be in this case.

Keywords:
Signalized intersection, RTOR, microscopic simulation, vissim, delay, traffic safety.

Sammanfattning

Titel: Evaluation of right-turn on red at signalized intersections with VISSIM - A pilot study for a more mobile Lund.

Författare: Nataša Ćosić

Handledare: Shanthi Krishnan, Jacobs Engineering, Phoenix, USA
Anders Sjöholm, Ramboll, Malmö, Sverige

Examinator: Thomas Jonsson, Trafik och Väg, LTH

I en allt mer växande trafik uppstår problem som trafikstockningar och köande. Beteendet och livsstilen hos dagens människor har förändrats över tid och kräver nya mängder energi för att utföra olika aktiviteter. Trafikstockningar i stadsområden är ett viktigt ämne eftersom det påverkar många stora delar av vår infrastruktur. Överdriven trängsel kan resultera i höga fördröjningstider för viktiga transporter som i en vidare bemärkelse kan påverka den ekonomiska tillväxten. För företag minskar den produktivitet och ökar arbetskostnaderna. Även från fordonens synvinkel leder trängseln till högre hastighetsvariationer och tätare stopp, vilket ökar bränsleförbrukningen och resulterar i högre utsläpp till miljön.

Det här examensarbetet tittar på hur ”right turn on red” (tillåten högersväng vid rött) lagstiftningen skulle påverka effektiviteten och fördröjningen på signalreglerade fyrvägskorsningar i Lund jämfört med signalreglerade fyrvägskorsningar i Phoenix i delstaten Arizona (USA). Eftersom korsningar i Sverige, speciellt Lund, vanligen har högre andel fotgängare och cyklister än korsningarna i Phoenix, visste man inte om prestandan av högersvängen på rött skulle utgöra ett bekymmer.

Syftet med denna uppsats är att studera effektiviteten i RTOR i Lund, vilket utförs genom att först studera RTOR i Phoenix (USA). Tanken var att överföra RTOR på en korsning med liknande villkor i Lund för att avgöra om detta var tillämpbart. Den centrala frågan är om lagstiftningen om RTOR är ett positivt och effektivt sätt att reducera fördröjningarna i transportnätverket i förhållande till vad det innebär för olycksriskerna.

Ett ytterligare syfte har varit att studera trafiksäkerheten, bränsleförbrukningen och utsläppen.

Metoden för examensarbetet består av tre större delar: litteraturstudie, datainsamling och analys. Detta för att täcka den kunskap som behövs för att förstå samt utföra denna studie. Litteraturstudien genomfördes under arbetets gång med fokus på ämnen som signalerade korsningar, aktuella lagstiftningar i USA och i Sverige, klassiska mått och definitioner såsom fördröjning, framkomlighet, tidsluckor och även teorin bakom mikrosimulering och VISSIM.

Datainsamlingen omfattar fältstudier, modellkonstruktion och databehandling. I analysen jämförs alla resultat och olika hypoteser testas.

Signalreglerade korsningar styrs av signaler som passerar genom tre på varandra följande perioder i en cykel – en grön, en gul och en röd period. Några av de faktorer som påverkar användningen av en RTOR är efterfrågan av högersvängar, siktförhållanden i korsningen, flödet av tvärkorsande rörelser och konflikter med fotgängare samt cyklister. RTOR kan blockeras om antalet fotgängare och cyklister som korsar vinkelrätt mot fordonen är för stort. Möjligheten att hitta en tidslucka för RTOR rörelsen blir svårare att utföra under den röda fasen.

Mikrosimuleringsmodeller beskriver ett trafiksystems enheter med dess aktiviteter och interaktioner på en högdetaljerad nivå och gör det möjligt att följa enskilda fordon genom trafiknätet. Det utvalda simuleringsprogrammet VISSIM använder en diskret, stokastisk, mikroskopisk tidstegsbaserad modell.

Tio signalerade korsningar i Phoenix med tillåten RTOR valdes till studieobjekt i examensarbetet. Korsningen Malmövägen och Ringvägen i Lund valdes som studieobjekt i Sverige eftersom det är en av de mest trafikerade korsningarna i Lund och antogs utgöra en någorlunda rättvis jämförelse med de valda amerikanska korsningarna.

Resultatet visade att RTOR är fördelaktigt för korsningarna i Phoenix och skulle även vara fördelaktigt för Malmövägen och Ringvägen i Lund. Det är ett effektivt sätt att reducera fördröjningen, särskilt högersvängsfördröjningen på signalreglerade korsningar. RTOR skulle göra större nytta i Lund än vad den gör för de observerade korsningarna i Phoenix. Resultaten visar också att högersvängsfältets längd spelar en viktig roll till en viss punkt, men att fördröjningen sannolikt påverkas mer av möjligheten att finna tillräckligt stora tidsluckor.

Genom fältstudier av varje korsning i Phoenix kunde det bekräftas att nästan inga bilar kommer till ett fullständigt stopp, utan snarare ett rullande stopp eller väjande manöver där RTOR tillämpas. Detta är en viktig faktor som påverkar både acceleration och fördröjning. Accelerationen och stoppmanövern är viktiga faktorer för hur effektiv RTOR kommer att vara i fallet.

Nyckelord:
Signalreglerad korsning, RTOR, mikroskopisk simulering, vissim, fördröjning, trafiksäkerhet.

Preface

This thesis was done at the Department of Technology and Society at Lund Institute of Technology, Lund University.

It is a pleasure to thank the many people who made this thesis possible. First and foremost, I would like to gratefully thank my examiner and associate professor Thomas Jonsson at Lund University; both my supervisors Shanthi Krishnan, at Jacobs Engineering Group Inc. in Phoenix, Arizona (USA) and Anders Sjöholm at Ramboll Sweden AB in Malmö for their dedication, direction, and discussions. All three of you have been very receptive to my ideas and your guidance, assistance, advice and comments have been very helpful and valuable to me in numerous ways. Without you I would not have achieved my goals for this thesis. Thank you also for introducing me to new and valuable contacts.

Secondly, special thanks and acknowledges to Allen Barakovic at Jacobs Engineering Group Inc. in Phoenix and Vinod Eadavalli at Jacobs Engineering Group Inc. in Florida. Both of you have always been there for me, especially weekends and late in the evenings. I would like to thank you both for introducing me to and guiding me through VISSIM, but more important and special for all your dedicated time, infinite patience, advice and for reviewing my work. You have both been very positive during the whole time and kept my motivation and mood up.

This thesis would have not also been possible without the support from Jacobs Engineering Inc. office in Phoenix for supplying workplace and VISSIM software. Thank you. An additional thanks to PTV AG in Germany for providing me with the student VISSIM license for my thesis work here in Sweden.

My final word goes to all the other people that I have been in contact with during the thesis progress, directly or indirectly, providing me with essential information and giving me the necessary support. I am highly thankful to all of you.

Lund, January 2012

Nataša Ćosić

MEASUREMENT CONVERSIONS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	foot	0.305	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
gal, us	US gallon	3.785	liters	L
gal, uk	British (imperial) gallon	4.546	liters	L
		SPEED & ACCELERATION		
ft/sec	feet per second	0.305	meter per second	m/s
mph	miles per hour	1.610	kilometer per hour	km/h
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.280	foot	ft
km	kilometers	0.621	miles	mi
		VOLUME		
L	liters	0.264	US gallon	gal, us
L	liters	0.220	British (imperial) gallon	gal, uk
		SPEED & ACCELERATION		
m/s	meter per second	3.281	feet per second	ft/sec
km/h	kilometer per hour	0.621	mile per hour	mph

Source: ADOT 2006, p.4

Contents

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ADOT	Arizona Department of Transportation
ALISS	Accident Location Identification Surveillance System
AASHTO	American Association of State Highway and Transportation Officials
Ave	Avenue
Dr	Drive
EBR	Eastbound right
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
KM	Kilometers per hour
LOS	Level of service
MAG	Maricopa Association of Governments
MCDOT	Maricopa County Department of Transportation
MPH	Miles per hour
NBR	Northbound right
NHTSA	National Highway Traffic Safety Administration
RTOR	Right turn on red
RT	Right-turn
SBR	Southbound right
St	Street
WBR	Westbound right

1 Introduction

1.1 Background

With increasing traffic environmental problems such as congestion and queuing are arising. Human behavior and lifestyle of today's people has changed over time and requires new amount of energy to perform various activities. Traffic congestion in urban areas is an important topic since it influences many major parts of our infrastructure. Heavy congestion can result in large delay times for important transportations which, in a wider sense, can affect economic growth. For businesses, it decreases productivity and increases labor costs. Also, from the drivers point, congestion leads to higher speed fluctuations and frequent stops which increases the fuel consumption and consequently results in higher emissions.

Right turn on red (RTOR) or simply right on red means that a vehicle at a traffic signal is allowed to turn right, during the red phase, provided no conflicts occur with intersecting traffic or other road users. Pedestrians, bicyclists and oncoming traffic must in other words be given priority (ADOT, 2011, p. 37). Stop duty always applies before reaching the crosswalk which is why the maneuver has also been referred to as right turn on red after stop or shortly RTORAS (McShane & Roess, 1990). The definition and treatment of RTOR specified in the Uniform Vehicle Code (UVC) §11-202(c)3 and established by the National Committee on Uniform Traffic Laws and Ordinances (NCUTLO) reads as follows:

"Except when a sign is in place prohibiting a turn, vehicular traffic facing any steady red signal may cautiously enter the intersection to turn right, or to turn left from a one-way street into a one-way street, after stopping as required by subsection (c)1 or subsection (c)2. After stopping, the driver shall yield the right of way to any vehicle in the intersection or approaching on another roadway so closely as to constitute an immediate hazard during the time such driver is moving across or within the intersection or junction of roadways. Such driver shall yield the right of way to pedestrians within the intersection or an adjacent crosswalk."

In 1937 RTOR was approved for the first time in the state of California in the United States of America (USA). At first, the legislation only applied to intersections with an authorized sign, but then came to change and applied at every intersection except where signs prohibited the movement (McShane & Roess 1990, p. 411).

The use of RTOR grew slowly and came to be associated by the Federal Government as part of possible energy efficiency measures in the 1970's oil crisis that the USA went through. Since January 1, 1980, all 50 states and the District of Columbia and Puerto Rico have adopted the definition and permitted drivers to make a RTOR when it is safe to do so or unless there is a sign or signal prohibiting this. The situation is only reversed in New York City where a sign is required to permit such act (McShane & Roess 1990, p. 411; NHTSA 1995, p.1, p.5).

The advantages and disadvantages of right-turn on red are usually the delay savings and accident risks respectively. Other advantages are the reduced congestion by decreasing approach delays, lower fuel consumption, and reduced emissions from cars (McShane & Roess 1990, p. 413).

It is generally illegal to turn right at a red light in the European Union member states unless otherwise is indicated or being illustrated by a green arrow on a red light, a flashing yellow arrow, a permanent green box next to the red light or similar. The arrow indicates the regulated direction (Trafikverket 2004, p. 20-21).

This thesis investigates how a RTOR movement would affect the efficiency and the delay at a four-legged signal controlled intersection in Lund, Sweden, to see whether it is possible to reduce the delay further for the right turning traffic by establishing the RTOR law. The amount of pedestrians and bicyclists perpendicular to the vehicles turning right on red are one important parameter for the RTOR movement and differs greatly between Phoenix, in the USA and Lund. Perhaps RTOR is something Lund or other cities in Sweden can adopt and begin to use as a possible energy efficient measure similar to the USA? The savings with a RTOR can possibly save fuel and money, especially with Swedish oil prices, without having a too big negative impact on the traffic safety.

1.2 Purpose

The purpose of this thesis is to study the efficiency of right turn on red (RTOR) in Lund, Sweden, which will be done by first studying the RTOR in Phoenix (USA) and then trying to apply it to similar conditions in Lund. The key question is whether the legislation of right turn on red is a positive and effective way to reduce delays in the transport network with regards to what it means for the accident risks?

Congestion leads to higher speed fluctuations and frequent stops which increases the fuel consumption and result in higher emissions. An additional purpose is to study the traffic safety and how it relates to vehicles, bicycles, and pedestrians; fuel consumption, and emissions with current oil prices.

1.3 Method

The method used in the thesis consists of three major parts: a literature study, data collection and data analysis. The data collection contains field studies, model building and data processing. In the data analysis all results were compared and different hypotheses were tested. This was done to cover the necessary information needed to understand and complete this thesis.

The literature study was carried out through the thesis with focus on subjects such as signalized intersections, current legislations in the USA and in Sweden, traffic safety with RTOR, classical measures and definitions such as delay, level of service, gap acceptance and also the theory behind micro simulation and the software VISSIM. The literature study was required to be able to make conclusions in the end and to understand how VISSIM works and processes different parameters.

VISSIM microscopic computer software was used for this traffic analysis since it is the most common traffic simulation software today in Sweden. The thesis in turn consists of two additional parts: an American and a Swedish part. The American part was implemented at Jacobs Engineering Group Inc in Phoenix and the Swedish part was performed in Sweden at Ramböll in Malmö.

All intersections were built in VISSIM for both the morning (AM) and the afternoon (PM) peak-hours. These two models were then modeled with both RTOR and without RTOR. The total number of models resulted in four models for each intersection. The models are identical in geometry but different in other aspects. Each individual model was run a total of ten times and the results were averaged. The models where then compared against one another to show the benefit, if such existed, of a RTOR movement. Using the average values obtained from each model, all hypothesis were tested either by comparing the difference in the intersection delay, approach delay or the right turn delay. The approach of the model building is shown in Figure 1.1.

Only one intersection, Malmövägen and Ringvägen, was considered and observed in Lund due to time limitations and the detail of the different tests that were carried out at the intersection. The intersection in Lund was exposed to changes, with and without RTOR, in the lane configuration, storage length, the cross-intersecting flow and in the amount of pedestrians and cyclists. It was then analysed.

Peak-hour turning movement volumes for the Phoenix intersections in this thesis were obtained through counts that were conducted in year 2010 between April 22 and June 10 by United Civil Group (UCG) and submitted to Jacobs Engineering Group Inc in Phoenix. Synchro plus Simtraffic 6 was used to optimize the signal timings for all the intersections in Phoenix since these couldn’t be received from the applicable jurisdiction. These were later imported in VISSIM. Several field studies and on-site visits were also performed to receive information of the signal control types (controller and signal heads) and to verify intersection lane configuration and storage lengths.

Field studies were also conducted on the Malmövägen and Ringvägen in Lund to receive the turning movement count data and pedestrian/bicycle data since recent data could not be received from the City of Lund or another source. Verification of the geometric, traffic and signalization conditions were studied and noted. Signal control types (controller and signal heads), intersection lane configuration and storage lengths were implemented during the on-site visit. Signal phasing plan (diagram) and functional description were obtained from the City of Lund, see Appendix A.

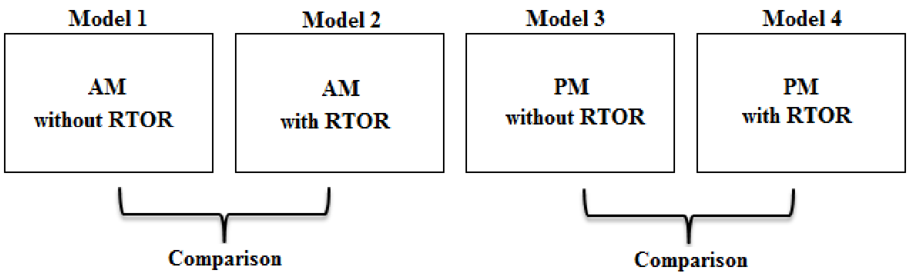


Figure 1.1 Simulation approach and model building.

1.4 Limitations

Due to time restraints, this study has been limited to only study RTOR. As described later in the thesis, VISSIM default values are used and explained where applicable. Default values from VISSIM were also used for the gap acceptance. A more detailed look at gap acceptance was not done because it would entail many more factors that would be outside of this study.

The investigated intersections, in both Phoenix and Lund, are also limited to only the intersections themselves. The contributions of surrounding intersections were not observed.

This thesis only has its focus on VISSIM since it is the leading microscopic simulation program in Europe and due to the time it takes to immerse into new software. Comparisons between VISSIM and other traffic software such as Synchro, CORSIM and others are not included in this thesis, which was originally intended.

1.5 Hypotheses

The first hypothesis H1 (a and b) and last hypothesis H7 were the base for this thesis and the other hypotheses were developed during the literature study, field study and VISSIM model building. The hypotheses are sorted by their appearance in the result chapter.

H1a - The delay at signalized intersection is lower where RTOR is permitted compared to where RTOR is prohibited in both AM and PM peak-hours.

H1b - The benefit from a RTOR will prove to be less for Malmövägen and Ringvägen (than the intersections in Phoenix) due to the pedestrians and bicyclists.

Hypotheses H1a and H1b are related and were formulated during the initiation of the study to evaluate the contribution of the efficiency to the transportation system with RTOR.

H2 - The right-turn movements have a bigger benefit in delay than the intersection as a whole.
H3 - Minor roads have a larger benefit in delay from RTOR than major roads.

Hypothesis H3 was formed to see the difference in benefit depending on if the road is a major or minor road and is a result of the reflection during the field studies. Minor streams always have lower priority and less green time than the major streams and that is why a RTOR should benefit the minor roads more in pursuit of the drivers taking advantage of RTOR.

H4 - Lane configuration plays an important role. An exclusive right-turn lane benefits the RTOR movement further and results in larger reduction in delay.

Hypothesis H4 is a result of a discovery during the field study and literature study. The existence of an exclusive right-turn lane will increase the usage of RTOR. If the right lane is a shared through and right-turn lane and RTOR is permitted and the approaching vehicle at the STOP bar is not a right-turning vehicle, the following right-turning vehicles will be prevented or blocked from making the RTOR maneuver by the through vehicle. The driver wanting to make a right-turn will be forced to wait until there is green signal display to make the turn. If, however, the approaching vehicle is a right-turning vehicle, the driver has the potential to make the RTOR movement and reduce its delay.

H5 – The reduction in delay will be small with an extended storage length.

The expected number of RTOR vehicles is greater with a sufficiently large storage length. On the other hand an infinitely long storage lane will in the end cause queuing and RTOR will be cancelled by the signal phase turning green.

H6 - The intersecting flow is of great importance for the implementation of a RTOR movement.

Hypothesis H6 was formulated due to the assumption that a larger intersecting flow will prevent more vehicles from making a RTOR because of a greater difficulty in finding an acceptable gap in joining the intersecting stream.

H7 – Pedestrians and bicyclists perpendicular to the right-turning vehicles have an impact on the effectiveness of RTOR.

Hypothesis H7 was formulated just as the hypothesis H1 during the initiation of the study since the intended RTOR movement can be affected or blocked if the number of pedestrians and bicyclists crossing perpendicularly to the vehicle is too large. The possibility to find a gap for the RTOR movement will become harder to execute during the red phase. Since the intersections in Sweden have generally more pedestrians and cyclists compared to the intersections in Phoenix (USA) it made this seen as a concern to perform a RTOR. This hypothesis will be of a critical nature to see whether RTOR is applicable to Lund´s transportation system.

1.6 The report's structure

This thesis starts in Chapter 2 with a literature study of the signal controlled intersections background and function. This is followed by a short description of what a traffic model is and how the traffic model VISSIM is built. This provides the background and understanding of how the model works.

Chapter 3 describes the data collection and the required input data. Chapter 4 explains how the VISSIM model has been built and simulated. Chapter 5 covers the calibration and validation of the VISSIM models while Chapter 6 provides an analysis of the traffic safety and accidents with RTOR. All the results are presented and discussed in Chapter 7. The report ends in Chapter 8 with conclusions and recommendations for further studies. The structure of this thesis is visualized in Figure 1.2.

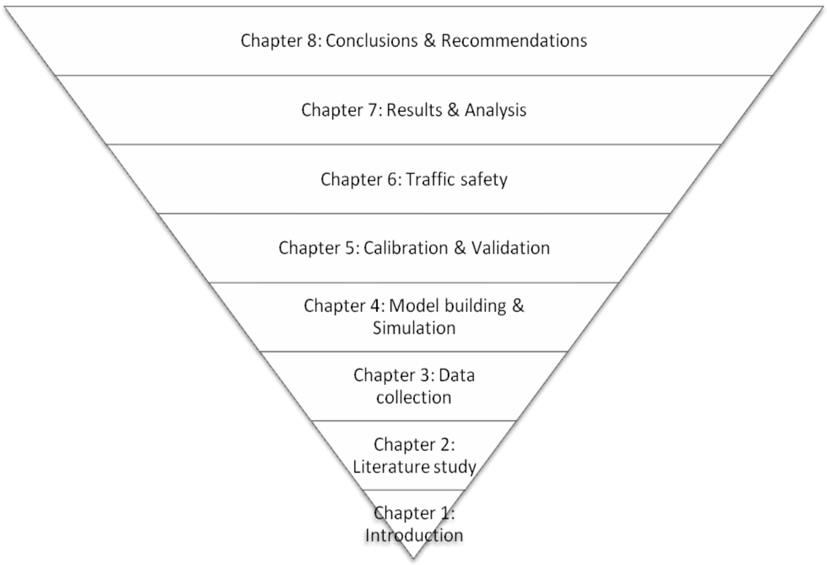


Figure 1.2 The report´s structure

2 Literature study

The literature study aims to provide the necessary qualification and understanding to complete this thesis. The literature study begins with general information about signalized intersections followed by current regulations with RTOR in the U.S. and Sweden. Traffic signal control type is one important key element. Traffic safety is another important factor in this thesis. The theory behind traffic simulation models is presented together with the selected software VISSIM to provide the essential understanding of how the model works.

2.1 Signalized intersections

General

An intersection is the area where two or more roads carrying traffic streams in different directions intersect or cross. The space which is common to all these roads is referred to as the intersection. Sidewalks and crosswalks are also considered to be within the intersection. Different traffic streams compete for the common space with each other, which is periodically given to some flows while other conflicting streams are blocked from entry at that time. The common space is separated in time between the different flows. The movements of users are assigned by traffic control devices such as yield signs, stop signs, and traffic signals (Chakroborty & Das 2005, p. 95-96). The signalized intersection consists of legs which are all controlled by signals and which pass through three successive periods repeated in a cyclic way- the green period, the amber period and the red period (Chakroborty & Das 2005, p. 134). See Figure 2.1 for the geometric design of an intersection and its key features.

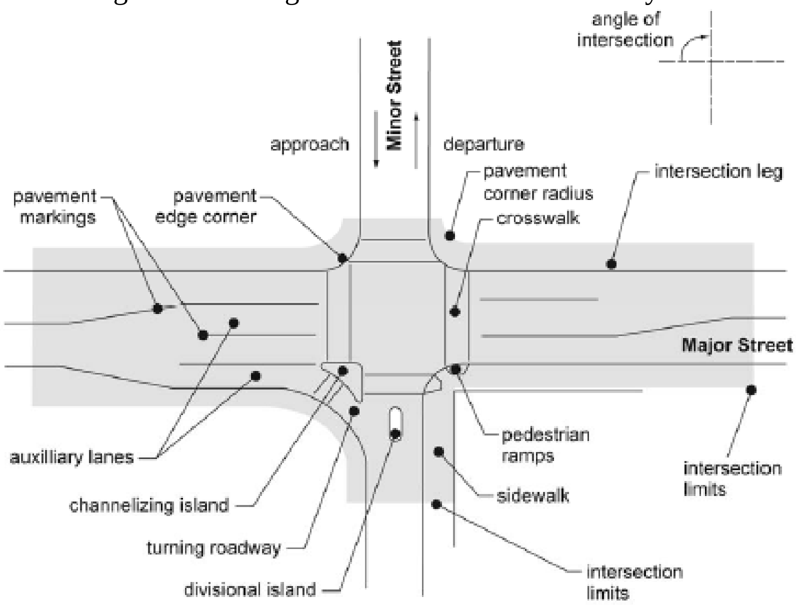


Figure 2.1 Intersection terminology (MassDOT 2006, p.6-4)

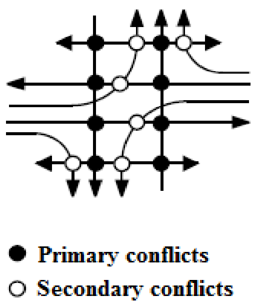
A signalized intersection is divided into two different traffic streams, major and minor streams. Minor streams have always lower priority than the major streams and are the intersecting street with less traffic volume and a smaller cross-section. The major street is the intersecting street with greater traffic volume, larger cross-section and has a higher functional class than the minor (MassDOT 2006, p. 6-3).

Additional lanes called *auxiliary* or *turning lanes* are sometimes added at the intersections which helps accommodate motor vehicles that make turns at the intersection. These auxiliary lanes can also be used to add through lanes through an intersection. In order to delineate the area in which vehicles can operate and to separate conflicting movements, the addition of *channelizing* and *divisional islands* may be necessary. These islands can also serve for pedestrian refuge. Both motorized and non-motorized traffic is assigned the right of way by *traffic control devices*. These traffic control devices include vehicular traffic signals, pedestrian traffic signals, pavement markings, signs and other devices (such as raised pavement markings, flashing beacons, and electronic blank-out signs)(MassDOT 2006, p. 6-4).

The principle of signal controlled intersections is to eliminate conflicts between crossing vehicle streams by the time and distribute the accessibility between different road users. Signalized intersections use traffic signals to control the use of the intersection. Signal control can be used to improve the level of service (LOS) for automobile traffic from the secondary road by allocating capacity between access points and road user groups, increase the road safety, reduce environmental impact, or give priority to public service vehicles and emergency vehicles (Hydén 2008, p. 329).

Intersection conflicts and conflict points

There are two different types of conflicts that occur at a signalized intersection, primary and secondary, as shown in Figure 2.2. Primary conflicts or orthogonal conflicts are defined as the conflicts between intersecting traffic streams from intersecting access points that can not have green signal simultaneously. The secondary conflicts are other conflicts, such as between left turns and oncoming vehicles or between right-turns vehicles and pedestrians. The primary conflicts are always regulated by signals by the time separator and the secondary by traffic laws (Trafikverket 2004, p.9-10).



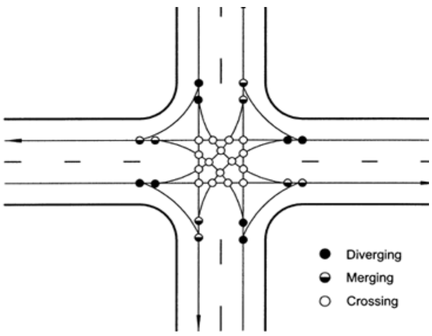


Figure 2.2 Intersection conflict points (Trafikverket 2004, p.10; FHWA 2004a, p.221).

There are a total of 16 crossing conflict points of which 12 crossing movements are related with left-turning vehicles. These types of conflicts are left turning vehicles interacting with oncoming vehicle. The four remaining crossing movements involve through movements on two adjacent approaches. All conflicts point are presented in Figure 2.2 (FHWA 2004a, p. 221).

During a permitted signal cycle phase, pedestrians cross the roads at signalized intersections perpendicular to the approaches. The pedestrian phase is included to coincide with the parallel traffic movement. One interaction that is not separated by time are the left- and right-turning vehicles interacting with pedestrians and cyclists, unless they have their own signal phase (FHWA 2004a, p.31). The typical conflicts between pedestrian/bicyclists and motor vehicles at a signalized intersection can be seen in Figure 2.3.

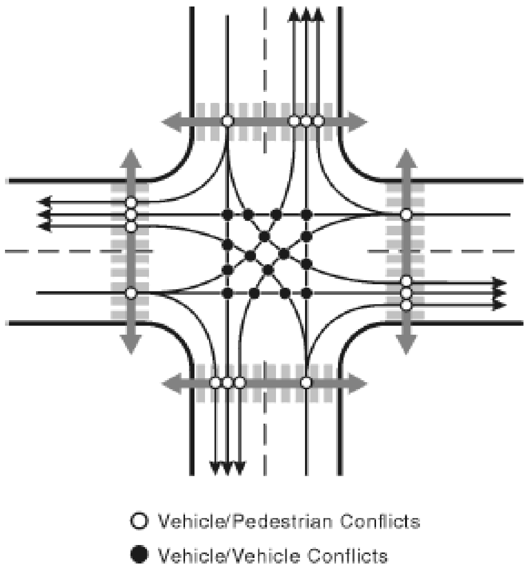


Figure 2.3 Pedestrian and bicyclist conflicts at signalized intersections (FHWA 2004a, p.31).

Four different types of conflicts are possible between vehicles and pedestrians/bicyclists. The first one is with vehicles turning right on red and pedestrians/bicyclists are crossing perpendicularly to the vehicle. The second collision type occurs in the same manner when vehicles are turning right on green without giving the right of way to pedestrians crossing in the parallel crosswalk. The third is with vehicles turning left on green at intersections with permissive left turns and pedestrians in the conflicting crosswalk. And the fourth is with vehicles running the red light and running over the conflicting crosswalks without any caution (FHWA 2004a, p.30-31).

Level of service

Level of service (LOS) for signalized intersections is defined in terms of the total average control delay per vehicle of all movements through an intersection. It is a measure of the delay occurred by motorists at an intersection. Each lane group is estimated and then aggregated for each approach and for the entire intersection, usually for a 15-min analysis period. LOS is directly related to the control delay value (TRB 2000, p. 16-2, p. 16-4, p.16-23). The control delay is a qualitative measure of the operational efficiency or effectiveness of a roadway. It is based on a number of different variables that relate to the driver discomfort, dissatisfaction, freedom to maneuver, fuel consumption and increased travel time. It is used to characterize operational conditions within a traffic stream (TRB 2000, p. 10-16).

Total delay is defined as the difference between the travel time in reality experienced and the reference travel time that would result during base conditions. Base conditions is the situation with absence of traffic control, delay caused by the geometrical design, possible incident and any other vehicles. It is a complex measure which depends on the development of movements through the intersection, the cycle length, the green ratio and the volume to capacity ratio (v/c) for the lane group (TRB 2000, p. 10-16).

The delay can later be translated into a level of service (LOS) description by facility type, based on the 2000 Highway Capacity Manual (HCM) definitions. Six (6) levels of service are defined and are designated by letters ranging from A through F, with LOS A representing the best range of operating conditions and LOS F representing the worst. The specific terms in which each level of service is defined vary with the type of facility involved. LOS D is acceptable for urban conditions while LOS B is acceptable for rural conditions (ADOT 2007, p.100-7). The LOS criteria for signalized intersections which are described in the Highway Capacity Manual 2000 (p. 10-16) are listed in Table 2.1.

The evaluation of the operation of signalized intersection requires analysis of both capacity and LOS conditions. LOS F does not necessarily indicate that the intersection, approach or lane group has exceeded its capacity, nor does an LOS E or better automatically indicate that the intersections has unused capacity available (TRB 2000, p. 10-16).

Two key outputs are received with the estimation and aggregation of the delay; the volume to capacity ratios for each lane group and for all of the critical lane groups within the intersection as a whole, and average control delays for each lane group and approach and for the intersection as a whole along with corresponding LOS.

A sign of actual or potential breakdown is characterized by a v/c ratio greater than 1.0 which requires further analyses. This means that the signal and geometric design provides insufficient capacity for the given traffic flows and that improvements need to be considered. Potential improvements may consist of basic changes in the intersection geometry with number and use of lanes, a longer signal cycle length and other changes in the signal phasing plan (TRB 2000, p. 16-23).

Intolerable high delays can appear at an intersection without any capacity problems, that is when the v/c ratio is low and still the delays appear high. These are the cases with poor progression or an inappropriately long cycle length, or both (TRB 2000, p. 16-24). Acceptable levels of delays can occur in two different situations with a v/c ratio near or above 1.0. One is if the time over which high v/c levels occur is short and the second is if the analysis is for only a single period and there is queue carryover (TRB 2000, p. 16-24).

LOS	**Description**	**Average Control Delay (sec/veh)**
A	Free flow. Operations with very low delay occurring with good progression and/or short cycle length. A few vehicles stop.	≤ 10
B	Stable flow with slight delays. Operations with low delay occurring with good progression and/or short cycle lengths.	> 10 – 20
C	Stable flow. Operations with acceptable delays resulting from rational progression and/or longer cycle lengths. Given green phase fail to serve queued vehicles and individual cycle failures begin to appear. Significant number of vehicles stopping, though many still pass through the intersection without stopping.	> 20 – 35
D	Approaching unstable flow with tolerable delay. Occasionally wait through more than one signal cycle before proceeding. Operations with unfavorable progression, long cycle lengths, or high volume to capacity (v/c) ratios. Many vehicles stop.	> 35 – 55
E	Unstable flow and intolerable delay. Operations with high delay values indicating poor progression, long cycle lengths, and high v/c ratios. Individual cycle failures arise more frequent. This is considered to be the limit of acceptable delay.	> 55 – 80
F	Forced flow with congestion. Operations with delays unacceptable to most drivers occurring due to over saturation, poor progression, or very long cycle lengths.	> 80

Table 2.1 Level of Service (LOS) criteria for signalized intersections (TRB 2000, p.10-16, p.16-2).

2.2 Gap Acceptance with RTOR

All unsignalized intersections consist of a hierarchy of streams. Some streams have total priority while others have to yield to higher order streams. The vehicles at unsignalized intersections must alone decide when it is safe to enter the intersection compared to the vehicles at signalized intersections which are controlled by the signal controller (Hydén 2008, p. 327). The vehicles at unsignalized intersections must respect the priority of other drivers and need therefore to look for a safe opportunity or adequately large “gap” in the traffic to enter the intersection. This procedure is defined as gap acceptance (Hydén 2008, p. 327; Troutbeck & Brilon 2002, p. 8-1, p.8-2).

A gap between two vehicles is the distance between the rear of the first vehicle and the front of the next vehicle and is measured in seconds, see Figure 2.4. A gap can be both accepted and rejected by a driver. If a driver uses a gap then the gap is accepted, if it is not accepted by the driver it is referred to as a rejected gap (Hydén 2008, p. 327; TRB 2000, p. 17-5; Troutbeck & Brilon 2002, p. 8-1, p.8-2).

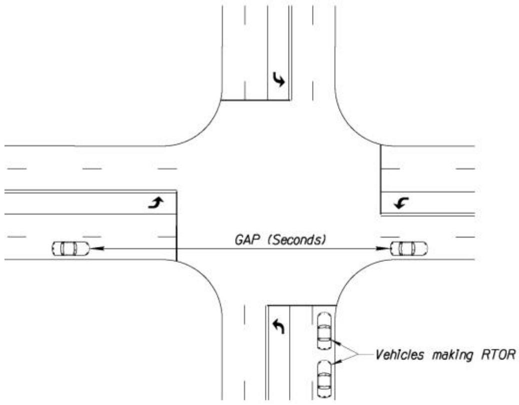


Figure 2.4 Definition of gap.

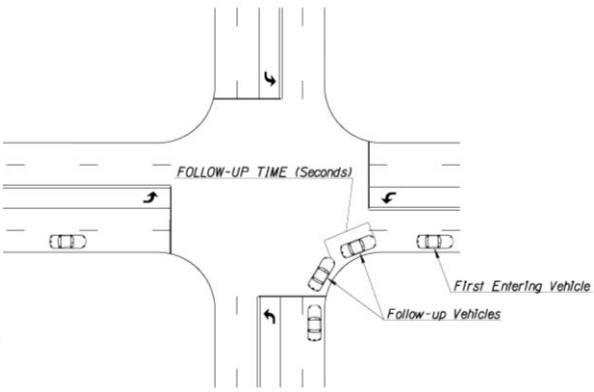


Figure 2.5 Definition of follow-up time.

Critical gaps and follow-up times are basic parameters in the gap acceptance theory. The critical gap is the smallest gap that a driver can accept to enter the intersection. All gaps smaller than the critical gaps are often rejected, and all gaps bigger than or equal to the critical gap are accepted (Hydén 2008, p.327; Troutbeck & Brilon 2002, p. 8-2). The following vehicles that are using a gap after the first vehicle are referred to as follow-ups. The follow-up time is the average time gap between two following vehicles entering the intersection, see Figure 2.5 (TRB 2000, p. 17-5; Troutbeck & Brilon 2002, p. 8-4).

The critical gap is individual and different drivers can have different views of how small of a distance they can accept or reject. It can also vary with the same driver, but for simplicity the same driver is idealized in the theory and expected to behave the same way every time at all similar situations (Hydén 2008, p.327; Troutbeck & Brilon 2002, p. 8-2).

Signalized intersections have two types of right-turns that use available gaps in the conflicting traffic stream. These are known as RTOR and the free right. (From this point right turn on red will be abbreviated as RTOR). A RTOR vehicle must stop at a red signal and may continue with the right-turn maneuver if an adequate gap appears in the conflicting traffic. A RTOR may be permitted from an exclusive right-turn lane or a shared lane. A free right is controlled by a yield sign and takes place from a separate and channelized right-turn lane. Before the free right-turn can be completed, the driver still needs to wait for an adequate gap to appear in the conflicting traffic stream. The distribution of available gaps at a signalized intersection will depend on the signal timing, traffic flows within each interval and other traffic characteristics (driver judgment in selecting gap to execute the right-turn, follow-up time and so on).

The gap can range in size from zero to a value on the order of the right-turn capacity while the signal is green for the approach serving the right-turn (Virkler & Krishna 1998, p. 47).

In 1998, Virkler and Krishna studied the gap acceptance for right-turns at signalized intersections through RTOR. They applied the existing methods of the Highway Capacity Manual (HCM), Sidra Intersection (previously called Sidra) and a stop sign analogy (SSA) at three signalized intersections and did a comparison between the measured and estimated gaps. Sidra Intersection is a micro-analytical traffic evaluation tool that complements Highway Capacity Manual as an advanced intersection analysis tool. It enables to evaluate alternative treatments involving signalized intersections, roundabouts, all-way stop sign control and more. The critical gap for the first intersection was observed for 186 vehicles of which 62 vehicles accepted a gap. The critical gap was measured to an average of 4.05 seconds. The second intersection observed 306 vehicles out of which 54 vehicles accepted a gap. The critical gap was measured to 4.47 seconds at this intersection. The third intersection had a critical gap of 5.54 seconds and 525 observed vehicles (36 accepted). The first follow-up time was measured to 2.89 seconds and the following to 2.56 seconds. Some of the measurements were close to the measured values. However, their conclusion in the end was that both the Sidra Intersection and SSA approaches have a tendency to overestimate the gap capacity. HCM procedures have a tendency to overestimate right-turn delay especially when RTOR maneuvers are observed. An over-estimated capacity leads to an underestimated delay and an incorrect determination of level of service and vice versa. They also concluded that a larger sample size would provide a better basis for their study since their study is based on a small sample size (Virkler & Krishna 1998, p. 53; Qureshi & Han 2001, p. 149).

There is no standard critical gap or procedure that can be applied when modeling with RTOR (Qureshi & Han 2001, p. 149). The Highway Capacity Manual (HCM) critical gap for a right-turn at an unsignalized intersection is 6.9 seconds for a four-lane street (two lanes in each direction) and 6.2 seconds for a two-lane street. The follow-up time for the same maneuver is 3.3 seconds. A greater gap than the critical gap will provide enough time for the first vehicle in a queue to make a right-turn. Gaps of 10.2 seconds (6.9+3.3 seconds) can provide enough time on a four-lane street for both the first and the second vehicle in the queue to execute a right-turn (TRB 2000, p. 17-7).

2.3 Traffic signal control type

Traffic signals are devices equipped with lights and audio signals that controls the signal indication at an intersection. The conflicting traffic flows are usually regulated by different signal indications in red, amber (yellow) and green light (TRB 2000, p. 10-16). A signal group can be in the following stages or switching sequences:

- Sleep mode
- Switching to green
- Green
- Switching to red
- Red

(Trafikverket 2004, p. 31-32).

The function of traffic control signals is to assign the right-of-way to the different traffic movements and affect the traffic flow (FHWA 2009, p.434). Their purpose is to increase road safety and to distribute the accessibility between different road users and road user types in different intersections in both rural and urban areas up to 70 km/h in Sweden (Trafikverket 2004, p. 9) and 96.5 km/h (60 mph) in Arizona (AASHTO 2004, p.72; ADOT 2007, p.100-3). The general recommendations and regulations for determination of controller phasing, permitted signal indication combinations for displays on an approach to a traffic control signal and the order in which signal indications can be displayed can be found in the *Manual on Uniform Traffic Control Devices (MUTCD)* in chapter 4.

There are various kinds of time sharing strategies between the different conflicting flows. A traffic signal can either operate in pre-timed or traffic actuated mode. Either type may be used in independent or coordinated operation with adjacent signal installations on the same route (Trafikverket 2004, p. 9-10; TRB 2000, p.10-14).

Pre-timed

A pre-timed traffic signal is provided with a predetermined time program which repeats at a fixed interval and cycle producing a constant cycle length. The green time and change and clearance interval is fixed for each phase (Hydén 2008, p.329; TRB 2000, p.10-14). Cycle length is referred as the sum of green, amber and red times for all movements (Chakroborty & Das 2005, p. 134). The time that a particular stream can use the intersection during the cycle length is known as the green time for that stream or movement. During the change over from green to red an amber signal is

shown to warn the driver that a red signal is pending. The vehicles of that movement are not allowed to use the intersection during the amber time, unless for preventing traffic hazard. The time during the cycle length which a certain movement cannot use the intersections is called the red time for that movement. Required time from one phase to the next or the time during which all indications are red, is defined as the safety time with the main purpose of evacuating the intersection before other traffic is admitted (Trafikverket 2004, p.9-10; TRB 2000, p.10-16).
All approaches get their share of green time during an entire cycle length. Approaches that get the green, amber and red indications at the same time are said to belong to the same phase. During a given cycle time a signalized intersection has usually two to six phases (Chakroborty & Das 2005, p. 134).

Fully actuated and semi- actuated

The traffic-controlled or actuated signal can be either fully actuated or semi actuated. Both types vary the amount of green time allocated to each phase based on traffic demand, and some phases may be skipped or displayed for their minimum duration if no demand is detected. Each phase has also a fixed minimum and maximum green time, which can be extended by reassigning unused green time from actuated phases with low demand. The fully actuated traffic signal controller is equipped with vehicle detectors on every approach while only some of the approaches (usually on the minor street) are provided with detectors where semi-actuated signal controller operates (TRB 2000, p. 10-14). An actuated-uncoordinated signal is not connected with the other traffic lights in the area. The opposite is for an actuated-coordinated signal (Husch & Albeck 2006, p. 4-5).

Both control the signal variation with the help from the different roadusers (motor vehicles, bicyclists and pedestrians) activating the detectors in the roadway and using the push button detectors (Hydén 2008, p.329). They have no predetermined time program and the cycle length varies from cycle to cycle (TRB 2000, p. 10-14).
Depending on the characteristics of the intersection and timing parameters (which are based on demand at the intersection) the time for each movement is received. A traffic-controlled signal provides lower delays as it adapts to the changing traffic conditions. The capacity is still the same for both the pre-timed and the traffic-controlled types of signal controls (Hydén 2008, p.329).

Signal modes

A traffic signal can either operate in a protected or permitted (permissive) mode or a as a combination of both for turning movements. A left or right-turn movement that is protected is given a green arrow signal on which only the turning traffic can be made during the display of the green signal indication, see Figure 2.9. This mode ensures the motorists, especially those making a left-turn, a period of time without conflict with other vehicles or pedestrians (Albeck & Husch 2006, p. 7-3, p. 7-5).

A permissive (or permitted) traffic signal, illustrated in Figure 2.10, is not protected and left and right-turning vehicles must yield during the permitted phase to any oncoming traffic and pedestrians in the crosswalk. Movements bound for the same link do not conflict with permitted left turns, and permitted through movements do not conflict with left turns bound for the same link (Albeck & Husch 2006, p. 7-3, p. 7-5).

A protected plus permissive mode is provided with a protected left turn phase during an exclusive green arrow indication and by a permitted left turn during the permissive left turn phase (green ball indication). During the permissive phase, left turns can be made when there are enough gaps in the opposing traffic to complete left turns safely. This combination of both signal modes is designed to help to reduce the unnecessarily delays by allowing vehicles to avoid waiting to turn left when there is no opposing traffic, which is a common situation that occurs during the periods of low traffic volumes. It is common to use four to five signal displays as illustrated in Figure 2.11 for the turn indications for a permitted plus protected phasing (Albeck & Husch 2006, p. 7-4).

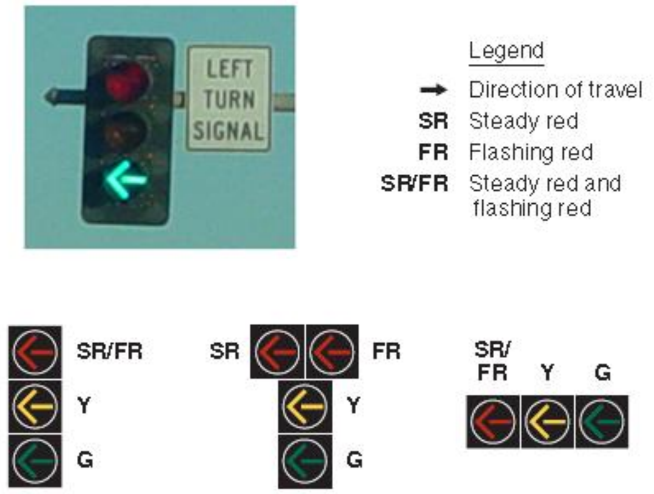


Figure 2.9 Protected signal mode (FHWA 2009, p.469).

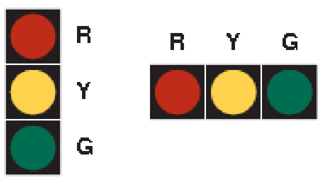


Figure 2.10 Permissive signal mode (FHWA 2004, p.467).

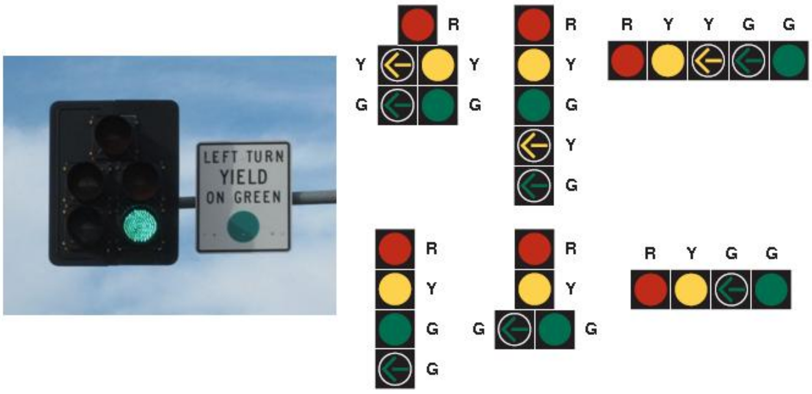


Figure 2.11 Protected plus permissive signal mode (FHWA 2004, p.471).

2.4 Pedestrian and bicyclists characteristics

Bicyclists and pedestrians both belong to the vulnerable road users. This road user group shares the roadway with motorists with absence of a protective shell or ability to accelerate as their motor vehicle counterparts. Speed and size are also differences between the vulnerable road users and the motor vehicles. The bike is however, in contrast to pedestrians, a vehicle user and must follow the same rules of the road like all drivers, motorcyclists and mopeds (FHWA 2004a, p.23).

The bike is also characterized by a higher speed than the pedestrian. A normal pedestrian walking speed is around 4-5 km/h (2,5-3 mph) and an average cycling speed is 16 km/h (10 mph). These values are site-specific and depend on the circumstances on the location and on the vehicle flow (Hydén 2004, p. 214).

In American literature a pedestrian walking speed varies between 2.88 km/h (1,8 mph) to 6.48 km/h (4 mph) (FHWA 2004a, p. 29). The Manual on Uniform Traffic Control Devices (MUTCD) uses a walk speed of 4,32 km/h (2,7 mph) for determining crossing times and the Federal Highway Administration (FHWA) recommends a lower speed of 4 km/h (2,5 mph) to accommodate users who require additional time to cross the roadway (FHWA 2004a, p.29).

A lower speed is recommended in areas where there are concentrations of children and or elderly persons. A walking speed of 4,32 km/h (2,7 mph) is recommended for calculations for footpaths where less than 20 percent of the total pedestrians are represented by elderly persons. If the proportion of elderly person are more than 20 percent of the total pedestrians, the average walking speed decreases to 3,6 km/h (2,2 mph) (TRB 2000, p. 18-1). A walking speed of 3,6 km/h (2,2 mph) to 4,32 km/h (2,7 mph) for crosswalk signal timing is usually accepted as a guideline for walking speed in crosswalks (MassDOT 2006, p. 6-5).

The 85th percentile free-flow speed of bicycles in Sweden is reported to be between 16 km/h (10 mph) and 28 km/h (17,4 mph). A Chinese study observed average bicycle speed between 10 km/h (6,2 mph) and 16 km/h (10 mph). The total average value for this study was approximately 12 km/h (7,5 mph) (Allen et al 1998, p. 30).

2.5 Regulations and guidelines with RTOR

United States

Right turn on red (RTOR) or simply right on red means that the vehicle in a country with right-hand traffic at a traffic light is allowed to turn right provided no conflicts occur with oncoming traffic or other road users. Pedestrians, bicyclists and oncoming traffic must in other words be given priority (ADOT, 2011, p. 37). Stop duty almost always applies before reaching the crosswalk that is why the maneuver also has been referred to as right-turn on red after stop or shortly RTORAS (McShane & Roess, 1990). In 1937 right-turn on red was approved for the first time in the state of California in the United States. At first, the legislation only applied at intersections with an authorized sign, but then came to change and applied at every intersection except where signs prohibited the movement (McShane & Roess 1990, p. 411).

There are no regulations or guidelines today in the United States for the amount of traffic that is appropriate at intersections where right-turn on red apply. The primary factor for prohibiting or restricting RTOR behaviors is inadequate sight distance. As a guidance for when a NO TURN ON RED sign should be considered, there are the following existing conditions that an engineering study needs to find one or more of according to the Manual on Uniform Traffic Control Devices, MUTCD (FHWA 2009, p.95-96):

A. Inadequate sight distance to vehicles approaching from the left (or right, if applicable).

B. Geometrics or operational characteristics of the intersection that might result in unexpected conflicts.

C. An exclusive pedestrian phase.

D. An unacceptable number of pedestrian conflicts with RTOR maneuvers, especially involving children, older pedestrians, or persons with disabilities.

E. More than three RTOR accidents reported in a 12-month period for the particular approach or

F. The skew angle of the intersecting roadways creates difficulty for drivers to see traffic approaching from their left.

Figure 2.7 show the most common traffic signs that can be found for RTOR and the signs that prohibit or give restrictions for RTOR in certain cases in the United States.

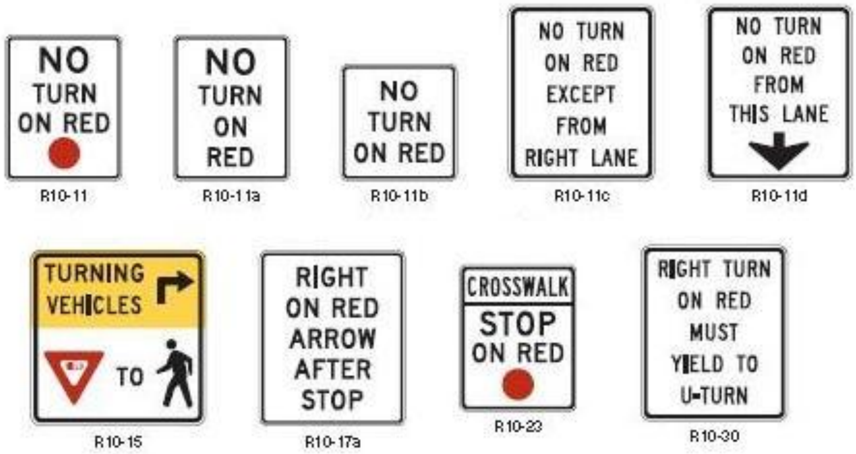


Figure 2.7 Traffic Signal Signs and Plaques for right turn on red and no turn on red (FHWA 2009, p.96)

Sweden

No law exists in Sweden today with the permitted RTOR. It is generally illegal to turn right at a red light in the European Union member states, unless otherwise is indicated with an additional signal. This can be illustrated by a green arrow on a red light controlling the right or left turn, a flashing yellow arrow, a permanent green box next to the red light or similar. The arrow indicates the regulated direction. An additional signal can be equipped with either one or two light openings and is used together with a main signal as illustrated in Figure 2.8 (Trafikverket 2004, p. 20-21).

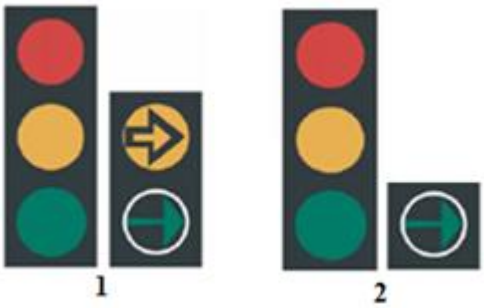


Figure 2.8 Additional signals with one (illustration 2) and two (illustration 1) light openings regulating left and right-turning traffic movements (Trafikverket 2004, p. 20-21).

2.6 Implementation of RTOR movements

The HCM states that the number of vehicles able to turn right during a red phase is the function of several complex variables:

- Approach lane allocation (shared or exclusive right-turn lane),
- Lane utilization,
- Demand for right-turn movements,
- Sight distance at the intersection approach,
- Degree of saturation of conflicting through movement,
- Arrival patterns over signal cycle,
- Left-turn signal phasing on conflicting street, and
- Conflicts with pedestrians (HCM 2000, p. 16-9).

A RTOR movement can be implemented during three different regimes; intersecting, opposing and shadowed left turns. The first opportunity is made with the cross-intersecting traffic from the left. The RTOR movement can be made when there are available and adequate gaps in the through traffic stream on the intersecting approach. RTOR must yield to those who have right of way during their respective signal phases (Creasey, Stamatiadis & Viele 2011, p. 8-9).

Another opportunity is with opposing left turns where left turns are taking place from the approach opposite the subject approach conflict with RTOR. RTOR can also here only be performed when there are available gaps within the opposing traffic stream. This type of regime occurs only when the opposing left turns operate during an exclusive or protected (i.e. a “green arrow” signal display) left turn phase (Creasey, Stamatiadis & Viele 2011, p. 8-9).

The third, shadowed left turns, is not a direct conflict and occur from the approach opposite the intersecting approach and do not conflict with RTOR from the subject approach. This regime occurs only when the left turns occur during an exclusive phase (Creasey, Stamatiadis & Viele 2011, p. 8-9). Figure 2.9 illustrates the different RTOR movements.

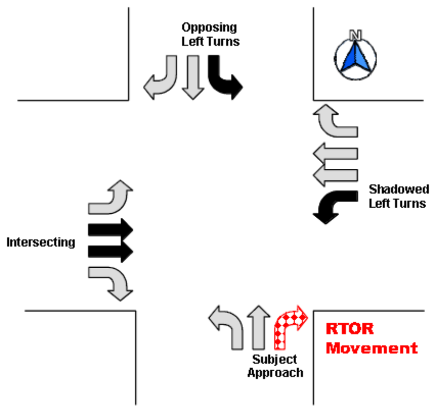


Figure 2.9 Right turn on red regimes (Creasey, Stamatiadis & Viele 2011, p. 8)

Situations with possible RTOR movements can also be prevented. One such situation is when the right lane is a shared lane with through traffic and the approaching vehicle at the STOP bar is not a right-turning vehicle but instead a through vehicle. This will block the RTOR maneuver and the following right-turning vehicles to proceed under red. The driver wanting to make a right-turn must wait until there is green signal display to make the turn (Creasey, Stamatiadis & Viele 2011, p. 8-9).

Another condition that can affect or block the intended RTOR movement is if the number of pedestrians and bicyclists crossing perpendicularly to the vehicle is too large. The possibility to find a gap for the RTOR movement will become harder to execute during the red phase (FHWA 2004a, p.30-31).

2.7 Traffic safety and crashes with RTOR

The Federal Highway Administration (FHWA) published a study, *Right turn on Red. Volume I: Final Technical report (1976)*, after the original 1970s act of encouraging states to adopt the law with RTOR. This study reviewed the economical consequences of permitting the RTOR maneuver. Crashes were analysed in a number of cities and counties that permitted RTOR. Number of crashes with right-turning vehicles during the red and green phase was compared, before and after RTOR was adopted. Their conclusion was that RTOR is related with a small or an insignificant number of accidents (typically 0.61 percent of all intersection accidents). This did not however directly address RTOR versus no RTOR but simply stated that they are a fraction of all intersection accidents and no more severe (NHTSA 1995, p.6; McShane & Roess 1990, p. 413).

The most common RTOR-related accidents were categorized as shown in Figure 2.10 with collision with crossing traffic as the most frequent type. These accidents are more illustrated in Figure 2.11. A problem that was especially noted was that the vehicles did not come to a full stop where RTOR applied (McShane & Roess 1990, p. 413).

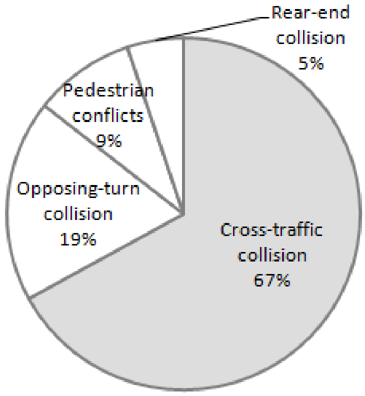


Figure 2.10 Main types of RTOR- accidents (McShane & Roess 1990, p. 413).

A very small scale study of RTOR was done by Parker et al. in 1976 where crash data at 20 intersections in Virginia were analysed before and after the adoption of RTOR. A small but statistically non-significant increase in the number of crashes was reported after the adoption of the above mentioned legislation (NHTSA 1995, p.6).

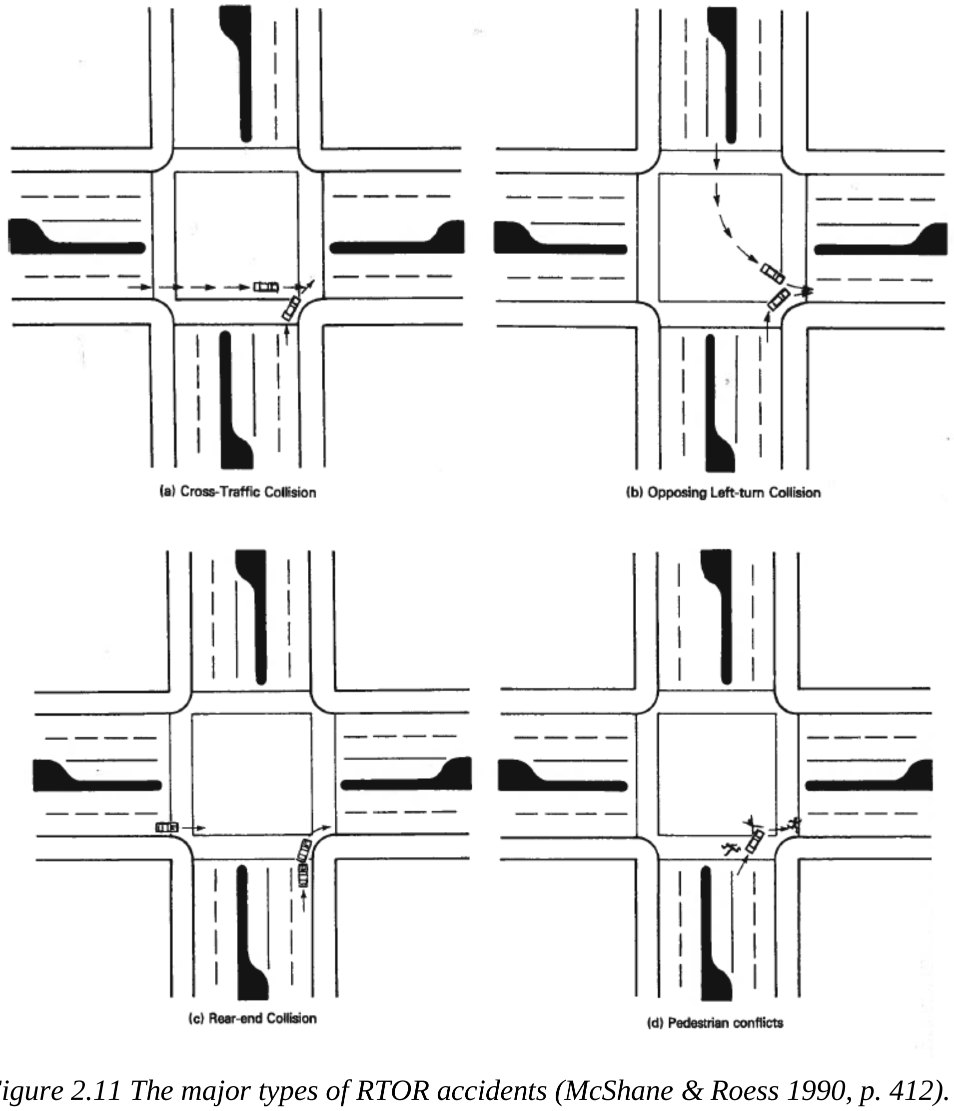


Figure 2.11 The major types of RTOR accidents (McShane & Roess 1990, p. 412).

In 1979 the American Association of State Highway and Transportation Officials (AASHTO) published a larger study, by the name *Safety and Delay Impact of Right-turn on Red,* of 732 signalized intersections in 14 large cities. An increase in the annual rate of right-turning accidents was noted with a 37 percent in crashes with vehicles performing a right-turning maneuver. No increase in crashes overall was noted (NHTSA 1995, p.6).

In 1982 Zador et al. published the *Adoption of right-turn on Red: Effects of Crashes at Signalized Intersections, Accident Analysis & Prevention.* Crash data from six states where RTOR were implemented from the year 1974 to 1977, as well as data from three states where the law in effect was unchanged throughout the same period, was examined by Zador et al. (1982). The occurrence of crashes involving vehicles making right-turning maneuvers at signalized intersections, both before and after the implementation of RTOR was compared, by Zador et al., with states in which the laws with respect to RTOR did not change during the study period. During the study period, the evaluation of the states adopting RTOR and comparison states showed that both experienced an increase in overall frequency of right-turning crashes. However, the states adopting RTOR had a 21 percent greater increase in the frequency of right-turning crashes than the comparison states. The authors attributed that increase to the adoption of RTOR (NHTSA 1995, p.7). This report was later reviewed in a new analysis by Zador (1984) which indicated an 18 percent right-turning accident increase at signalized intersections where RTOR maneuvers were permitted in the study areas. Zador also reviewed existing literature where Zador found that a 23 percent increase is estimated to occur at signalized intersections where RTOR is allowed to perform. Zador also approximated the pedestrian crashes to increase by around 60 percent and bicyclist crashes by around 100 percent (NHTSA 1995, p.7).

Crashes involved with right-turning maneuvers before and after adoption of RTOR were also examined by Preusser et al (1981) to see how pedestrians and bicyclists were affected by the RTOR. Three states plus one city in a fourth state worked as basis for this study. The study showed that RTOR lead to a noticeable increase in pedestrian and bicyclist crashes with right-turning vehicles at signalized intersections. The increase varied from 43 percent to 107 percent for pedestrians and from 72 percent to 123 percent for the bicyclists in the three states studied. The proportion of all pedestrian crashes, right-turning crashes at signalized intersections increased 55 percent (from 1.47 percent before RTOR to 2.28 percent after RTOR). The proportion of all bicyclist crashes, right-turning crashes at signalized intersections increased 99 percent (from 1.40 percent before RTOR to 2.79 percent after RTOR). Even though the pedestrian and bicycle crashes increased a lot, they are still a small number (2.28 percent respectively 2.79 percent) of total crashes (NHTSA 1995, p.7).

It is to be noted that the studies mentioned in this section involve both vehicles turning right on red and right during the green light phase at signalized intersections. It cannot be assumed that all right-turning crashes occurred during the green light phase at intersections where RTOR is prohibited. Vehicles may have made a right-turn during the red light phase. Furthermore, some of the studies mentioned before looked at crashes at intersections where RTOR is allowed while others looked at all signalized intersections. One must keep in mind that the studies mentioned are based on RTOR laws which were adopted almost forty years ago (from the 1970s). The present estimation of the safety impact of RTOR cannot completely be based on the older studies and data. The extent in increase of right-turning crashes, resulting from the implementation of the RTOR law during the 1970's, is not possible to estimate and may not be predictive of the present situation (NCHRP & TRB 2008, p. 11-12).

What makes it even more difficult to estimate the impact is the fact that all states have had RTOR for a long time. Preferably, to determine the safety impact of RTOR, one would look at the increased number of crashes, injuries and fatalities of permitting RTOR. This would require analyzing crashes at intersections before and after the implementation of the RTOR law, or comparing crash data from essentially identical intersections where RTOR is and is not permitted (NCHRP & TRB 2008, p. 11-12).

In 1992, the Energy Policy Act required a study of the status implementation of laws permitting right and left turns at red lights to be conducted by the National Highway Traffic Safety Administration (NHTSA). This later resulted in a report presenting the results of the analysis of the safety impact of permitting RTOR. The Fatal Accident Reporting System (FARS) and data from four state crash data files (Illinois, Indiana, Maryland and Missouri) were used for the study. The difference between these two sources is that the FARS does not include information about the traffic signal indication, i.e. whether a vehicle was turning right on red at the time of the crash, only that the vehicle was turning right at the time of the crash at an intersection where RTOR is permitted. The four-state files make it possible to determine when a RTOR maneuver was executed (NCHRP & TRB 2008, p. 5-6, p. 13).

The FARS data in the study showed that during an 11 year time period from 1982 to 1992, a total average of 84 fatal crashes occurred per year involving right-turning vehicles at intersections where RTOR is permitted. This data can be seen in Figure 2.12. A total of 485,104 fatalities occurred during the same time period. Therefore, the fatalities involving a right-turning vehicle maneuver at an intersection where RTOR is permitted was less than 0.2 percent. However, the data in FARS does not separate the color of the traffic signal indication. So the right-turn could have been executed on a green or red indication. The study states that, for the reason mentioned above, the actual number of RTOR crashes that resulted in a fatality is somewhere between zero and 84 and may be closer to zero than 84. Furthermore, 44 percent of the fatal RTOR crashes in Figure 2.12 involved a pedestrian, 10 percent involved a bicyclist, and in 33 percent involved one vehicle striking another vehicle as visualized in Figure 2.13 (NCHRP & TRB 2008, p. 5-6, p. 13-14).

It should be made clear that the interaction of motorists is perpendicular to the pedestrians at RTOR, and parallel at right turns on a green light.

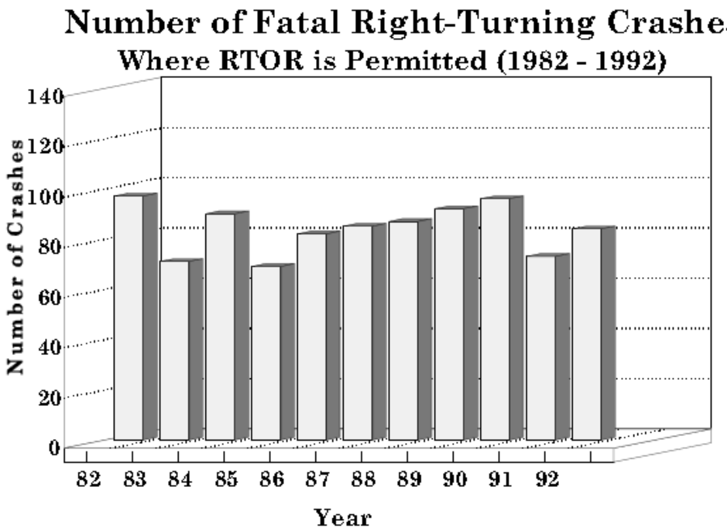


Figure 2.12 The FARS data for 1982-1992 fatal crashes involving right-turning vehicle maneuvers where RTOR was permitted (NCHRP & TRB 2008, p. 13).

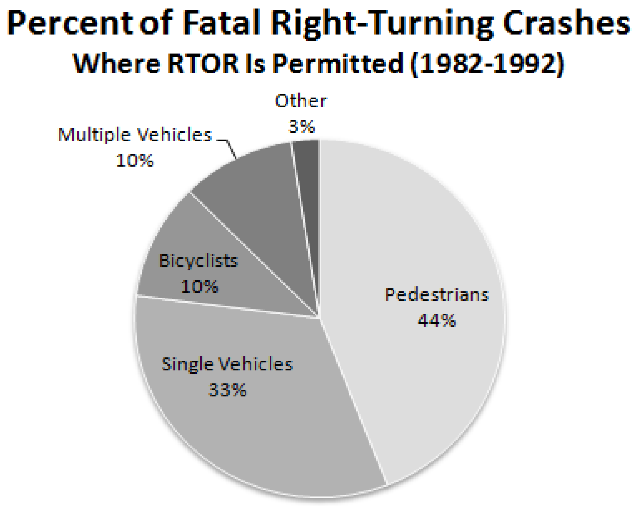


Figure 2.13 The FARS data for 1982-1992 fatal right-turning crashes over the 11 year period by crash type (NCHRP & TRB 2008, p. 14).

The state data from the four states (Illinois, Indiana, Maryland and Missouri) showed that RTOR crashes represent a very small number of the total number of traffic crashes (0.05 percent). The analysis showed that the injury and fatal crashes involving RTOR represent a fraction of 1 percent of all injury and fatal crashes (0.06 percent).

As can be seen in Table 2.2, there were 316,269 signalized intersection crashes, of which 1277 (0.4 percent) involved a RTOR. The conclusion drawn from here is that a very small amount of crashes involve RTOR at signalized intersections (NCHRP & TRB 2008, p. 15-17).

Percentage of All Crashes At Signalized Intersections
That Are Right-Turn-On-Red (RTOR) Crashes*

	Signalized Intersection Crashes	RTOR Crashes	% RTOR to Signalized Intersection Crashes
Property Damage	197,001	836	0.42
Injury	118,580	437	0.37
Fatal	688	4	0.58
TOTAL	316,269	1277	0.40

* Data from Indiana, Maryland, and Missouri, 89-92; no signalized intersection data available for Illinois.

Table 2.2 The four state data for the number and percentage of all crashes at signalized intersections and RTOR crashes by crash severity (NCHRP & TRB 2008, p. 18).

A pedestrian or bicyclist is often involved when a RTOR crash occurs. The proportion of RTOR pedestrian or bicyclist crashes to all RTOR crashes was 22 percent. RTOR pedestrian or bicycle crashes resulting in injury was 93 percent. RTOR pedestrian or bicycle crashes resulting in a fatality were only 1 percent. It is to be noted that significantly less than one percent (0.2 percent) of all fatal pedestrian and bicyclist crashes resulted from a RTOR vehicle maneuver as presented in Table 2.3 (NCHRP & TRB 2008, p. 19-20).

Percentage of All Fatal Pedestrian and Bicyclist Crashes That Are
Right-Turn-On-Red (RTOR)*

	All Fatal Pedestrian/ Bicyclist Crashes	RTOR Fatal Pedestrian/ Bicyclist Crashes	Percent RTOR
Fatal	2194	4	0.18%

* Data from Indiana, Maryland and Missouri, 1989 - 1992; Illinois, 1989 - 1991

Table 2.3 The number and percent of all pedestrian and bicyclist fatal crashes to RTOR fatal crashes (NCHRP & TRB 2008, p. 20).

The study concluded that there were a rather small number of injuries and deaths each year caused by RTOR crashes. Moreover, the RTOR crashes represent a very small percentage of all crashes, injuries and deaths. Due to the small number of crashes caused by RTOR, the study concluded that the impact on traffic safety has also been small.

A recent study that analyzed the conflicts between right-turn vehicles and pedestrians at signalized intersections where RTOR is permitted, found that an increased traffic volume and pedestrian flow will increase the number of conflicts, but will decrease the conflict rate per hundred pedestrian. The number of severe conflicts at large radius is at the same time higher than at small radius. The study also suggest a model to describe the relation between traffic conflicts and influencing factors with different right-turn radiuses to provide direction for actions that can be made to reduce the number of crashes (Zhao et al 2011).

2.8 Traffic simulation

Traffic simulation gives, usually within a limited range, the opportunity to create a visual overview of the real traffic environment that can’t be analysed directly with other means (Trafficware 2003a, p. 2). Another major advantage is the animation, which means that you get an overview of the traffic and you can see where problems arise with congestion. Changes can then be done to study how different measures affect the traffic before implementing them for real, which is also more economically effective. A visual representation provides a better understanding for the problems and solutions for everyone (Austroads 2006, p. 5).

The model is composed of a number of elements, objects and components that interact with each other, all with basis on mathematical and logical analyses. Larger and more complex systems require however a model simulation due to the amount of different entities involved (Trafficware 2003a, p. 2; Irvenå & Randahl 2010, p. 23).

The difference between macro and micro simulation modeling is the study detail. Micro simulation is more extensive since it is much more detailed and requires more data than macro modeling. Macro simulation models evaluate traffic flow as a whole without regard to the features and characteristics of individual vehicles in the traffic stream. Micro simulation is the opposite of the macro simulation and takes into account the individual vehicles in the traffic stream. The consideration of the features and characteristics of the individual vehicles (acceleration, deceleration, lane changes, turning movement execution, gap acceptance etc) is included in the micro model by using car following logic and algorithms to predict and model the movement of each vehicle in the traffic stream. The microscopic models hold the ability to be more accurate if calibrated correctly. The calibration is however not easily done, due to the complexity of the model and its large number of parameters to define and data that needs to be collected and implemented to the model (TRB 2000, p. 31-4, p. 31-5; Yand 2005, p. 1-2, p. 4).

Working process

To ensure that nothing is left out when working on a study with microsimulation, the FHWA Traffic Analysis Tools Team has developed a general procedure and summarized it in six steps. This procedure serves as support and guidance when applying a microsimulation model to a specific traffic analysis problem. The procedures for the creation of a system model for simulation are as follows:

1. Identification of study purpose, scope and approach
2. Data collection and preparation
3. Base model development
4. Error checking
5. Calibration and validation
6. Final Report (FHWA 2004c, p.4).

STEP 1: The first step in this process is to identify the problem to be solved by the model. Together with a defined delimitation, appropriate software needs to be selected in order to accomplish and solve the stated questions and problems (FHWA 2004c, p.11).

STEP 2: Data collection and preparation is for the most part used to understand how the system that will be modeled is working but is also needed as input in the simulation model. The data is at last used as data for calibration and validation of the constructed model to real-world conditions (FHWA 2004c, p.23).

Input data varies for different microsimulation studies but the majority will require basic input data such as the road geometry (lengths, lanes, curvature), traffic control (signal timing, signs), entry volumes and turning movements, desired destinations, transit and bicycle/pedestrian data, speed data, capacity, queues and travel times. Vehicle and driver characteristics (vehicle length, acceleration rate, driver behavior etc.) can also be required which is harder to measure in the field and why the software supplies the user with various default values (FHWA 2004c, p.23-24).

The calibration and validation data consist usually of capacity, traffic counts, travel times, speeds, delays and queues. It is important that the data required for error checking and calibration (travel times, speeds, delays and queue lengths) is gathered at the same time with the traffic counts to be useful in the calibration (FHWA 2004c, p.27).

STEP 3: Base model development is about building the model based on the input from the data collection. The process can have more or less complex and time-consuming steps specific to the selected software chosen for the microsimulation analysis (FHWA 2004c, p.35).

STEP 4: The error checking is important in order to make a correct model coding and to eliminate errors that occur within the model, see Appendix B. One example of this can be cars crashing into each other or cars passing through the red light. Errors within the model can misrepresent the model calibration process and cause adoption of incorrect values in the calibration process (FHWA 2004c, p.45).

The error check includes diverse tests of the network (connections, lengths, number of lanes, control type, lane closures, prohibited turns etc.) and demand data (i.e.

vehicle mix proportions, turning movements, signal phasing) to identify incorrect input data in the model (FHWA 2004c, p.45).

STEP 5: The main objective of model calibration and validation is to modify the parameter values to obtain an ideal match between the simulated results and field measurements. No microsimulation model can include all the variables that affect the traffic conditions in the real world and needs therefore to be modified to local conditions. The key issue is to identify the calibration parameter values for the model that best reproduce observed traffic conditions and behavior in the field. Calibration continues until the model is validated which occurs when the output data corresponds to the independent observed data in the field (FHWA 2004c, p.53).

The validated model is eventually used to test all different scenarios that were identified in the first step of the project. Normally there is a baseline scenario (existing conditions) that corresponds to the current situation at the site. This scenario is then often compared to different future scenarios to determine future network demands or behaviors (FHWA 2004c, p.53).

STEP 6: The final report summarizes the assumptions and documents the steps and results of the analysis with final conclusions. It is also important to write an understandable report to ensure that the decision makers know what assumptions and inputs the study is based on. Adequate documentation is required for future analysts to reproduce the results (FHWA 2004c, p.93).

The final report should include 1) Study Objectives and Scope, 2) Overview of Study Approach (tools used and methodology), 3) Data Collection (sources and methods), 4) Calibration Tests and Results (which parameters were modified and why), 5) Forecast Assumptions (assumed growth inside and outside of the study area, street improvements, etc.), 6) Description of Alternatives and 7) Results (FHWA 2004c, p.93).

2.9 VISSIM

VISSIM (Verkher In Städten SIMulation) was developed at the University of Karlsruhe, Germany during the early 1970s (Park et al. 2005, p. 4). The name is German for "Traffic in cities simulation". The commercial distribution of VISSIM began in 1993 by PTV, Planung Transport Verkehr, AG. PTV AG cooperate today with Innovative Transportation Concepts, Inc. in North America to continue to develop, distribute and maintain VISSIM (Trueblood & Dale 2003, p. 3).

The VISSIM package consists of two different programs, the traffic simulator and the signal state generator. The simulation generates an online visualization of traffic operations and offline it generates an output of desired statistical data such as travel times, delays, queue lengths, emissions etc (PTV 2011, p. 23).

Traffic simulator includes of car-following and lane changing logic and it is capable of simulating up to one tenth of second. The VISSIM traffic simulator takes not only into account the preceding vehicles, but also neighboring vehicles on adjacent travel lanes. Furthermore drivers approaching traffic signals will gain a higher alertness (PTV 2011, p. 23-24). The signal state generator is a signal control software polling detector information from the simulation on a discrete time step basis (down to one tenth of a second). It then determines the signal status for the next time step and returns the information to the simulation (PTV 2011, p. 23).

VISSIM is a discrete, stochastic, microscopic time step and behavior based simulation model developed to model urban traffic and public transit operations and pedestrian flows (PTV 2011, p. 21). That it is microscopic means that it captures the moment of every vehicle. The traffic flow is simulated by moving driver vehicle units through a network, where every driver is assigned to a specific behavior characteristic (PTV 2011, p. 24-25; TRB 2000, p.31-4).

The program can analyze traffic and transit operations under constraints such as lane configuration, traffic composition, traffic signals, transit stops, etc. This makes it a useful tool for the evaluation of various alternatives based on transportation engineering and planning measures of effectiveness (MOE's) such as control delay, speed, volume/density, travel times and queue lengths (PTV 2011, p. 24). These can later be translated into a level-of-service (LOS) description by facility type, based on the 2000 Highway Capacity Manual definitions.

VISSIM considers a physical and physiological aspect of the driver developed by Rainer Wiedemann in 1974 (PTV 2011, p. 24; Trueblood & Dale 2003, p. 4). The Wiedemann model is a car-following logic which uses dynamic speeds. Stochastic distributions of speed and spacing thresholds reproduce individual driver behavior characteristics (PTV 2011, p. 24). The Wiedemann model consists of the assumption that a driver can be in one of four driving modes:

- Free driving is the mode where the vehicle is not affected by previous vehicles and the driver is trying to reach and maintain his individually desired speed. This mode is an iterative process of acceleration and deceleration and can not be held constant in the reality due to imperfect throttle control of the driver (PTV 2011, p. 129).

- Approaching is the mode where the vehicle is adapting his speed to the lower speed of a preceding vehicle. A deceleration is applied while approaching in order to achieve zero speed differentials between the two vehicles in the same moment as the driver reaches his desired safety distance (PTV 2011, p. 129).

- Following is the mode which occurs when a driver follows a preceding car. The safety distance is more or less constant. As in free driving mode the speed difference oscillate around zero due to imperfect throttle control and imperfect judgment (PTV 2011, p. 129).

- Braking is the very last mode where the driver applies medium or high deceleration rates when the distance to preceding vehicle drop under the desired safety distance. The speed of the driver will fall below the preceding vehicle. Braking can occur when vehicles change lanes in front of each other or if the preceding vehicle suddenly changes his speed (PTV 2011, p. 129).

The acceleration is for every mode described as a result of speed, speed difference, distance and the individual driver-vehicle characteristics. The driver changes from one mode to another as soon as he or she reaches a certain threshold which is shown as speed and distance differences. The ability to perceive speed differences and to estimate distances are individual as well as the desired speeds and safety distances. Different vehicle features creates together with the above characteristics the individual driving behavior in the model. This is also why the model is referred to as a psycho-physical car-following model (PTV 2011, p. 24, p.129).

VISSIM has a very flexible geometry coding which allows the user to control vehicle paths and the interaction of vehicles within intersections. VISSIM uses a link and connector structure to build up the geometry. In addition to the link connector structure the developers have also made it possible to import CAD drawings, which brings more accuracy into the geometry. The links are the normal road segments and are coded with the number of lanes, lane width, driving behavior and lane restrictions such as allowing lane change or not and more. The connectors are the connection between links and are used to create a road network. In order for vehicles to continue from one link to another, connectors are necessary to bind the two links. Connectors are especially important since they serve to model turning movements at intersections (PTV 2011, p. 184, p. 193, Trueblood & Dale 2003, p. 4-5).

The vehicle distribution is set by the user and is individual for each entry position. The vehicles are assigned routes upon entry in which it is decided how the vehicles will desire to travel through the network. The routes have both a start point and an end point to a defined destination. The routes may end anywhere in the network and other routes may start at those ends. If a route is not decided, vehicles will follow the current link until the end (PTV 2011, p. 210-215, Trueblood & Dale 2003, p. 4-5).

Vehicle speed is playing an important role in VISSIM. Each vehicle is assigned its own unique speed within a range based on an empirical curve defined by the user to match the studies or field data. The posted speed limit can also be used. Each vehicle oscillate around their desired speed until speed zones or roadway geometry forces the vehicle to change its speed. Speed zones are created using the desired speed decisions to achieve a traffic behavior similar to the reality where the user can give vehicles a new speed, either a lower or higher, from the relevant speed as it cross over the desired speed decision line. A deceleration is usually required before making a turn because of the curvature of the road. After passing over the reduced speed area vehicles begin to accelerate back to their previous desired speed. All speed distributions in VISSIM are vehicle-type-dependant which let the user set different distribution for cars compared to trucks and other heavy vehicle goods Trueblood & Dale 2003, p. 4-5).

The priority rules features of VISSIM are used when building unsignalized intersections. A priority rule consists of one stop line and one or more conflict markers that are associated with the stop line. The stop line ensures the vehicles to cross or not. Two conditions need to be satisfied in order to allow the vehicle to cross the stop line: minimum headway (distance) and minimum gap time. The minimum headway is defined as the length of the conflict area and the current gap time is the time in every step that an approaching vehicle has left before reaching the conflict marker assuming that it continues travelling with its current speed. The vehicles will be stopped at the stop line if current gap time is less than defined minimum entry gap (PTV 2011, p. 258).

Conflict areas are a new alternative to priority rules to define priority in intersections. They are the recommended solution in most cases because they can be modeled more easily and the resulting vehicle behavior is more intelligent (PTV 2011, p. 270). Wherever two links/connectors overlap a conflict area can be defined. For each conflict area, the user can select which of the conflicting links has right of way (if any) (PTV 2011, p. 271).

The drivers make a decision how they will approach and cross the conflict area. Yield applies for entering vehicles on to the main road and adaption of speed and acceleration is taken into account to create a suitable gap. More time to cross the conflict area will also be taken into calculation and added if there is a stop or deceleration because of other vehicles behind the conflict area. In some scenarios the driver will decide not to go at all, for example if there is too much congestion beyond the conflict area (PTV 2011, p. 271).

Both vehicles on the minor and major road are affected by the conflict area and all vehicles will search for a sufficient space before they decide to enter the area.

This means that if a vehicle on the minor road enters a conflict area and for some reason is unable to leave before a vehicle on the main road approaches, the main road vehicle will slow down or even stop before the conflict area. Conflict areas adopts a more intelligent behavior in the interaction between vehicles since it makes them more aware of other vehicles at conflict points in the network (PTV 2011, p. 271-272).

Two units that are related to gap acceptance in the conflict area feature in VISSIM are the front and rear gap illustrated in Figure 2.14. Front gap is defined as the smallest gap in seconds between the rear end of a vehicle on the main road and the front end of a vehicle on the minor road. Rear gap is the smallest gap in seconds between the rear end of a vehicle on the minor road and the front end of a vehicle on the main road (PTV 2011, p. 274).

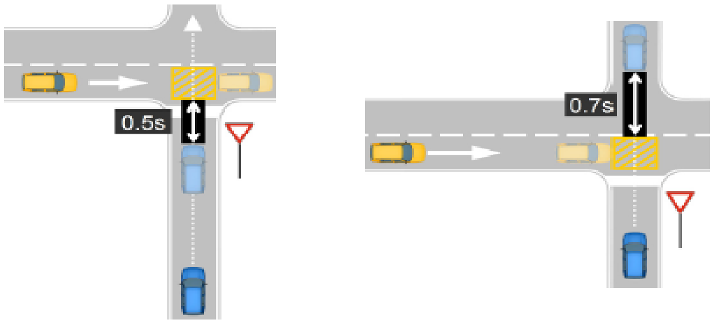


Figure 2.14 Front gap (left) and rear gap (right) in VISSIM (PTV 2011, p. 274).

The most common control signal, simulating fully actuated and semi-actuated (detector controlled) intersections, used at most intersections in the United States is the standard National Electrical Manufacturers Association (NEMA) ring-and-barrier structure, shown in Figure 2.15. VISSIM has NEMA controller models available. It is the default actuated signal controller featured in North American releases of VISSIM. The standard NEMA controller has been replaced by the Ring Barrier Controller (RBC) in VISSIM version 5.30 (FHWA 2004a, p. 59; PTV 2011, p. 282, p. 292-293).

The Ring Barrier Controller (RBC) uses the Dual Ring Logic which basically organizes phases to prevent conflicting movements (for example eastbound and southbound through movements) from entering simultaneously while allowing non-conflicting movements (for example northbound and southbound through movements) to time together. Through selective allocation of phases to the standard NEMA ring-and-barrier structure, most of the signal phasing patterns in use can be simulated (FHWA 2004a, p. 59).

A multi-ring controller unit, which has all rings interlocked, uses a barrier (compatibility line) as a reference point in the preferred sequence. The barriers assure that selection and timing of conflicting phases for traffic movements in different rings do not happen at the same time. To select and time phases on the other side, all the rings cross the barrier simultaneously (FHWA 2004a, p. 59).

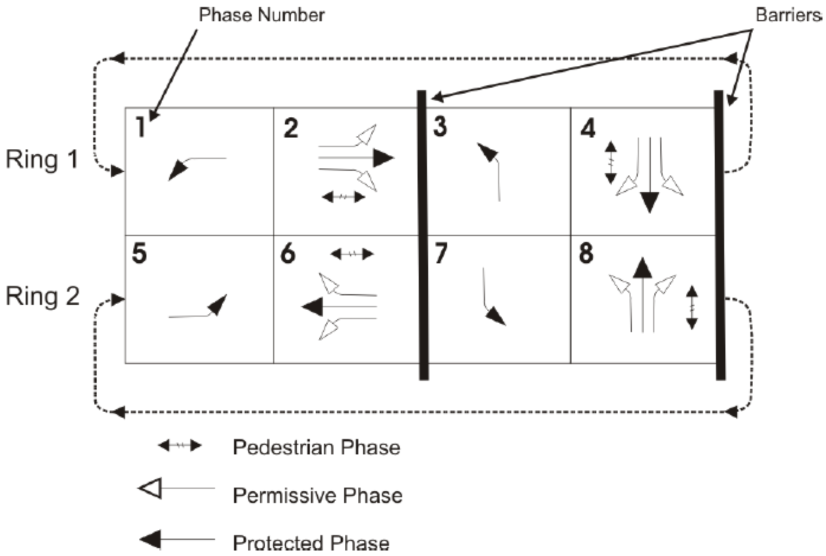


Figure 2.15 Standard NEMA ring- and barrier structure (FHWA 2004a, p. 60)

The ring-and-barrier structure uses 2 to 8 (four through and four left turns) phases depending on the complexity of the intersection. The individual movements around the intersection are assigned to a specific phase number. Odd numbers (1, 3, 5 and 7) are usually used for left turn signals and the even numbers (2, 4, 6 and 8) for through signals. A rule of thumb is that at the sum of the through movement and the adjacent left turn is equal to seven or eleven. Main street through movements are usually assigned as phases 2 and 6. The ring-and-barrier structure assigns the pedestrian movements parallel to vehicle movements, which are also illustrated in Figure 2.15. Every signal group needs to be defined for every turning movement (FHWA 2004a, p. 60).

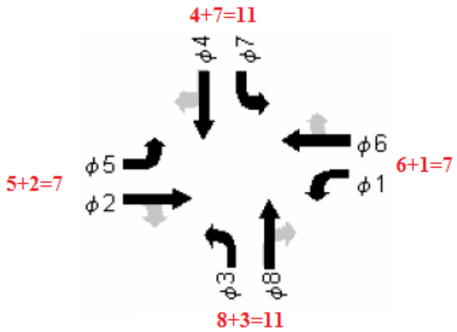


Figure 2.16 Assigning of movements with the ring-and-barrier structure (FHWA 2004a, p. 60).

The phases 1, 2, 5 and 6 are separated by a barrier from phase 3, 4, 7 and 8 since they are the conflicting movements and to avoid direct collision with each other and vice versa. They can never go simultaneously. All movements from one street (usually the major street) have to be assigned to the left side of the barrier and in the same way; all movements from the other street (the minor street) must be assigned to the right side of the barrier (FHWA 2004a, p. 60).

A series of conflicting phases that occur in an established order are described as the ring. A ring may be a single ring, dual ring, or multi-ring. Phases 1 through 4 are included in ring 1, and phases 5 through 8 are included in ring 2. The two rings operate separately, except that their control must cross the barrier at the same time. One phase from ring 1 and one phase from ring 2 will be displayed by the controller at any time. Both phases must be either from the left side of the barrier or from the right side of the barrier. Phase 1 can be displayed with phase 5 or 6 for example, but not with any other phase (FHWA 2004a, p. 60).

The phasing plan begins with determining the left-turn phase at the intersection, phases 1 and 5 for example in the first barrier. This is later followed by the phases 2 and 6, pedestrians and bicyclist included. After the phases in the first barrier are completed, the stream for phases 3 and 7 can start to use the intersection if such demand exists. Finally the two last phases 4 and 8 can use the intersection and the circle can close and start from the beginning with phases1 and 5 (FHWA 2004a, p. 60).

2.10 Synchro plus SimTraffic

Synchro plus SimTraffic 6 is a traffic analysis software that is developed by the Trafficware Corporation in Albany, California. The Trafficware Corporation was founded in 1993 and is privately held (Trafficware 2003a, p. 2). Synchro is a software application which manages optimizations and capacity analysis at a macroscopic level. Synchro plus includes also the software application SimTraffic which performs micro simulation and animation of vehicle traffic for both signalized and unsignalized intersections (Husch & Albeck 2006, p. 19-20, Trafficware 2006b, p.7).

Synchro uses the Intersection Capacity Utilization (ICU) 2003 method to determine the capacity of the intersection. The method compares the current volume to the intersections capacity. Synchro is a HCM based model that uses the methods of the 2000 Highway Capacity Manual (Chapter 15, 16 and 17; Urban Streets, Signalized Intersections and Unsignalized Intersections) are implemented in the software (Husch & Albeck 2006, p. 19).

Synchro 6 includes a term for the queuing delay, also called queue interaction blocking delay which gives a result closer to the reality. The total delay is calculated as the sum of the control delay and the queue delay (Husch & Albeck 2006, p. 19).

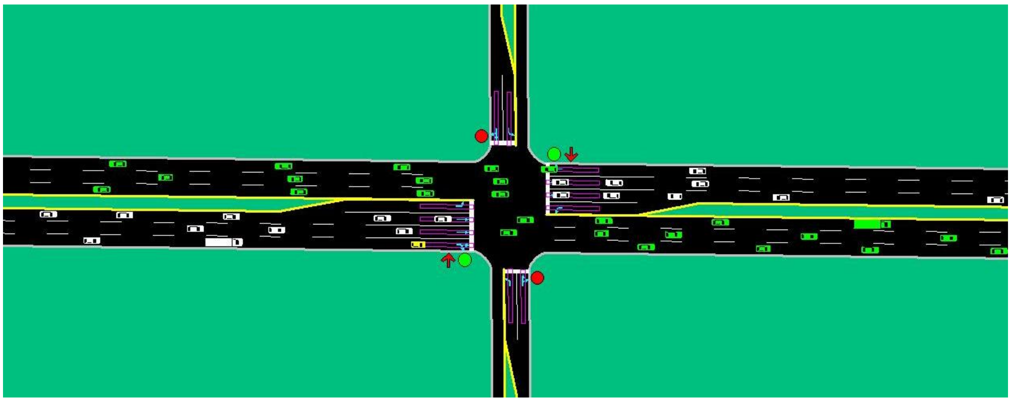


Figure 2.17 Map view in Synchro plus SimTraffic 6 for Bell Road and Burns Drive in Phoenix, Arizona.

Control delay is defined as the delay due to the type of control at the intersection and is measured in comparison to the uncontrolled condition. It is the difference between the travel time that would have occurred in the absence of intersection control and the travel time that results from the presence of intersection control. The queue delay is the delay that occurs due to the queue blockages in unused green time (TRB 2000, p. 10-16, 15.5).

To eliminate the need to search for the optimal timing plan, Synchro tests all possible cycle lengths and selects the shortest cycle length that clears the critical traffic for each phase. The cycle length in an actuated controller unit is dependent on the frequency of calls on all phases while it is a complete sequence of signal indications in a pretimed controller. In addition to calculation capacity and optimization of cycle lengths Synchro also optimizes split times and offsets for the intersection to minimize driver stops and delays (Husch & Albeck 2006, p. 20, Trafficware 2006b, p.5-7).

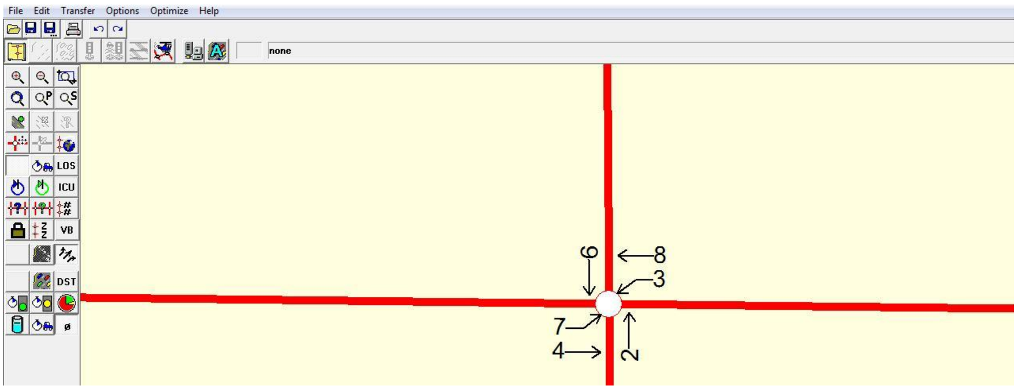
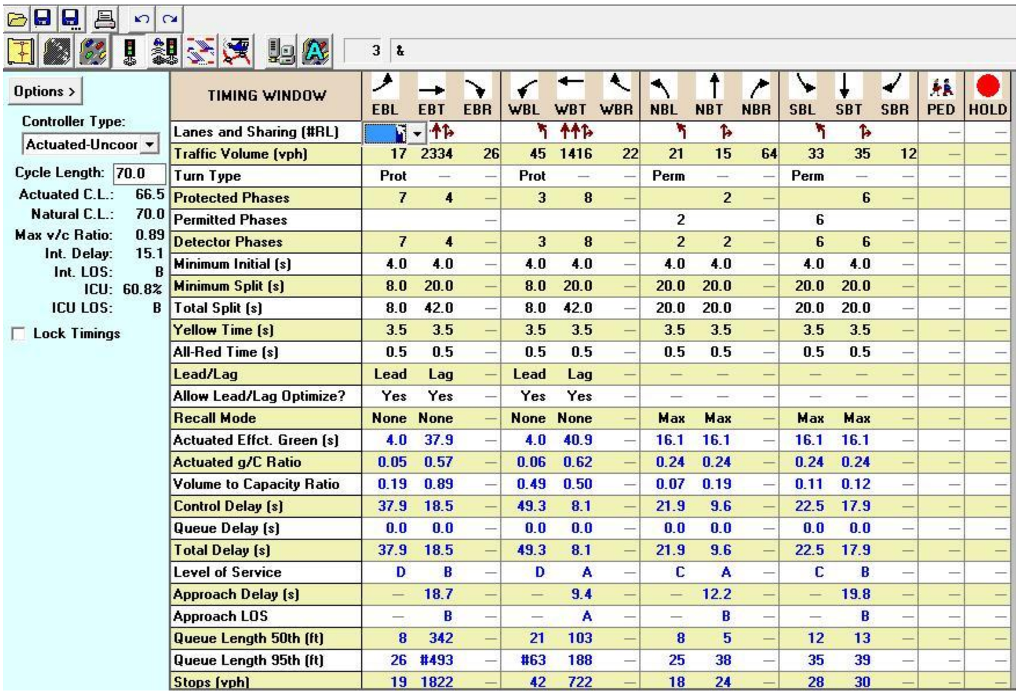


Figure 2.18 Phases in Synchro plus SimTraffic 6 for Bell Road and Burns Drive in Arizona.

A split is referring to the time of a cycle length that is split between all the different phases. The split in an actuated controller unit is given to a phase and in a pretimed controller unit to an interval. Optimizing splits means that Synchro is calculating the best splits for each phase to get the best overall LOS (Husch & Albeck 2006, p.4-7; Trafficware 2006b, p.7).

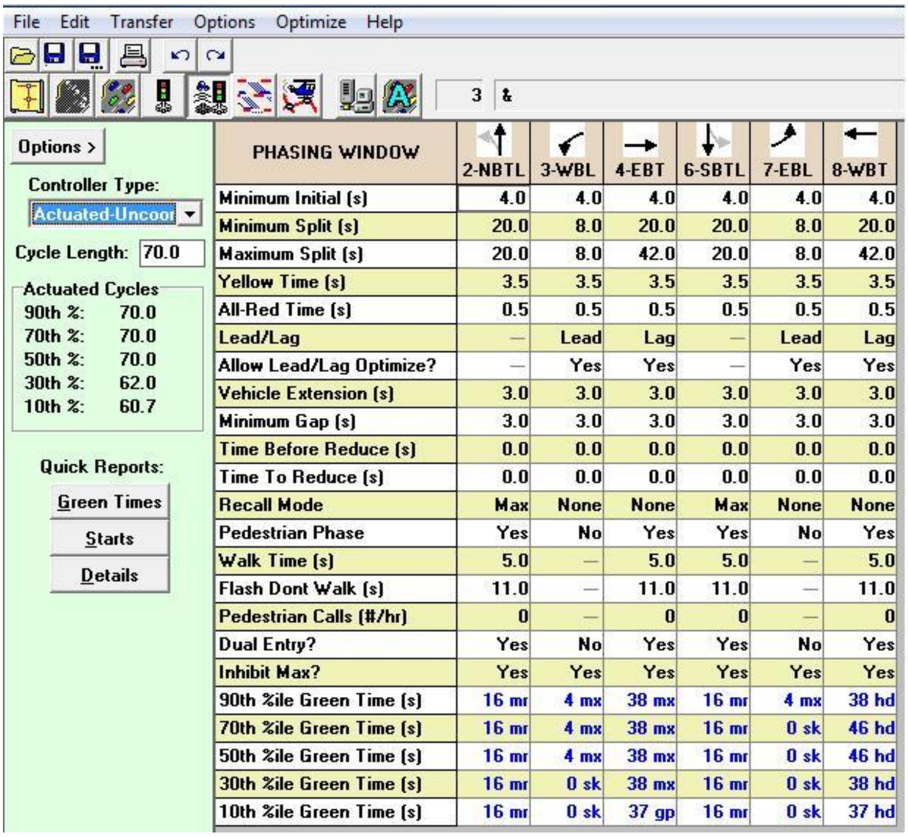
Offset optimization is used with coordinated signals and is needed to help the flow. It considers compatible cycle lengths of neighboring intersections even if they are assigned to different zones (Husch & Albeck 2006, p. 4-3, 4-11).


Options >
Controller Type: Actuated-Uncoor
Cycle Length: 70.0
Actuated C.L.: 66.5
Natural C.L.: 70.0
Max v/c Ratio: 0.89
Int. Delay: 15.1
Int. LOS: B
ICU: 60.8%
ICU LOS: B
Lock Timings

TIMING WINDOW	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR	PED	HOLD
Lanes and Sharing (#RL)													—	—
Traffic Volume (vph)	17	2334	26	45	1416	22	21	15	64	33	35	12	—	—
Turn Type	Prot	—	—	Prot	—	—	Perm	—	—	Perm	—	—	—	—
Protected Phases	7	4	—	3	8	—		2	—		6	—		
Permitted Phases			—			—	2		—	6		—	—	—
Detector Phases	7	4	—	3	8	—	2	2	—	6	6	—	—	—
Minimum Initial (s)	4.0	4.0	—	4.0	4.0	—	4.0	4.0	—	4.0	4.0	—	—	—
Minimum Split (s)	8.0	20.0	—	8.0	20.0	—	20.0	20.0	—	20.0	20.0	—	—	—
Total Split (s)	8.0	42.0	—	8.0	42.0	—	20.0	20.0	—	20.0	20.0	—	—	—
Yellow Time (s)	3.5	3.5	—	3.5	3.5	—	3.5	3.5	—	3.5	3.5	—	—	—
All-Red Time (s)	0.5	0.5	—	0.5	0.5	—	0.5	0.5	—	0.5	0.5	—	—	—
Lead/Lag	Lead	Lag	—	Lead	Lag	—	—	—	—	—	—	—	—	—
Allow Lead/Lag Optimize?	Yes	Yes	—	Yes	Yes	—	—	—	—	—	—	—	—	—
Recall Mode	None	None	—	None	None	—	Max	Max	—	Max	Max	—	—	—
Actuated Effct. Green (s)	4.0	37.9	—	4.0	40.9	—	16.1	16.1	—	16.1	16.1	—	—	—
Actuated g/C Ratio	0.05	0.57	—	0.06	0.62	—	0.24	0.24	—	0.24	0.24	—	—	—
Volume to Capacity Ratio	0.19	0.89	—	0.49	0.50	—	0.07	0.19	—	0.11	0.12	—	—	—
Control Delay (s)	37.9	18.5	—	49.3	8.1	—	21.9	9.6	—	22.5	17.9	—	—	—
Queue Delay (s)	0.0	0.0	—	0.0	0.0	—	0.0	0.0	—	0.0	0.0	—	—	—
Total Delay (s)	37.9	18.5	—	49.3	8.1	—	21.9	9.6	—	22.5	17.9	—	—	—
Level of Service	D	B	—	D	A	—	C	A	—	C	B	—	—	—
Approach Delay (s)	—	18.7	—	—	9.4	—	—	12.2	—	—	19.8	—	—	—
Approach LOS	—	B	—	—	A	—	—	B	—	—	B	—	—	—
Queue Length 50th (ft)	8	342	—	21	103	—	8	5	—	12	13	—	—	—
Queue Length 95th (ft)	26	#493	—	#63	188	—	25	38	—	35	39	—	—	—
Stops (vph)	19	1822	—	42	722	—	18	24	—	28	30	—	—	—

Figure 2.19 The timing window in Synchro 6 for Bell Road and Burns Drive in Arizona.

Synchro is relatively easy to use. An intersection in Synchro can be made and evaluated in a matter of minutes. Of course, you need to know the basic intersection layout, turn types (protected, permissive, etc.) storage lengths, lane configurations and volumes. The signal timings can either be manually input (if you have the signal timing chart) or they can be optimized in Synchro (Husch & Albeck 2006, p.7-2).



PHASING WINDOW	2-NBTL	3-WBL	4-EBT	6-SBTL	7-EBL	8-WBT
Minimum Initial (s)	4.0	4.0	4.0	4.0	4.0	4.0
Minimum Split (s)	20.0	8.0	20.0	20.0	8.0	20.0
Maximum Split (s)	20.0	8.0	42.0	20.0	8.0	42.0
Yellow Time (s)	3.5	3.5	3.5	3.5	3.5	3.5
All-Red Time (s)	0.5	0.5	0.5	0.5	0.5	0.5
Lead/Lag	—	Lead	Lag	—	Lead	Lag
Allow Lead/Lag Optimize?	—	Yes	Yes	—	Yes	Yes
Vehicle Extension (s)	3.0	3.0	3.0	3.0	3.0	3.0
Minimum Gap (s)	3.0	3.0	3.0	3.0	3.0	3.0
Time Before Reduce (s)	0.0	0.0	0.0	0.0	0.0	0.0
Time To Reduce (s)	0.0	0.0	0.0	0.0	0.0	0.0
Recall Mode	Max	None	None	Max	None	None
Pedestrian Phase	Yes	No	Yes	Yes	No	Yes
Walk Time (s)	5.0	—	5.0	5.0	—	5.0
Flash Dont Walk (s)	11.0	—	11.0	11.0	—	11.0
Pedestrian Calls (#/hr)	0	—	0	0	—	0
Dual Entry?	Yes	No	Yes	Yes	No	Yes
Inhibit Max?	Yes	Yes	Yes	Yes	Yes	Yes
90th %ile Green Time (s)	16 mr	4 mx	38 mx	16 mr	4 mx	38 hd
70th %ile Green Time (s)	16 mr	4 mx	38 mx	16 mr	0 sk	46 hd
50th %ile Green Time (s)	16 mr	4 mx	38 mx	16 mr	0 sk	46 hd
30th %ile Green Time (s)	16 mr	0 sk	38 mx	16 mr	0 sk	38 hd
10th %ile Green Time (s)	16 mr	0 sk	37 gp	16 mr	0 sk	37 hd

Figure 2.20 The phasing window in Synchro 6 for Bell Road and Burns Drive in Arizona.

Synchro uses the Percentile Delay Method for modeling actuated signal controllers which uses several traffic scenarios to model traffic conditions. These percentile scenarios are likely to occur during the hour for which volume data is provided. Five scenarios are modeled with Synchro; they are called the 90th, 70th, 50th, 30th and 10th percentiles as can be seen in Figure 2.20. By adjusting the traffic volumes for each approach, up or down, the different percentile scenarios can be modeled under a range of traffic conditions. As one example, if the traffic is observed for 100 cycles, the 90th percentile would be the 90th busiest, the 10th percentile would be the 10th busiest, and the 50th percentile would represent average traffic (Husch & Albeck 2006, p. 8-2).

3 Data Collection

This chapter describes the study objects and the identified, gathered and prepared input data for the study areas in both Phoenix and Lund and that the models in VISSIM are based on, most of them obtained from field studies.

3.1 Study objects

The first step of the data collection was to find signalized intersections that are located in the Phoenix area, see Figure 3.1, with a permitted RTOR located in urban areas. Jacobs Engineering Group Inc in Phoenix offered already collected peak-hour turning movement volumes for 30 intersections in Phoenix that could be used for this thesis. Ten intersections were then selected to work as basis for this thesis, based on the highest volume. They are all four-legged signalized intersections and some of the intersections have an exclusive right-turn lane. The intersections are presented in Table 3.1.

Major	Direction	Minor	Direction	AM	PM	Total
Bell Road	E-W	Burns Drive	N-S	4040	4013	**8053**
Bell Road	E-W	98th Avenue	N-S	3840	4080	**7920**
Bell Road	E-W	99th Avenue	N-S	5219	5601	**10820**
Bell Road	E-W	Boswell Boulevard	N-S	4514	5005	**9519**
Bell Road	E-W	Del Webb Boulevard	N-S	4507	5603	**10110**
Olive Avenue	E-W	107th Avenue	N-S	2839	3235	**6074**
Olive Avenue	E-W	111th Avenue	N-S	2979	3200	**6179**
Olive Avenue	E-W	103rd Avenue	N-S	2879	3360	**6239**
Thunderbird Road	E-W	99th Avenue	N-S	2791	3258	**6049**
Indian School Road	E-W	99th Avenue	N-S	2774	3309	**6083**
Malmövägen	N-S	Ringvägen	E-W	1388	2140	**3528**

Table 3.1 AM and PM peak-hour volumes for the ten American intersections in Phoenix and Malmövägen and Ringvägen in Lund.

Various intersection designs were analysed in this study but all of the study objects had to meet the following criteria:

- Four-legged intersection
- Permitted right-turn on red (in Phoenix) on all approaches
- Located in urban area
- Different lane configurations and designs
- Major intersections
- Desirable speed limit 50 km/h

It is hard to find signalized intersections in Sweden´s Lund that are saturated just as much as the intersections in Phoenix. The main idea was to find an intersection that would later make a somewhat fair comparison to the chosen Phoenix intersections. The choice finally fell on the intersection of Malmövägen and Ringvägen, see Figure 3.2, which meets the previously listed criteria. Furthermore, the intersection of Malmövägen and Ringvägen appears to have adequate sight distance on all four legs which is a significant factor in the implementation of RTOR. The target destinations near the area are the highway 16 and freeway E22 which forms important connections between Malmö and Lund among other important key connections.

Figure 3.1 Phoenix in the state of Arizona, USA (GoogleMaps 2011)

Figure 3.2 Location of Malmövägen and Ringvägen in Lund (GoogleMaps 2011).

Below follows a detailed description of each study object, listed in Table 3.1, in the U.S. and Sweden.

1 - Bell Road and Burns Drive

This is a four-legged signalized intersection, where Bell Road runs in the east-west direction and Burns Drive runs in the north-south direction. Both the eastbound and westbound Bell Road approaches have one (1) left- turn lane, two (2) through lanes, and one (1) shared through/right-turn lane. The left-turns on Bell Road are "protected-only". Both the northbound and southbound Burns Drive approaches have one (1) left-turn lane, and one (1) shared through/right-turn lane. The left-turns on Burns Drive are "permissive". The speed limit on Bell Road is 45 mph (72,4 km/h) in both approaches and 35 mph (56,3 km/h) on Burns Drive on both approaches.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

Figure 3.3 Bell Road and Burns Drive in Phoenix, USA (Maricopa County Assessor Map, 2011).

2 - Bell Road and 98th Avenue

This is a four-legged signalized intersection, where Bell Road runs in the east-west direction and 98th Avenue runs in the north-south direction. Both the eastbound and westbound Bell Road approaches have one (1) left- turn lane, two (2) through lanes, and one (1) shared through/right-turn lane. The left-turns on Bell Road are "protected-only". Both the northbound and southbound 98th Avenue approaches have one (1) left-turn lane, and one (1) shared through/right-turn lane. The left-turns on 98th Avenue are "permissive". The speed limit on Bell Road is 45 mph (72,4 km/h) in both approaches and 25 mph (40,2 km/h) on 98th Avenue on both approaches.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

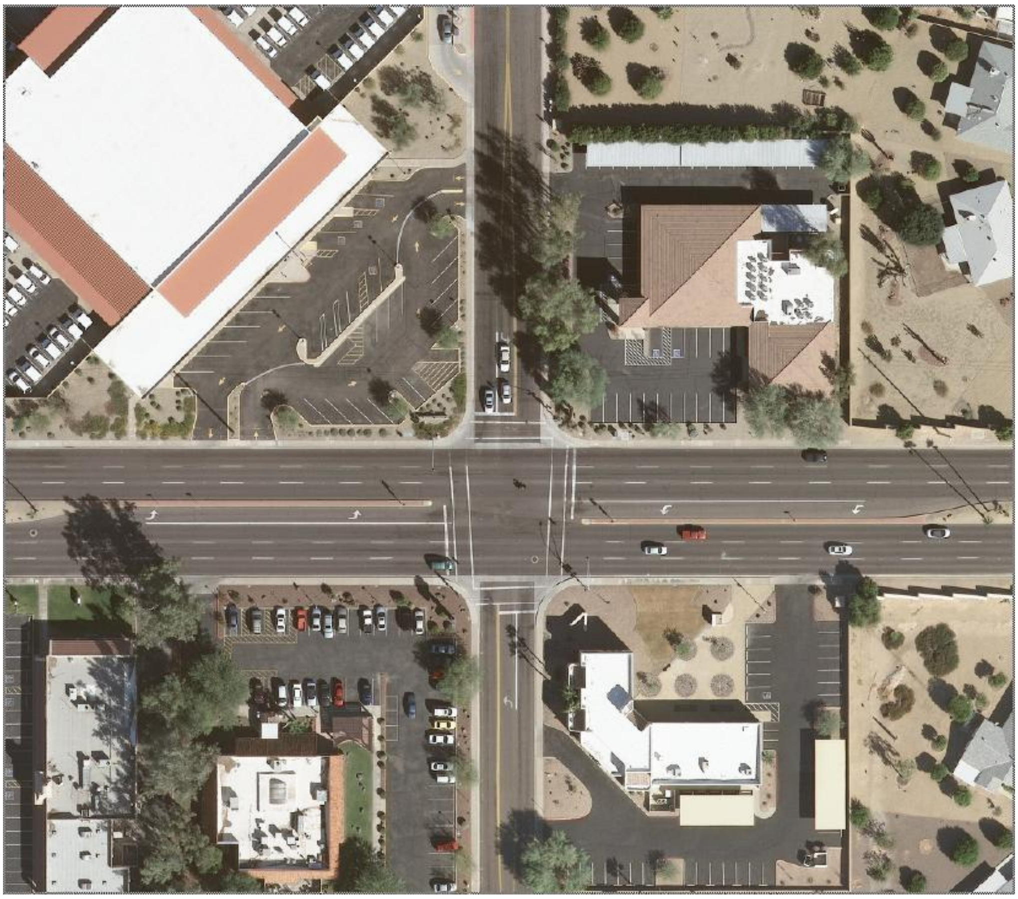


Figure 3.4 Bell Road and 98th Avenue in Phoenix, USA (Maricopa County Assessor Map, 2011).

3 - Bell Road and 99th Avenue

This is a four-legged signalized intersection, where Bell Road runs in the east-west direction and 99th Avenue runs in the north-south direction. Both the eastbound and westbound Bell Road approaches have two (2) left- turn lanes, two (2) through lanes, and one (1) shared through/right-turn lane. The left-turns on Bell Road are "protected-only". Both the northbound and southbound 99th Avenue approaches have two (2) left-turn lanes, two (2) through lanes, and one (1) shared through/right-turn lane. The left-turns on 99th Avenue are "protected-only". The speed limit on Bell Road is 45 mph (72,4 km/h) in both approaches and 40 mph (64,4 km/h) on 99th Avenue on both approaches.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

Figure 3.5 Bell Road and 99th Avenue in Phoenix, USA (Maricopa County Assessor Map, 2011).

4 - Bell Road and Boswell Boulevard

This is a four-legged signalized intersection, where Bell Road runs in the east-west direction and Boswell Boulevard runs in the north-south direction. Both the eastbound and westbound Bell Road approaches have one (1) left- turn lane, two (2) through lanes, and one (1) shared through/right-turn lane. The left-turns on Bell Road are “protected-only”. The northbound approach on Boswell Boulevard has one (1) left-turn lane, and one (1) shared through/right-turn lane. The southbound approach on Boswell Boulevard has one (1) left-turn lane, one (1) through lane, and one (1) channelized right-turn lane. The left-turns on Boswell Boulevard are “permissive”. The speed limit on Bell Road is 45 mph (72,4 km/h) in both approaches and 30 mph (48,3 km/h) on Boswell Boulevard on both approaches.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

Figure 3.6 Bell Road and Boswell Boulevard in Phoenix, USA (Maricopa County Assessor Map, 2011).

5 - Bell Road and Del Webb Boulevard

This is a four-legged signalized intersection, where Bell Road runs in the east-west direction and Del Webb Boulevard runs in the north-south direction. Both the eastbound and westbound Bell Road approaches have two (2) left- turn lanes, two (2) through lanes, and one (1) shared through/right-turn lane. The left-turns on Bell Road are "protected-only". Both the northbound and southbound Del Webb Boulevard approaches have two (2) left-turn lanes, two (2) through lanes, and one (1) shared through/right-turn lane. The left-turns on Del Webb Boulevard are "protected-only". The speed limit on Bell Road is 45 mph (72,4 km/h) in both approaches and 30 mph (48,3 km/h) on Del Webb Boulevard on both approaches.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

Figure 3.7 Bell Road and Del Webb Boulevard in Phoenix, USA (Maricopa County Assessor Map, 2011).

6 – Olive Avenue and 107th Avenue

This is a four-legged signalized intersection, where Olive Avenue runs in the east-west direction and 107th Avenue runs in the north-south direction. Both the eastbound and westbound Olive Avenue approaches have one (1) left- turn lane, one (1) through lane, and one (1) shared through/right-turn lane. The left-turns on Olive Avenue are “permissive”. The southbound approach on 107th Avenue has one (1) left-turn lane, and one (1) shared through/right-turn lane. The northbound approach on 107th Avenue has one (1) left-turn lane, one (1) through lane, and one (1) right-turn lane. The left-turns on 107th Avenue are “permissive”. The speed limit on Olive Avenue is 45 mph (72,4 km/h) in both approaches and 30 mph (48,3 km/h) on 107th Avenue on both approaches.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

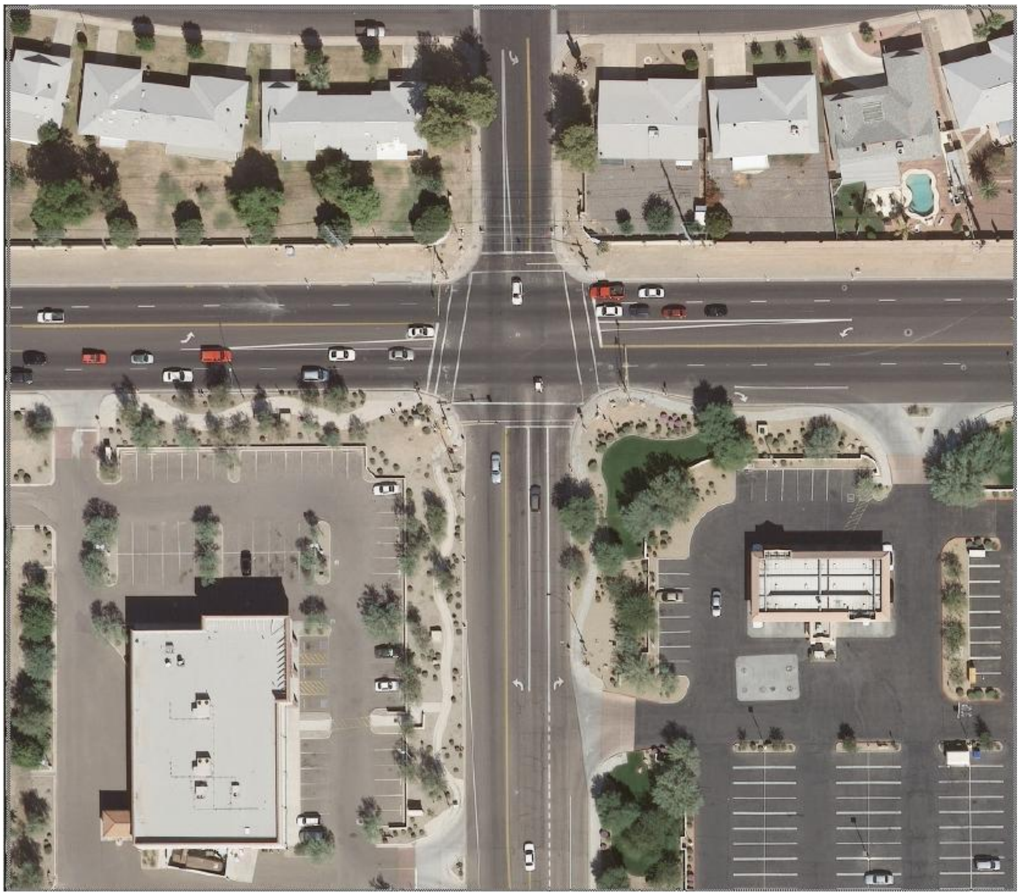


Figure 3.8 Olive Avenue and 107th Avenue in Phoenix, USA (Maricopa County Assessor Map, 2011).

7 – Olive Avenue and 111th Avenue

This is a four-legged signalized intersection, where Olive Avenue runs in the east-west direction and 111th Avenue runs in the north-south direction. Both the eastbound and westbound Olive Avenue approaches have one (1) left- turn lane, one (1) through lane, and one (1) shared through/right-turn lane. The left-turns on Olive Avenue are "protected-permissive". The southbound approach on 111th Avenue has one (1) left-turn lane, and one (1) through lane, and one (1) shared through/right-turn lane. The northbound approach on 111th Avenue has one (1) left-turn lane, one (1) through lane, and one (1) very short right-turn lane. The left-turns on 111th Avenue are "permissive". The speed limit on Olive Avenue is 45 mph (72,4 km/h) in both approaches and 35 mph (56,3 km/h) on 111th Avenue on both approaches.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

Figure 3.9 Olive Avenue and 111th Avenue in Phoenix, USA (Maricopa County Assessor Map, 2011).

8 – Olive Avenue and 103rd Avenue

This is a four-legged signalized intersection, where Olive Avenue runs in the east-west direction and 103rd Avenue runs in the north-south direction. Both the eastbound and westbound Olive Avenue approaches have one (1) left- turn lane, one (1) through lane, and one (1) shared through/right-turn lane. The left-turns on Olive Avenue are “protected-permissive”. The southbound approach on 103rd Avenue has one (1) left-turn lane, and one (1) through lane, and one (1) shared through/right-turn lane. The northbound approach on 103rd Avenue has one (1) left-turn lane, one (1) through lane, and one (1) very short right-turn lane. The left-turns on 103rd Avenue are “permissive”. The speed limit on Olive Avenue is 45 mph (72,4 km/h) in both approaches, 35 mph (56,3 km/h) on 103rd Avenue northbound, and 30 mph (48,3 km/h) on 103rd Avenue southbound.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

Figure 3.10 Olive Avenue and 103rd Avenue in Phoenix, USA (Maricopa County Assessor Map, 2011).

9 –Thunderbird Road and 99th Avenue

This is a four-legged signalized intersection, where Thunderbird Road runs in the east-west direction and 99th Avenue runs in the north-south direction. The westbound approach on Thunderbird Road has two (2) left-turn lanes, two (2) through lanes, and one (1) right-turn lane. The eastbound approach on Thunderbird Road has one (1) left-turn lane, one (1) through lane, and one (1) shared through/right-turn lane. The left-turns on Thunderbird Road are "protected-only". The southbound approach on 99th Avenue has two (2) left-turn lanes, one (1) through lane, and one (1) shared/right-turn lane. The northbound approach on 99th Avenue has two (2) left-turn lanes, two (2) through lanes, and one (1) right-turn lane. The left-turns on 99th Avenue are "protected-only". The speed limit on Thunderbird Road is 30 mph (48,3 km/h) in both approaches and 40 mph (64,4 km/h) on 99th Avenue on both approaches.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

Figure 3.11 Thunderbird Road and 99th Avenue in Phoenix, USA (Maricopa County Assessor Map, 2011).

10 – Indian School Road and 99th Avenue

This is a four-legged signalized intersection, where Indian School Road runs in the east-west direction and 99th Avenue runs in the north-south direction. Both the eastbound and westbound Indian School Road approaches have one (1) left- turn lane, one (1) through lane, and one (1) shared through/right-turn lane. The left-turns on Indian School Road are “protected-permissive”. Both the northbound and southbound 99th Avenue approaches have one (1) left- turn lane, one (1) through lane, and one (1) shared through/right-turn lane. The left-turns on 99th Avenue are “protected-permissive”. The speed limit on Indian School Road is 45 mph (72,4 km/h) in both approaches and 50 mph (80,5 km/h) on 99th Avenue on both approaches.

The traffic signal controller operates as semi actuated. Both roads have detectors, either because they are a minor street or because of the left-turn movement, or both.

Figure 3.12 Indian School Road and 99th Avenue in Phoenix, USA (Maricopa County Assessor Map, 2011).

Malmövägen and Ringvägen, Lund

This is a four-legged signalized intersection, where Ringvägen runs in the east-west direction and Malmövägen runs in the north-south direction. The westbound approach on Ringvägen has one (1) left-turn lane and one (1) shared through/right-turn lane. The eastbound approach on Ringvägen has one (1) left-turn lane, one (1) through lane, and one (1) right-turn lane. The left-turns on Ringvägen are “permissive”. However, the westbound approach has a “protected- only” phase which is activated by a detector in the westbound left-turn lane if necessary. The southbound approach on Malmövägen has one (1) left-turn lane, one (1) through lane, and one (1) shared through/right-turn lane. The northbound approach on Malmövägen has one (1) left-turn lane, two (2) through lanes, and one (1) right-turn lane. The left-turns on Malmövägen are “permissive”. The speed limit on Malmövägen and Ringvägen is 31 mph (50 km/h) in all four approaches. The traffic signal controller operates as fully actuated for the intersection of Malmövägen and Ringvägen. The entire intersection is operated by detectors as well as for pedestrians and bicyclists. Pedestrian and bicyclists will not be granted green-time unless they press the push-button. The intersection operates with four (4) permissive phases, and if necessary, a separate protected phase for WBL (westbound left) turning vehicles which also allows vehicle with a green arrow from the northbound to turn right simultaneously. The busiest approaches are the eastbound, northbound and the westbound. The RTOR from west to south and from south to east are of greatest interest because of the key connections of the highway 16 and freeway E22.

Figure 3.13 Malmövägen and Ringvägen in Lund, Sweden (Municipality of Lund, 2011).

3.2 Input data

The input data required to perform computations for this study were as follows:

- Road geometry (lengths, lanes, curvature)
- Traffic control (signal timing, signs)
- Entry volumes and turning movements (vehicular, pedestrian and bicycle)
- Speed data
- Default values

Road Geometry: The ten Phoenix aerial photographs were obtained from the geographical information system, Maricopa Association of Governments (MAG) Assessors Map, and for the intersection of Malmövägen and Ringvägen the aerial photograph was received from the Surveying Department of the Municipality of Lund. Together with field inspections and visits the necessary road geometry with its lengths and the number of lanes for each intersection were received. Lane widths were standard widths in both USA and Sweden. In the USA, the standard lane widths are 10-12 feet (3,04-3,66 meters) and in Sweden around 11,5 feet (3,5 meter). Vehicle storage length were obtained from the aerial images and field verified.

Traffic Controls: Control data with the location of traffic control devices and signal-timing settings were obtained through field inspection and aerial photographs. Existing signal timings in Phoenix were not available and were therefore optimized in the software Synchro. For the intersection of Malmövägen and Ringvägen the existing signal timing was obtained from Lund Municipality agency operating the traffic control at the intersection. These were also verified in the field.

Demands: Existing peak-hour turning movement volumes for the American intersections in Phoenix were obtained through counts that were conducted in year of 2010 between April 22 and June 10 by United Civil Group (UCG) and submitted to Jacobs Engineering Group Inc in Phoenix. Both morning and afternoon peak-hour volumes were received and considered in the study. Traffic volumes and turning-movement counts for the intersection of Malmövägen and Ringvägen in Lund were collected through field measurements for both the morning and afternoon peak-hour. This was done because AM and PM peak-hour traffic usually travels in opposite directions and will have a differing flow rate in the AM and PM model. The geometry is still the same. One example of this case is if there is much commuting and RTOR only affects one direction in the morning and another one in the afternoon.

The data was collected for the peak-hour volumes, during the morning peak period (7:30 am to 8:30 am) and during the afternoon peak period (4:30 pm to 5:30 pm). The field study was implemented during Wednesday, September 14 and Thursday 15 September 2011. All vehicle inputs can be found in Appendix C.

Vehicle Characteristics: The default vehicle mix and characteristics (vehicle dimensions and vehicle performance) provided with the microsimulation software were used in this analysis. The mix of different vehicle types, such as cars and heavy vehicles are defined in the vehicle composition prior to the input flow definition. The vehicle mix for the intersections in Phoenix were coded as 98 percent as cars and 2 percent as heavy vehicles in both the AM- and PM-hour traffic. From the field data collected, 95 percent of the AM peak-hour traffic was coded as cars and 5 percent as heavy vehicles in the model for the intersection of Malmövägen and Ringvägen in Lund. In the PM peak-hour, 98 percent of the traffic was coded as cars and 2 percent as heavy vehicles.

Traffic volumes were then defined for each link and enter the roadway network from the end of each link. The traffic volumes coded for this intersection were coded using the data collected in the field for both the AM and PM peak-hours.

Default values: Default values were used were applicable. Literature and article search resulted in no major success for a definite value for gap acceptance where RTOR applied. The Highway Capacity Manual (HCM) critical gap for a right-turn at an unsignalized intersection is 6.9 seconds for a four-lane street (two lanes in each direction) as described in section 2.2. No specific value for the critical gap could therefore be applied on the intersection of Malmövägen and Ringvägen and on the ten intersections in Phoenix. Therefore the following default VISSIM values for gap acceptance were used:

- Visibility: 100 meters
- Front Gap: 0.5 seconds
- Rear Gap: 0.5 seconds
- Safety Distance Factor: 1.5

The descriptions of the above mentioned options and default values can be found in the VISSIM User Manual under section 6.6.2.3 or in this thesis in section 2.9.

4 Model building and simulation

VISSIM microscopic computer software was used for this traffic analysis. This section describes the model building process for the VISSIM model that was made for both the American intersections and the intersection in Sweden. At first a base model was created for each intersection, one for the morning peak-hour named AM and one for the afternoon peak-hour named PM. These two models were then modeled with both RTOR and without RTOR. The total number of models resulted in four models for each intersection. The models were named by their intersection name followed by either the AM_RTOR, AM_noRTOR, PM_RTOR or the PM_noRTOR extension.

4.1 VISSIM inputs

4.1.1. Background image

The aerial JPEG-image obtained from Lund municipality and Maricopa Association of Governments (MAG) Assessors Map was inserted as the background for the VISSIM model and its geometry. This image was then edited to obtain the correct scale and geometry for the model. The scale of the model was verified by measuring a distance in the model and comparing with the actual field distance.

4.1.2 Links

Each link represents a segment of the roadway such as a one-lane, two-lane etc., section. The first step in coding the VISSIM network was to trace all the links on the aerial image and to put the correct distances of lanes and lane configurations for the intersection. The scaled background image helped with drawing and tracing the lane configurations and curvature of the road. Some of the links needed to get extended after the signal head to prevent vehicles from driving on red light later when the model started to run, but also to make space for the vehicles to decide their route earlier to make the model much more realistic. It was also important for the links to be drawn in the traffic direction to obtain a correct traffic simulation.

4.1.3. Connectors

After the links were drawn, connectors were added in order to connect the links and create a road network. In order for vehicles to continue from one link to another, connectors are necessary to bind the two links. Connectors are especially important since they serve to model turning movements at intersections. All connectors except the right-turn (RT) connectors had to be placed past the signals. If signals are placed on connectors, vehicles will not stop and just run the red light. Therefore, stop bars were placed, for right-turning vehicles, making them come to a complete stop before turning right on red.

4.1.4 Reduced speed areas

Reduced speed areas are typically used on curves or sharp turns. These reduced speed areas take into account the real-world driving behavior and make the model more realistic. Since these areas are normally on curves or sharp turns, they are usually placed on connectors instead of links. In this model, the vehicle speed was reduced to 25 km/h for cars and 20 km/h for heavy vehicles in these areas from the posted speed limit. An assumption was made for modeling purposes that 15 percent of all vehicles will drive 5 mph (8.04 km/h) above regulated speed and 85 percent will drive just as the signed speed. The reduced speed areas were set to 20 feet (6.09 meter).

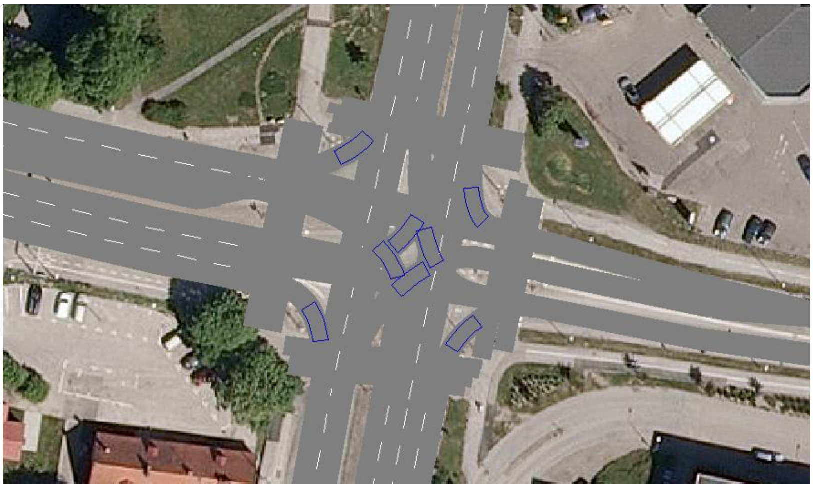


Figure 4.1 Reduced speed areas for Malmövägen and Ringvägen.

4.1.5 Desired speed decisions

Desired speed decisions are located at places where a permanent speed change should become effective. They are most important for right and left turns. As each vehicle crosses over the desired speed decision the vehicle gets a new speed distribution, either increasing or decreasing from its previous speed distribution (PTV, 2011, p.204). In the vicinity of this intersection, all posted speed limits were coded as 50 km/h as they appear in the field on Malmövägen and Ringvägen. The speed limit were coded in the same way for the Phoenix intersections, i.e. as they appear in the field. The speed at each intersection can be found in detail in section 3.1.

4.1.6 Vehicle inputs (Traffic volumes and vehicle composition)

The different flows and turning movement volumes for the intersections in Phoenix were obtained through counts that were conducted in year 2010 between April 22 and June 10 by United Civil Group (UCG) and submitted to Jacobs Engineering Group Inc in Phoenix (see Appendix C). The vehicle mix for the intersections in Phoenix were coded as 98 percent as cars and 2 percent as heavy vehicles in both the AM- and PM-hour traffic. The same data for the intersection of Malmövägen and Ringvägen in Lund were obtained through a field study.

The mix of different vehicle types, such as cars and heavy vehicles are defined in the vehicle composition prior to the input flow definition. From the field data collected, 95 percent of the AM peak-hour traffic was coded as cars and 5 percent as heavy vehicles in the model. In the PM peak-hour, 98 percent of the traffic was coded as cars and 2 percent as heavy vehicles. Traffic volumes were then defined for each link and enter the roadway network from the end of each link. The traffic volumes coded for this intersection were coded using the data collected in the field for both the AM and PM peak-hours (see Figure 4.2).

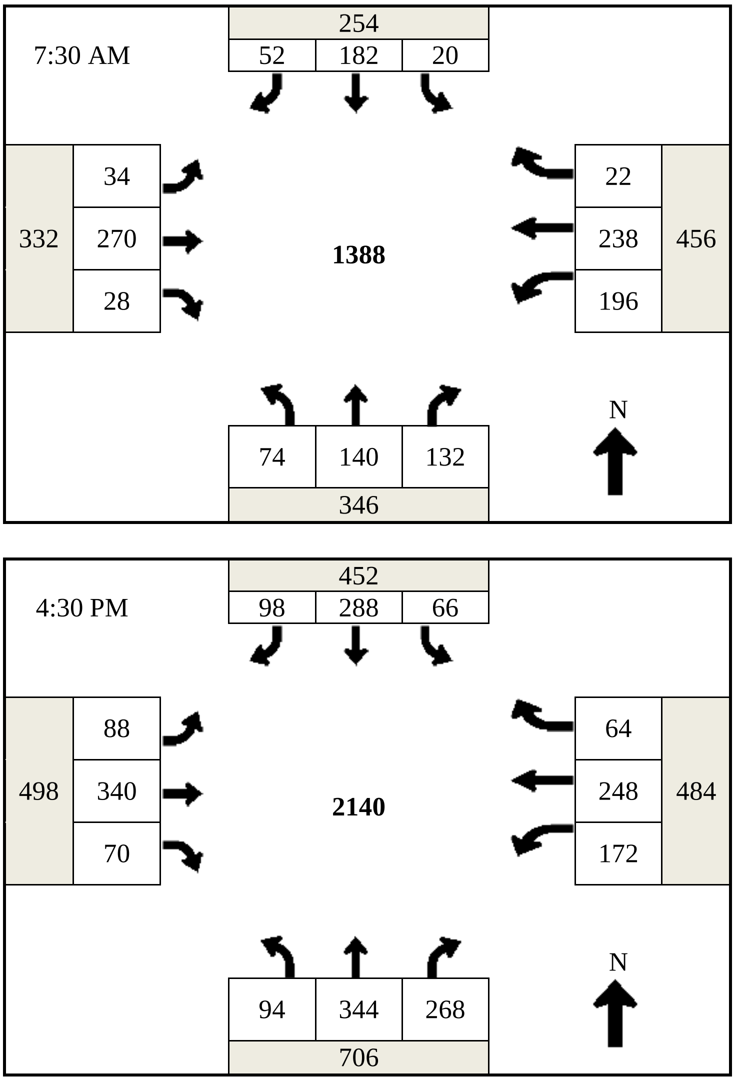


Figure 4.2 Field collected vehicle data for the intersection of Malmövägen and Ringvägen from September14 th (Wednesday) and September 15 th (Thursday) 2011.

4.1.7 Routing decisions and routes

A route is a fixed sequence of links and connectors that can consist of several destination points. It has both a start point and an end point to a defined destination. The different routes were drawn for every approach and lane with respective vehicle distributions and inputs for each direction.

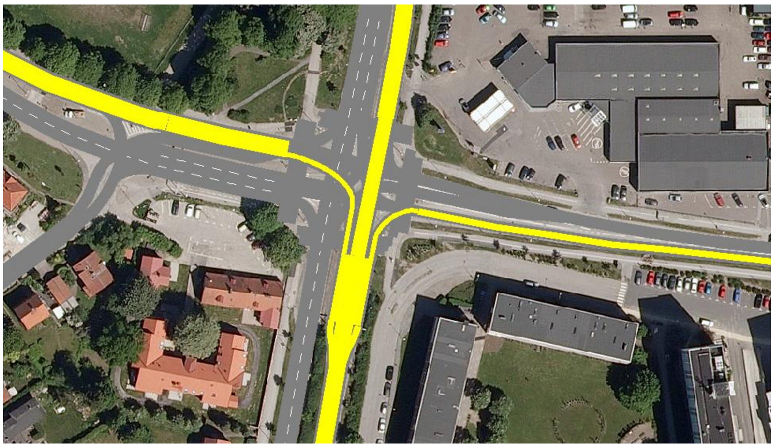


Figure 4.3 Drawing routes in VISSIM. Snapshot taken for the intersection of Malmövägen and Ringvägen in Lund.

4.1.8 Conflict areas

Conflict areas were used to define priority in the intersection since they are normally used for signalized intersections. Conflict areas are also more easily defined and the resulting vehicle behavior is more intelligent (PTV 2011, p. 270). A conflict area occurs whenever two links/connects overlap in the network. For each conflict area a right of way was given to the link that has priority according to existing traffic regulations. Yielding drivers have to cross the conflict area, and in order to do that they have to observe the approaching vehicles and find a gap in the stream. The vehicles which have priority in any given situation also have to react on the conflict area. For example, if a yielding vehicle did not correctly estimate the gap time, the vehicle with priority will start to break or even stop in order to avoid an accident.

Some of the given conflicts do not appear with traffic signals installed which are therefore more important to consider if the intersection is controlled by traffic signs (yield and/or stop). The conflict areas were for this reason adjusted and not considered. This is since too many defined conflict areas may result in a yield interaction that takes places in the "wrong" place which is a place before the location of the conflict area. This type of behavior does not occur in reality. The vehicle in reality will approach the intersection as close as possible to make a specific turning movement. This was noted in one of the models for the intersection of Malmövägen and Lund.

Figure 4.4 Conflict areas for Malmövägen and Ringvägen to the left and Burns Drive and Bell Road to the right.

4.1.9 Stop sign control

Just like in the real world, the STOP sign forces the vehicles to stop for at least one time step regardless of the presence of conflicting traffic. STOP signs were used for right-turn connectors and were placed just before the stop-bar for the traffic signal. The option *Only on Red* had to be checked since there are no regular STOP signs at the intersection in field. For RTOR, the STOP sign is only active when the allocated signal group has a red light.

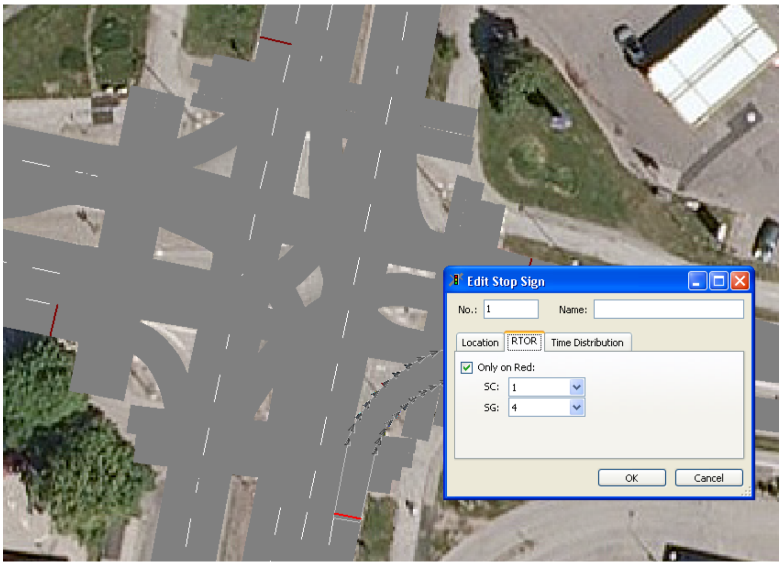


Figure 4.5 Stop sign control and RTOR for Malmövägen and Ringvägen.

4.1.10 Signal controllers

Signal controllers are a critical part for any intersection and are a key component of the VISSIM model. Every signal controller has individual signal phases as its smallest control unit. These signal phases match the phasing of the intersection in the field. Signal heads are coded and the actual device is shown in the VISSIM model. Each signal head is placed on the signal stop line and is coded for every lane. The signal controller type used for the intersection of Malmövägen and Ringvägen was the ring-and-barrier controller (RBC). The signal controller type used for the 10 intersections in the Phoenix was NEMA Standard, which is the same as the RBC. The NEMA Standard and RBC signal controllers were used because it can simulate fully and semi-actuated signal controls. This is the type of signal control that is common in the American releases of VISSIM.

Existing signal timings in Phoenix were not available and were therefore optimized in the software Synchro. The traffic signal phasing and timing for Malmövägen and Ringvägen was not optimized in Synchro since they were obtained from the City of Lund. The schedule can be found in the Appendix. The signal phasing and timing was field verified to make sure that the signal sheet is still current. It was then converted to the standard RBC phasing, see Figure 4.6.

The traffic signal controller operates as fully actuated for the intersection of Malmövägen and Ringvägen. The entire intersection is operated by detectors as well as for pedestrians and bicyclists. Pedestrian and bicyclists will not be granted green-time unless they press the push-button. The intersection operates with four (4) permissive phases (phase 2, 4, 6 and 8), and if necessary, a separate protected phase (phase 5) for WBL (westbound left) turning vehicles. The lagging protected phase is only activated if cars are detected in the WBL turn lane. If the protected WBL turn phase is activated, the NBR turning vehicles will also receive a protected phase which overlaps with phase number five.

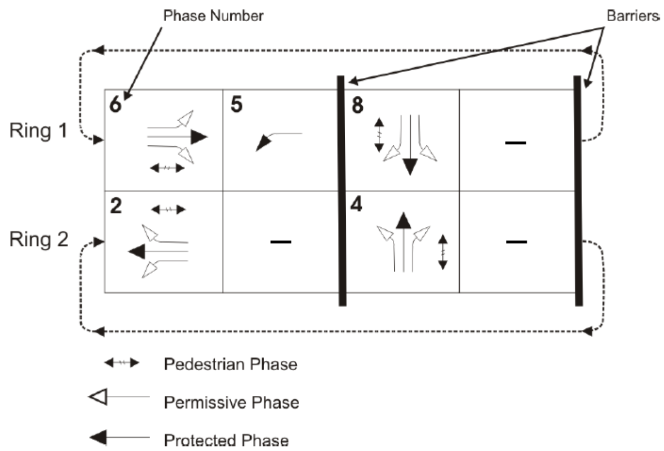


Figure 4.6 The valid signal phases for Malmövägen and Ringvägen converted and translated to RBC- phases (2, 4, 5, 6 and 8).

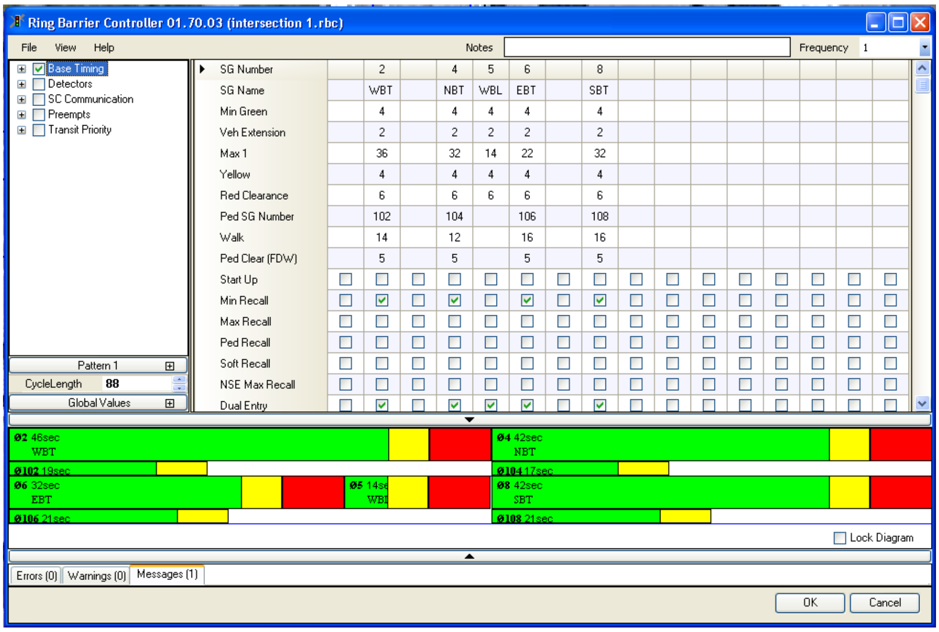


Figure 4.7 Using the Ring Barrier Controller for Malmövägen and Ringvägen.

4.1.11 Detectors

The detection of vehicle and pedestrian/bicyclists in real life are usually achieved using various methods as induction loops, video cameras, push buttons etc. VISSIM models each detector type as a network element of user-definable length. As soon as a vehicle approaches the detector with its front, and another one when it leaves it with its tail, a message impulse is transmitted to the signal controller and activates it.

Detectors were placed close to the stop- bar and before the signals in order to activate the fully or semi-actuated signal control. If not, it would make some vehicles go against the red light when running the model. An undefined conflict area would also make the vehicles go against the red light. The vehicle detectors were set to a length of 30 ft (≈ 9,14 m). The length of the vehicle detectors may be perceived as short and should have maybe been extended to twice the length or more. This since a cars length is about 5-6 meter long and there is a space of approximately one meter between two cars and behind the car to the next car in the queue. The problem which occurs with a too short vehicle detector is that the detectors will probably not detect more than two cars at one time and lead to a too short green cycle length. The problem could be solved by adding the vehicle extension to 2 seconds per vehicle (default value) in the signal control window.

Detectors, which act as pushbuttons, were also placed for pedestrians and bicycles in the VISSIM model (only for Malmövägen and Ringvägen in Lund). All pedestrian and bicycle detectors were placed on the pedestrian and bicycle links and islands.

Detectors on Malmövägen and Ringvägen in Lund were placed with help from the signal plan for in Appendix A, Figure A.2.

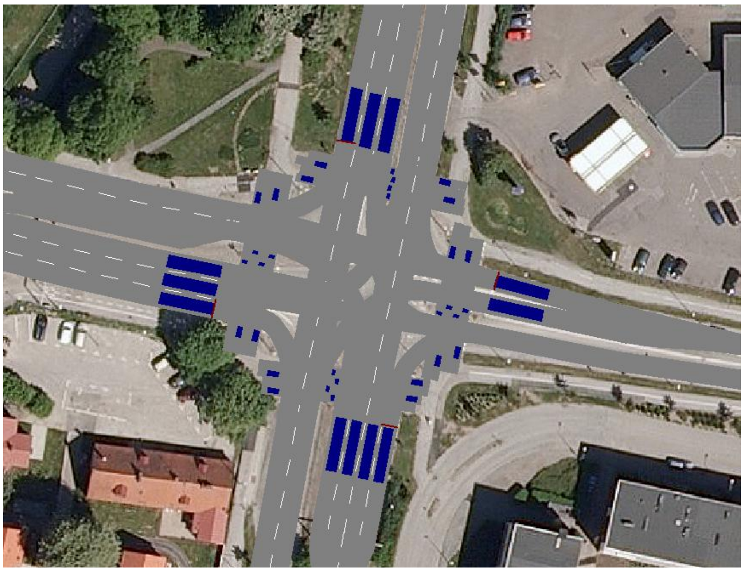


Figure 4.8 Detector positions for Malmövägen and Ringvägen.

4.1.12 Pedestrian and bicycle inputs

Similar as for the vehicle inputs, inputs for pedestrians/bicycles can be defined for a preferred walk-able space or a pedestrian link. The mix of different types of pedestrians, both walking and cycling was defined in the 'vehicle types' prior to the input flow definition. The pedestrians were coded on links which are defined as 'footpath' and bicyclists were coded on links which are defined as 'cycle-track'. The walking speed for pedestrians was coded as 5 km/h (Hydén 2008, p.214) and the cycling speed was coded as 12 km/h in this for this intersection since bikes mostly have to stop and then start again (Allen 1998, p.30; Eadavalli 2012). VISSIM creates pedestrians at random points in time according to the pedestrian compositions and inputs volume from the field data collected in Figure 4.9

The pedestrian volumes were defined for each pedestrian and bicycle link using the data collected in the field for both the AM and PM peak-hours. The data was collected during two typical weekdays (Wednesday and Thursday) in September 2011 and during the peak-hours, to include normal weekday traffic conditions. The weather was mainly cloudy and windy with a dry surface. The AM peak-hour was collected from 7:30 to 8:30 and the PM peak-hour data was collected from 16:30 to 17:30. The total number of pedestrian and bicycle traffic was divided and equally distributed as 50 percent walking pedestrians and 50 percent bicycle riders. The simplification had to be done since the collected data for the number of each road user type was not separated in the field. Pedestrians and bicyclists were given rights of way over cars.

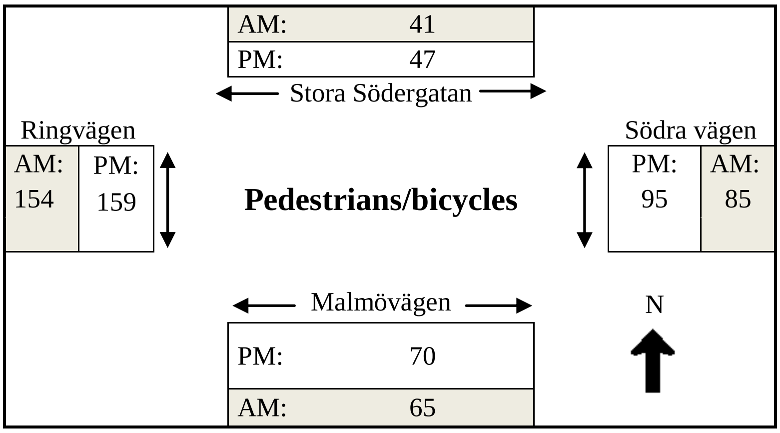


Figure 4.9 Field data collected pedestrian and bicycle inputs and their movements for Malmövägen and Ringvägen from September 14th and 15 th 2011.

4.1.13 Simulation time and model run

At the completion of all the VISSIM inputs, the model was run in a defined simulation time. A start and end time of the data collection was specified as well as the interval at which the data is collected.

Data was collected every hour (3600 seconds). In order to avoid impacting the results due to an initially empty network, data collection started at 15 minutes (900 seconds) after the initiation of the simulation (seeding period). The simulation time used for this project was therefore 4500 seconds (1 hour and 15 minutes). The model began at 0 seconds and was run until 4500 seconds. For the first 900 seconds (15 minutes) the model was being seeded with vehicles, pedestrians and bicycles but the results were not recorded. As stated before, the results were recorded and extracted only from 900 seconds to 4500 seconds. This since it usually takes a while until the model starts to work and the vehicles populate the model. The results that were extracted represent the AM and PM peak-hour (60 minutes). Each VISSIM model (scenario) was run 10 times and the results were averaged out in order to get a good sample size of runs and confident results.

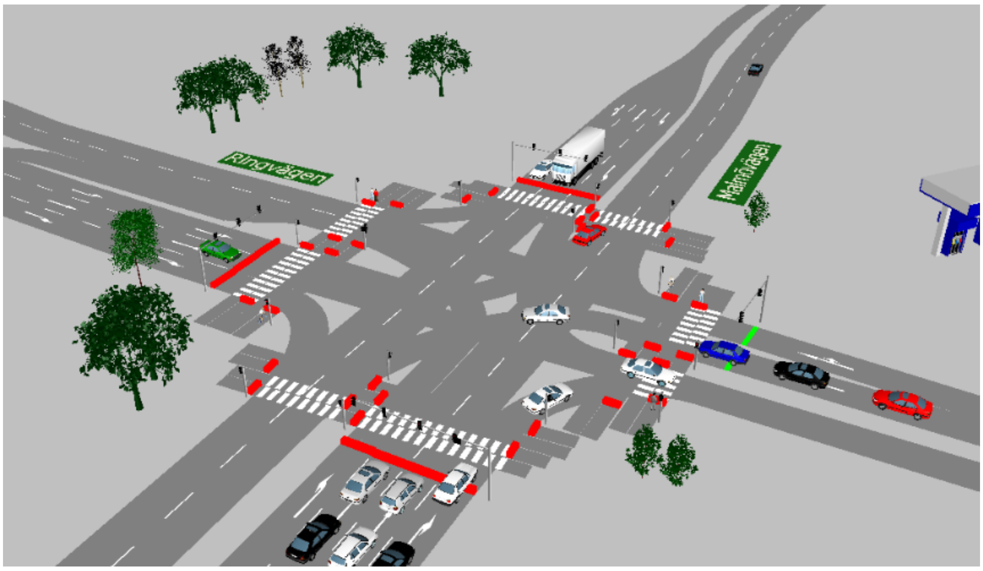


Figure 4.10 The simulated VISSIM model with RTOR for Malmövägen and Ringvägen in Lund.

4.2. VISSIM outputs and data processing

VISSIM provides a large number of options for output, all of which can be tailored to the needs of the user. In order to get the desired output data, a node evaluation configuration file has to be created. VISSIM provides several parameters and settings for node evaluation. Parameters and other settings need to be selected by the user. These are then saved to a node evaluation configuration file which has the extension *.knk. In this case, the node evaluation was set to report the following compiled data:

- Node
- From Link
- To Link
- Movement
- Number of Vehicles (all vehicle types)
- Average Queue Length
- Maximum Queue Length
- Delay Time (all vehicle types)
- Fuel consumption
- Emissions CO
- Emissions NOx
- Emissions VOC

The results of a node evaluation are then grouped by turning movements and saved to a file with a *.kna extension which contains following compiled data:

- File title
- Path and name of the input file (File)
- Simulation comment (Comment)
- Date and time of the evaluation (Date)
- Version no. with Service pack no. and Build no. (VISSIM)
- List of selected parameters with brief description, as listed above
- Data block with a column for each selected parameter.

These serve the purpose of collecting information on the volume of vehicles entering at each approach as well as the turning movement volumes at the intersections. Information was also collected on the delay that the vehicles experienced at the intersection. The kna-files were imported in Microsoft Excel and sorted.

The results were then compared in the successive runs with the respective field data. The results were processed and an analysis of the results can be found in the *Results and analysis* chapter. The LOS was also calculated and translated into the A through F classifications. Emissions and fuel consumption were also recorded in each simulation. Microsoft Excel was used to create diagrams and graphs. Microsoft Excel was also used to calculate the different statistical data and to do Student´s t-tests in order to test and prove the different hypotheses in the thesis.

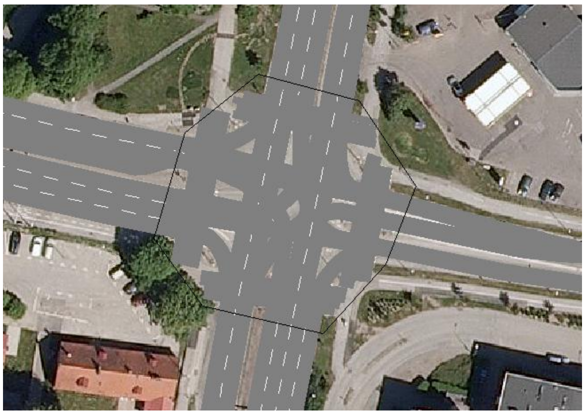


Figure 4.11 The evaluated node for the intersection of Malmövägen and Ringvägen.

	A	B	C	D	E	F	G	H	I	J
1										
2	Node evaluation									
3										
4	File: c:\users\natasa\desktop\vissim\1- burns- bell\am\1 - burns-bell_am.inp									
5	Comment:									
6	Date: Tuesday, August 09, 2011 4:17:51 PM									
7	VISSIM: 5.10-12 [24505]									
8										
9	Node 1: 1- Burns- Bell									
10										
11	Node: Node Number									
12	FromLink: Number of the link entering node									
13	ToLink: Number of the link leaving node									
14	Movement: Movement (Bearing from-to)									
15	Veh(All): Number of Vehicles, All Vehicle Types									
16	Delay(All): Average delay per vehicle [s], All Vehicle Types									
17	aveQueue: Average Queue Length [ft]									
18	maxQueue: Maximum Queue Length [ft]									
19	FuelCons: Fuel Consumption [gal]									
20	EmissCO: Emissions CO [g]									
21	EmissNOx: Emissions NOx [g]									
22	EmissVOC: Emissions VOC [g]									
23	tStopd(All): Average stopped delay per vehicle [s], All Vehicle Types									
24	Stops(All): Average number of stops per vehicles, All Vehicle Types									
25										
26	Node	FromLink	ToLink	Movement	Veh(All)	Delay(All)	aveQueue	maxQueue	FuelCons	EmissCO
27	1	1	6	E-N	24	6,6	14,9	142,9	0,17	11,7
28	1	1	2	E-W	1391	8,3	19,4	151	11,25	786,09
29	1	3	8	W-S	34	6,8	31,4	259	0,24	17
30	1	3	4	W-E	2307	10,3	40,4	278,2	19,58	1368,55
31	1	5	4	S-E	59	6,1	0,2	67,5	0,4	28,12
32	1	5	6	S-N	14	18,4	1,1	80,6	0,15	10,43

KNA1 | KNA2 | KNA3 | KNA4 | KNA5 | KNA6 | KNA7 | KNA8 | KNA9 | KNA10 | Avg | LOS

Figure 4.12 The imported KNA-file to Microsoft Excel.

AM Peak Hour
Analysis Year 2011
Delay/ LOS

Intersection	Approach Direction	Movement	From Link	To Link	Delay (All Veh) by movement (sec)	Volume (Output) (All Veh) by (vph)	Approach Volume (Output)	Approach Volume (Input) (vph)	Output / Input	Intersection (vph)	Mvmt. % Approach Volume	Approach % Total Volume	Mvmt. Delay Weighted by Volume	Delay (All Veh) by movement	Weighted Delay by Approach	Approach LOS	Intersection Delay	Intersection LOS	Avg Queue (feet)	Max Queue (feet)	FuelCons	EmissCO	EmissNOx	EmissVOC	tStopd(All)	Stops(All)	Link Concatenate
1 - Burns-Bell_AM	SB	R	7	2	3,5	12				4004,2	14%		0,51	3,5			11,64	B	0,8	56,0	0,1	5,4	1,1	1,3	1,5	0,2	72
		T	7	8	17,0	35	82	80	103%		42%	2%	7,13	17,0	14,92	B			2,7	68,6	0,4	25,0	4,9	5,8	12,1	0,6	78
		L	11	4	16,8	36					43%		7,29	16,8					2,6	52,4	0,4	24,5	4,8	5,7	12,6	0,6	114
	WB	R	1	6	6,3	24					2%		0,10	6,3					15,2	164,8	0,2	11,6	2,3	2,7	2,4	0,4	16
		T	1	2	8,5	1397	1463	1483	99%		95%	37%	8,11	8,5	9,41	A			19,6	172,8	11,3	793,0	154,3	183,8	3,8	0,3	12
		L	9	8	41,1	43					3%		1,20	41,1					9,1	77,1	0,6	43,9	8,5	10,2	34,7	1,0	98
	NB	R	5	4	8,0	65					65%		5,19	8,0					0,5	58,4	0,5	32,8	6,4	7,6	2,8	0,9	54
		T	5	6	17,8	16	101	100	101%		15%	3%	2,75	17,8	11,31	B			1,6	71,5	0,2	11,4	2,2	2,7	12,2	0,6	56
		L	12	10010	16,9	20					20%		3,37	16,9					1,4	47,5	0,2	13,9	2,7	3,2	11,9	0,7	1210010
	EB	R	3	8	9,7	28					1%		0,11	9,7					32,9	274,2	0,2	14,9	2,9	3,5	4,1	0,5	38
		T	3	4	10,7	2314	2358	2377	99%		98%	59%	10,52	10,7	10,92	B			42,1	293,4	19,8	1386,2	269,7	321,3	4,6	0,4	34
		L	10	6	39,6	17					1%		0,29	39,6					3,2	54,4	0,3	17,5	3,4	4,1	33,0	1,0	106

Figure 4.13 The processed results for Burns Drive and Bell Road.

5 Calibration and validation

Calibration and validation of the model needs to be performed to ensure that the model performance actually gives a reasonable approximation of the reality (field measurements). The calibration is done by running the model with the data set describing the existing network and traffic scenarios and then comparing the simulation model results with the observed data collected in the field.

Since this study only looks at the intersection and not the entire network there have been problems to perform a calibration on the model. The travel time runs, speed and/or the delay could therefore not be easily measured in the field. It makes it even harder to measure the travel time and other calibration parameters for the Phoenix intersections since the current signal timings could not be received and an optimization was needed to be implemented. Usually, when analyzing entire networks actual travel times for the study corridor are then compiled from a series of travel time runs driven along the eastbound and westbound or the southbound and northbound directions during the AM and PM peak-hour. The average travel times calculated from field data could therefore also not be utilized in the calibration process to compare actual travel times experienced to travel times observed in the model.

The VISSIM model was calibrated using existing traffic counts collected on intersection. Only one field collected data point was used during each of calibration and validation tests even if is more desirable to collect several data points, collected over time, of field data to account for the day-to-day variability. The model has been validated more than calibrated. Each intersection was evaluated to verify that at least 85 percent of the input volumes (according to the calibration criteria in Figure 5.1) are being processed in the VISSIM model. The accuracy of processed volumes was 98 percent or higher.

Another approach has simply been observing the model visually and looking for things that differ from reality case according to the checklist in Appendix B. The model has been studied and modeled to match the field conditions. The reality is based on what was observed during the several on-site visits. It could for example be seen where most of the queues arise and later compared to where most of the queues occur in the model. This type of check is also a great indicator of how accurately the signals are performing in the model. This is of great importance since they are not easy to simulate especially for detector controlled intersections. The simulated intersection could be recognized and accepted.

Each model was run ten times with different random seeds to receive better average data for the entire peak-hour. The calibration criteria used for the VISSIM model can be found in *Table 4. Wisconsin DOT freeway model calibration criteria* in the *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software*.

Criteria and Measures	Calibration Acceptance Targets
Hourly Flows, Model Versus Observed	
Individual Link Flows	
Within 15%, for 700 veh/h < Flow < 2700 veh/h	> 85% of cases
Within 100 veh/h, for Flow < 700 veh/h	> 85% of cases
Within 400 veh/h, for Flow > 2700 veh/h	> 85% of cases
Sum of All Link Flows	Within 5% of sum of all link counts
GEH Statistic < 5 for Individual Link Flows*	> 85% of cases
GEH Statistic for Sum of All Link Flows	GEH < 4 for sum of all link counts
Travel Times, Model Versus Observed	
Journey Times, Network	
Within 15% (or 1 min, if higher)	> 85% of cases
Visual Audits	
Individual Link Speeds	
Visually Acceptable Speed-Flow Relationship	To analyst's satisfaction
Bottlenecks	
Visually Acceptable Queuing	To analyst's satisfaction

Figure 5.1 Calibration targets (FHWA 2004c, p. 64).

Since this study makes a comparison with RTOR and without RTOR for the same intersection, it was assumed that any errors would be identical in both cases and cancel each other when comparing the two cases with RTOR and without RTOR.

6 Traffic safety and RTOR

Traffic safety is measured by rates of traffic accidents and consequences. By consequences we mean the number of killed or injured people and also the number of property damages (PDO) and their severity. It can be measured directly by simply counting the number of accidents occurring during a given period of time. A research was made in existing literature and studies in Chapter 2 to see whether it is possible to verify the current safety impact of RTOR in terms of the number of increased crashes, deaths and injuries. This showed not to be achievable since crash data from a time before to the adoption of the RTOR is not available or are too outdated (20 or more years) to be compared to the current crash rates. It is impossible to draw a conclusion if the observed increases in right-turning crashes of the current situation are a result from adoption of the RTOR legislation in the 1970's or if something else has contributed to the increase. The vehicle characteristics, traffic volume, driver behavior and more has changed over time and there is also no easy way to measure these changes.

However, the potential size of the problem could be measured in terms of the number of fatalities and the relative frequency in right-turning crashes by using state crash data where available. The collection of the crash data differ between the states. Some states keep track of RTOR crashes while others do not classify them as RTOR crashes.

6.1 Phoenix, USA

Crash data was obtained from Arizona Department of Transportation (ADOT) section for a four-year period from January 1st in 2007 to December 31st in 2010 for the all ten Phoenix intersections within the study area. At the time of this study, that was the most recent 4-year crash data available from ADOT. ADOT TSS is an abbreviation of Arizona Department of Transportation and Traffic Safety Section, and is a network for data related to accidents and injuries in the road transportation system in Arizona. Every municipality in Arizona reports its crashes to ADOT. The ADOT system ALISS (Accident Location Identification Surveillance System), is only based on data from police reports and does not include any hospital reports (Cherry et al 2006, p. 4).

The crash data was obtained in Microsoft Excel format from ADOT TSS and their (state accident file) database for fatal accident reporting system. Raw data was received and later sorted to find the appropriate categories such as 'manner of collision' and 'severity of crashes'. The crash data was analyzed to identify deficiencies and problem areas within the study area by comparing it to the Swedish intersection. This was done to see if there are any differing crash patterns that can be related to the permitted RTOR maneuver.

The information that was received does not include any information on whether a vehicle was turning right on red at the time of the crash, only that the vehicle was turning right at the time of the crash at an intersection where RTOR is permitted.
The injury classification for motor vehicle traffic crashes that are used in the crash data applies to any person involved in such crashes which are either in or outside a motor vehicle. It describes the severity of motor traffic crashes in terms of the degree of injuries sustained. The entire crash is therefore categorized according to the most serious injury sustained by any person involved (TxDOT 2008, p. 10). The injury classifications are as follows:

- Fatal Injury (Fatality) – Any injury sustained in a motor vehicle traffic crash that results in death within thirty days of the motor vehicle traffic crash (TxDOT 2008, p. 10).

- Incapacitating Injury – Any injury, other than a fatal injury, which prevents the injured person from walking, driving or normally continuing the activities he was capable of performing before the injury occurred (TxDOT 2008, p. 10).

- Non-Incapacitating Injury - Any injury, other than a fatal or an incapacitating injury, which is evident to observers at the scene of the crash in which the injury occurred (TxDOT 2008, p. 10).

- Possible Injury – Any injury reported or claimed which is not a fatal, incapacitating or non- incapacitating injury (TxDOT 2008, p. 10).

- No Injury - is a situation in which there is no reason to believe that the person received any physical injury from the motor vehicle traffic crash in which involved (TxDOT 2008, p. 10).

The classification can be done by ordinary observation at the time of the crash or from information submitted on the crash report form (TxDOT 2008, p. 10).

Results from ADOT analysis

The data from ADOT showed a clear pattern over the most common accidents types during the four-year period. These seemed to be rear end collisions between motor vehicles (total 261 accidents for the ten intersections, 79 resulting in an injury or possible injury), angle collisions (total 75 accidents, 36 resulting in an injury or possible injury, and three fatal) and sideswipe collisions in the same direction (total 55 accidents, six resulting in an injury or possible injury) as also can be seen summarized in Table 6.1 and 6.2.

Accident Type	Total	Bell Road and Burns Drive	Bell Road and 98th Avenue	Bell Road and 99th Avenue	Bell Road and Boswell Boulevard	Bell Road and Del Webb Boulevard	Olive Avenue and 107th Avenue	Olive Avenue and 111th Avenue	Olive Avenue and 103rd Avenue	Thunderbird Road and 99th Avenue	Indian School Road and 99th Avenue
Rear End	**261**	16	32	33	29	41	25	21	21	18	25
Angle	**75**	6	14	12	9	4	6	5	5	3	11
Sideswipe (same direction)	**55**	8	4	12	5	8	2	2	3	7	4
Left Turn	**45**	2	4	1	2	4	7	6	8	1	10
Single Vehicle	**21**	2	0	4	3	2	4	3	1	2	0
Other	**9**	0	1	1	0	1	0	1	1	1	3
Unknown	**4**	0	0	1	1	0	1	0	0	1	0
Rear to Side	**3**	0	0	0	0	1	0	0	1	1	0
Head On	**3**	0	0	1	0	0	0	0	2	0	0
Total	**476**	**34**	**55**	**65**	**49**	**61**	**45**	**38**	**42**	**34**	**53**

Table 6.1 Number of accidents by accident type, based on the data from 2007 to 2010 (ADOT 2011).

Injury type	Total	Bell Road and Burns Drive	Bell Road and 98th Avenue	Bell Road and 99th Avenue	Bell Road and Boswell Boulevard	Bell Road and Del Webb Boulevard	Olive Avenue and 107th Avenue	Olive Avenue and 111th Avenue	Olive Avenue and 103rd Avenue	Thunderbird Road and 99th Avenue	Indian School Road and 99th Avenue
No Injury	**319**	25	42	44	34	41	28	28	22	26	29
Possible Injury	**88**	7	9	13	11	10	9	4	11	6	8
Non Incapacitating Injury	**49**	2	3	6	3	8	3	2	6	1	15
Incapacitating Injury	**17**	0	1	1	1	2	3	4	3	1	1
Fatal	**3**	0	0	1	0	0	2	0	0	0	0
Total	**476**	**34**	**55**	**65**	**49**	**61**	**45**	**38**	**42**	**34**	**53**

Table 6.2 Injury type based on the data from 2007 to 2010 (ADOT 2011).

The number of accidents and the number of accidents by accident type for all the ten intersections in Phoenix individually, in the four past years (from 2007 to 2010) can be found in Appendix F. A number of 476 accidents have been reported for these intersections, or approximately around 12 accidents per year and intersection. 17 accidents resulted in incapacitating injuries. However, the majority of the accidents resulted in non incapacitating injuries, possible injuries, or no injuries. A total of 3 accidents resulted in fatalities. Two of the fatal accidents occurred on Olive Avenue and 107th Avenue and the third one occurred on the intersection of Bell Road and 99th Avenue. Most number of accidents seemed to occur on the Bell Road and 99th Avenue (65 accidents) of which 44 accidents resulted in no injury.

In the ten intersections, only four accidents involved a pedestrian and three involved a bicycle during the four year period. These are presented in Table 6.3 together with their type of injury, time of the day and accident type. The majority of them suffered from incapacitating injuries and two of the accidents were caused by an angle accident type that was other than a left turn. This may have been caused by a right-turning vehicle that was executing a RTOR movement or it may have been a right-turn on green as well. This type of information is not available and therefore unknown. Most accidents occurred in the year 2007, a total of 147 accidents as can be seen in Figure F.11 in Appendix F.

Major Road	Minor Road	First Harmful	Time of Day	Year	Injury	Accident Type
Bell Rd	Burns Dr	Bicycle	Daylight	2008	Possible	Single Vehicle
Bell Rd	Boswell Blvd	Bicycle	Daylight	2010	Incapacitating	Angle (other than left-turn)
Indian School Rd	99th Ave	Bicycle	Daylight	2009	Possible	Other
Bell Rd	Del Webb Blvd	Pedestrian	Daylight	2010	Incapacitating	Angle (other than left-turn)
Olive Ave	107th Ave	Pedestrian	Dark	2008	Incapacitating	Single Vehicle
Olive Ave	107th Ave	Pedestrian	Daylight	2007	Incapacitating	Single Vehicle
Thunderbird Rd	99th Ave	Pedestrian	Daylight	2007	No Injury	Single Vehicle

Table 6.3 Crash and accidental data involved with pedestrian and bicycles, based on the data from 2007 to 2010 (ADOT 2011).

6.2 Lund, Sweden

The traffic safety (crashes) was analyzed for the intersection of Malmövägen and Ringvägen for a ten-year period from 2001 to 2010, by studies of reported accidents in the national database STRADA. STRADA is an abbreviation of Swedish Traffic Accident Data Acquisition and is a database for data related to accidents and injuries in the Swedish road transportation system. The system is based on data from two sources, both the police and the health care, which contribute to a greater understanding of road accident victims (Hydén 2008, p. 91-92).

Raw data was obtained in Microsoft excel format from the Swedish Transportation Board (Transportstyrelsen) and later sorted to find the appropriate categories that can be compared to the American intersections. The crash data was analyzed to identify deficiencies and problem areas within the study area by comparing it to the Phoenix intersections. This was done to see if there are any differing crash patterns that can be related to the allowed RTOR maneuver.

Results from STRADA analysis

In the past ten years (from 2001 to 2010) a number of 22 accidents have been reported for this intersection, or approximately two accidents per year. None of the accidents resulted in fatal consequences. Three of the accidents, occurring in the years 2001, 2002 and 2003, resulted in severe injuries. But the majority of the accidents resulted in minor injuries as shown in Figure 6.1**.** Most accidents occurred in the year 2008, a total of 5 accidents.

All three of the severe injuries occurred on Ringvägen. The first severe injury was caused by one crossing vehicle turning right from Stora Södergatan colliding with a bicyclist at the bicycle crossing on Ringvägen. The second severe injury involved a vehicle making a left turn from Malmövägen and colliding with a bicyclist at the crossing. The third and the latest accident occurred between two crossing vehicles, one approaching Malmövägen from Ringvägen and the other one turning left from Södra vägen to Malmövägen.

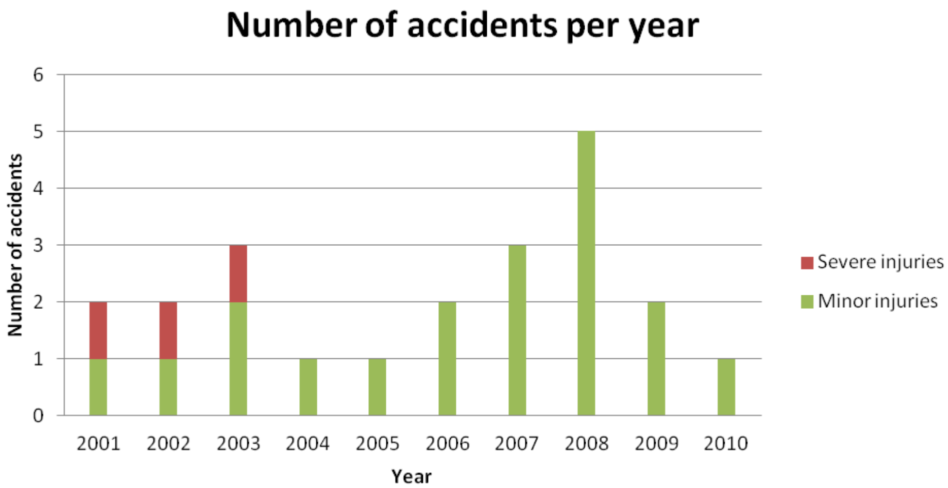


Figure 6.1 Summary of crashes between 2001 to 2010 for Malmövägen and Ringvägen registered in STRADA.

The data from STRADA showed a clear pattern over the most common accidents types during a ten year period, as presented in Figure 6.2. These seemed to be:

- rear end collisions between motor vehicles (three accidents),
- crossing collision between motor vehicles
(four accidents, one of them serious),
- bicycle and/or moped collisions with motor vehicles
(11 accidents, two of them serious),
- drive-off for motor vehicles (one accident)
- and single accidents for pedestrians, bicycles and mopeds (three accidents).

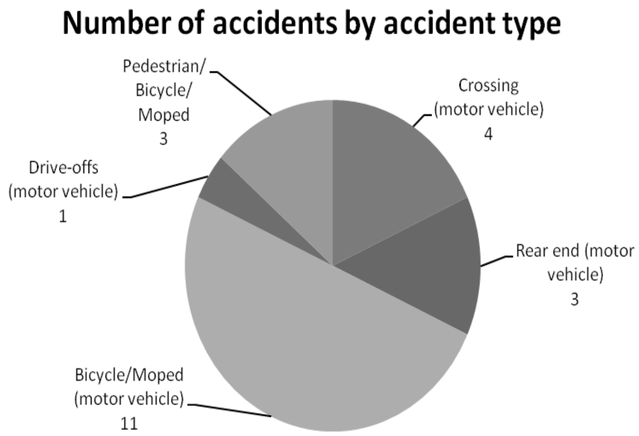


Figure 6.2 Summary of accidents by accident type for Malmövägen and Ringvägen registered in 2001-2010 in STRADA.

In those 22 registered accidents a total of 47 people were registered by the police. Three suffered severe injuries, 27 people had minor injuries and 15 people were uninjured. Information about two people involved in the accident was missing.

There seemed to be no accidents involved with a single motor vehicle only, no head-on accidents between motor vehicles, and no accidents between motor vehicles and pedestrians.

Almost all of the accidents involved with motor vehicles happened in the middle of the intersection, which is one major conflict point. Some of the accidents occurred at the pedestrian and bicycle crossings as can be seen Figure 6.3.

For single accidents of pedestrians and bicyclists, loose gravel and a slippery surface was a main cause.

Bicyclists and mopeds involved in accidents with motor vehicles were mainly due to inattention and irresponsible behavior (11 accidents). In two of the cases, there were cyclists that crossed the bicycle crossing during the red light and were hit by a car which had priority. In 9 (one of them serious) of the accidents, bicyclists and motor vehicles did not notice the bicyclist on the bicycle crossing and hit the bicyclist.

Crossing cars (four accidents, two of them serious accidents) that had collisions were mainly due to unawareness of given priority, lack of attention and negligence of cars in queues (three accidents). Uncertainty about the meaning of some of the traffic signs can also be a possible cause for the accidents that occurred.

The severe accidents occurred during the dark time of the day. This could be due to poor visibility during this time of the day, which leads to a bad overview of the current traffic situations and increases the probability of accidents.

As a whole, the accidents seem to occur at all seasons of the year but mostly during autumn and winter. These are the seasons with usually the highest precipitation (rain, snow, and ice), which can make the surface slippery and cause a bad overview of the current traffic situation. These factors can lead to accidents. Loose gravel and sand can also be a possible cause of accidents.

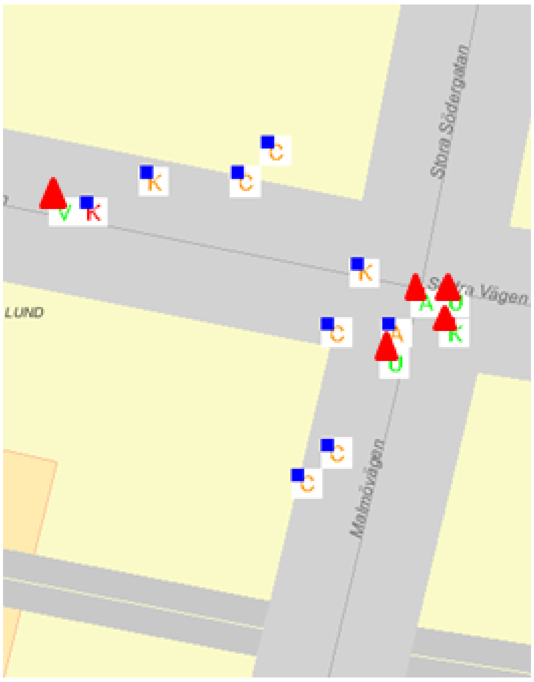


Figure 6.3 Place of registered hospital (triangles) - and policereported (squares) accidents on Malmövägen and Ringvägen from STRADA.

7 Results and analysis

This chapter summarizes and analyzes the results for both the Phoenix intersections and the intersection in Lund. The different hypotheses found in Chapter 1.5 are also being tested in numerical order. Eight hypotheses were examined. All the hypotheses consider the changes with the RTOR and without the RTOR and are compared against one another to show the benefit, if such exists, of a RTOR movement. The Student's t-test was used to compare the means of two samples and is also presented in this chapter after each hypothesis.

The analyses were performed for the 2010 existing conditions in Phoenix and 2011 existing conditions in Lund. Since the morning situation in the intersections is somewhat different from the afternoon, the result in VISSIM from the two separate models in VISSIM is divided. A value for the morning and afternoon is presented. Each test was simulated with ten iterations and the average of the ten iterations is used.

All the values less than one second have been ignored since these changes are considered as irrelevant and may be a result from the model and the simulation. Microsoft excel was used to create tables and graphs.

Intersection number	Major	Direction	Minor	Direction
1	Bell Road	E-W	Burns Drive	N-S
2	Bell Road	E-W	98th Avenue	N-S
3	Bell Road	E-W	99th Avenue	N-S
4	Bell Road	E-W	Boswell Boulevard	N-S
5	Bell Road	E-W	Del Webb Boulevard	N-S
6	Olive Avenue	E-W	107th Avenue	N-S
7	Olive Avenue	E-W	111th Avenue	N-S
8	Olive Avenue	E-W	103rd Avenue	N-S
9	Thunderbird Road	E-W	99th Avenue	N-S
10	Indian School Road	E-W	99th Avenue	N-S
Lund	Malmövägen	N-S	Ringvägen	E-W

Table 7.1 The ten intersections in Phoenix and the intersection in Lund with their directions and corresponding number.

For simplicity, in following graphs and tables in this chapter, the Phoenix intersections in Arizona described in Chapter 3 have been assigned a number from one through ten as can be seen in Table 7.1. Since only one intersection, Malmövägen and Ringvägen, was observed in Sweden it was chosen to be called simply “Lund” which is the city name of this intersection. Something to keep in mind while looking at the results is that all the ten intersections in Phoenix have a permitted RTOR today.

7.1 Intersection and right-turn delay

Hypotheses H1 (a and b) and H2 listed below relate directly to the contribution of the efficiency to the transportation system, with existing conditions, when RTOR applies compared to if it does not. The hypotheses are:

H1a - The delay at signalized intersection is lower where RTOR is permitted compared to where RTOR is prohibited in both AM and PM peak-hours.

H1b - The benefit from a RTOR will prove to be less for Malmövägen and Ringvägen (than the intersections in Phoenix) due to the pedestrians.

H2 - The right-turn movements have a bigger benefit in delay than the intersection as a whole.

To test hypotheses H1 (a and b) and H2, a comparison was made between the results in both the intersections delay and for the right-turn delay only when RTOR applied and when it did not. The difference is visualized in Table 7.2 and Table 7.3. The right-turn delay was evaluated for each approach movement per vehicle in seconds and the intersection delay for the entire intersection, also per vehicle and in seconds. The other approach movements were not taken into consideration since results show that these are not affected much or at all.

The results from the intersection delay show that the intersection delay is lower where RTOR is permitted compared to where RTOR is prohibited in both AM and PM. The benefit is significant; benefits between 0,5 and 2 seconds are received in delay savings per vehicle with the RTOR-movement for the entire intersection. The results are inconsequent and depend much on the charachteristics (geometry, speed, driver behaviour, intersection volumes et cetera) of the studied intersection.

A weighted average (per traffic volume) of about 1,1 seconds in the AM peak-hour and 1,2 seconds in the PM peak-hour are recevied with RTOR for the 11 intersections. The benefit seems to be somewhat greater in the afternoon peak-hour. The advantages with RTOR appears to be bigger in Lund with around 2 seconds, than for the observed intersections in Phoenix as can be seen in Table 7.2 and Table 7.3.

INTERSECTION DELAY per vehicle in seconds, AM peak-hour			
Intersection	**Delay with RTOR**	**Delay without RTOR**	**Delta , Δ**
1	11,6	13,5	**1,8**
2	10,9	12,4	**1,5**
3	27,4	27,9	**0,5**
4	16,4	17,1	**0,7**
5	21,4	22,0	**0,6**
6	11,8	12,9	**1,1**
7	10,5	11,8	**1,3**
8	12,0	13,1	**1,1**
9	17,2	18,7	**1,5**
10	14,9	15,4	**0,5**
Lund	17,6	19,5	**1,9**
Weighted average	**16,3**	**17,4**	**1,1**

Table 7.2 Intersection delay per vehicle in seconds for the AM peak-hour.

INTERSECTION DELAY per vehicle in seconds, PM peak-hour			
Intersection	**Delay with RTOR**	**Delay without RTOR**	**Delta , Δ**
1	10,2	12,0	**1,8**
2	12,1	13,1	**1,0**
3	25,5	26,2	**0,7**
4	14,4	15,8	**1,4**
5	25,6	26,6	**1,0**
6	11,7	12,4	**0,7**
7	11,5	12,7	**1,2**
8	12,4	14,2	**1,8**
9	17,5	18,5	**1,0**
10	15,3	16,0	**0,7**
Lund	19,4	21,6	**2,2**
Weighted average	**16,7**	**17,9**	**1,2**

Table 7.3 Intersection delay per vehicle in seconds for the PM peak-hour.

The average delta values for each intersection were compared in a Student´s t-test (paired two sample for means) to see whether the delay is lower where RTOR is permitted. A Student's t-test also shows that there is a difference between the mean values and therefore the null hypothesis is rejected. Null hypothesis is a statement that there is no difference. A rejected null hypothesis means that the RTOR treatment is significant and has an effect which shows hypothesis H1a. The difference is visualized in Table 7.4.

It was assumed in hypothesis H1b that the benefit from a RTOR would be lower for the intersection in Lund than for the intersections in Phoenix. The delta delay values (no RTOR-RTOR) were compared for each individual run between the Lund and Phoenix intersections for the statistical test (two-sample assuming unequal variances). Since we are only interested in one direction, a one-tail test is used. The Student´s t-test shows that null hypothesis is not true and that there is a significant difference of the means, but it was noted that the difference goes in the other direction. This means that the RTOR have significantly higher gain in Lund than in Phoenix which rejects hypothesis H1b. The results are presented in Table 7.5.

t-Test: Paired Two Sample for Means				
	AM		PM	
	Without RTOR	With RTOR	Without RTOR	With RTOR
Mean (s)	16,74	15,61	17,19	15,97
Number of Observations	11	11	11	11
P-Value (one-tail)	1,19E-05≤0,05		1,15E-05≤0,05	

Table 7.4 presents the comparison between the RTOR and no RTOR in seconds for each intersection.

t-Test: Two-Sample Assuming Unequal Variances				
	AM		PM	
	Lund Δ	Phoenix Δ	Lund Δ	Phoenix Δ
Mean (s)	1,90	0,38	2,06	0,41
Standard Deviation (s)	1,23	0,48	2,21	0,44
Number of Observations	10	100	10	100
Standard Error (s)	0,39	0,05	0,70	0,04
P-Value (one-tail)	0,002≤0,05		0,022≤0,05	

Table 7.5 presents the comparison between the Lund and Phoenix intersections in seconds.

One possible explanation for the bigger benefit in Lund may be due to the smaller volumes in Lund and the even distribution of traffic on all four approaches. The distribution of traffic in Phoenix was uneven and divided into major and minor approaches. The major traffic flow disadvantage Phoenix because RTOR becomes more difficult to implement, why these had a smaller benefit from the RTOR. Another explanation can be that the RTOR movement was prevented. This occurs in situations when right lane is a shared lane with through traffic and the approaching vehicle at the STOP bar is not a right-turning vehicle but instead a through vehicle.
The underlined values in Table 7.6 and Table 7.7 represent the approaches that have the exclusive right-turn lane.

RIGHT-TURN DELAY per vehicle in seconds, AM peak-hour												
Intersection	**Delay with RTOR**				**Delay without RTOR**				**Delta , Δ**			
	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR
1	3,5	6,3	8,0	9,7	14,9	8,9	16,2	10,6	**11,4**	**2,6**	**8,1**	**0,9**
2	5,6	8,3	8,1	7,4	14,2	10,8	12,3	9,9	**8,5**	**2,6**	**4,1**	**2,5**
3	23,2	10,0	19,0	14,3	32,5	12,6	29,5	15,3	**9,3**	**2,6**	**10,5**	**1,0**
4	5,7	7,7	13,5	8,5	21,1	8,9	20,1	11,0	**15,4**	**1,2**	**6,6**	**2,5**
5	<u>17,4</u>	9,8	12,6	14,7	<u>24,9</u>	13,2	21,4	17,5	**<u>7,5</u>**	**3,4**	**8,8**	**2,8**
6	5,9	4,6	<u>8,1</u>	7,5	14,9	6,5	<u>16,5</u>	8,5	**9,0**	**1,9**	**<u>8,4</u>**	**1,0**
7	5,5	4,5	<u>8,4</u>	6,8	14,1	6,7	<u>13,1</u>	7,8	**8,6**	**2,2**	**<u>4,6</u>**	**0,9**
8	6,9	5,1	<u>11,0</u>	8,7	13,7	8,2	<u>16,8</u>	10,2	**6,8**	**3,0**	**<u>5,8</u>**	**1,5**
9	6,4	<u>4,7</u>	<u>6,7</u>	15,5	9,4	<u>16,1</u>	<u>15,2</u>	19,5	**2,9**	**<u>11,4</u>**	**<u>8,5</u>**	**4,0**
10	8,2	10,1	8,7	12,9	14,0	14,1	16,3	16,0	**5,8**	**4,0**	**7,5**	**3,1**
Lund	6,8	12,1	<u>7,3</u>	<u>5,5</u>	19,5	15,7	<u>15,0</u>	<u>21,7</u>	**12,7**	**3,6**	**<u>7,8</u>**	**<u>16,2</u>**

Table 7.6 Right-turn delay per approach and vehicle in seconds for the AM peak-hour, exclusive right-turn lanes underlined.

RIGHT-TURN DELAY per vehicle in seconds, PM peak-hour												
Intersection	Delay with RTOR				Delay without RTOR				Delta , Δ			
	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR
1	4,3	9,7	3,5	11,4	10,3	11,9	12,0	13,1	**6,1**	**2,2**	**8,5**	**1,7**
2	7,5	9,3	6,6	6,9	14,6	10,4	14,6	9,7	**7,1**	**1,1**	**8,0**	**2,7**
3	21,1	15,0	19,8	13,9	29,1	17,1	28,7	16,9	**7,9**	**2,1**	**8,8**	**2,9**
4	10,4	9,9	12,2	8,0	20,3	10,8	19,4	9,5	**9,9**	**1,0**	**7,3**	**1,5**
5	23,3	15,1	15,7	13,9	30,7	16,3	28,4	15,9	**7,4**	**1,2**	**12,7**	**2**
6	9,2	7,5	4,7	6,0	13,9	8,7	12,8	7,8	**4,7**	**1,2**	**8,1**	**1,8**
7	8,5	6,9	5,8	5,1	15,1	8,2	12,9	5,5	**6,6**	**1,3**	**7,1**	**0,3**
8	10,0	8,8	7,9	7,2	17,6	9,5	18,2	7,9	**7,6**	**0,6**	**10,4**	**0,7**
9	7,5	5,1	6,2	15,6	11,3	16,3	13,5	19,2	**3,8**	**11,2**	**7,3**	**3,6**
10	10,1	13,1	9,9	11,1	16,0	16,0	14,4	14,3	**5,9**	**3,0**	**4,5**	**3,2**
Lund	9,0	12,9	9,8	7,3	19,8	18,1	17,9	20,3	**10,8**	**5,3**	**8,1**	**13,1**

Table 7.7 Right-turn delay per approach and vehicle in seconds for the PM peak-hour, exclusive right-turn lanes underlined.

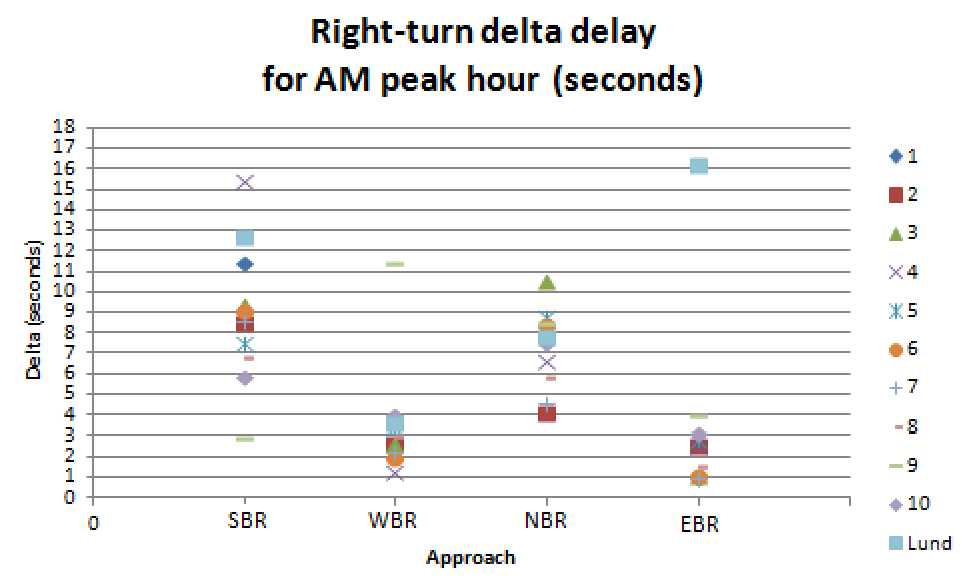


Figure 7.1 The right-turn delta delay for AM peak-hour per vehicle in seconds as also shown in Table 7.6.

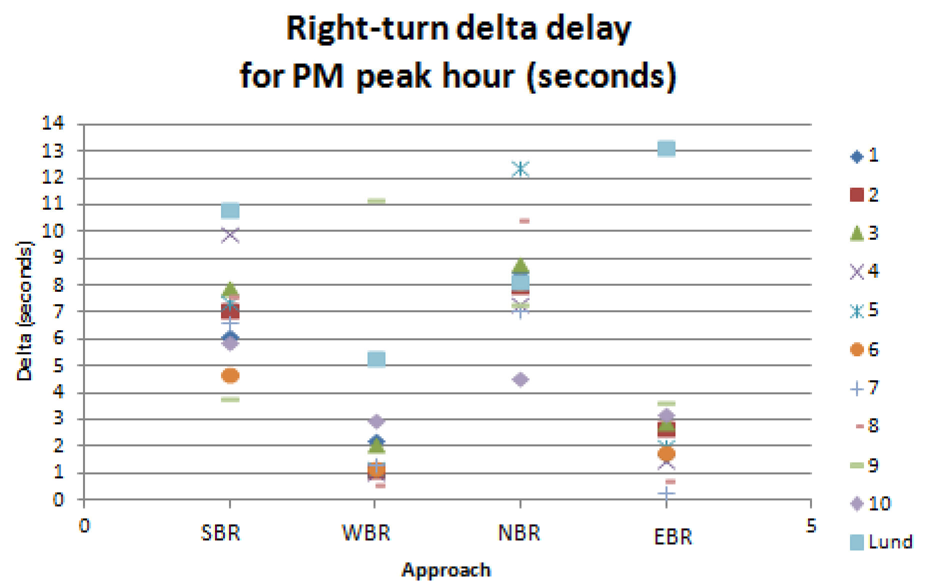


Figure 7.2 The right-turn delta delay for PM peak-hour per vehicle in seconds as also shown in Table 7.7.

The right-turn delay increased significantly without the RTOR in some of the approach movements as can be seen in Table 7.6 and Table 7.7. The benefit on the ten intersections in Phoenix is more significant on the northbound (NBR) and southbound (SBR) directions in both AM and PM peak-hour. These are also all the minor approaches for all ten intersections which have been clarified in Table 7.1.

For Malmövägen and Ringvägen in Lund, eastbound right (EBR) and southbound right (SBR) movements benefit the most in both the AM and PM peak-hour. These are also the approach movements that have the highest delays during both the AM and PM peak-hour when RTOR does not apply. Both these approach movements have to pass the west leg in order to make a right-turn.

One reason for the benefit can be that the EBR is an exclusive right-turn lane and can turn right on red without much interference from cars ahead of them. Despite the many pedestrians perpendicularly to the vehicles on the eastbound (west leg approach), EBR still has a significant benefit with a permitted RTOR movement. This may have to do with the signal timing. The phase that allows EBT, EBL and EBR movements belong to signal phase number six which has the lowest green time and therefore also has the highest delay. By allowing RTOR, the EBR will find gaps and make the RTOR and gain benefits in delay savings.

One reason for the SBR in the north leg which is a shared through and right-turn lane, could be that they can turn right on red light without a high interference of pedestrian and bicyclists (41 in the AM and 47 in PM). Pedestrians and bicyclists crossing perpendicularly to the vehicles are the lowest on the north leg and highest on the west leg (154 in AM and 159 in PM). When SBR has the red light, the pedestrians and bicyclists crossing the west leg also have a red light which means that they cannot go and therefore SBR is not interfered by the highest number of pedestrians. (The volumes for the intersection of Malmövägen and Ringvägen can be found in Chapter 4.1.6.)

The tables show that the delay with RTOR legislation is smaller for all the four approaches on every intersection. The right turning vehicles at the intersection of Malmövägen and Ringvägen would save between approximately 3 and 16 seconds per vehicle in the morning and between approximately 5 and 13 seconds per vehicle in the afternoon with a RTOR legislation. Today’s delay at the intersection is between approximately 15 and 22 seconds per vehicle in the AM peak-hour and between approximately 17 and 20 seconds per vehicle during the PM peak-hour.

The right-turn movements have a bigger benefit in delay than the intersection as a whole, thus indicating that hypothesis H2 is true. The contribution from a RTOR legislation varies from 1 to approximately 16 seconds per vehicle for AM peak-hour while it varies from 0,5 to 13 seconds per vehicle for PM peak-hour.

By comparing the delta (no RTOR-RTOR) for each individual run between the entire intersection and right-turn lane only, the null hypothesis could be rejected.
A Student´s t-test (two-sample assuming unequal variances) also shows that there is a significant difference between the means. The hypothesis H2 is indicated to be true, which means that the right-turn movements have a bigger benefit in delay than the intersection as a whole. The results are presented in Table 7.8.

t-Test: Two-Sample Assuming Unequal Variances				
	AM		PM	
	Intersection Δ	Right-turn Δ	Intersection Δ	Right-turn Δ
Mean (s)	1,13	5,76	1,22	5,28
Standard Deviation (s)	0,51	3,97	0,50	3,61
Number of Observations	11	44	11	44
Standard Error (s)	0,15	0,60	0,15	0,54
P-Value (one-tail)	6,55E-10≤0,05		1,66E-9≤0,05	

Table 7.8 Mean and standard deviation for the intersection delay and right-turn delay in seconds.

The increase is most significant for the intersection in Lund in both AM and PM peak-hour followed by intersection number four, Bell Road and Boswell Boulevard in the AM peak-hour and intersection number 5, Bell Road and Del Webb Boulevard during the PM peak-hour. A weighted average of about 1 second in the AM peak-hour and 1,2 seconds in the PM peak-hour are recevied with RTOR for the 11 intersections and their intersection delay.

The cross traffic from WB for the fourth intersection, Bell Road and Boswell Boulevard, is smaller in the AM than the in PM peak-hour, and therefore right-turning vehicles can make the SBR turn more frequent on red. The opposite is in the PM peak-hour for the fifth intersection, Bell Road and Boswell Boulevard, where the cross traffic from EB is smaller in the PM than in the AM peak-hour.

Tables 7.2-7.8 show the positive contributions that a RTOR legislation leads to. The delay is lower for every intersection and each approach movement with a permitted RTOR movement. The intersection delay was not much affected by the RTOR compared to the right-turn delay for all approaches which is where the RTOR legislation benefit contributions are most notable. The contribution from RTOR legislation at the intersection of Malmövägen and Ringvägen would bring right-turn time savings between 3 and 16,5 seconds per vehicle in the AM peak-hour and between 3 and 18 seconds per vehicle in the PM peak-hour.

7.2 Minor and major roads

Hypothesis H3 below is related to the traffic volumes and aims to see how the benefit from RTOR differs depending on if the road is a major or minor road.

H3 - Minor roads have a larger benefit in delay from RTOR than major roads.

Hypothesis H3 was tested by comparing the difference in the approach delay for minor roads and the approach delay for major roads, with and without RTOR. The result is visualized in Table 7.10 and Table 7.11. The delay was evaluated for each approach movement per vehicle in seconds and summarized two by two as minor and major roads. Northbound (NB) and southbound (SB) are the minor approaches for the ten intersections in Phoenix. This was confirmed by looking at the peak-hour volumes and number of lanes on each leg and is also clarified in Table 7.1. The same check was done for Malmövägen and Ringvägen in Lund and it appeared that both roads could be classified as major or minor since the volumes are almost evenly distributed. Lund was therefore excluded from this analysis.

As can be seen in Table 7.10 and Table 7.11 the major roads for the ten intersections in Phoenix are listed as EB+WB, which is the summed approach volume for eastbound and westbound. The minor roads are similarly presented as SB+NB, which is the sum of the approach volumes for southbound and northbound.

The results show greater benefits (delay savings) with RTOR on the minor approaches for these intersections. The benefits range from approximately 2 seconds to approximately 7 seconds in both AM and PM peak-hour. The major approaches for these intersections, experience minor benefits of up to approximately 1,5 seconds in both the AM and PM peak-hour. The hypothesis H3 is true for the intersections in Phoenix. This may be due to the fact that minor streets get less green time and therefore cars are more likely to use RTOR more frequent. The Student´s t-test (two-sample assuming equal variances) shows that that there is a statistically significant difference between the means and thus the null hypothesis is rejected. Hypothesis H3 is probably true. The result of the Student´s t-test is presented in Table 7.9.

t-Test: Two-Sample Assuming Equal Variances				
	AM		**PM**	
	Major Δ	**Minor Δ**	**Major Δ**	**Minor Δ**
Mean (s)	0,90	3,69	0,90	3,94
Standard Deviation (s)	1,80	1,83	1,79	1,88
Number of Observations	10	10	10	10
Standard Error (s)	0,54	0,55	0,54	0,57
P-Value (one-tail)	0,0009≤0,05		0,0005≤0,05	

Table 7.9 The mean and standard deviation of delay depending on type of road (in seconds).

APPROACH DELAY per vehicle in seconds, AM peak-hour														
Intersection	Delay with RTOR (existing)						Delay without RTOR						Delta , Δ	
	Approach				Major	Minor	Approach				Major	Minor	Major	Minor
	EB	WB	SB	NB	EB+WB	SB+NB	EB	WB	SB	NB	EB+WB	SB+NB	EB+WB	SB+NB
1	10,9	9,4	14,9	11,3	20,3	26,2	11,1	9,4	16,7	16,7	20,5	33,4	**0,2**	**7,2**
2	10,9	10,8	9,5	12,2	21,8	21,7	11,0	11,1	14,4	13,2	22,1	27,6	**0,3**	**5,8**
3	16,4	15,5	35,7	42,0	31,9	77,7	16,5	15,3	36,5	43,3	31,8	79,8	**0,0**	**2,1**
4	10,2	9,7	25,3	20,4	19,9	45,7	10,4	9,9	26,2	21,9	20,3	48,1	**0,4**	**2,3**
5	17,0	16,9	26,4	25,3	34,0	51,6	17,5	17,2	26,7	26,8	34,7	53,5	**0,7**	**1,9**
6	8,5	9,6	14,6	14,4	18,1	29,0	8,6	9,4	16,4	17,2	18,0	33,6	**-0,1**	**4,6**
7	9,2	7,5	13,4	12,0	16,7	25,4	9,2	7,9	15,7	14,2	17,1	30,0	**0,4**	**4,6**
8	10,4	8,1	16,2	13,4	18,5	29,5	10,5	8,3	17,2	16,3	18,8	33,5	**0,3**	**4,0**
9	20,7	18,9	18,1	11,3	39,5	29,4	20,7	20,3	18,3	15,4	41,1	33,7	**1,5**	**4,3**
10	16,6	14,9	14,2	14,0	31,5	28,1	16,8	14,8	14,7	15,2	31,6	29,9	**0,1**	**1,8**

Table 7.10 The approach delay per vehicle in seconds during AM peak-hour for the major and minor roads at the ten intersections in Phoenix, with and without RTOR.

APPROACH DELAY per vehicle in seconds, PM peak-hour														
Intersection	**Delay with RTOR (existing)**						**Delay without RTOR**						**Delta , Δ**	
	Approach				**Major**	**Minor**	**Approach**				**Major**	**Minor**	**Major**	**Minor**
	EB	**WB**	**SB**	**NB**	**EB+WB**	**SB+NB**	**EB**	**WB**	**SB**	**NB**	**EB+WB**	**SB+NB**	**EB+WB**	**SB+NB**
1	12,9	12,1	9,9	6,1	24,9	16,0	12,9	12,1	11,4	11,7	25,0	23,2	**0,0**	**7,1**
2	10,7	11,5	14,1	12,0	22,2	26,1	10,7	11,5	16,3	14,0	22,2	30,3	**0,0**	**4,2**
3	18,6	17,4	31,1	35,0	36,0	66,1	18,8	17,8	31,8	36,5	36,6	68,3	**0,7**	**2,2**
4	10,1	10,6	17,7	19,3	20,70	37,0	10,1	10,6	21,4	21,0	20,6	42,5	**-0,1**	**5,5**
5	16,7	19,1	31,5	35,0	35,8	66,4	17,1	19,7	33,2	36,4	36,8	69,6	**1,0**	**3,1**
6	8,3	9,8	14,2	14,7	18,1	28,8	8,5	9,8	15,2	16,0	18,3	31,3	**0,2**	**2,4**
7	9,5	8,8	14,1	13,6	18,3	27,7	9,4	8,9	16,6	15,7	18,3	32,3	**0,0**	**4,7**
8	9,8	10,2	15,6	14,1	20,0	29,8	9,9	10,2	18,7	18,0	20,1	36,7	**0,1**	**7,0**
9	20,9	18,3	17,8	12,9	39,2	30,7	20,8	19,9	18,3	15,0	40,7	33,3	**1,5**	**2,6**
10	15,5	17,2	13,7	14,9	32,7	28,6	15,9	17,3	15,7	15,2	33,2	30,9	**0,5**	**2,3**

Table 7.11 The approach delay per vehicle in seconds during PM peak-hour for the major and minor roads at the ten intersections in Phoenix, with and without RTOR.

7.3 Lane configuration

Hypothesis H4 aims to compare the benefit from RTOR if the right lane is a shared through/right-turn lane or an exclusive right-turn lane. This is to determine if drivers in an exclusive right-turn lane will use the RTOR more or not compared to those cars that are prevented of making a RTOR by the through vehicle in the same lane. The hypothesis is:

H4 - Lane configuration plays an important role. An exclusive right-turn lane benefits the RTOR movement further and results in larger reduction in delay.

Five of the ten studied intersections in Phoenix have an exclusive right-turn lane. These are underlined in Table 7.6 and Table 7.7 and can also be seen in Table 7.12. The intersection in Lund has, in existing conditions, two exclusive right-turn lanes, the northbound-right (NBR) and eastbound-right (EBR). The other intersections and approaches that are not presented here are shared through/right-turn lanes (T+RT).

Intersection	Exclusive RT-lane
4	SBR
6	NBR
7	NBR
8	NBR
9	NBR and WBR
Lund	NBR and EBR

Table 7.12 The exclusive right-turn lanes for the studied intersections in Phoenix and in Lund.

The delta in delay for shared through/right-turn lanes was compared to the exclusive right-turn lanes. Figure 7.3 and Figure 7.4 display the comparison of delay depending on the lane configuration. The deltas for the exclusive right-turn (RT) lanes were plotted on the Y-axis separate from the deltas for the shared through/right-turn lane (T+RT) to identify any potential differences in the delta.

The difference in delay during the AM peak-hour in Figure 7.3 is not obvious even if two values are above the delta values for the shared through/right-turn lanes. Lund show the largest reduction in delay with its exclusive right-turn lane on the eastbound (EB) movement with a saving of around 16 seconds during the AM peak-hour and 13 seconds during the PM peak-hour.

Figure 7.4 presents the results from the PM peak-hour. The exclusive right-turn lanes appear to benefit more from the RTOR than the case in AM. Table 7.13 show the average of all the 11 intersections that were observed in this thesis.

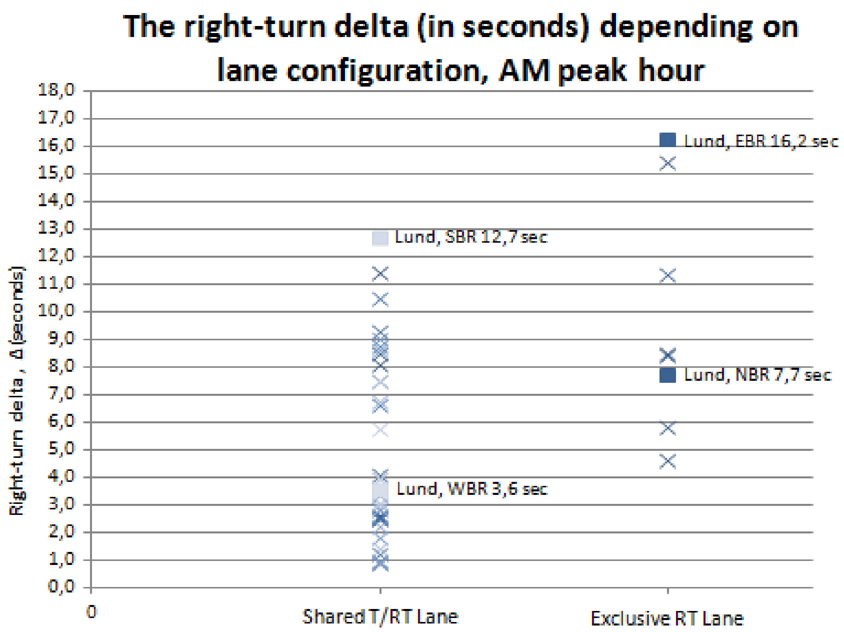


Figure 7.3 The AM peak-hour right-turn delta (seconds per vehicle) for all ten studied intersections in Phoenix and Malmövägen and Ringvägen in Lund.

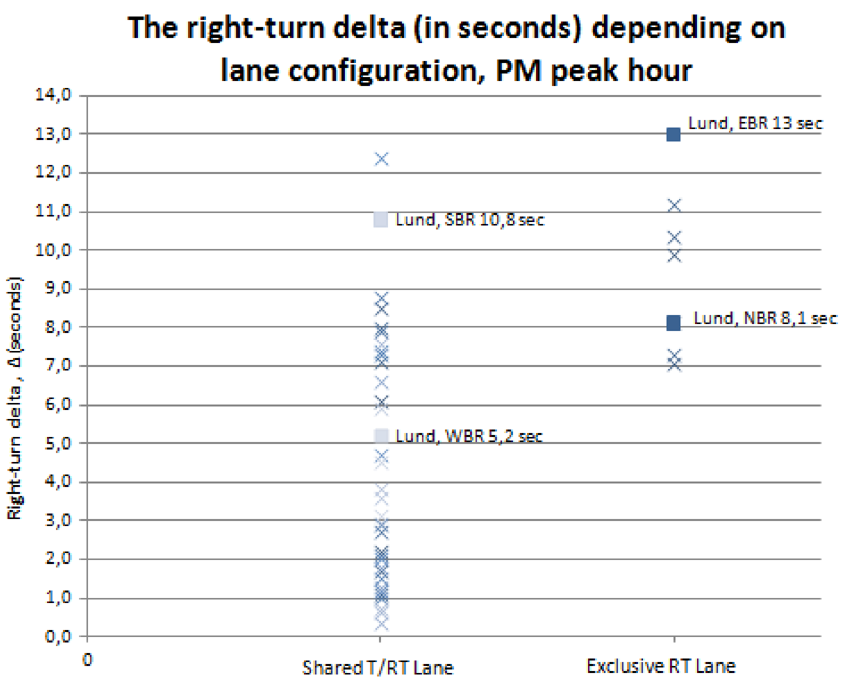


Figure 7.4 The PM peak-hour right-turn delta (seconds per vehicle) all ten studied intersections in Phoenix and Malmövägen and Ringvägen in Lund.

Table 7.13 show that the delay reduction for right-turn with an exclusive right-turn lane is twice as large as the for shared through/right-turn lane in both the AM and PM peak-hour, approximately 5 seconds and 10 seconds per vehicle respectively. Lund is near or above the mean values.

Average right-turn delta per vehicle in seconds		
	Shared T/RT lane	Exclusive RT lane
AM peak-hour	4,9	9,8
PM peak-hour	4,4	9,4

Table 7.13 The average for right-turn delta for the ten studied intersections in Phoenix and for Malmövägen and Ringvägen in Lund compared to if RTOR did not apply.

This would seem to show that hypothesis H4 is true, but it is still not conclusive because most of the exclusive right-turn lanes in Phoenix are either SBR or NBR, which means that they are on the minor streets. The benefit could therefore be from either because they are a minor street or because of the exclusive right-turn lane. This makes it difficult to draw conclusions and further studies would be required for the ten intersections in Phoenix. The hypothesis H4 is however true for the Swedish intersection in Lund.

Due to some of the differences (volume, speed, driver behaviour etc.) between the intersections in Phoenix and the intersection in Lund, this case was evaluated in more detail for the intersection in Sweden by adding and removing the exclusive right-turn lane and later comparing the results.

The exclusive right-turn (RT) lane was removed and the furthest lane on the right became a shared through/ right-turn (T+RT) lane. The NBR (northbound right) turn lane was removed since this is the busiest right-turn lane with the highest right-turning traffic during both the morning (128 vehicles) and afternoon (268 vehicles) peak-hours. This was done to see how a change in the current lane configuration can affect the delay at the intersection of Malmövägen and Ringvägen and how the blocking vehicles in front of a RTOR turning vehicle affect its delay and ability to turn right on red. The results are presented in Table 7.14 and Table 7.15.

By removing the NBR lane the delay increased in this approach movement in both the AM and PM peak-hour. With existing conditions, the northbound delay at the intersection of Malmövägen and Ringvägen would increase by 7,6 seconds, in both the AM and PM peak-hour, without the exclusive right-turn lane. With a permitted RTOR, and no NBR lane, the delay would increase by 4,3 seconds per vehicle in the AM peak-hour and by 9 seconds per vehicle in the PM peak-hour. This is in other words, how much the exclusive right-turn lane saves with permitted RTOR.

A permitted RTOR saves close to 3,5 seconds in delay per vehicle in the AM peak-hour and shows no bigger benefit in the PM peak-hour. This may be due to that the high number of right-turning vehicles from NBR has difficulty finding gaps to join the cross-intersecting flow coming from the west approach.

RIGHT-TURN DELAY per vehicle in seconds, AM peak-hour												
Intersection	Current delay				Delay with RTOR				Delta , Δ			
	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR
Lund, existing	20,0	15,7	15,0	22,0	6,8	12,1	7,3	5,5	**12,7**	**3,6**	**7,7**	**16,2**
Lund, no NBR lane	19,0	15,7	22,6	22,0	7,3	9,4	11,6	6,1	**11,8**	**6,3**	**11,0**	**16,3**
Delta , Δ	-0,4	0,0	7,6	0,7	0,5	-2,7	4,3	0,6	**-0,9**	**2,7**	**3,3**	**0,1**

Table 7.14 The AM peak-hour right-turn delay on every approach at Malmövägen and Ringvägen in Lund with existing conditions and when removing the northbound right lane, with and without the RTOR.

RIGHT-TURN DELAY per vehicle in seconds, PM peak-hour												
Intersection	Current delay				Delay with RTOR				Delta , Δ			
	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR
Lund, existing	19,8	18,1	17,9	20,3	9,0	12,9	9,8	7,3	**10,8**	**5,2**	**8,1**	**13,0**
Lund, no NBR lane	22,1	17,3	25,5	25,0	9,3	14,1	18,8	7,3	**12,8**	**3,2**	**6,7**	**17,7**
Delta , Δ	2,3	-0,8	7,6	4,7	0,3	1,2	9,0	0,0	**2,0**	**-2,0**	**-1,4**	**4,7**

Table 7.15 The PM peak-hour right-turn delay on every approach at Malmövägen and Ringvägen in Lund with existing conditions and when removing the northbound right lane, with and without the RTOR.

Table 7.16 and Table 7.17 show that the absence of an exclusive right-turn lane contributes to higher delays in that approach at Malmövägen and Ringvägen in Lund. This is whether RTOR is permitted or not. However, the RTOR contributes to smaller delays, without the exclusive right-turn lane. The NBR lane is removed in the second row of Table 7.16 and Table 7.17 and represents the delay for shared through/right-turn lanes while the values in the first row, Lund existing, represent the lane configuration with an exclusive right-turn lane.

NORTHBOUND DELAY per vehicle in seconds, AM peak-hour						
Intersection	**Current delay**		**Delay with RTOR**		**Delta , Δ**	
	NB		**NB**		**NB**	
	Through	**Right**	**Through**	**Right**	**Through**	**Right**
Lund, existing	17,3	15,0	18,8	7,3	-1,5	7,7
Lund, no NBR lane	18,1	22,6	17,5	11,6	0,6	11,0
Delta , Δ	0,8	7,6	-1,3	4,3	2,1	3,3

Table 7.16 Effect of exclusive right-turn lane for the AM peak-hour.

NORTHBOUND DELAY per vehicle in seconds, PM peak-hour						
Intersection	**Current delay**		**Delay with RTOR**		**Delta , Δ**	
	NB		**NB**		**NB**	
	Through	**Right**	**Through**	**Right**	**Through**	**Right**
Lund, existing	19,7	17,9	19,2	9,8	0,5	8,1
Lund, no NBR lane	19,7	25,5	20,0	18,8	-0,3	6,7
Delta , Δ	0,0	7,6	0,8	9,0	-0,8	-1,4

Table 7.17 Effect of exclusive right-turn lane for the PM peak-hour.

Table 7.16 and Table 7.17 show that the delta for the vehicles in the through-lane is very small and the vehicles are almost not affected by the added right-turning vehicles from the removed NBR lane. The delay increases by 7,6 seconds per vehicle during both the AM and PM peak-hour when the exclusive NBR lane is removed and when no RTOR is permitted. It also shows how much a RTOR reduces the delay in such cases.

Different lane configurations affect the delay differently at the intersection of Malmövägen and Ringvägen and an exclusive right-turn lane does facilitate the RTOR movement further. The existing NBR lane reduces the delay and is meaningful. The reduction in delay is 7,3 seconds per vehicle in the AM peak-hour and 9,8 seconds per vehicle in the PM peak-hour with an exclusive right-turn lane. The delay without the RTOR movement for the same scenario would be 15,0 seconds per vehicle in the AM peak-hour and 17,9 seconds in the PM peak-hour. This shows hypothesis H4 and the importance of having the exclusive right-turn lane

A Student´s t-test (two-sample assuming unequal variances) also shows the advantage of the exclusive right-turn lane during the morning peak-hour with significant differences of the means, but not during the afternoon peak-hour. Hypothesis H4 could be rejected in the morning peak-hour but not in the afternoon peak-hour. The results can be seen in Table 7.18.

t-Test: Two-Sample Assuming Unequal Variances				
	AM		PM	
	with RT lane Δ	w/o RT lane Δ	with RT lane Δ	w/o RT lane Δ
Mean (s)	7,79	11,02	7,33	6,67
Standard Deviation (s)	2,04	4,18	1,90	6,32
Number of Observations	10	10	10	10
Standard Error (s)	0,64	1,32	0,60	2,00
P-Value (one-tail)	0,02≤0,05		0,38≥0,05	

Table 7.18 The comparison between the existence of an exclusive right-turn lane and without it (in seconds).

7.4 Storage length

Hypothesis H5 below is testing the length of the storage in a right-turning lane and how a shorter or longer storage length affects the delay for the vehicles using the RTOR movement. The belief is that a too long or an infinitely long storage length will not have any bigger benefit. The hypothesis is:

H5 - The reduction in delay will be small with an extended storage length.

The required subject to test the hypothesis is the right-turn delay for an existing storage lane and exposes it to changes. This hypothesis was only evaluated for the intersection in Lund. The existing exclusive NBR storage lane which is approximately 22 meters (space for about 4-5 cars) was extended by 50 percent (to 33 meters) and by 100 percent (to 44 meters). The results between the changes and the baseline were then compared. The results are presented in Table 7.19 and Table 7.20.

According to Table 7.19 and Table 7.20, an increase for the current storage length does not show a significant benefit in delay. With a 50 percent longer storage, which makes the storage 33 meters long, the delay on the NBR lane would decrease by approximately 1 second in the AM peak-hour and by 1,5 seconds in the PM peak-hour without the RTOR. With a permitted RTOR movement the delay would be almost half as much regardless of the length of the right-lane storage. The 100 percent length increase gave even smaller benefits in delay, a half of a second in the PM peak-hour and a tenth of second in the AM peak-hour. The delay with RTOR was also here half as much as without the permitted RTOR movement.

The storage length may have an important role to a certain point, but the delay is probably more affected by other factors such as the cross-intersecting flow and finding sufficient gaps. Hypothesis H5 shows that there is no point of making the storage even longer than it already is since all these vehicles will not be able to make a right-turn on red and the delay will either be the same or increase.

STORAGE LENGTH & RIGHT-TURN DELAY per vehicle in seconds, AM peak-hour			
Intersection	**Delay without RTOR**	**Delay with RTOR**	**Delta , Δ**
Lund	NBR	NBR	NBR
22 m	15,0	7,3	**7,7**
33 m	13,9	7,2	**6,7**
44 m	15,1	7,5	**7,6**

Table 7.19 The right-turn delay for the NBR lane at Malmövägen and Ringvägen in Lund, AM peak-hour.

STORAGE LENGTH & RIGHT-TURN DELAY per vehicle in seconds, PM peak-hour			
Intersection	**Delay without RTOR**	**Delay with RTOR**	**Delta , Δ**
Lund	NBR	NBR	NBR
22 m	17,9	9,8	**8,1**
33 m	16,4	9,9	**6,5**
44 m	17,4	10,4	**7,0**

Table 7.20 The right-turn delay for the NBR lane at Malmövägen and Ringvägen in Lund, PM peak-hour.

A Student´s t-test also shows that that there is no significance at the 95 percent confidence interval. The null hypothesis is rejected. The treatment shows no significant difference which indicates that hypothesis H5 is true. Table 7.21 visualises the difference in means and standard deviation of the Student´s t-test for hypothesis H5.

t-Test: Two-Sample Assuming Unequal Variances				
	AM		PM	
	Regular	Plus 50%	Regular	Plus 50%
Mean (s)	7,79	6,67	7,33	6,48
Standard Deviation (s)	2,04	0,89	1,90	0,96
Number of Observations	10	10	10	10
Standard Error (s)	0,64	0,28	0,60	0,30
P-Value (one-tail)	0,07≥0,05		0,11≥0,05	
	AM		PM	
	Regular	Plus 100%	Regular	Plus 100%
Mean (s)	7,79	7,65	7,33	7,02
Standard Deviation (s)	2,04	2,30	1,90	2,00
Number of Observations	10	10	10	10
Standard Error (s)	0,64	0,73	0,60	0,63
P-Value (one-tail)	0,44≥0,05		0,36≥0,05	

Table 7.21 The difference in means and standard deviation of the Student´s t-test for hypothesis H5 (in seconds).

7.5 Cross-intersecting flow

Hypothesis H6 aims to compare the benefit of RTOR if the cross-intersecting flow is reduced or increased. This is to determine if drivers with a larger cross-intersecting flow will have a chance to make the RTOR movement; difference in savings in the delay; and if there may be a limit which RTOR reaches in having a positive effect. The hypothesis is:

H6 - The cross-intersecting flow is of great importance for the implementation of a RTOR movement.

Hypothesis H6 was tested by comparing the right-turn delay, with and without RTOR, for the right-turning vehicles that are affected by a specific cross-intersecting flow by first reducing it by 30 percent to the existing condition (0 percent) and by later increasing it by 30 percent from the existing condition. This hypothesis was only evaluated for the intersection in Lund.

The cross-intersecting flow was changed, one by one, for the eastbound-through (EBT), westbound-through (WBT), southbound-through (SBT) and for the northbound-right (NBR) movement. The right-turn delay was then evaluated for the affected right-turning movement. The delay is presented in seconds per vehicle for the AM and PM peak-hour. The results are presented in Table 7.22 and Table 7.23. The empty spaces in the tables have not been evaluated since they are not relevant for hypothesis H6.

RIGHT-TURN DELAY per vehicle in seconds, AM peak-hour												
Intersection	**Delay without RTOR**				**Delay with RTOR**				**Delta , Δ**			
Lund	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR
Existing	*19,5*	*15,7*	*15,0*	*21,7*	*6,8*	*12,1*	*7,3*	*5,5*	*12,7*	*3,6*	*7,7*	*16,2*
EBT, -30 percent			14,6				6,4				**8,2**	
EBT, +30 percent			13,6				7,4				**6,2**	
WBT, -30 percent	17,9				6,0				**11,9**			
WBT, +30 percent	20,5				6,9				**13,6**			
SBT, -30 percent				20,0				5,5				**14,5**
SBT, +30 percent				21,1				5,4				**15,7**
NBR, -30 percent			13,4				6,9				**6,5**	
NBR, +30 percent			15,7				7,1				**8,6**	

Table 7.22 Cross-intersecting flow and affected right-turn delay for AM peak-hour.

The eastbound-through (EBT) flow was changed to see how the northbound-right (NBR) turn lane will be affected by the changes. No significant changes in the northbound-right delay were achieved by changing the EBT cross-intersecting flow with 30 percent.

The westbound-through (WBT) flow was changed to see how the southbound-right (SBR) turn lane will be affected by the changes. Even here no significant changes in the southbound-right delay were achieved by changing the WBT cross-intersecting flow with 30 percent.

The southbound-through (SBT) flow was changed to see how the eastbound-right (EBR) turn lane will be affected by the changes. No significant differences in delay were achieved by this change. As can be seen a permitted RTOR would decrease the delay for these movements down to a quarter (1/4) in the morning peak-hour and to one third (1/3) in the afternoon peak-hour.

The final change was done for the northbound-right (NBR) flow to see how the right-turn lane in the northbound would be affected. Also in this case no significant differences were revealed.

RIGHT-TURN DELAY per vehicle in seconds, PM peak-hour												
Intersection	**Delay without RTOR**				**Delay with RTOR**				**Delta , Δ**			
Lund	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR
Existing	*19,8*	*18,1*	*17,9*	*20,3*	*9,0*	*12,9*	*9,8*	*7,3*	**10,8**	**5,2**	**8,1**	**13,0**
EBT, -30 percent			16,9				8,0				**8,9**	
EBT, +30 percent			17,0				10,5				**6,5**	
WBT, -30 percent	22,6				9,1				**13,5**			
WBT, +30 percent	21,7				11,1				**10,6**			
SBT, -30 percent				23,1				6,2				**16,9**
SBT, +30 percent				22,9				10,8				**12,1**
NBR, -30 percent			15,8				8,4				**7,4**	
NBR, +30 percent			20,0				12,1				**7,9**	

Table 7.23 Cross-intersecting flow and affected right-turn delay for PM peak-hour.

The benefit of RTOR with a reduced or increased cross-intersecting flow did not show any bigger differences except that the delay increases somewhat with increased vehicle volumes. Drivers with a larger cross-intersecting flow have a bigger approach delay than with a smaller cross-intersecting traffic flow. However RTOR did not stop to have a positive effect in this study. The literature study that was done also showed that there are no regulations or guidelines today in the United States for the amount of traffic that is appropriate at intersections where RTOR applies. The primary factor for prohibiting or restricting RTOR behaviors is inadequate sight distance.

It should be noted that the RTOR for the existing intersection have already decreased the delay so much so that its benefit is not shown when adjusting the different volumes for the cross-intersecting flow. Another thing to keep in mind is that by adjusting the volume 30 percent above or below the existing volume no significant differences were exhibited. This might be because the intersection of Malmövägen and Ringvägen is a relatively small intersection compared to the ten studied intersections in Phoenix and their traffic volumes.

The cross-intersecting flow shows an importance for the implementation of a RTOR movement, but the volumes have to probably be significantly higher than those at the intersection of Malmövägen and Ringvägen in Lund.
The ten studied intersections in Phoenix all manage to make a RTOR movement despite the higher volumes. The size of the intersection of Malmövägen and Ringvägen in Lund makes it hard to draw conclusions about the hypothesis H6, even though it is proven for the intersection in Lund.

It was assumed in hypothesis H6 that the cross-intersecting flow is of great importance for the implementation of a RTOR movement. The Student´s t-test shows that null hypothesis is true and that there is no significant difference between the means. Tables 7.24-7.27 visualises the meanvalues for each direction.

t-Test: Two-Sample Assuming Unequal Variances				
	AM		PM	
Change EBT volume	NBR Δ	Minus (-) 30% Δ	NBR Δ	Minus (-) 30% Δ
Mean (s)	7,79	8,18	7,33	9,01
P-Value (one-tail)	0,65≥0,05		0,98≥0,05	
	AM		PM	
Change EBT volume	NBR Δ	Plus (+) 30%	NBR Δ	Plus (+) 30% Δ
Mean (s)	7,79	6,21	7,33	6,54
P-Value (one-tail)	0,96≥0,05		0,87≥0,05	

Table 7.24 The meanvalues for the northbound-right movement (in seconds).

t-Test: Two-Sample Assuming Unequal Variances				
	AM		PM	
Change WBT volume	SBR Δ	Minus (-) 30% Δ	SBR Δ	Minus (-) 30% Δ
Mean (s)	12,72	11,85	12,78	13,52
P-Value (one-tail)	0,24≥0,05		0,61≥0,05	
	AM		PM	
Change WBT volume	SBR Δ	Plus (+) 30%	SBR Δ	Plus (+) 30% Δ
Mean (s)	12,72	13,55	12,78	10,66
P-Value (one-tail)	0,27≥0,05		0,87≥0,05	

Table 7.25 The meanvalues for the southbound-right movement (in seconds).

t-Test: Two-Sample Assuming Unequal Variances				
	AM		PM	
Change SBT volume	EBR Δ	Minus (-) 30% Δ	EBR Δ	Minus (-) 30% Δ
Mean	16,21	14,55	15,33	16,82
P-Value (one-tail)	0,15≥0,05		0,89≥0,05	
	AM		PM	
Change SBT volume	EBR Δ	Plus (+) 30%	EBR Δ	Plus (+) 30% Δ
Mean	16,21	15,68	15,33	12,09
P-Value (one-tail)	0,63≥0,05		0,81≥0,05	

Table 7.26 The meanvalues for the eastbound-right movement (in seconds).

t-Test: Two-Sample Assuming Unequal Variances				
	AM		PM	
Change NBR volume	NBR Δ	Minus (-) 30% Δ	NBR Δ	Minus (-) 30% Δ
Mean	7,79	6,50	7,33	7,40
P-Value (one-tail)	0,14≥0,05		0,53≥0,05	
	AM		PM	
Change NBR volume	NBR Δ	Plus (+) 30%	NBR Δ	Plus (+) 30% Δ
Mean	7,79	7,55	7,33	7,90
P-Value (one-tail)	0,63≥0,05		0,37≥0,05	

Table 7.27 The meanvalues for the northbound-right movement (in seconds). In this scenario the NBR volumes (right-turning volumes) were changed instead of the NBT (the cross-intersecting volume).

7.6 Pedestrians and bicyclists

Hypothesis H7 aims to see how pedestrians and bicyclists affect the right-turning vehicles. The hypothesis is:

H7 - Pedestrians and bicyclists perpendicular to the right-turning vehicles have an impact on the effectiveness of RTOR.

Hypothesis H7 was formulated just as the hypothesis H1 during the initiation of the study since the intended RTOR movement can be affected or blocked if the number of pedestrians and bicyclists crossing perpendicularly to the vehicle is too large. The possibility to find a gap for the RTOR movement will become harder during the red phase.

The intersections in Sweden have generally higher proportion of pedestrians on the pedestrian crossings compared to the intersections in Arizona (USA).

Malmövägen and Ringvägen in Lund works as the study object for Lund (Sweden). No pedestrians or sometimes only one pedestrian was encountered at the ten intersections in Phoenix. It may have to do with many other factors as well (temperature, time of year, geographic location etc.), but these are not analysed in this thesis.

The large amount of pedestrians in Lund was one factor that was of main concern before the start of this study, which is why it was chosen to be further analysed to see whether RTOR is applicable to Lund´s transportation system.

Hypothesis H7 was tested by collecting the intersection delay and the right-turn delay at Malmövägen and Ringvägen with existing volumes of vehicles and pedestrians/bicyclists in a separate model and by removing all pedestrians and bicyclists in another model. To test hypotheses H7, a comparison was made between the results in both the intersection delays and for the right-turn delay when RTOR applied and when it did not. The difference in the intersection delay is visualized in Table 7.28 and Table 7.29 while the right-turn delay is found in Table 7.30 and Table 7.31.

The scenario where all pedestrians were removed is also the scenario that is most similar to the traffic conditions that were encountered at the intersections in Phoenix.

INTERSECTION DELAY per vehicle in seconds, AM peak-hour			
Intersection	**Delay without RTOR**	**Delay with RTOR**	**Delta , Δ**
Lund, existing	19,5	17,6	**1,9**
Lund, no pedestrians/bicycles	16,3	14,6	**1,7**
Delta , Δ	**3,2**	**3,0**	**0,2**

Table 7.28 The intersection delay at Malmövägen and Ringvägen in Lund with and without pedestrians and bicyclists, AM peak-hour.

INTERSECTION DELAY per vehicle in seconds, PM peak-hour			
Intersection	**Delay without RTOR**	**Delay with RTOR**	**Delta , Δ**
Lund, existing	21,6	19,4	**2,2**
Lund, no pedestrians/bicycles	19,2	17,0	**2,2**
Delta , Δ	**2,4**	**2,4**	**0,0**

Table 7.29 The intersection delay at Malmövägen and Ringvägen in Lund with and without pedestrians and bicyclists, PM peak-hour.

As can be seen in Table 7.28 and Table 7.29, pedestrians and bicyclist have an important role for the intersection delay at Malmövägen and Ringvägen. The intersection delay decreased by around 3 seconds during the AM peak-hour and close to 2,5 seconds in the PM peak-hour without the pedestrians and bicyclists.

Table 7.30 and 7.31 shows that in all four approaches and for both AM and PM peak-hour the remove of pedestrians and bicyclists resulted in benefits and time savings between approximately 0,5 and 6 seconds per vehicle in AM and between 1 and 5 seconds per vehicle in PM. The right-turn delay with RTOR legislation is already smaller than the delay without RTOR for all the four approaches on Malmövägen and Ringvägen with pedestrians and bicycles, between approximately 5 and 12 seconds per vehicle in the AM and between 7 and 12 seconds per vehicle in the PM peak-hour.

By removing the pedestrians and bicyclists, improvements are achieved for the intersection. Some of the approaches achieved significant differences and delay savings.

RIGHT-TURN DELAY per vehicle in seconds, AM peak-hour												
Intersection	**Delay without RTOR**				**Delay with RTOR**				**Delta , Δ**			
	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR
Lund, existing	19,5	15,7	15,0	22,0	6,8	12,1	7,3	5,5	**12,7**	**3,6**	**7,7**	**17**
Lund, no pedestrians/bicycles	17,2	9,8	11,3	16,2	5,4	6,7	6,7	4,8	**11,8**	**3,1**	**4,6**	**11,4**
Delta , Δ	**2,3**	**5,9**	**3,7**	**5,8**	**1,4**	**5,4**	**0,6**	**0,7**	**0,9**	**0,5**	**3,1**	**5,1**

Table 7.30 The right-turn delay at Malmövägen and Ringvägen in Lund with and without pedestrians and bicyclists, AM peak-hour.

RIGHT-TURN DELAY per vehicle in seconds, PM peak-hour												
Intersection	**Delay without RTOR**				**Delay with RTOR**				**Delta , Δ**			
	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR	SBR	WBR	NBR	EBR
Lund, existing	19,8	18,1	17,9	20,3	9,0	12,9	9,8	7,3	**10,8**	**5,2**	**8,1**	**13**
Lund, no pedestrians/bicycles	18,1	13,3	14,2	19,4	7,2	8,3	8,3	5,6	**10,9**	**5,0**	**5,9**	**13,8**
Delta , Δ	**1,7**	**4,8**	**3,7**	**0,9**	**1,8**	**4,6**	**1,5**	**1,7**	**-0,1**	**0,2**	**2,2**	**-0,8**

Table 7.31 The right-turn delay at Malmövägen and Ringvägen in Lund with and without pedestrians and bicyclists, PM peak-hour.

A possible explanation for the small differences for the delay with the RTOR between the existing and with no pedestrians/bicyclists scenario, may be that stop duty always applies before reaching the crosswalk with RTOR and that every vehicle makes a complete stop for 3 seconds in the VISSIM model. That is why the difference is not larger than one may expect. The vehicles are making the complete stop and need more time to accelerate. The same maneuver has to be done in the absence of the pedestrians/bicycles and that is why there are no greater gains by removing pedestrians and bicycles.

By doing on-site visits in Phoenix it could be confirmed and verified that almost no vehicles do a complete stop but rather a rolling stop or yielding maneuver where RTOR applied. This is an important factor that affects the acceleration. The stopping maneuver and acceleration are the factors that have impacts on how effective RTOR will be in this case.

Some of the analysed hypotheses at the intersection of Malmövägen and Ringvägen did not provide significant change or benefits. The scenario that provides the most significant delay savings is the last hypothesis, H7, in which all pedestrians and bicyclist were removed. Pedestrians and bicyclists have a significant influence on vehicle capacities of turning movements at signalized intersections. By removing the pedestrians and bicyclist better RTOR possibilities could be achieved.

The average values for each intersection were compared in a Student´s t-test (paired two sample for means). The intersection delay was compared with and without pedestrians/bicycles, with and without RTOR. The Student´s t-test shows that there is a difference between the mean values and that the null hypothesis is rejected. A rejected null hypothesis means that the treatment is significant. The delay is smaller without the pedestrians/bicycles and with RTOR. RTOR is not a big success in this case. Table 7.32 visualises the results from the statistical test.

t-Test: Paired Two Sample For Means				
	AM		**PM**	
	No RTOR Regular	**No RTOR – No Peds/Bikes**	**No RTOR Regular**	**No RTOR – No Peds/Bikes**
Mean (s)	19,47	16,26	21,47	19,17
Number of Observations	10	10	10	10
P-Value (one-tail)	8,60E-06		3,36E-06	
	AM		**PM**	
	RTOR Regular	**RTOR – No Peds/Bikes**	**RTOR Regular**	**RTOR – No Peds/Bikes**
Mean (s)	17,57	14,58	19,41	16,97
Number of Observations	10	10	10	10
P-Value (one-tail)	1,55E-06		0,02	

Table 7.32 Mean values and standard deviation of delay in seconds.

The interested reader can find a list for the LOS for each hypothesis in Appendix E.

7.7 Fuel consumption

An increase in fuel consumption and emissions impacts our environment by the greenhouse effect, the social health by pollution and our economy by increased fuel prices. VISSIM traffic analysis software was used to determine the projected amount of fuel consumed during the AM and PM peak-hour for the intersection of Malmövägen and Ringvägen in Lund. The analysis was performed for the existing condition. VISSIM estimates the fuel consumption emission second by second from each individual vehicle in US gallons and is obtained summed for all vehicles that pass through the intersection. Below is the tabulated representation of the AM (one hour) and PM (one hour) peak-hour fuel consumption of the study area in both US gallons (U.S gallons in parentheses) and liters for all the vehicles that were output in the VISSIM model. Table 7.32 shows the VISSIM volume output for Malmövägen and Ringvägen. The accuracy between the model output and input is approximately 99 percent.

AM peak-hour (vehicle/hour)	PM peak-hour (vehicle/hour)
without RTOR	**without RTOR**
1385	2085
with RTOR	**with RTOR**
1384	2133

Table 7.32 VISSIM volume output (vehicle per hour) for Malmövägen and Ringvägen.

Without RTOR		**With RTOR**	
AM peak-hour	**PM peak-hour**	**AM peak-hour**	**PM peak-hour**
65,9 (17,4)	104,8 (27,7)	64,0 (16,9)	104,1 (27,5)

Table 7.33 Fuel consumption in liter and in U.S gallons in parentheses for all vehicles at Malmövägen and Ringvägen for one hour, during the peak-hour.

The AM (one hour) and PM (one hour) showed a small difference (1,9 liters for AM and 0,7 liters in PM for all vehicles in Table 7.32) and that is why the fuel consumption was also considered for one year as tabulated in Table 7.3.

Without RTOR		**With RTOR**	
AM peak-hour	**PM peak-hour**	**AM peak-hour**	**PM peak-hour**
17 134 (4 524))	27 248 (7 202)	16 640 (4 394)	27 066 (7 150)

Table 7.34 Fuel consumption in liters and in U.S gallons in parentheses for all vehicles at Malmövägen and Ringvägen for one year of peak-hours (260 days).

By looking at the difference in fuel consumption for one year it appeared to be still small (494 liters for AM and 182 liters for PM). The savings are approximately 3 percent for AM and slightly less than 1 percent for PM according to Table 7.34.

RTOR legislation provides the advantage of shorter stops made by vehicles which minimizes the amount of fuel consumption for vehicles. However, RTOR requires stopping which is a disadvantage for the fuel consumption since vehicles need to stop and then accelerate back to the design speed of the road. This maneuver interrupts the continuity of right-turning vehicles.

An estimate of cost and peak-hour savings was made with Swedish oil prices today. The peak-hour fuel consumption was calculated for a period of 52 weeks in a year and 5 days in a week. The weekends were not considered since the VISSIM model is based on the weekday peak-hours. The current oil price at the time of writing (February 29th 2012) in Lund was approximately 14,68 SEK (Bensinpriser 2012) The savings which can be gained at the intersection of Malmövägen and Ringvägen are presented in Table 7.35.

Without RTOR		**With RTOR**	
AM peak-hour	**PM peak-hour**	**AM peak-hour**	**PM peak-hour**
all vehicles per year		all vehicles per year	
251 527,1 SEK	400 000,6 SEK	244 275,2 SEK	397 328,9 SEK
per vehicle per year		per vehicle per year	
181,7 SEK	189,7 SEK	176,4	188,4 SEK

Table 7.35 The fuel cost in SEK for one year at Malmövägen and Ringvägen in Lund.

The total economic savings for all vehicles at the intersection of Malmövägen and Ringvägen today would save around 7 252 SEK in the AM peak-hour and 2 672 SEK in the PM peak-hour. The total saving per vehicle and per year would be approximately 5,20 SEK in the AM peak-hour and around 1,30 SEK in the PM peak-hour. It is important to remember that the savings are calculated for Malmövägen and Ringvägen which represents one of many intersections in Sweden. The savings are not large but still RTOR saves fuel and is more economic especially with Swedish oil prices. By optimizing signal timings the fuel consumption and emission can be reduced and maybe the reason for the small differences may depend on that the traffic signals at Malmövägen and Ringvägen already work efficient since they are actuated. The current oil price in Phoenix averages 3,71 USD per gallon (Slinger 2012) which represents approximately 25,41 SEK per gallon. A dollar is currently 6,85 SEK according to FOREX currency exchange. A liter fuel in Phoenix cost around 6,70 SEK, which is almost as half as much as in Sweden. The effect of implementing RTOR on most intersections in Sweden would probably show savings worth mentioning. This gives the reader maybe something to think about.

An emission analysis and environmental impact of traffic in terms of substances as the CO, NO_x and VOC was also determined for the intersection of Malmövägen and Ringvägen with VISSIM traffic analysis software. However, since emissions are directly linked to fuel consumption in VISSIM these were selected to be presented for the interested reader in Appendix D instead.

8 Conclusions

The purpose at the start of this thesis was to see how RTOR legislation would affect the efficiency and the delay at a four-legged signal controlled intersection in Lund compared to the intersections in Phoenix (USA). Since the intersections in Lund have generally higher pedestrian and bicycle volumes compared to the intersections in Phoenix, a concern was raised about the performance of RTOR. Furthermore, it was not sure whether a RTOR would be applicable to Lund´s transportation system due to these many bicyclists and pedestrians.

Too many conflicts that can be caused with the RTOR maneuvers, especially involving children, elderly pedestrians or persons with disabilities can, according to the Manual on Uniform Traffic Control Devices (MUTCD)(FHWA 2009, p.95-96), prohibit the RTOR movement. During the conduct of this study, additional hypotheses came up and were developed as a result of the reflection during the literature study and field studies and were chosen to be included in the thesis as well.

All the hypotheses consider the changes with the RTOR and without the RTOR and are compared against one another to show the benefit, if such existed, of a RTOR movement. It is important to remember that the results and conclusions that are presented and made in this thesis only apply to the studied intersections but would most likely correspond well in other cases with the same type of intersection. Below is a review of each hypothesis:

H1a - The delay at signalized intersection is lower where RTOR is permitted compared to where RTOR is prohibited in both AM and PM peak-hours.

H1b - The benefit from a RTOR will prove to be less for the intersection of Malmövägen and Ringvägen (than the intersections in Phoenix) due to the pedestrians and bicyclists.

H2 - The right-turn movements have a bigger benefit in delay than the intersection as whole.

These three hypotheses, all related to the contribution of the efficiency in the transportation system, came from the belief that right-turning vehicles will benefit more from RTOR than other vehicles at the intersection, which will also reduce the delay for the entire intersection. The result from the intersection delay showed that the intersection delay was lower where RTOR is permitted compared to where RTOR was prohibited in both AM and PM peak-hours. At some of the studied intersections in Phoenix, the benefit for the entire intersection proved to be very insignificant (benefits between 0,5 and 2 seconds were received per vehicle) and could very much depend on the characteristics (geometry, speed, driver behaviour, intersection volumes etc.) of the studied intersection. The benefits seemed to be greater in the PM peak-hour, however.

The study also showed that the delay with RTOR legislation was smaller for all the four approaches at every intersection. The right turning vehicles at the intersection of Malmövägen and Ringvägen would save between approximately 3 and 16 seconds per vehicle in the morning and between approximately 5 and 13 seconds per vehicle in the afternoon with a RTOR legislation. Today's right-turn delays at the intersection are between approximately 15 and 22 seconds per vehicle in the AM peak-hour and between approximately 17 and 20 seconds per vehicle during the PM peak-hour. The intersection delay was not much affected by the RTOR compared to the right-turn delay for all approaches which is where the RTOR legislation benefit contributions are most notable. Hypothesis H2 could be proven and it could be seen that the right-turn movements had a bigger benefit in delay than the intersection as whole. The contribution from a RTOR legislation, for all right turning movements for the intersections analyzed in Phoenix and Lund, varies from 1 to approximately 16 seconds per vehicle for AM peak-hour while it varies from 0,5 to 13 seconds per vehicle for PM peak-hour.

It was expected in hypothesis H1b that the benefit from a RTOR would prove to be smaller in Lund because of the pedestrians and bicyclists. The study showed that the benefits with RTOR would be greater in Lund with approximately 2 seconds (in intersection delay), than for the observed intersections in Phoenix. So hypothesis H1b was surprisingly untrue. A possible explanation for the bigger benefit in Lund was the smaller volumes in Lund and the even distribution of traffic on all four approaches. The distribution of traffic in Phoenix was uneven and divided into major and minor approaches and therefore these had a smaller benefit from the RTOR. The major traffic flow disadvantage Phoenix because RTOR becomes more difficult to implement, why these had a smaller benefit from the RTOR. Another explanation can be that the RTOR movement was prevented. This occurs in situations when right lane is a shared lane with through traffic and the approaching vehicle at the STOP bar is not a right-turning vehicle but instead a through vehicle

H3 - Minor roads have a larger benefit in delay from RTOR than major roads.

Hypothesis H3 is related to the traffic volumes and was formed to see the difference in benefit resulting from a road being a minor or major road, which was observed during field reviews. Minor streams always have lower priority and less green time than the major streams and that is why a RTOR should benefit the minor roads more in pursuit of the drivers taking advantage of RTOR. The comparison between the approach delay for minor roads and the approach delay for the major roads resulted in a true H3 hypothesis for the ten intersections in Phoenix.

I believe that this may be due to the fact that minor streets get less green time and therefore cars are more likely to use RTOR more frequent.

H4 - Lane configuration plays an important role. An exclusive right-turn lane benefits the RTOR movement further and results in larger reduction in delay.

This hypothesis is a result of a discovery during the field study and literature study. The existence of an exclusive right-turn lane will increase the usage of RTOR. In the case where the lane closest to the sidewalk is a shared through/ right-turn lane (and RTOR is permitted) and the approaching vehicle at the STOP bar is not a right-turning vehicle , the following right-turning vehicles will be prevented or blocked from making the RTOR maneuver by the through vehicle. The driver wanting to make a right-turn will be forced to wait until there is a green signal to make the turn. If, however, the approaching vehicle is a right-turning vehicle, the driver has the potential to make the RTOR movement.

The delay reduction for shared through/right-turn lanes was compared to the exclusive right-turn lanes and resulted in double-saving in the delay reduction for right-turn with an exclusive right-turn lane, which proves hypothesis H4 right. However, more samples or detailed studies would be desirable since most of the exclusive right-turn lanes in Phoenix were on the minor streets. The benefit could therefore be coming either because they are a minor street as proven in hypothesis H3 or because of the exclusive right-turn lane. The hypothesis H4 could however be proven for the intersection in Lund.

H5 - The reduction in delay will be small with an extended storage length..

The idea behind hypothesis H5 is to see how the length of the storage in a right-turn lane affects the delay for the vehicles using the RTOR movement. It was expected that the number of RTOR vehicles would be greater with enough space and sufficiently large storage length, but that an infinitely long storage length would in the end cause queuing and RTOR would be cancelled by the signal phase turning green.

Hypothesis H5 was proven right. There is no point of making the storage even longer (between 22 meters and 44 meters) than it already is since all these vehicles will not be able to make a right-turn on red. The delay for the right-turning vehicles, with an extended right-turn lane, will either be the same or increase. It is concluded that the storage length probably plays an important role to a certain point, but the delay is most likely more affected by other factors such as the cross-intersecting flow and finding sufficient gaps. This hypothesis was only evaluated for the intersection in Lund so the sample size was small.

H6 - The cross-intersecting flow is of great importance for the implementation of a RTOR movement.

Hypothesis H6 was formulated due to the belief that a larger cross-intersecting flow will prevent more vehicles from making a RTOR because of a greater difficulty in finding an acceptable gap in joining the cross-intersecting stream.

The benefit of RTOR with a reduced or increased cross-intersecting flow did not show any bigger differences except that the delay increases somewhat with increased vehicle volumes. Drivers with a larger cross-intersecting flow have a bigger approach delay than with a smaller cross-intersecting traffic flow. However RTOR did not stop to have a positive effect in this study. The literature study that was done also showed that there are no regulations or guidelines today in the United States for the amount of traffic that is appropriate at intersections where right-turn on red applies. The primary factor for prohibiting or restricting RTOR behaviors is inadequate sight distance.

The cross-intersecting flow shows an importance for the implementation of a RTOR movement, but the volumes have to probably be significantly higher than those at the intersection of Malmövägen and Ringvägen in Lund. The 10 studied intersections in Phoenix all manage to make a RTOR movement despite the higher volumes. The size of the intersection at Malmövägen and Ringvägen in Lund makes it difficult to draw conclusions about the hypothesis H6, even though it is proven for the intersection in Lund. This hypothesis was only evaluated for the intersection in Lund so this does not mean that the hypothesis will be true for other intersections. The Student´s t-test shows that null hypothesis is true and that there is no significance difference of the means.

H7 - Pedestrians perpendicular to the right-turning vehicles have an impact on the effectiveness of RTOR.

Hypothesis H7 was formulated, just as the hypothesis H1, during the initiation of the study since the intended RTOR movement can be affected or blocked if the number of pedestrians and bicyclists crossing perpendicularly to the vehicle is too large. The possibility to find a gap for the RTOR movement will become harder to execute during the red phase. The intersections in Lund have generally more pedestrians and bicyclists compared to the intersections in Phoenix. Therefore, a concern was raised about the performance of RTOR and it was not sure whether a RTOR would be applicable to Lund´s transportation system due to the large amount of bicyclists and pedestrians.

By removing the pedestrians and bicyclists at the intersection of Malmövägen and Ringvägen (assuming this traffic group chooses another road to cross, maybe a viaduct), improvements were achieved. Between 2,5 and 3 seconds in delay savings were achieved per vehicle for the entire intersection. Furthermore, between 0 and 5 seconds in delay savings per vehicle were achieved for the right-turn delay with a RTOR and with the absence of pedestrians and bicycles. This result proved hypothesis H7 for the intersection of Malmövägen and Ringvägen.

If RTOR were implemented at the intersection in Lund, the flow and safety of pedestrians and bicycles would have to be greatly considered. Since it is not realistic to remove pedestrians and bicyclists from the intersection, one option would be to build a pedestrian/bicycle bridge when the number of pedestrians/bicycles is too large and prevents vehicles from doing the RTOR maneuver. Another solution may be to completely separate the pedestrian/bicycle phases from the vehicular phases.

This way the pedestrians/bicycles would have their own phase in which they can cross the road straight or diagonally while all vehicular traffic is stopped with a red light. On the other hand, vehicles could make RTOR maneuvers without pedestrian/bicycle interference since these would have a red light. Both these options would have to be investigated in more detail, with respect to cost and safety, before being implemented in the case of a RTOR maneuver in Lund.

In some of the approaches no significant benefits were achieved. A possible explanation for the small differences for the delay with the RTOR, between the existing scenario and without pedestrians/bicycles scenario, may be that stop duty always applies before reaching the crosswalk. With RTOR, every vehicle makes a complete stop for 3 seconds in the VISSIM model. The vehicles are making the complete stop and need more time to accelerate. The same maneuver has to be done in the absence of the pedestrians/bicycles and that is why maybe the difference is not larger than one might expect.

By doing on-site field visits of every intersection in Phoenix it could be confirmed and verified that almost no vehicles come to a complete stop but rather a rolling stop or yielding maneuver where RTOR applied. This is a key factor that affects the acceleration and delay. The acceleration and stopping maneuver are significant factors on how effective RTOR will be in this case. The VISSIM model possibly could have been done with a yield sign to achieve more realistic results, but this would not reflect the actual RTOR law and it is hard to know the proportion of vehicles that do not stop.

Some of the analysed hypotheses at the intersection of Malmövägen and Ringvägen did not provide significant change or benefits. The scenario that provides the most significant delay savings was the last hypothesis, H7, in which all pedestrians and bicyclist were removed. Pedestrians and bicyclists have a significant influence on vehicle capacities of turning movements at signalized intersections. By removing the pedestrians and bicyclists, better RTOR possibilities could be achieved. This study showed, despite the higher pedestrian and bicycle volumes compared to the intersections in Phoenix, there are no bigger problems of performing the RTOR at the intersection of Malmövägen and Ringvägen in Lund and so is the case probably at similar intersections. The development of a RTOR law in Lund would be possible and would contribute to lower delays.

RTOR is beneficial for the intersections in Phoenix and would also be beneficial at the intersection of Malmövägen and Ringvägen in Lund. It is an effective way to reduce the delay, especially the right-turn delay at signalized intersections.

The RTOR movement would probably be most beneficial during nighttime or off-peak-hours when there is less vehicular traffic and almost no pedestrians and bicycles. The traffic from minor roads would also be the one that would reduce its delays and save time the most.

RTOR is standard practice in Phoenix and all intersections have RTOR unless prohibited by a sign. In Lund, perhaps we could have RTOR on a case by case basis. This would only require a sign allowing the movement. The cost for the installation of foundations, posts and signs would not be expensive. The introduction of a RTOR law in Lund would require legislative change but also driver training and education or public information for pedestrians, bicyclists and other road users in order to bring more awareness and to make it a habit.

I believe that the signal control type is of high importance for RTOR and that RTOR would have more effect and show bigger benefits at intersections with a pre-timed signal controller. A traffic-controlled signal provides lower delays as it adapts to the changing traffic conditions (Hydén 2008, p.329), which is perhaps why some of the changes were not significant with a RTOR for the intersections in this thesis.

RTOR legislation provides the advantage of shorter stops made by vehicles which minimizes the amount of fuel consumption for vehicles. However, RTOR requires stopping which is a disadvantage for the fuel consumption since vehicles need to come to a complete stop and then accelerate to make the right-turn. This maneuver interrupts the continuity of right-turning vehicles. Fuel consumption and emissions were calculated for the intersection in Lund with current oil prices. The savings are approximately 3 percent for the AM peak-hour and slightly less than 1 percent for PM peak-hour per year per vehicle.

The total economic savings per year for all vehicles at Malmövägen and Ringvägen today would be around 7 252 SEK in the AM peak-hour and 2 672 SEK in the PM peak-hour. The total saving per vehicle per year would be approximately 5,20 SEK in the AM peak-hour and around 1,30 SEK in the PM peak-hour. It is important to remember that the savings are calculated only for the intersection of Malmövägen and Ringvägen, and only for the two peak-hours, which represents one of many intersections in Sweden. The savings are not large but still RTOR saves fuel and is more economic especially with Swedish oil prices. As a comparison, a liter fuel in Phoenix cost around 6,70 SEK, which is approximately as half as much as in Sweden.

Moreover, by optimizing signal timings the fuel consumption and emission can be reduced. As stated before, the reason for the small differences may depend on that the traffic signals at the intersection of Malmövägen and Ringvägen already work efficient since they are actuated. The effect of implementing RTOR on most intersections in Sweden would probably show savings worth mentioning.

The majority of the research regarding the traffic safety and crashes with RTOR, based on previous research, stated that RTOR is related with a small or an insignificant number of accidents (typically 0,61 percent of all intersection accidents). It also concluded that there were a rather small number of injuries and deaths each year caused by RTOR crashes and that the impact on traffic safety is small (NHTSA 1995, p.6; McShane & Roess 1990, p. 413). These statements and conclusions were however based on older studies from 1992 and older. It was very difficult to find any updated research about the safety impact of RTOR.

A recent study that analyzed the conflicts between right-turning vehicles and pedestrians at signalized intersections, where RTOR is permitted, found that an increased traffic volume and pedestrian flow will increase the number of conflicts, but will decrease the conflict rate per hundred pedestrian. The number of severe conflicts at large radius is at the same time higher than at small radius (Zhao et al 2011).

The results from the ADOT crash analysis showed that the most common accidents types during the four-year period (from 2007 to 2010) seemed to be rear-end collisions between motor vehicles, angle collisions and sideswipe collisions in the same direction. The most common accidents types, according to the data from STRADA (Swedish Traffic Accident Data Acquisition), during the ten year period (from 2001 to 2010) for the intersection of Malmövägen and Ringvägen seemed to also be rear-end collisions between motor vehicles, collision between motor vehicles, bicycle and/or moped collisions with motor vehicles, drive-off for motor vehicles and single accidents for pedestrians, bicycles and mopeds. The accidents type did not deviate particularly between the intersections in Phoenix (where RTOR is permitted) and the intersection of Malmövägen and Ringvägen in Lund.

At the ten intersections in Phoenix, only four accidents involved a pedestrian and three involved a bicycle during the four year period (from 2007 to 2010). The majority of them suffered from incapacitating injuries and two of the accidents were caused by an angle collision type that was other than a left turn. They may have been caused by a right-turning vehicle that was executing a RTOR movement or a vehicle that was executing a right-turn on green as well. This type of information is not available in the ADOT system ALISS and is therefore unknown. So there could not be any conclusions made whether these accidents had any connection with the RTOR movement. Additionally, ALISS does not include data from the health care which provides a poorer understanding of road accident victims and severity of injuries.

It may seem to be a very subjective opinion. I would conclude that the indication of RTOR is more positive than negative by comparing the delay and fuel savings (3 percent) to the number of accidents at intersections with RTOR (let us assume that this is the typically 0,61 percent of all intersection accidents), but the percentage increase in accidents is probably higher in Sweden than in USA.

So, is the legislation of RTOR a positive and effective way to reduce delays in the transport network in terms of what it means for the accident risks? The small decrease in fuel consumption (3 percent) needs to be measured against the small increase in traffic accidents (0,6 percent in the US, but might be somewhat higher in Sweden due to more pedestrians and bicyclists). To be able to make a proper judgment a larger study needs to be performed where also the safety effects in a larger scale are studied.

Further study possibilities

If I were going to do a further study, subsequent to this study, I would probably do it on a more detailed level for the intersections in Phoenix or try to find one intersection in Phoenix that correspond as close as possible to the intersection of Malmövägen and Ringvägen in Lund. Other possibilities for further researches would be to analyze and compare these results to intersections with a pre-timed signal controller.

The gap acceptance for this study used default values from VISSIM. A more detailed look at gap acceptance where RTOR is permitted could be studied in the field to see if it differs much from the gap acceptance at unsignalized intersections.

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Appendix A

Figure A.1 Functional description for Malmövägen and Ringvägen, Lund.

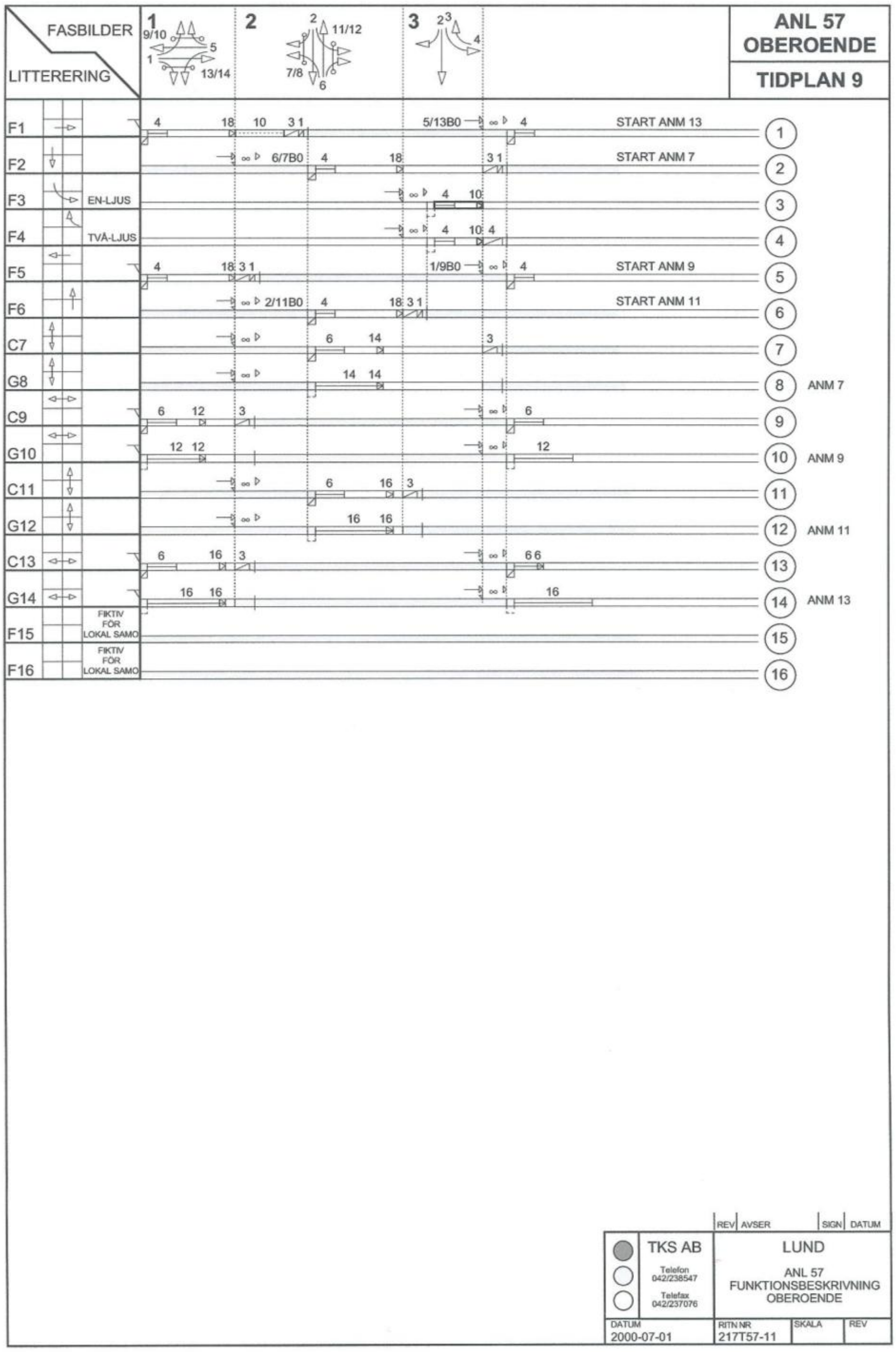
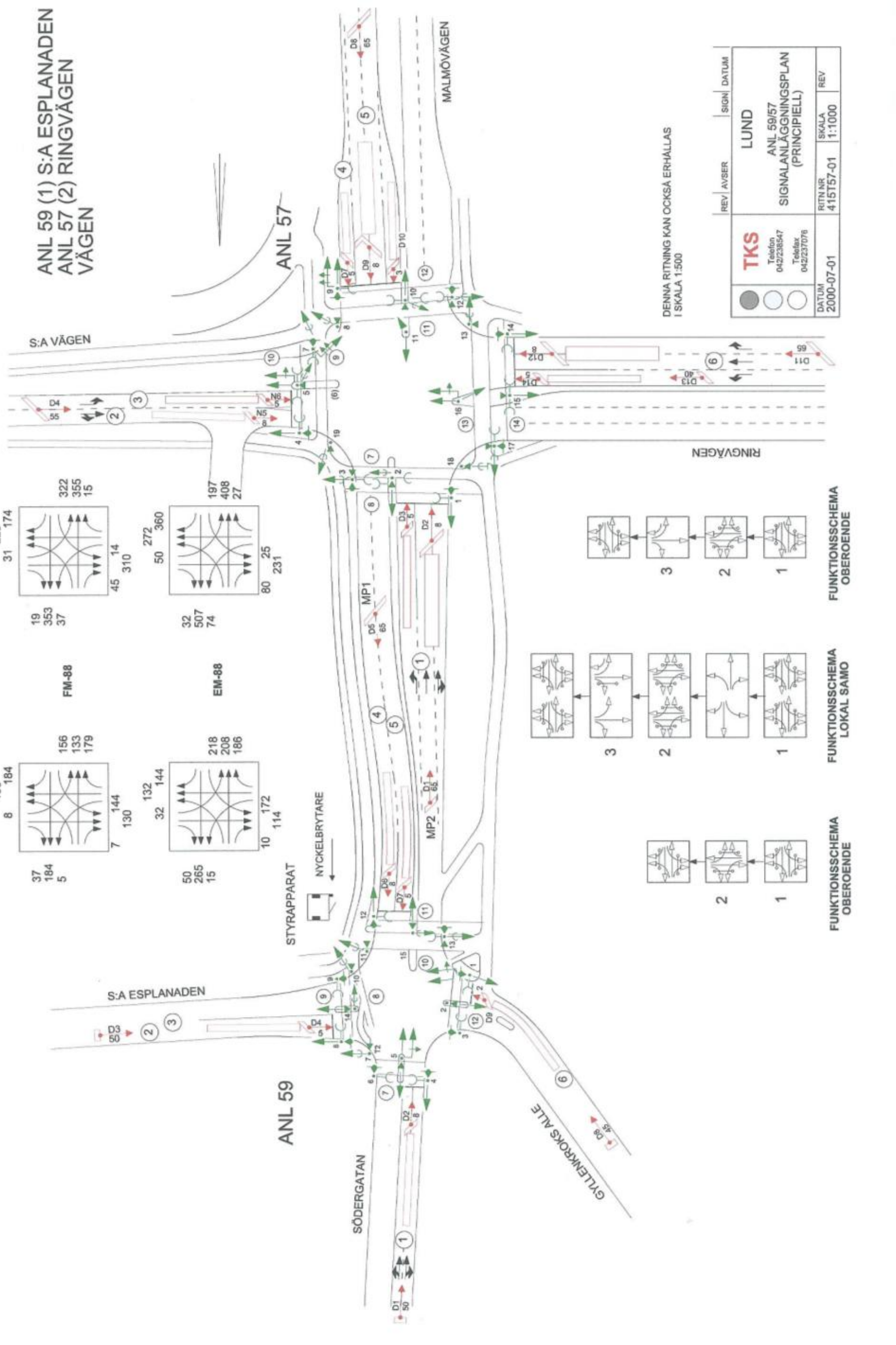


Figure A.2 Signal plan for Malmövägen and Ringvägen in Lund.



Appendix B

Figure B.1 Checklist for VISSIM model.

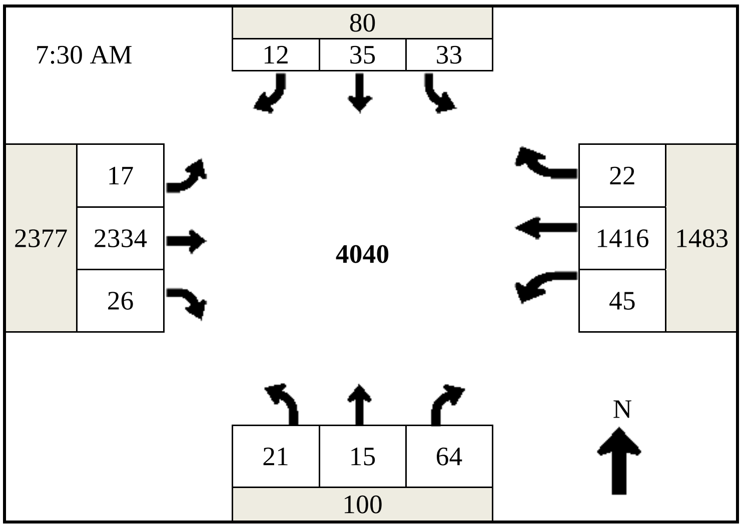
	Checks 1	Checks 2	Checks 3	List of Items to Check in a Microsimulation VISSIM Model
1				Change the Language Units before uploading the background
2				Check the Background is to the scale or not
3				Check various links types to diffentiate different roadway types
4				Check the Speed Limits for all the roadway types
5				Check various traffic compositions for all the Entry Links
6				Check the Network (All Links and Connectors)
7				Priority Rules (These can coded after running the model)
8				Stop Sign
9				Speed Limits
10				Vehicle Inputs
11				Vechile Models
12				Traffic Composition
13				Reduced Speed Areas
14				Routing Decision and Input Volume
15				Signal Controller
16				Signal Head and Detectors Numbers
17				Check Stop Signs for Right Turn on Red
18				Check the Simulation time
19				Check the model while running

	Name	Signature	Date
Check 1	___________	_______________	_______
Check 2	___________	_______________	_______
Check 3	___________	_______________	_______

Insert a check "√ " or a "Y" in the box to indicate a required QC activity
Insert a "X' or an "N" to indicate that the QC activity is not required

Appendix C

Figure C.1 Vehicle inputs (AM and PM) for Bell Road and Burns Drive.



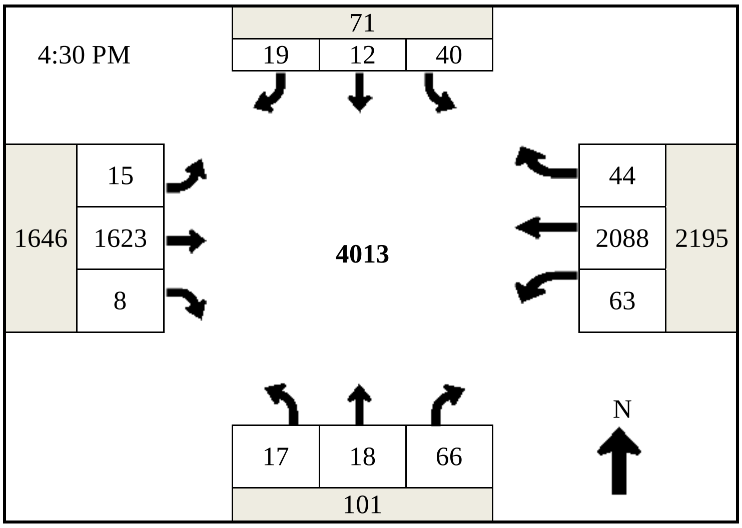
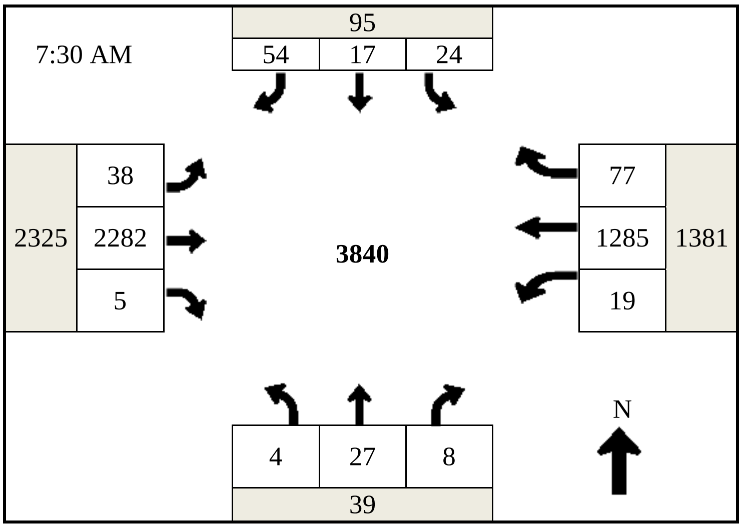


Figure C.2 Vehicle inputs (AM and PM) for Bell Road and 98th Avenue.



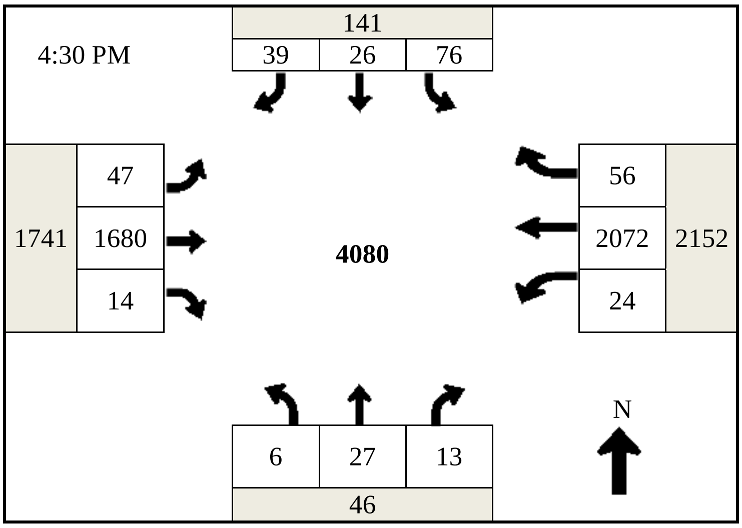
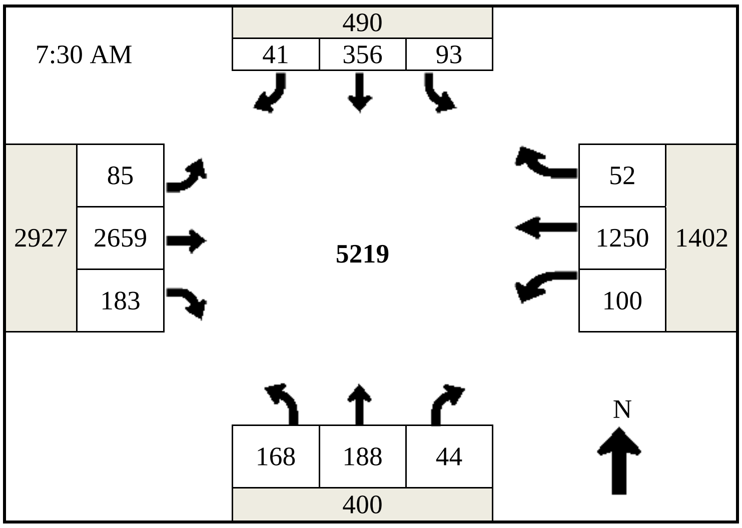


Figure C.3 Vehicle inputs (AM and PM) for Bell Road and 99th Avenue.



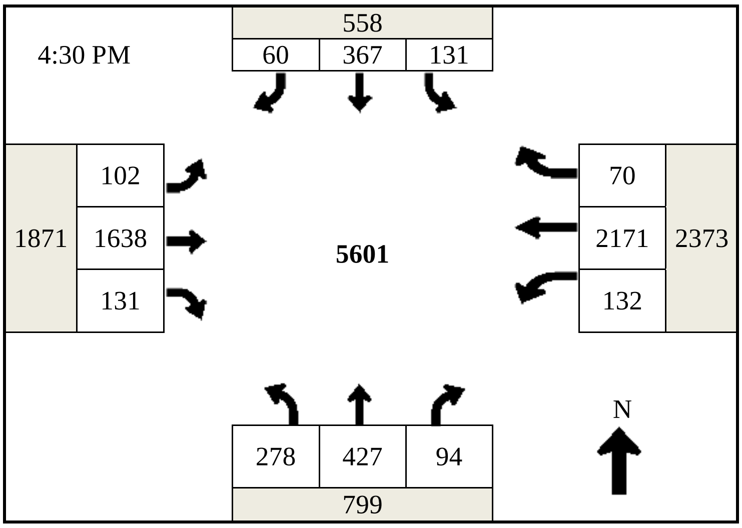
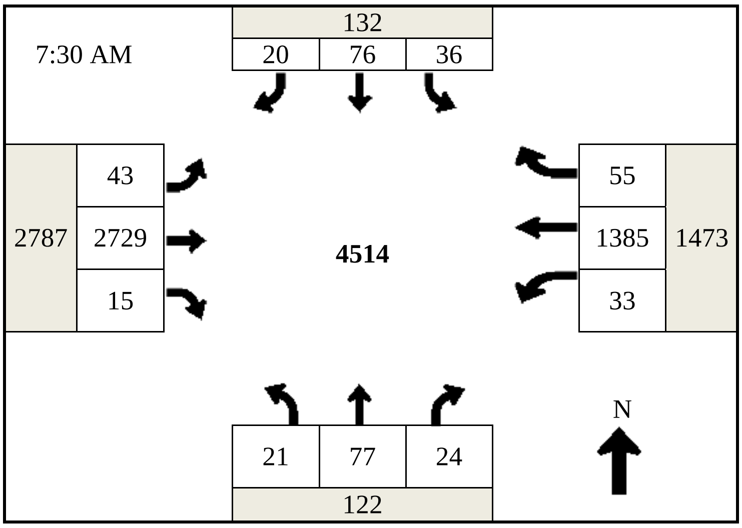


Figure C.4 Vehicle inputs (AM and PM) for Bell Road and Boswell Boulevard.



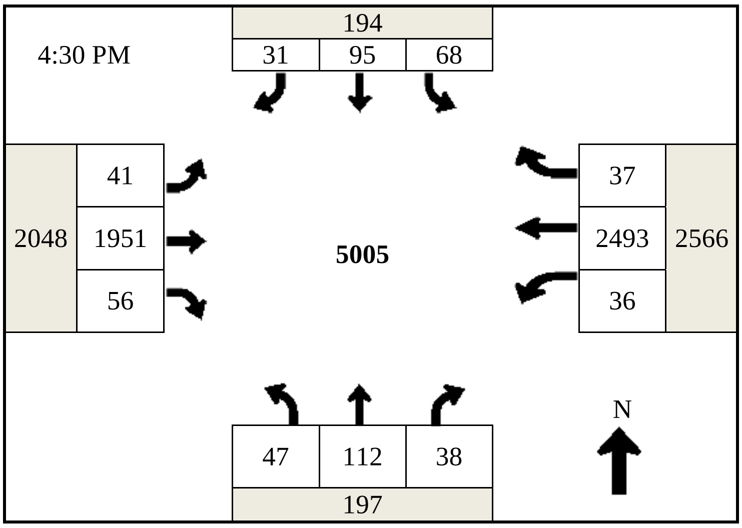
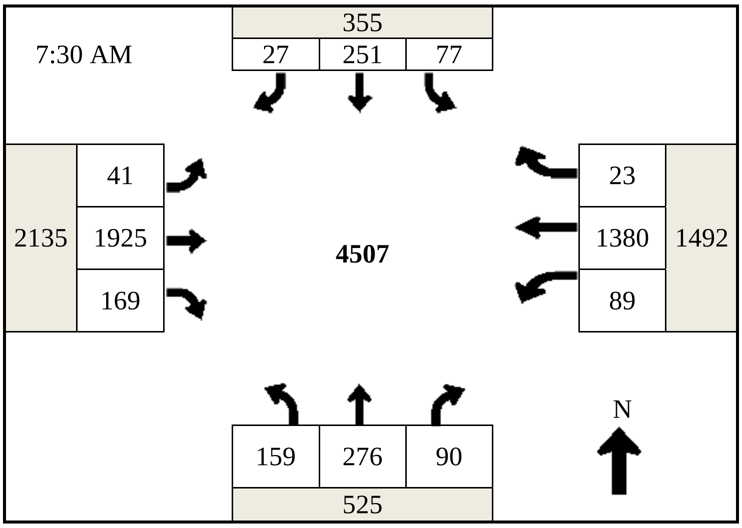


Figure C.5 Vehicle inputs (AM and PM) for Bell Road and Del Webb Boulevard.



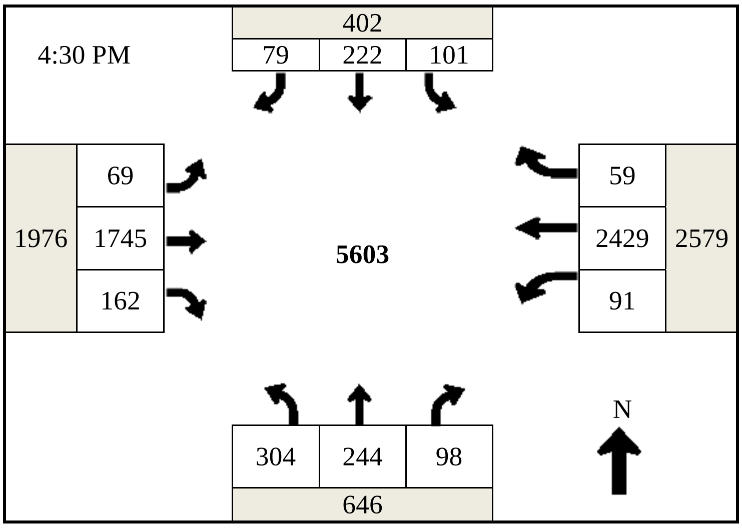
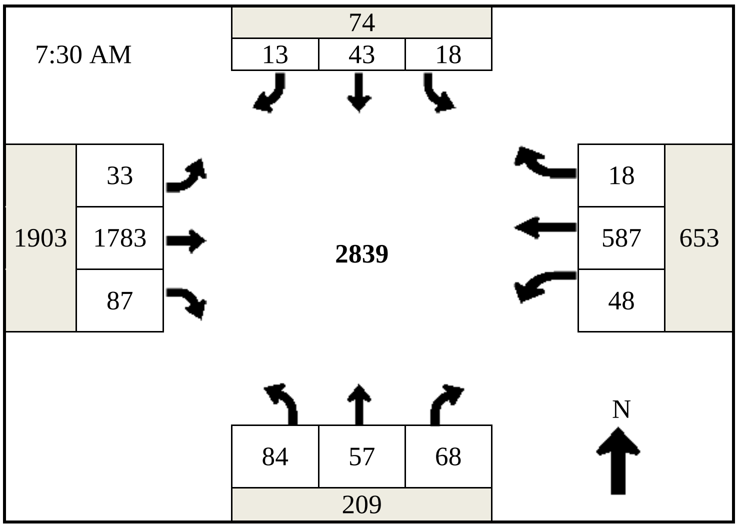


Figure C.6 Vehicle inputs (AM and PM) for Olive Avenue and 107^{th} Avenue.



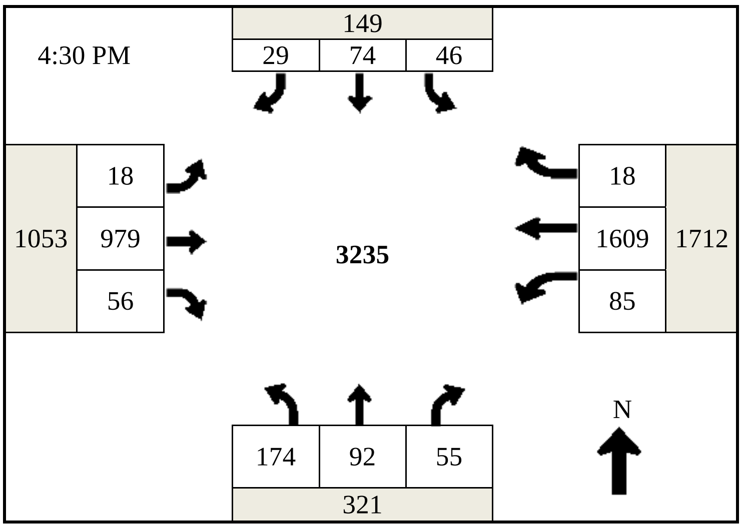
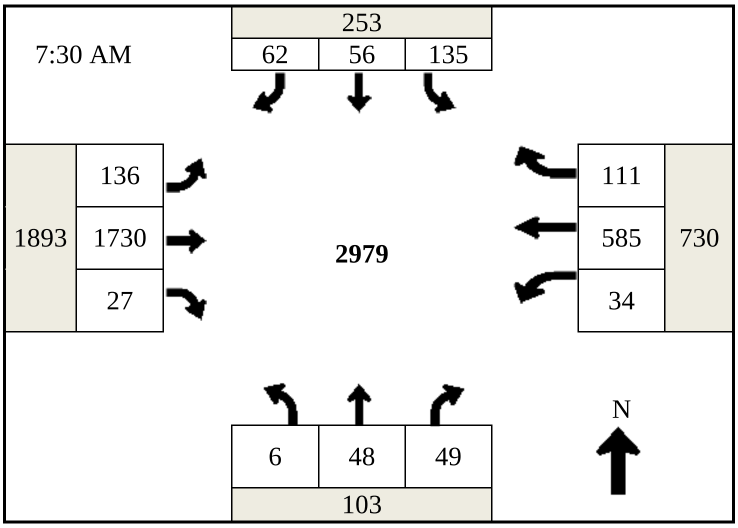


Figure C.7 Vehicle inputs (AM and PM) for Olive Avenue and 111th Avenue.



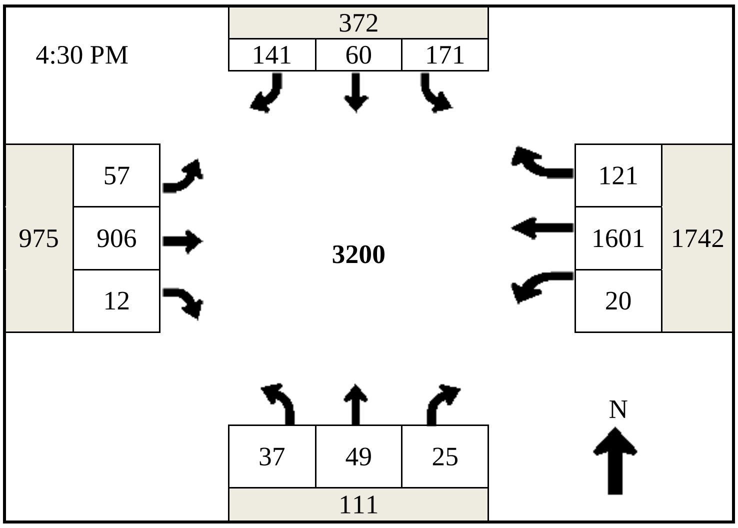
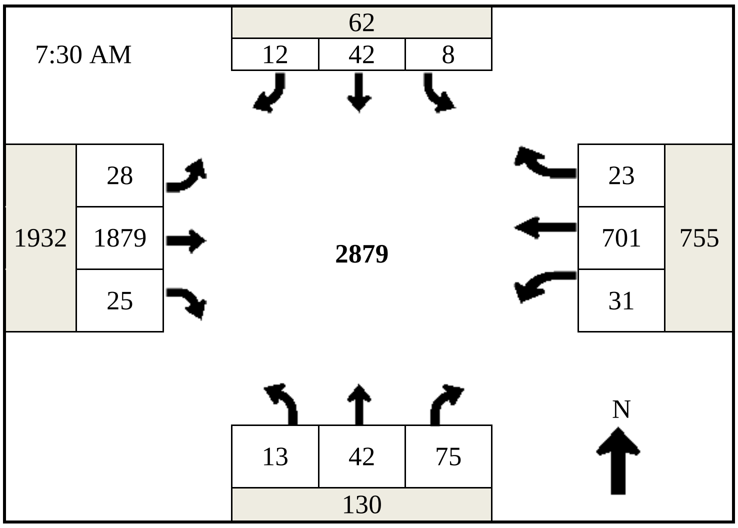


Figure C.8 Vehicle inputs (AM and PM) for Olive Avenue and 103rd Avenue.



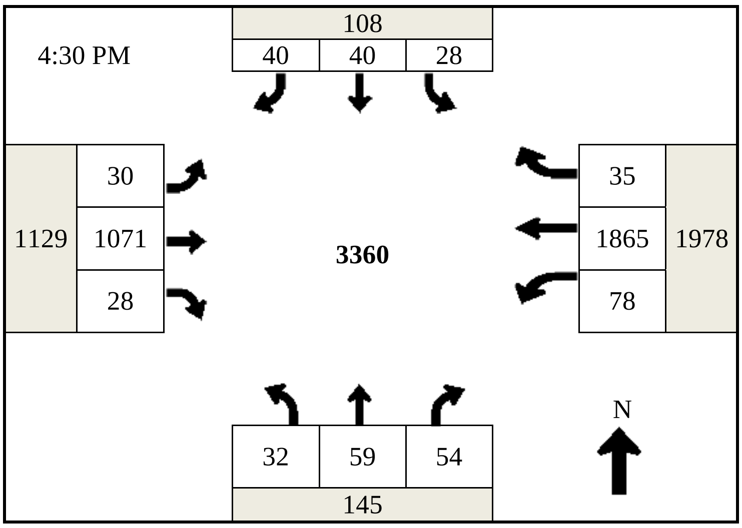
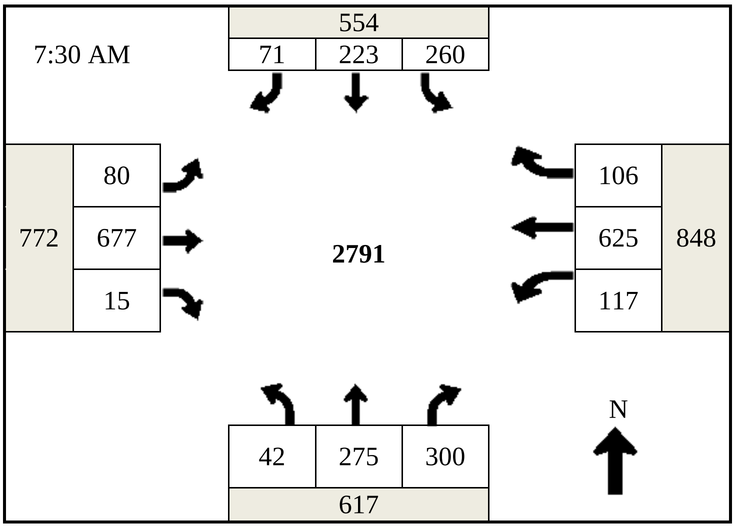


Figure C.9 Vehicle inputs (AM and PM) for Thunderbird Road and 99th Avenue.



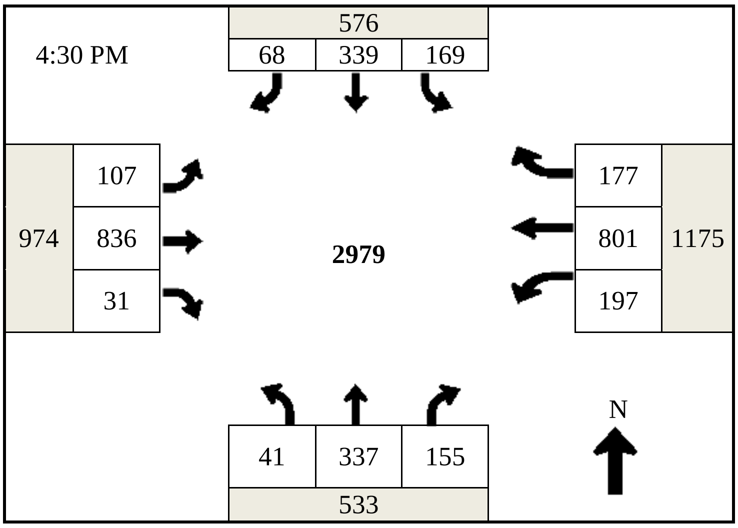
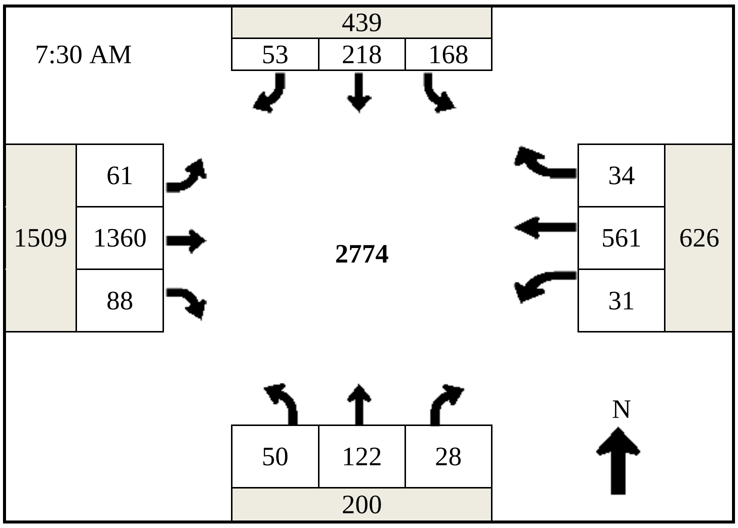
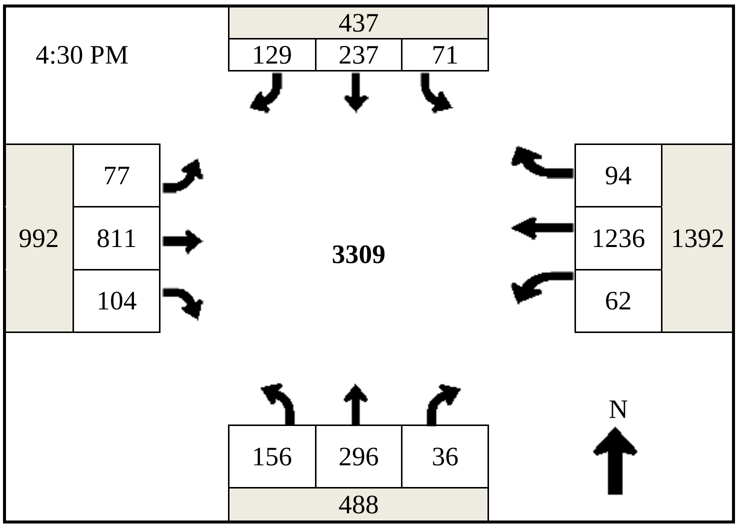


Figure C.10 Vehicle inputs (AM and PM) for Indian School Road and 99th Avenue.





Appendix D
Emission analysis

An increase in emissions impacts our environment by the greenhouse effect and the social health by pollution. The environmental impact of traffic in terms of substances as the CO, NO_x and VOC was therefore also determined for the intersection of Malmövägen and Ringvägen with VISSIM traffic analysis software. The analysis was performed for the current situation, during the AM and PM peak-hour. VISSIM estimates the total emission amount of CO, NO_x and VOC in grams (g) and is obtained summed for all vehicles that pass through the intersection. Below is the tabulated representation of the AM (one hour) and PM (one hour) peak-hour exhaust emissions of the study area in grams for all the vehicles that were output in the VISSIM model. Table 7.22 in Section 7.7 Fuel consumption shows the VISSIM volume output for Malmövägen and Ringvägen.

Without RTOR		**With RTOR**	
AM peak-hour	**PM peak-hour**	**AM peak-hour**	**PM peak-hour**
CO in grams		CO in grams	
1 217	1 934,4	1 181	1 924,7
NOx in grams		NOx in grams	
236,8	376,4	229,8	374,5
VOC in grams		VOC in grams	
282,1	448,3	273,7	446,1

Table D1. Exhaust emissions for all vehicles at Malmövägen and Ringvägen during the peak-hour.

As presented in Table D1, the VISSIM analysis presents smaller reductions in the concentration of the vehicular emissions for Malmövägen and Ringvägen for the RTOR versus the existing conditions without RTOR. The savings are approximately 3 percent for AM and slightly less than 1 percent for PM according to Table D1. AM (one hour) and PM (one hour) showed a small difference why the exhaust emissions were also considered for one year as tabulated in Table D2.

Without RTOR		**With RTOR**	
AM peak-hour	**PM peak-hour**	**AM peak-hour**	**PM peak-hour**
CO in grams		CO in grams	
316 420	502 944	307 060	500 422
NOx in grams		NOx in grams	
61 568,0	97 864,0	59 748,0	97 370,0
VOC in grams		VOC in grams	
73 346,0	116 558,0	71 162,0	115 986,0

Table D2. Exhaust emissions for all vehicles at Malmövägen and Ringvägen for one year.

By looking at the difference in exhaust emissions for one year it appeared to be still insignificant (for CO it appeared to be 9360 grams for AM and 2522 grams for PM; NOx decreased by 1820 grams in AM and by 494 grams; VOC decreased by 2184 grams in AM and by 572 grams in PM). The decrease in the emission of CO, NOx and VOC are approximately 3 percent for AM and slightly less than 1 percent for PM for one year according to Table N. The emission of CO, NOx and VOC in the peak-hour for the entire year and for each vehicle is tabulated in Table D3.

Without RTOR		**With RTOR**	
AM peak-hour	**PM peak-hour**	**AM peak-hour**	**PM peak-hour**
CO (g) per vehicle per year		CO (g) per vehicle per year	
228,5	238,5	221,7	237,3
NOx (g) per vehicle per year		NOx (g) per vehicle per year	
44,5	46,4	43,1	46,2
VOC (g) per vehicle per year		VOC (g) per vehicle per year	
53,0	55,3	51,4	55,0

Table D3. The emission of CO, NOx and VOC in the peak-hour per vehicle for the entire year.

From the result in Table D3 one can see the small exhaust decreases with RTOR legislation at the intersection of Malmövägen and Ringvägen. The decrease in the emission of CO, NOx and VOC are approximately 3 percent for AM and slightly less than 1 percent for PM peak-hour per year and one vehicle. A possible explanation to the insignificant change in the emission exhaust may be that even with RTOR all the standing vehicles need to first come to a complete stop before they are allowed to turn right on red. This is the same scenario with standing vehicles waiting for the green light to turn right at Malmövägen today. All the standing vehicles, with or without RTOR, need to accelerate and even more fuel is consumed. However, RTOR contributes to less consumed fuel due to the shorter delays and because of fewer engines idle.

Appendix E

Results of the level of service

Table E.1 The right-turn delay per approach for Malmövägen and Ringvägen in Lund, AM peak-hour.

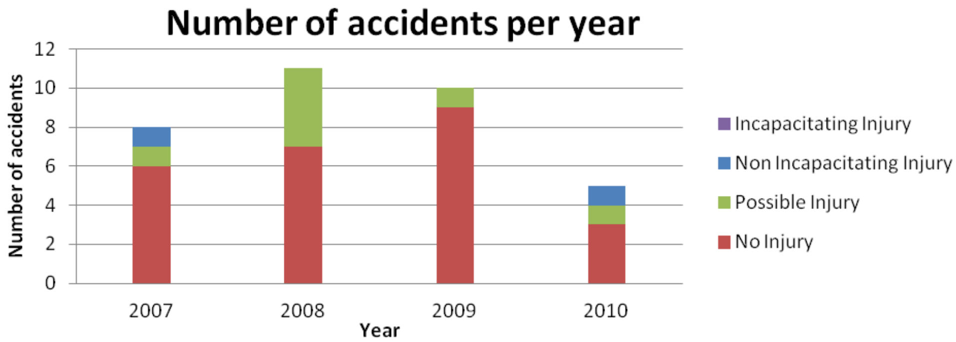
AM peak-hour (delay in seconds per vehicle)									
Scenario		**SBR**	**LOS**	**WBR**	**LOS**	**NBR**	**LOS**	**EBR**	**LOS**
Existing	**RTOR**	6,8	A	12,1	B	7,3	A	5,5	A
	No RTOR	19,5	B	15,7	B	15,0	B	21,7	C
No NBR-lane	**RTOR**	7,3	A	9,4	A	11,6	B	6,1	A
	No RTOR	19,1	B	15,7	B	22,6	C	22,4	C
EBT, -30%	**RTOR**	8,7	A	11,9	B	6,4	A	5,7	A
	No RTOR	16,1	B	16,6	B	14,6	B	20,3	C
EBT, +30%	**RTOR**	6,4	A	10,8	B	7,4	A	6,0	A
	No RTOR	21,2	C	16,7	B	13,6	B	18,6	B
WBT, -30%	**RTOR**	6,0	A	9,0	A	7,6	A	5,5	A
	No RTOR	17,9	B	16,8	B	14,4	B	18,7	B
WBT, +30%	**RTOR**	6,9	A	13,1	B	7,0	A	5,2	A
	No RTOR	20,5	C	15,9	B	13,8	B	20,3	C
SBT, -30%	**RTOR**	6,1	A	10,2	B	6,9	A	5,5	A
	No RTOR	18,9	B	14,5	B	13,8	B	20,0	C
SBT, +30%	**RTOR**	7,3	A	9,8	A	7,5	A	5,4	A
	No RTOR	18,3	B	14,5	B	14,7	B	21,1	C
NBR, -30%	**RTOR**	6,8	A	11,3	B	6,9	A	5,3	A
	No RTOR	19,3	B	15,1	B	13,4	B	19,4	B
NBR, +30%	**RTOR**	6,9	A	11,5	B	7,1	A	7,8	A
	No RTOR	20,0	B	19,5	B	14,7	B	19,3	B
Storage, +50%	**RTOR**	7,6	A	10,0	A	7,2	A	5,5	A
	No RTOR	19,6	B	16,8	B	13,9	B	20,1	C
Storage, +100%	**RTOR**	7,5	A	9,5	A	7,5	A	5,4	A
	No RTOR	19,5	B	16,8	B	15,1	B	20,3	C
No pedestrians and bikes	**RTOR**	5,4	A	6,7	A	6,7	A	4,8	A
	No RTOR	17,2	B	9,8	A	11,3	B	16,2	B

Table E.2 The right-turn delay per approach for Malmövägen and Ringvägen in Lund, PM peak-hour.

PM peak-hour (delay in seconds per vehicle)									
Scenario		**SBR**	**LOS**	**WBR**	**LOS**	**NBR**	**LOS**	**EBR**	**LOS**
Existing	**RTOR**	9,0	A	12,9	B	9,8	A	7,3	A
	No RTOR	19,8	B	18,1	B	17,9	B	20,3	C
No NBR-lane	**RTOR**	9,3	A	14,1	B	18,8	B	7,3	A
	No RTOR	22,2	C	17,3	B	25,5	C	25,0	C
EBT, -30%	**RTOR**	8,1	A	13,5	B	8,0	A	6,5	A
	No RTOR	21,4	C	19,5	B	17,0	B	24,2	C
EBT, +30%	**RTOR**	13,0	B	12,9	B	10,5	B	8,3	A
	No RTOR	25,7	C	17,4	B	17,0	B	24,3	C
WBT, -30%	**RTOR**	9,1	A	10,3	B	9,6	A	6,5	A
	No RTOR	22,6	C	16,9	B	16,7	B	23,9	C
WBT, +30%	**RTOR**	11,1	B	14,0	B	9,4	A	6,8	A
	No RTOR	21,7	C	18,5	B	17,5	B	23,0	C
SBT, -30%	**RTOR**	7,6	A	12,8	B	9,4	A	6,2	A
	No RTOR	19,7	B	19,3	B	17,8	B	23,1	C
SBT, +30%	**RTOR**	10,7	B	13,5	B	9,2	A	10,8	B
	No RTOR	19,9	B	17,5	B	16,9	B	22,9	C
NBR, -30%	**RTOR**	8,9	A	13,2	B	8,4	A	6,9	A
	No RTOR	22,7	C	16,9	B	15,8	B	20,2	C
NBR, +30%	**RTOR**	8,5	A	14,4	B	12,1	B	6,9	A
	No RTOR	21,0	C	19,6	B	20,0	C	21,3	C
Storage, +50%	**RTOR**	8,5	A	13,2	B	9,9	A	7,2	A
	No RTOR	20,9	C	18,2	B	16,4	B	22,4	C
Storage, +100%	**RTOR**	9,0	A	11,6	B	10,4	B	6,3	A
	No RTOR	21,9	C	16,9	B	17,4	B	21,9	C
No pedestrians and bikes	**RTOR**	7,2	A	8,3	A	8,3	A	5,6	A
	No RTOR	18,1	B	13,3	B	14,2	B	19,4	B

Appendix F

Figure F.1 Number of accidents per year and number of accidents by accident type for Bell Road and Burns Drive.



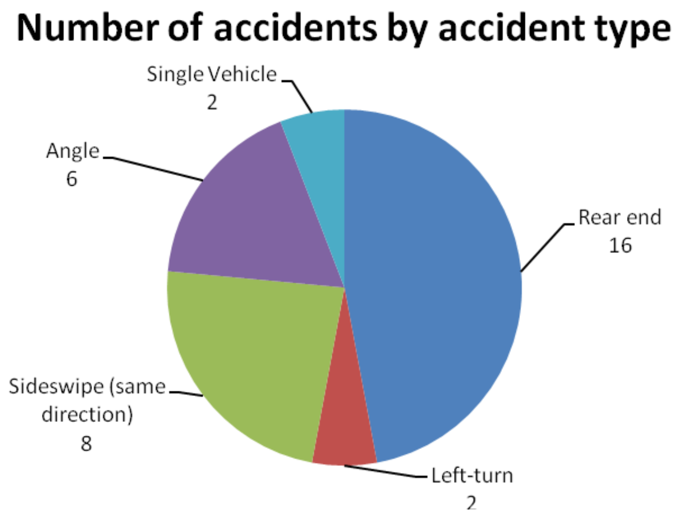
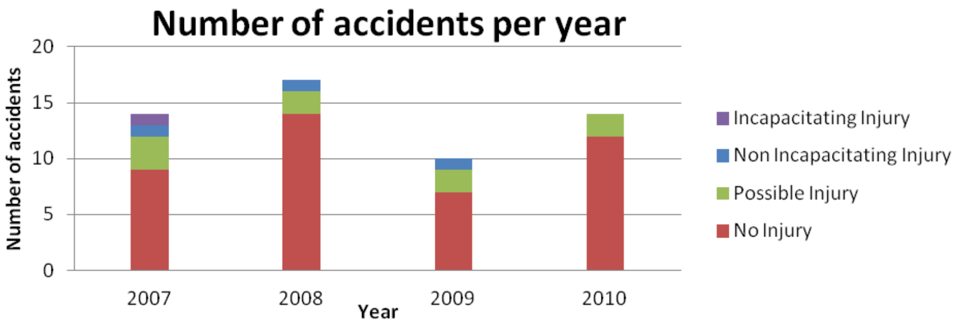


Figure F.2 Number of accidents per year and number of accidents by accident type for Bell Road and 98th Avenue.



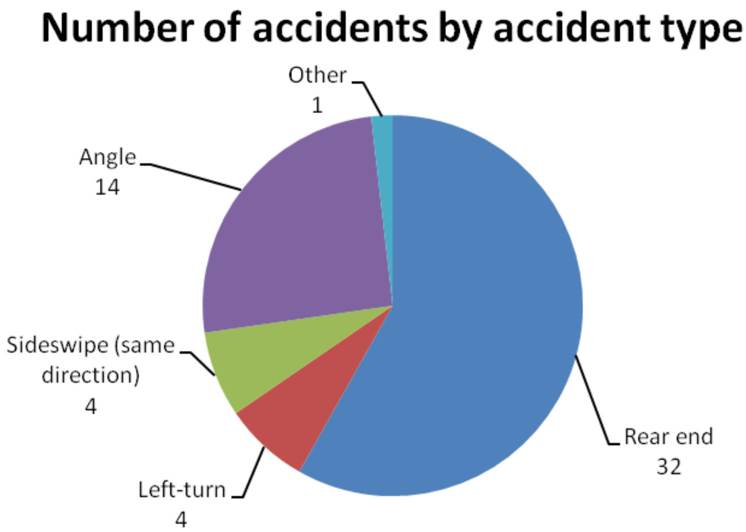
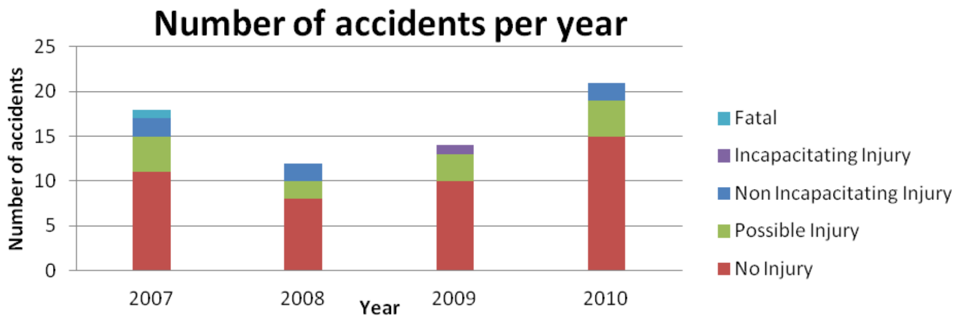


Figure F.3 Number of accidents per year and number of accidents by accident type for Bell Road and 99th Avenue.



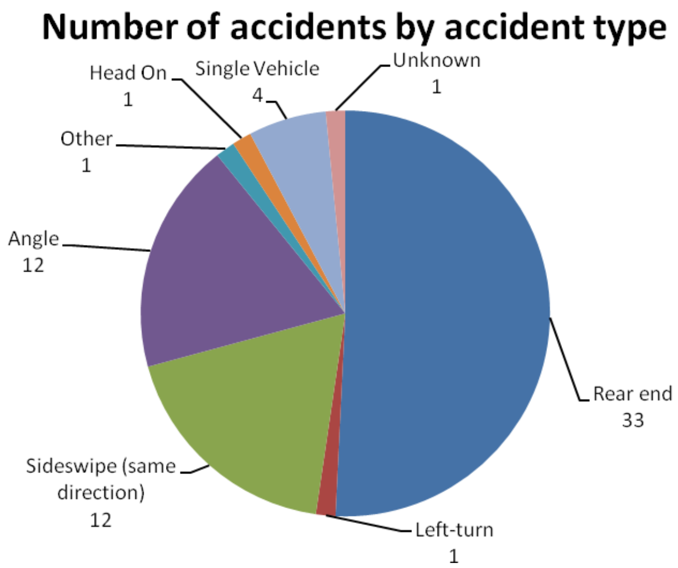
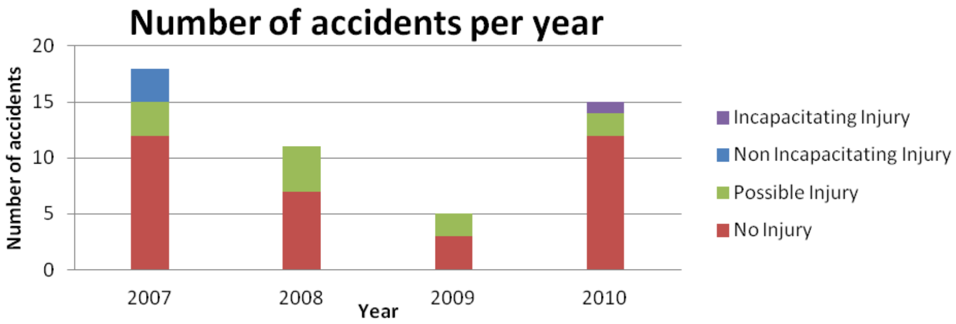


Figure F.4 Number of accidents per year and number of accidents by accident type for Bell Road and Boswell Boulevard.



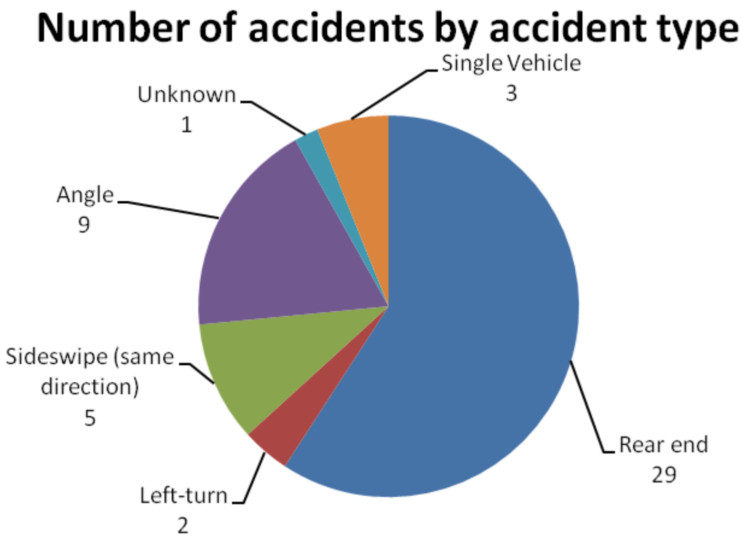
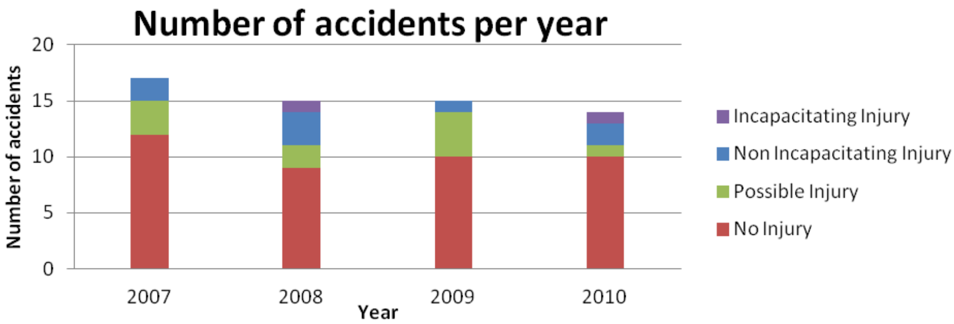


Figure F.5 Number of accidents per year and number of accidents by accident type for Bell Road and Del Webb Boulevard.



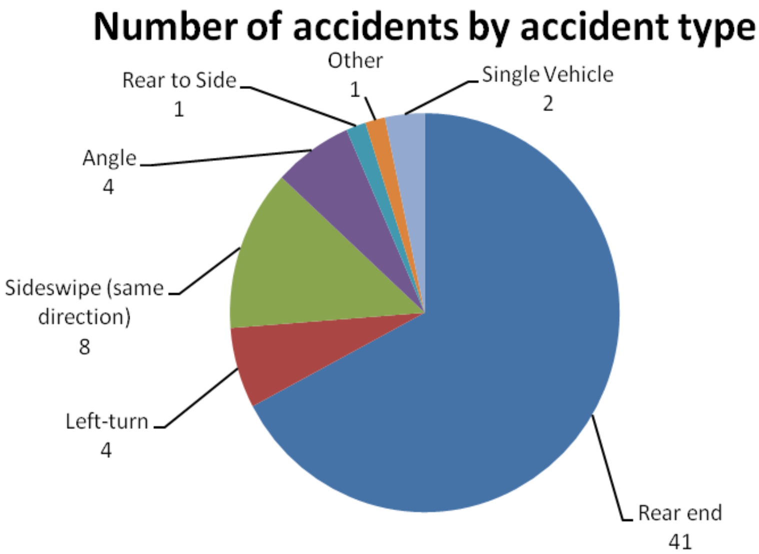
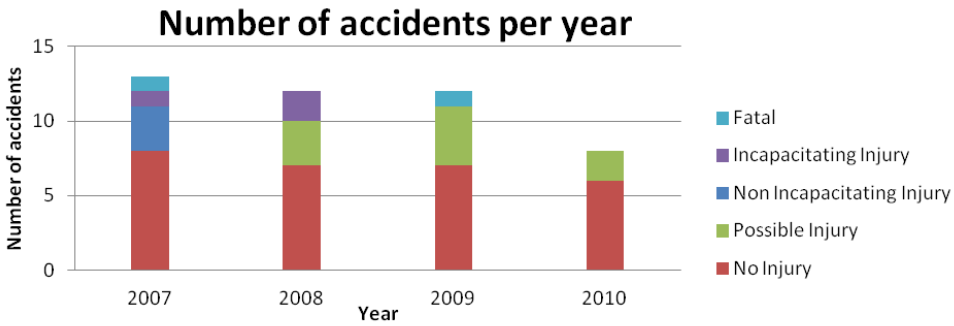


Figure F.6 Number of accidents per year and number of accidents by accident type for Olive Avenue and 107th Avenue.



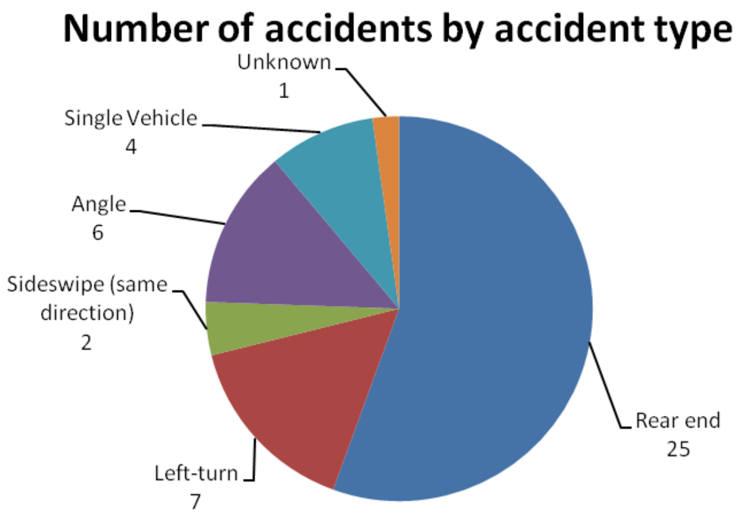
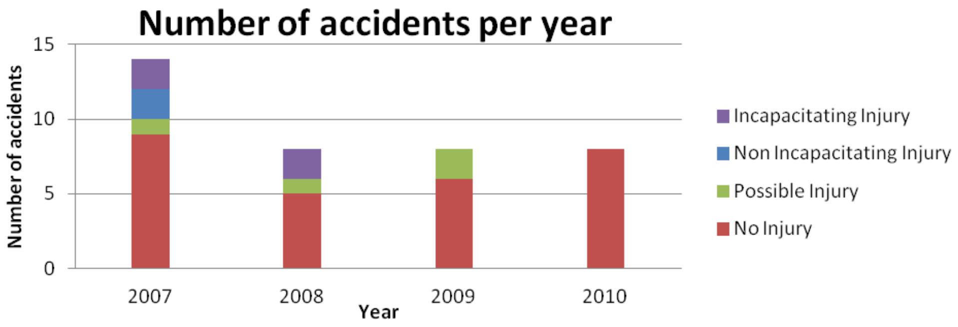


Figure F.7 Number of accidents per year and number of accidents by accident type for Olive Avenue and 111th Avenue.



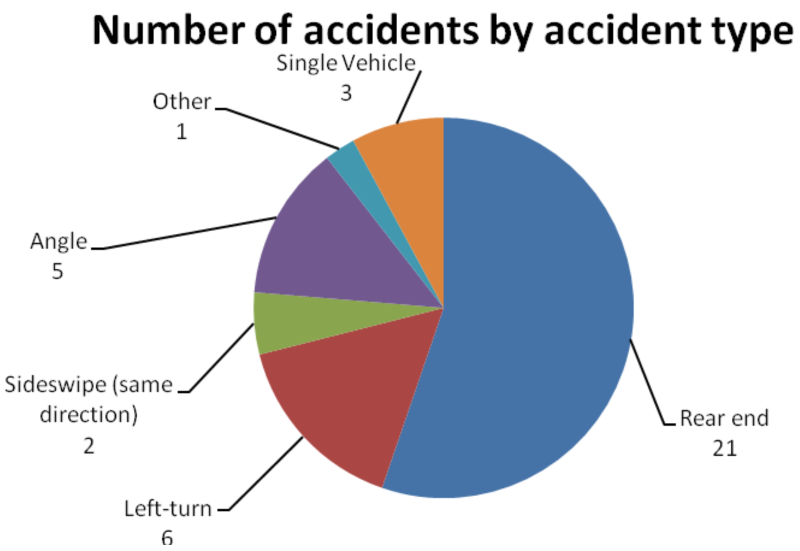
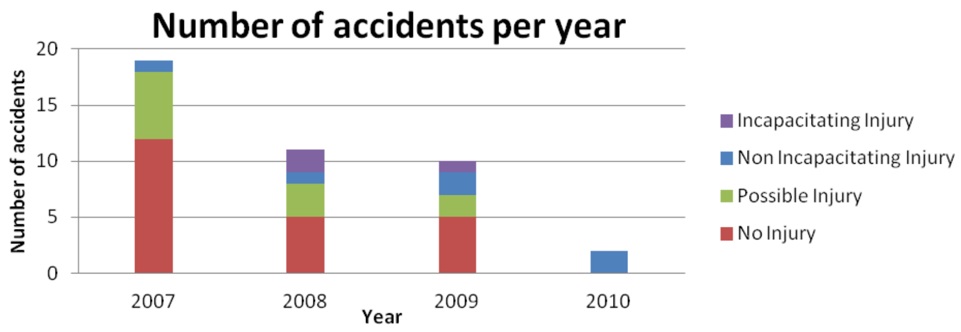


Figure F.8 Number of accidents per year and number of accidents by accident type for Olive Avenue and 103rd Avenue.



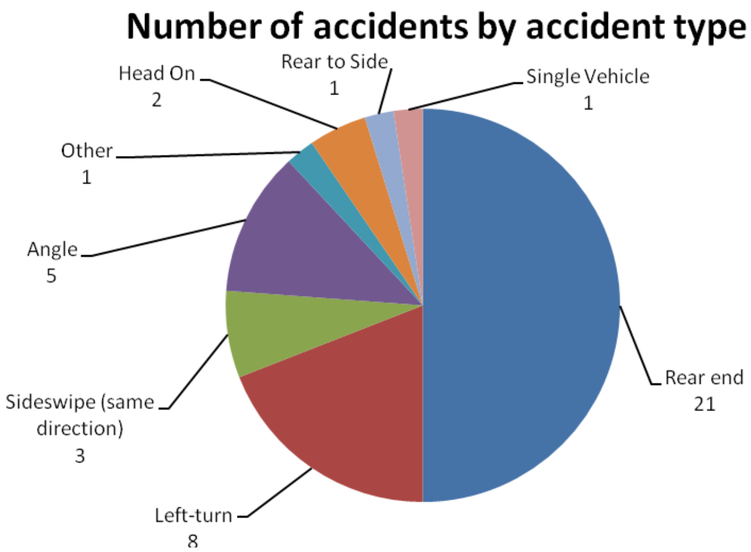
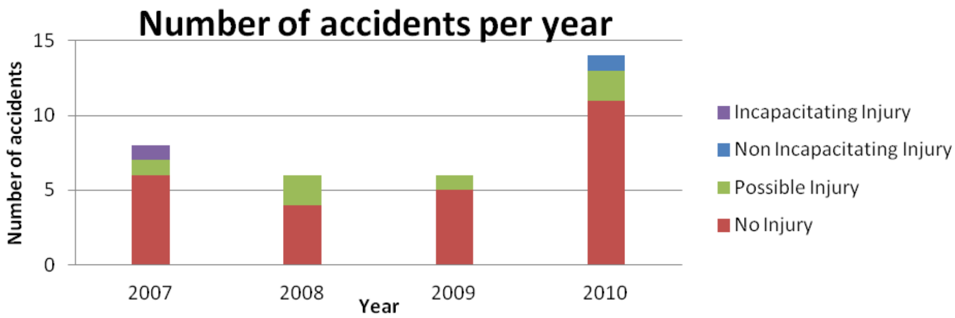


Figure F.9 Number of accidents per year and number of accidents by accident type for Thunderbird Road and 99th Avenue.



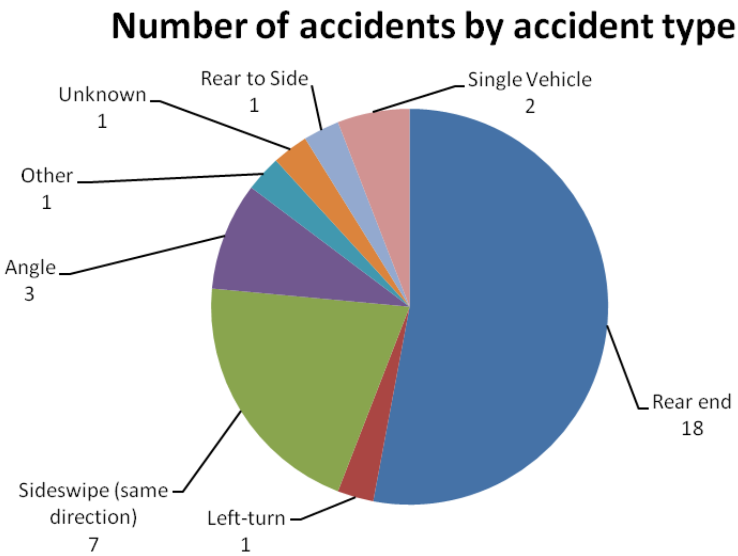
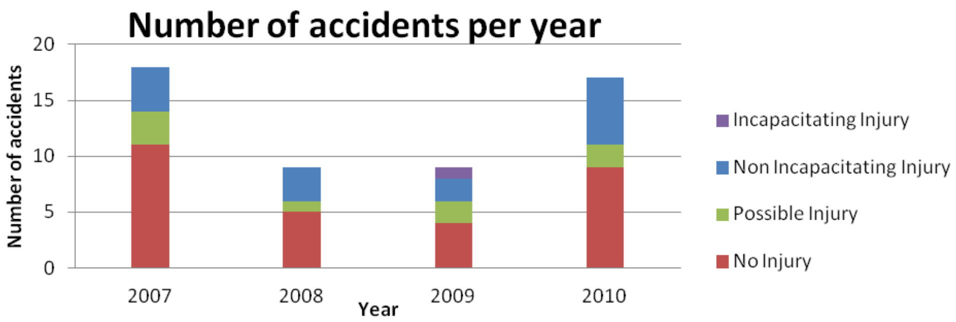


Figure F.10 Number of accidents per year and number of accidents by accident type for Indian School Road and 99th Avenue.



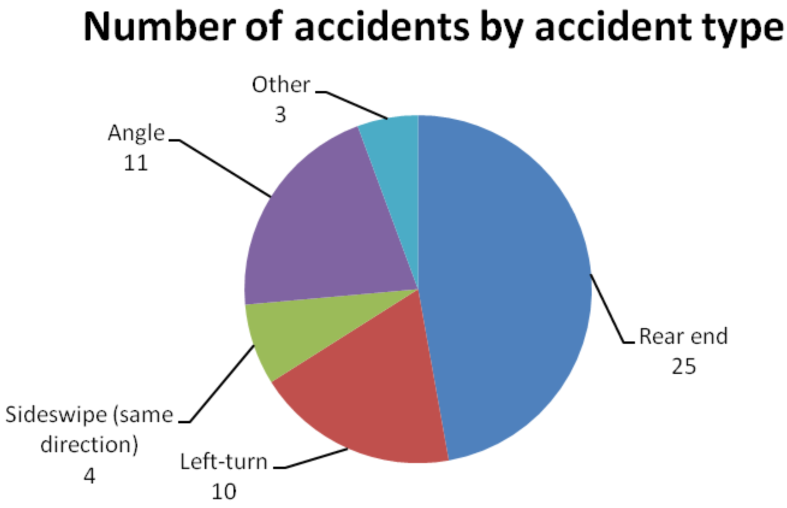


Figure F.11 Total number of accidents per year for all ten intersections in Phoenix.

Year	Bell Road and Burns Drive	Bell Road and 98th Avenue	Bell Road and 99th Avenue	Bell Road and Boswell Boulevard	Bell Road and Del Webb Boulevard	Olive Avenue and 107th Avenue	Olive Avenue and 111th Avenue	Olive Avenue and 103rd Avenue	Thunderbird Road and 99th Avenue	Indian School Road and 99th Avenue	Total
2007	8	14	18	18	17	13	14	19	8	18	**147**
2008	11	17	12	11	15	12	8	11	6	9	**112**
2009	10	10	14	5	15	12	8	10	6	9	**99**
2010	5	14	21	15	14	8	8	2	14	17	**118**
Total	**34**	**55**	**65**	**49**	**61**	**45**	**38**	**42**	**34**	**53**	**476**