# NEAR EAST UNIVERSITY

## GRADUATE SCHOOL OF APPLIED SCIENCES

# A COMPARISON OF TRAFFIC FLOW PERFORMANCE OF ROUNDABOUTS AND SIGNALIZED INTERSECTIONS USING MITSIMLAB

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**Mohammad Al_Momani: A COMPARISON OF TRAFFIC FLOW PERFORMANCE OF ROUNDABOUTS AND SIGNALIZED INTERSECTIONS USING MITSIMLAB**

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**Master of Science in Computer Engineering**

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# ABSTRACT

Traffic flow performance at road junctions becomes a major issue as the number of vehicles added to a traffic system grows especially without major additions or modifications to existing road network infrastructure. In this thesis, we investigate the operational performance of roundabouts and pre-timed signalized intersections using simulation. In our approach, we use hypothetical network scenarios including one, two, three, and four road junctions with either roundabouts or signalized intersections and compare the traffic flow performance of these networks under identical conditions. For each scenario, we vary the traffic volume, and, additionally, for each intersection scenario, we vary the green time interval. Then we compare the performance of a signalized intersection with the best green time interval to a compatible roundabout under different traffic volumes. To determine the best green time interval, we devised a signal optimization model. We implemented our approach using the MITSIMLab microscopic traffic simulator, and we analyzed the data generated by the simulator using public domain software and additional software we implemented. We compare the performance of individual vehicles one-to-one, and we also compare the averages for each traffic volume case for each network scenario using the Student's t-test using travel time as evaluation metric. The results show that the operational performance of roundabouts is statistically better than that of signalized intersections under all traffic volumes with 99% confidence in the case of one-to-one paired comparisons. Our results also show that the performance of roundabouts is statistically better than that of intersections with at least 95% confidence when average travel times are compared.

**Keywords:** microscopic traffic simulation, statistical comparison, Student's t-test, green interval time, optimization, roundabouts, signalized intersections, traffic signals, MITSIMLab.

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I am ever grateful to Allah, the Creator and the Guardian, to whom I owe my very existence.

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I thank the researchers at MIT Civil Engineering Department for their help in modifying the MITSIMLab source code for our purposes. I thank Mr. Taner Aksu for sharing his expertise in traffic engineering with us and providing us suggestions for our work.

Last but certainly not least, I extend my sincere appreciation and love to my parents, brother, and sisters for their great love and support. I am greatly indebted to my parents who have given me love, encouragement, and confidence. Special thanks to my uncle Kamal Momani for his worthy support and help.

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| | |
|---|---|
| ITS | Intelligent Transport System |
| LCS | Lane control signs |
| LUS | Lane use signs |
| MIT | Massachusetts Institute of Technology |
| MITSIMLab | Microscopic Traffic Simulation Laboratory |
| MITSIM | Microscopic Traffic Simulator |
| MOEs | Measures of Effectiveness |
| NDOT | Nevada Department of Transportation |
| NETSIM | NETwork SIMulation |
| OD | Origin-destination |
| TMS | Traffic Management Simulator |
| TS | Traffic signals |
| vd | Vehicle demand (#vehicles/hour) |
| VRC | Vehicle-to-roadside communications |

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Traffic congestion is a reality in many countries because of rapid increase in the number of vehicles, limited capacity of existing transportation infrastructure, and inconvenience of the traffic management systems that are currently in use. Therefore, the traffic flow performance of a road network is of great importance, since an underperforming system may lead to great economic loss and have a negative impact on the quality of life.

One common approach to handle traffic congestion is to build more infrastructure such as roads, bridges, overpasses and so on. However, this approach is difficult to sustain for many reasons such as high cost, lack of space, and environmental damage that may result from building new road structures. Another approach is to use an effective traffic management system that may comprise pre-timed traffic signals, roundabouts, adaptive traffic signals, signalized roundabouts, and stop signs that are much lower in cost compared to building new infrastructure from scratch.

With the development of computer technology, traffic simulation has been widely used in traffic research, especially in the evaluation of alternative traffic management systems. Traffic simulation involves the representation of traffic systems in the real world by establishing computer models that represent those traffic systems.

Mandavilli et al. studied the impact modern roundabouts in cutting down vehicular emission in six different sites in Kansas and Nevada using the SIDRA software package where roundabouts replaced stop signs at intersections. They found that roundabouts help cut down vehicular emissions (Mandavilli et al., 2008). Bared and Edara studied the impact of roundabouts placed between two signalized intersections using the SIDRA software package. They showed that, with the roundabout placed in the network, the traffic flow is better when vehicle volume is below full capacity of the network (Bared and Edara, 2005). Thorson et al. studied the impact of roundabout, stop signs, and traffic signals on an intersection in Nevada, USA. Their study showed that roundabouts have the lowest time delay compared to traffic signals and stop signs (Thorson et al., 2001).

In this thesis, we compare the traffic flow performance of roundabouts and signalized intersections using simulation. We created road network models that involve one, two, three, and four junctions, at which we placed either a roundabout or a signalized intersection. For each network, we varied the traffic volume between the same set of origin-destination pairs so that we could analyze the performance of that network with increasing traffic volume based on travel time. In the case of intersections, we also varied the traffic signaling timing in order to determine the "best" performing intersection setup to compare to the corresponding roundabout scenario under the same traffic volume.

To compare the performance of roundabout and intersection scenarios we studied, we used *travel time* as our main evaluation metric. We set up the simulator to generate the identical sequence of vehicles for corresponding roundabout and intersection scenarios, so that a one-to-one paired comparison of compatible roundabout and intersection experiments would be possible. In addition to this one-to-one comparison, we also compared the average travel times under different traffic volumes. Thus, this approach allowed us to compare roundabouts to intersections under identical and idealized conditions.

Our research is different from the work reported in the literature on three points. First, we use vehicle travel time as evaluation metric for our study, while most work reported in the literature use parameters such as traffic capacity, fuel consumption, and level of service. Second, we came across no research work that compared the performance of individual vehicles one-to-one using simulation. Third, we found no work that uses an open source simulator for studying the difference between roundabouts and signalized intersections.

Our results show that roundabouts perform statistically better than signalized intersections with "optimal" pre-timed signaling plans in all tested scenarios.

We implemented our work using a publicly available simulator, namely the MITSIMLab microscopic traffic simulator. Most other simulators that are currently available were either proprietary or inappropriate for our work due to their lack of features. Using an open source software package such as MITSIMLab allowed us to both study source code and modify it according to our needs.

## 1.2 Thesis Goal

The goal of this thesis is to study the operational performance of two different traffic management strategies using simulation, one involving roundabouts and the other involving signalized intersections. Our work investigates the impact of each strategy on traffic flow performance based on travel time in order to determine which of the two alternatives may lead to a more efficient traffic flow and under what conditions. With both the results and products of this study, we also wish to contribute to the practical study of road infrastructure and traffic management choices for both existing and future road networks using software that is freely available.

In addition, our goal is to use open source software in all simulation and analysis phases so that we could share our contributions with the research community such that our work can be reproduced, if needed.

## 1.3 Contributions

This thesis makes several contributions to the field of traffic research:

- A comparison of roundabouts and pre-timed signalized intersections on traffic flow performance using travel time as the main evaluation metric.
- A basic method for optimizing 4-phase traffic signal timing plans.
- A port of the MITSIMLab microscopic traffic simulator from old GNU/Linux systems to latest GNU/Linux systems in order to help invigorate research using open source traffic simulation software. At the least, discovery of bugs and limitations of existing software may help develop better software that is available to everyone for future studies. Another benefit is that work done at one institution may be reproduced at another institution.

## 1.4 Thesis Organization

The remaining chapters of this thesis are organized as follows:

- *Chapter 2* **(BACKGROUND)** describes the fundamentals of both roundabouts and traffic signals control strategies, traffic simulation models and their categories. It provides an overview of the MITSIMLab microscopic traffic simulator including its components, simulation framework, and the underlying algorithms it uses. This chapter also discusses research work closely related to our study.
- *Chapter 3* **(METHODOLOGY)** describes the approach proposed in this thesis in order to study the impact of roundabouts and signalized intersections on traffic flow performance.
- *Chapter 4* **(IMPLEMENTATION)** describes in detail our implementation of the ideas we describe in this thesis using the MITSIMLab simulator.
- *Chapter 5* **(RESULTS AND DISCUSSION)** presents and discusses the results of the experiments we carried out for the work reported in this thesis.
- *Chapter 6* **(CONCLUSIONS)** presents conclusions and future work.

# CHAPTER 2

# BACKGROUND

## 2.1 Overview

Traffic simulation is now widely used to study the impact of various traffic control strategies and infrastructure choices. In this thesis, we use the MITSIMLab microscopic simulator as our simulation platform in order to compare the performance of roundabouts and signalized intersections with varying traffic volume (YuanLi et al., 2004; Pursula, 1999).

## 2.2 Roundabouts

A roundabout is a type of road junction at which traffic enters a one-way stream around a central island. A roundabout may be of various types according to its geometrical design and speed limit imposed as well as other parameters for matching various traffic environments and needs (Wikipedia, 2009a).

Traffic flow control in roundabouts is handled by a set of rules that all vehicle-driver pairs have to comply with. Mainly these rules are as follows (McDonald, 2003; SNRA, 2004):

- Each vehicle must slow down when approaching a roundabout and yield to the vehicles already traveling in the roundabout, since vehicles in a roundabout have the right of way.
- Each vehicle must wait for a proper gap in the traffic stream before merging in with the traffic in the roundabout.
- No vehicles are allowed to stop in the roundabout since parking in roundabouts is not allowed.
- Each vehicle must continue through the roundabout until it reaches the desired outgoing link and never change lanes except when it reaches its desired outgoing link.
- Each vehicle must signal its desire to exit the roundabout.

## 2.3 Traffic Signals (TS)

Traffic signals (or traffic lights) are signaling devices that control traffic flow and conflicting movements in intersections to avoid accidents.

Traffic signals control the traffic flow using three standard colors, namely red, yellow, and green. Each color conveys a different meaning (Wikipedia, 2009b):

- Red interval indicates that vehicles must come to a stop and yield to other vehicles traveling through the same intersection.
- Yellow interval indicates caution.
- Green interval indicates that vehicles have the permission to use the intersection.

  A complete rotation through all of the traffic signal intervals is called the *traffic signal cycle* (Homburger et al., 2007) .

Timing plan of traffic signal intervals (red, yellow, green) cannot be arbitrary and should be optimized in order to achieve the maximum flow performance through signalized intersections. A study that aims to optimize traffic signaling periods usually takes into consideration many system variables such as traffic volume, speed limits, turning movements, vehicle types, and travel distances.

## 2.4 Traffic Simulation Models

There are various types of traffic simulation models available for use. Most are closed systems and only commercially distributed. Only a few are open systems and freely available on the Internet. Each type has its own scope and set of capabilities.

Traffic simulation models are classified into four categories, as macroscopic, microscopic, mesoscopic, or nanoscopic according to their scope and capabilities for modeling various traffic infrastructures, control systems, route guidance systems, and other aspects of a traffic system (Turley, 2007).

Macroscopic traffic simulation models are used to model large regional areas. They are based on the deterministic relationship of the flow, speed, and density. The simulation takes place on a section-by-section basis without tracking individual vehicle movements. However, macroscopic models have the ability to model networks with only basic roadway sections. Intersections and control and route guidance systems not explicitly modeled and cannot be represented in as much detail as in microscopic models (Alexiadis et al., 2004).

Microscopic traffic simulation models represent network elements in more detail. They explicitly model most of the traffic elements such as vehicle types, driver groups, control devices, intersections, route guidance systems, source and destination for each vehicle, and vehicles movement using various algorithms. They also model behaviors such as car following, lane changing, gap acceptance, and event responding.

A microscopic model keeps track of individual vehicles that enter a given network. Source and destination, acceleration, deceleration, speed, and many other parameters are assigned to each vehicle-driver pair. Motion of an individual vehicle is simulated in small step sizes, and each vehicle is tracked from the time it is generated and entered into the network until that vehicle exits the network so that vehicle-driver pair behavior and interaction with control devices and other vehicles can be studied (Olstam, 2005).

Mesoscopic traffic simulation models combine the features and capabilities of both macroscopic and microscopic models. The unit of the traffic flow is individual vehicles as in microscopic models and vehicles move as in the macroscopic approach, but their movement is governed by the average speed of the link. In addition, the dynamic speed/volume relationships are not considered (Alexiadis et al., 2004).

Nanoscopic traffic simulation models make it possible to study the drivers' steering behavior and other safety issues. Nanoscopic models become important as a new field in traffic simulation, since vehicles in microscopic traffic simulation models are programmed to avoid collisions and do not have the capability to simulate the steering behavior of drivers (Turley, 2007).

## 2.5 MITSIMLab

MITSIMLab is an open-source microscopic traffic simulator that was developed for evaluating the impact of alternative traffic management systems. MITSIMLab was developed at the Massachusetts Institute of Technology (MIT) for the Intelligent Transportation Systems (ITS) Program (MIT-ITS, 2009b). MITSIMLab was implemented in C++, and it runs on

GNU/Linux operating systems (MIT-ITS, 2009a).

### 2.5.1 Evaluation Framework of MITSIMLab

*Figure 2.1* illustrates the framework used for the evaluation of different traffic control strategies with MITSIMLab. In this framework, the traffic control strategies are first specified to achieve the identified objectives. Scenarios are defined to represent traffic demands, events, and the behavior of vehicle-driver pairs.

A candidate traffic control strategy is tested over a range of scenarios and the corresponding performance is computed. The performance measures obtained from the simulation indicate the intensity of the effect in each given scenario (Ben-Akiva et al., 2003).

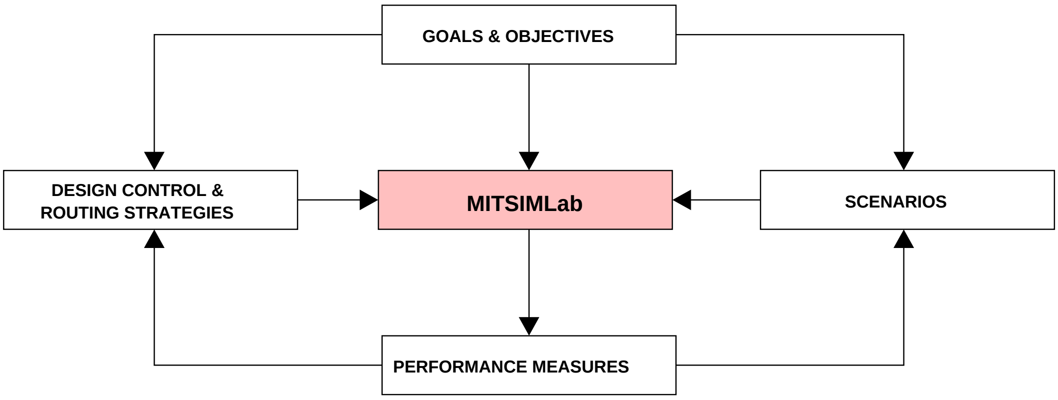


**Figure 2.1**: Evaluation framework of MITSIMLab: Objectives for a system are assigned first. Then the control strategies are designed to achieve those goals. Scenarios represent the traffic demand and events. Control and routing strategies are simulated and measures of effectiveness (MOEs) are produced as a result of simulation.

Measures of effectiveness (MOEs) are then used to design additional scenarios that further examine the robustness of the control strategy under study. Therefore the scenarios under which each design is tested are generated in an iterative manner by the user. Note that the design of new scenarios is an input into the framework, and the simulator makes no attempt to refine it. A refinement framework would require manual modification of the traffic control strategies if the MOEs are unacceptable (Ben-Akiva et al., 2003).

### 2.5.2 MITSIMLab Components

MITSIMLab comprises three modules:

1. Microscopic Traffic Simulator (MITSIM),

2. Traffic Management Simulator (TMS), and
3. Graphical User Interface (GUI).

Each module has its own components, functions, characteristics, and it interacts with other modules to simulate or help visualize various types of traffic system designs (Burghout, 1999). The MITSIM or the TMS module may be used alone or together with or without the GUI module.

### Microscopic Traffic Simulator (MITSIM)

The role of MITSIM is to represent traffic and network elements. The main elements of MITSIM are as follows:

**Network Components:** The network components represent three major elements:

- *Network Infrastructure*: Network infrastructure element represents roadways, roundabouts, overpasses, and tunnels using various types of nodes, links, segments, and lanes.

  Links are made up of segments, and segments are made up of lanes, which are the lowest level elements in the network infrastructure. Lanes are used connect segments and links. Each element is distinguished from other elements with a unique identifier.
- *Surveillance Sensors*: The surveillance sensors are used to extract data about traffic flow in the network, and this information is used by TMS to accomplish tasks such as guiding vehicles to avoid congestion and implementation of adaptive traffic signals. Various types of sensors are available to extract traffic data such as speed, traffic count, and specific information on individual vehicles (MIT-ITS, 2001).
- *Control Devices*: The role of control devices is to control traffic flow, help avoid accidents, and improve the quality of the overall traffic system. MITSIMLab supports a number of different types of control devices such as traffic signals for intersection controls, ramp metering for ramp controls, and lane use signs (LUS) for controlling main lines (MIT-ITS, 2001).

**Travel Demand and Route Choice:** The traffic demand represents the traffic volume between each pair of origin-destination nodes. The traffic volume for an entire network is organized in time-dependent origin-destination (OD) tables. Each OD table specifies the time duration when it is active in a given simulation.

MITSIMLab also provides a probabilistic route choice model, which selects alternative routes to lead guided vehicles to their destinations over various routes (Burghout, 1999).

**Driving Behavior:** Movement of individual vehicles in a network is controlled by MITSIM. For each vehicle-driver pair, MITSIM assigns behavior parameters such as desired speed, acceleration, and deceleration. MITSIM uses four models to safely lead vehicles to their destinations without collisions. These models are car following, lane changing, gap acceptance, and event responding models (Burghout, 1999).

### Traffic Management Simulator (TMS)

The TMS is responsible for controlling and managing the operation of the route guidance and control systems that are modeled in MITSIM. TMS generates the control signals and route guidance system information based on real-time data received from the surveillance system in MITSIM. For example, the TMS module generates adaptive traffic lights signals according to data received from installed sensors in specific locations (Ben-Akiva et al., 2003).

Besides providing a vehicle route guidance system, the TMS module can simulate a number of traffic control devices:

- Intersection controls such as traffic signals, yield signs, and stop signs.
- Ramp controls such as ramp metering signs and speed limit signs.
- Mainline controls including portal signals and lane control signs (LCS).

Signals and signs are controlled by four types of controllers, namely static, pre-timed, adaptive, and metering controllers (MIT-ITS, 2001).

### Graphical User Interface (GUI)

MITSIMLab provides a GUI that may be used for debugging simulation setup and visualizing traffic (Ben-Akiva et al., 2000). *Figure 2.2* is a snapshot of an intersection experiment running in the MITSIMLab GUI showing the state of the traffic lights at an intersection and vehicles moving. *Figure 2.3* is a snapshot of a roundabout experiment run in the MITSIMLab GUI showing vehicles moving in and around a roundabout.

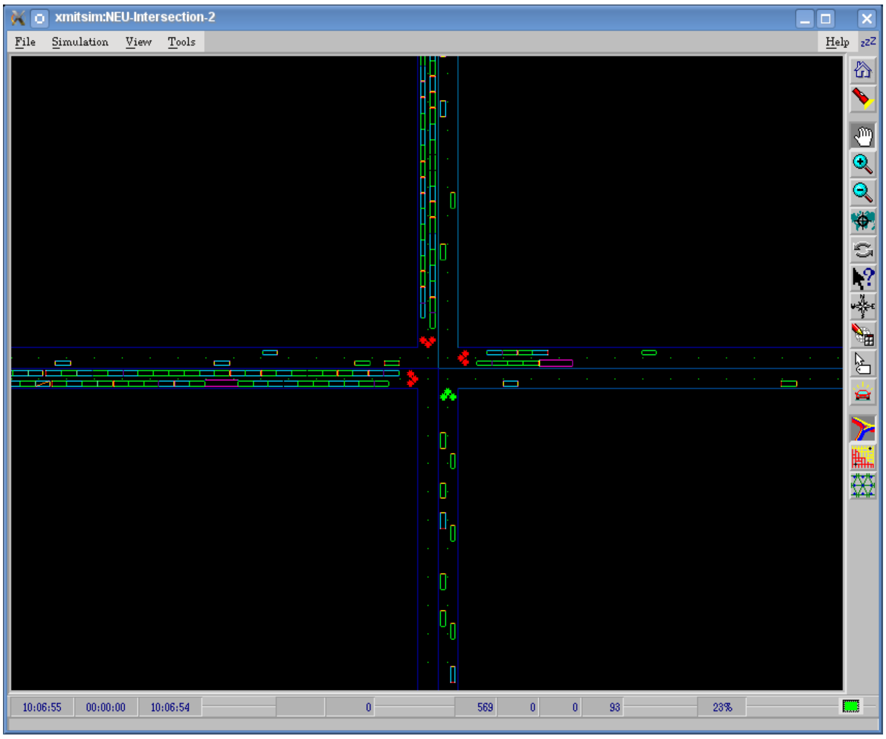


**Figure 2.2**: A snapshot of an intersection experiment running in the MITSIMLab GUI.

MITSIMLab can also be controlled from the command-line.

## 2.6 Simulation Framework

*Figure 2.4* depicts the simulation framework and the interaction between various MITSIMLab modules.

The TMS module generates the behaviors of traffic control devices and provides route guidance to guided vehicles that are modeled in MITSIM. MITSIM simulates driver behavior and the interactions of drivers with other drivers. TMS simulates traffic control devices such as traffic signals and stop signs. MITSIM sends feedback about traffic flow and density to TMS in order to restructure the behavior of both control devices and the route guidance system. In short, MITSIMLab functionality is based on the communication between both MITSIM and TMS modules (Burghout, 1999).

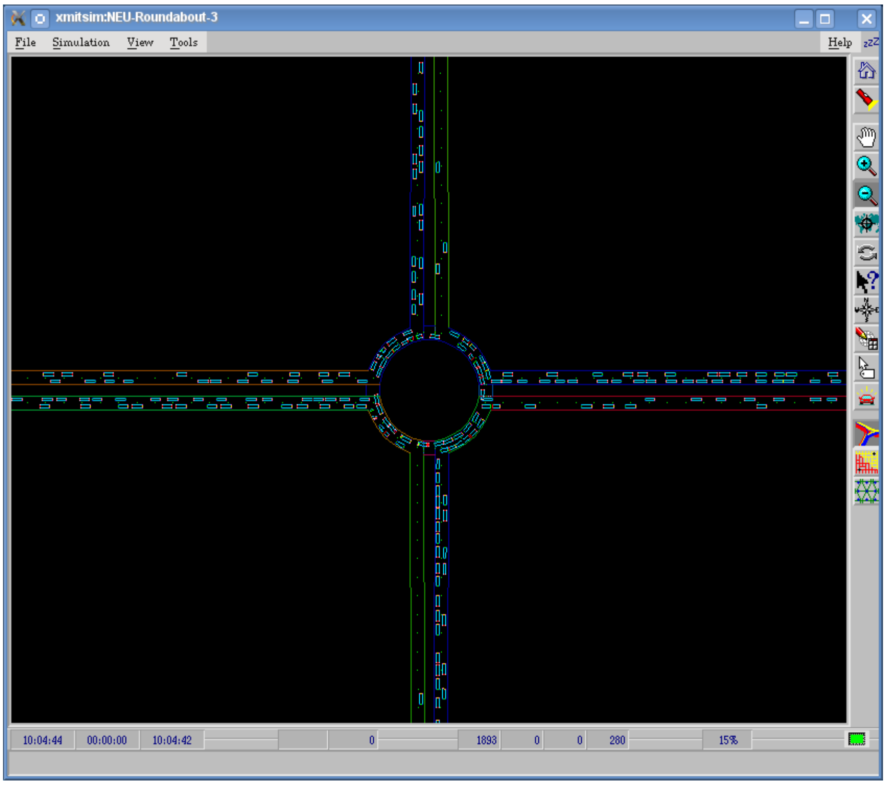


**Figure 2.3**: A snapshot of a roundabout experiment running in the MITSIMLab GUI.

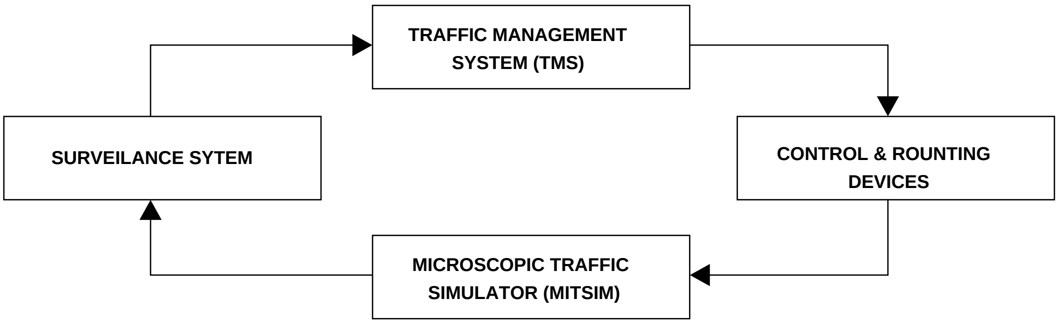


**Figure 2.4**: MITSIMLab simulation framework: The TMS module generates control and route guidance system behaviors, and the MITSIM module controls the behavior of vehicle-driver pairs and sends traffic information through surveillance sensors and devices to TMS to regenerate new behaviors.

## 2.7 MITSIMLab Algorithms

Vehicle movement and interactions either to control devices or other vehicles in MITSIMLab are implemented through various algorithms that safely lead vehicles to their designations. These major algorithms MITSIMLab implements involve car following, lane changing, gap acceptance, and event responding.

- Car following algorithm: This algorithm calculates and determines the spacing between individual vehicles. In other words, it determines how vehicles interact among themselves to avoid accidents (Burghout, 1999; Steven L. Jones et al., 2004).
- Lane changing algorithm: This algorithm controls how vehicles merge into a stream and change lanes within a traffic stream. The algorithm works based on the differences in speed, acceleration, and distance within adjacent lanes. It allows lane changes if an acceptable gap exists in the desired lane for each vehicle that wishes to switch to a given lane. It also computes the differences in both speed and acceleration in order for the lane change to succeed (Steven L. Jones et al., 2004).
- Gap acceptance algorithm: Gap acceptance algorithm controls vehicle movements across conflicting traffic streams such as that in U-turns, intersections, and on entrance to roundabouts. Vehicles that wish to move through other conflicting streams need to yield to other vehicles that are already in the destination stream by waiting until there is a proper gap in order to proceed without collision.
- Event responding: This algorithm implements the interactions of drivers with control devices such as traffic signals and stop signs. In addition, yielding to other vehicles, switching into the same lane, and anticipation of connection to downstream link are controlled as event responses (Burghout, 1999).

## 2.8 Related Work

In this section, we will discuss research studies closely related to our work.

- **Comparison of roundabouts and traffic signals using NETSIM**: This study evaluates the performance of different traffic management designs of a four-leg single intersection with a single-lane approach using the microscopic computer simulator called NETSIM (NETwork SIMulation).

The work was conducted for the Nevada Department of Transportation (NDOT) to study the impact of roundabouts, traffic signals, and stop signs on a single intersection in Carson City, Nevada, USA.

The evaluation method is based on the average time delay and fuel consumption. Intersections were modeled using either four-way stops, roundabouts, or signalized intersections, and each model was simulated for 30 minutes.

This study showed that the roundabout had the lowest average time delay and fuel consumption compared to the four-way stop and signal controlled intersection models (Thorson et al., 2001).

- **Evaluation of a roundabout between two signalized intersections using VISSIM**: This research evaluated three intersections within a three one-quarter mile corridor with two-lane approach using the VISSIM microscopic simulator.

  This study considered two scenarios. The first scenario had coordinated signalized intersections, and the second had two signalized intersections with a roundabout in the middle.

  This study found that the roundabout had less delay when the system operated below its capacity while the signalized scenario resulted in slightly less overall delay when the system approached its full capacity (Isebrands, 2009).

- **Evaluation of roundabouts and traffic signals using PARAMICS**: This study used the PARAMICS micro-simulation software to evaluate the operational performance of roundabouts and traffic signals on a highway off-ramp intersection in Ottowa, Canada.

  Three different diameters, namely 20m, 30m and 40m, were modeled and compared with signalized intersections using various vehicle types with appropriate weight, dimension, and performance parameters for each.

  This study concluded that roundabouts improve the operational performance at intersections and reduce delay in all roundabout configurations considered. In addition, the effect of roundabout size may vary depending on the volume of conflicting movements (Oketch et al., 2004).

## 2.9 Summary

This chapter discusses traffic signals, roundabouts, traffic simulation models, and simulation types. It describes the components, evaluation framework, simulation framework, and the algorithms of the MITSIMLab microscopic traffic simulator. In addition, it describes work closely related to the study reported in this thesis.

# CHAPTER 3

# METHODOLOGY

## 3.1 Overview

The objective of this thesis is to compare the impact of roundabouts and signalized intersections in simulation using vehicle travel time as evaluation metric. Other measures of effectiveness (MOEs) such as density, travel-time variance, speed, delay, queue size, and number of stops or a combination of these factors may also be used (Dowling, 2007).

We use the MITSIMLab traffic simulator for our work. MITSIMLab is a capable simulator that provides microscopic traffic flow simulation and traffic management, and it supports the simulation of signalized intersections.

In our study, traffic networks under evaluation are restricted hypothetical networks with straight links. In addition, studying hypothetical networks where all vehicles and drivers behave perfectly –that is, traffic hampering events such as accidents do not take place– provides a basis for comparison to traffic behavior in real settings. Since our study aims to study traffic flow performance, a study involving the impact of traffic hampering events such as accidents on traffic flow may be a consideration for a future study.

To compare the traffic flow performance of roundabouts and intersections, our approach considers four sets of networks. We compare the performance of a network with only a single roundabout and that with a single signalized intersection, a network with two roundabouts and that with two signalized intersections, a network with three roundabouts and that with three signalized intersections, and finally a network with four roundabouts and that with four signalized intersections. We perform these comparisons using statistical methods.

For each pair of compatible roundabout and intersection networks, all configuration parameters such as link length, vehicle demand, source and destination node pairs, driver types, vehicle types, vehicles departure times, and so on are kept identical. The only difference is the traffic control strategy used at each junction.

Roundabouts are self-controlled but signalized intersections are controlled using traffic signals based on the green time interval. Unlike signalized intersections, the traffic flow in a roundabout can be considered *optimized* since roundabouts do not have control devices. Therefore, to best compare a roundabout with an intersection, the green signal interval of each intersection must be optimized according to the evaluation metric, in this case, vehicle travel time.

## 3.2 Approach

The underlying approach in this thesis involves the simulation of hypothetical roundabout networks and intersection networks with varying complexity and comparison of performance using statistical methods. We use travel time as our main evaluation metric. Using travel time as basis, we compare the traffic flow performance of compatible intersection and roundabout networks at two levels. At the low level, we compare the travel time of a vehicle in an intersection experiment to the travel time of the identical vehicle in a compatible roundabout experiment. At the high level, we compare the average travel time achieved in an intersection experiment with the average travel time achieved in the compatible roundabout experiment.

In order to compare the travel time of a particular vehicle in one roundabout experiment to the same exact vehicle in a compatible intersection experiment, we ensure that the simulator generates an identical sequence of *(vehicle, origin node, destination node, departure time)* tuples. For example, if the simulator introduces vehicle 549 at time 10:15:00 at source node 30 and that vehicle is to travel to destination node 40 in a roundabout experiment, then, in the corresponding intersection experiment, the simulator must introduce vehicle 549 at time 10:15:00 at node 30 to travel to node 40 as well. That is, as long as all traffic generated for a given pair of roundabout and intersection experiments and for a given level of traffic volume is identical, a vehicle-to-vehicle comparison is possible.

Similarly, to get a wider perspective on the overall difference in behavior between a pair of roundabout and intersection experiments, we compare average travel times at each level of traffic volume.

In our approach, for both vehicle-to-vehicle and average-to-average comparisons, we only use vehicles that complete their trips in both corresponding experiments so that a one-to-one comparison is possible. For example, if vehicle 549 completed its trip in both a given roundabout experiment and the corresponding intersection experiment, we take into account the trip time of vehicle 549. Otherwise, we discard its trip time. As it turns out, the smallest set of vehicle-to-vehicle comparisons we conducted still had over 250 trip times, and this quantity provides a sample set that is well sufficient for conducting statistical comparisons.

Moreover, since all completed trips are available to us, we can also compare the total number of trips between a roundabout experiment and an intersection experiment that are governed by an identical set of input parameters. Even if this comparison is not based on a statistical measure of difference, we can still obtain additional information about overall performance, given that, in statistical analysis, we discard trip times of vehicles that are not in the intersection set.

Given the output data produced by the simulator, we considered the Student's t-test as a strong method for comparing the performance of roundabouts and intersections. Hence, results can be reported with statistical significance, when such significance applies. Since our approach uses only the data for identical vehicles in two compatible tests, we perform paired two-tailed t-tests.

### 3.2.1 Networks

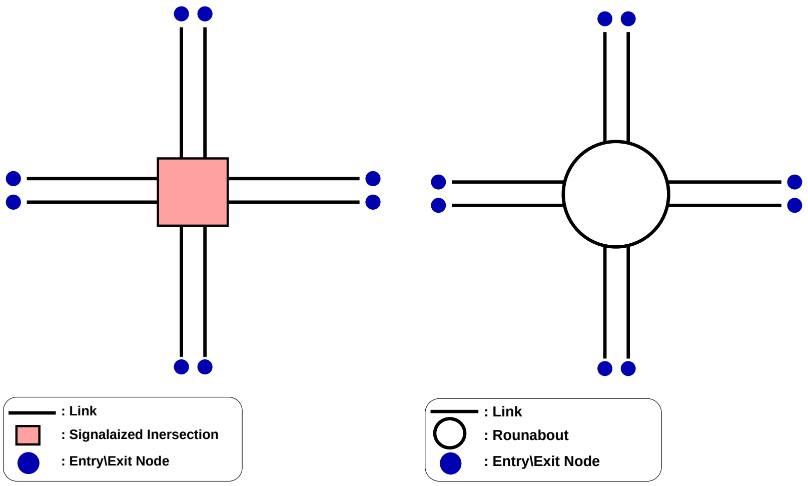
We use four major scenarios to compare the performance of roundabouts and signalized intersections. In each scenario, we compare a pair of compatible roundabout and intersection networks. That is, we compare a single roundabout network to a single intersection network and so on. Using a set of increasingly complex networks makes it possible to study how traffic flow performance would vary with each type of network as traffic volume increases.

Each compatible network is governed by an identical set of parameters such as link length, speed limits, number of lanes per link, and list of source-destination nodes. In other words, except for the control strategy and the network infrastructure at junctions, remaining configurations are pairwise identical for each given corresponding of roundabout and intersection experiment.

The four major scenarios we considered in this thesis are as follows:

1. A single roundabout versus a single signalized intersection: *Figure 3.1* illustrates the

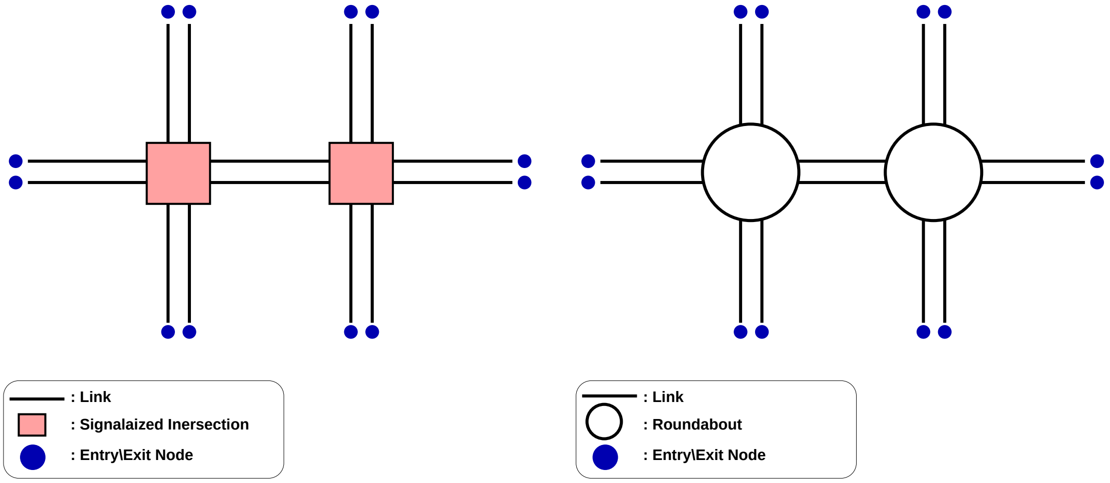
networks for this comparison scenario.



(a) A single signalized intersection (b) A single roundabout

**Figure 3.1**: A single roundabout and a single signalized intersection

2. Two roundabouts versus two signalized intersections: *Figure 3.2* shows the networks for this comparison scenario.

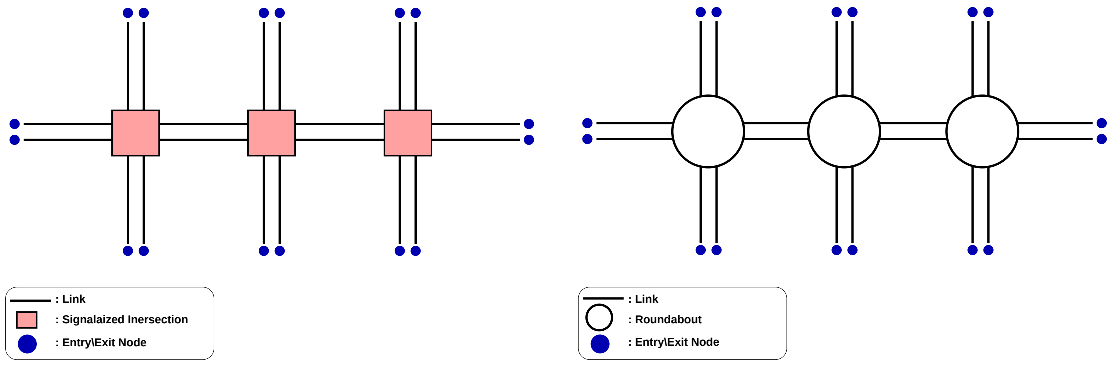


(a) Two signalized intersections (b) Two roundabouts

**Figure 3.2**: Two roundabouts and two signalized intersections

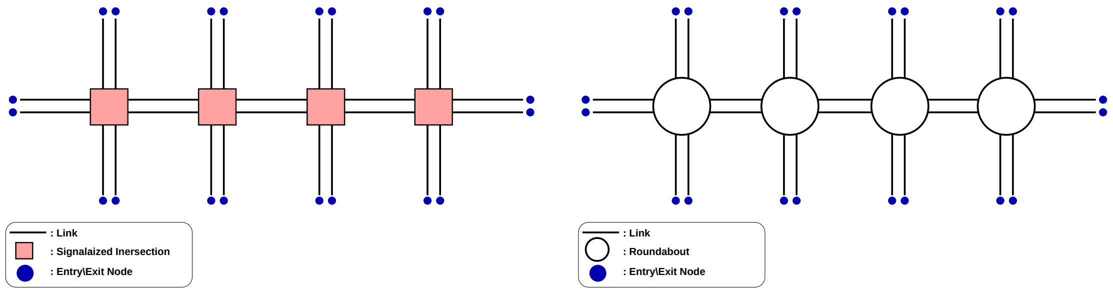
3. Three roundabouts versus three signalized intersections: Networks for this comparison scenario are illustrated in *Figure 3.3*.

4. Four roundabouts versus four signalized intersections: Networks for this comparison scenario are illustrated in *Figure 3.4*.



(a) Three signalized intersections (b) Three roundabouts

**Figure 3.3**: Three roundabouts and three signalized intersections



(a) Four signalized intersections (b) Four roundabouts

**Figure 3.4**: Four roundabouts and four signalized intersections

### 3.2.2 Evaluation Method

In order to be pairwise comparable, a pair of compatible intersection and roundabout networks must be simulated under identical conditions from all aspects except for the traffic management strategies used at junctions –i.e., a junction is either implemented with a signalized intersection or a roundabout. A number of issues must be dealt with in this regard:

- **Vehicle demand**: Each compatible pair of roundabout and intersection networks must first share the identical origin-destination (OD) table, in which the vehicle demand value for each OD pair is identical for both networks.

  In addition, we need to ensure that the simulator generates identical sequences of vehicles with identical IDs, departure times, types, and driver groups for each given OD pair in the OD table that is shared between a roundabout experiment and an intersection experiment.

  Since simulators employ random number generators to decide on these factors for each given run, using the same seed for the random number generator ensures that the sequence of vehicles in two compatible experiments will be identical. [1]

- **Optimized traffic signaling**: Traffic flow in roundabouts is essentially self-optimized by design, but the traffic flow through signalized intersections is not. Therefore, to have a fair comparison between a roundabout and a signalized intersection, green signal interval times for the intersection need to be optimized.

  For this purpose, we propose a basic method for optimizing green time intervals for all intersection networks considered in our study. The main idea behind this optimization approach is to assign factors for each traffic signal in a given network according to the expected volume of vehicles that will be moving through each intersection. Hence, in our approach, our method aims to optimize the green time interval with respect to the traffic volume.

- **Behavior under different traffic volumes**: We compare each pair of compatible roundabout and intersection networks across a series of vehicle demand levels so that we can study the behavior of traffic as traffic volume increases.

- **Determination of the best green time interval**: For signalized intersections, a series of green time intervals need to be simulated so that the best green time can be determined. Among the simulated values, the best best green time is then the green time that leads to the minimum average vehicle travel time. Each green time interval in our approach is a base time value that is multiplied by the traffic signal factor that is assigned to each interval of each of the four traffic signals at an intersection. The value resulting from this multiplication is the actual green time for each phase of a traffic signal.

- **Statistical analysis**: In order to compare each pair of compatible roundabout and intersection networks, we perform statistical analysis using the Student's t-test so that we can determine whether the trip times or average trip times produced by the compared networks are significantly different.

---

[1] *Appendix B* lists the C source code that we used to reproduce the identical sequence of vehicles in MITSIMLab.

We apply the algorithm in *Figure 3.5* for simulating and analyzing the networks we study:

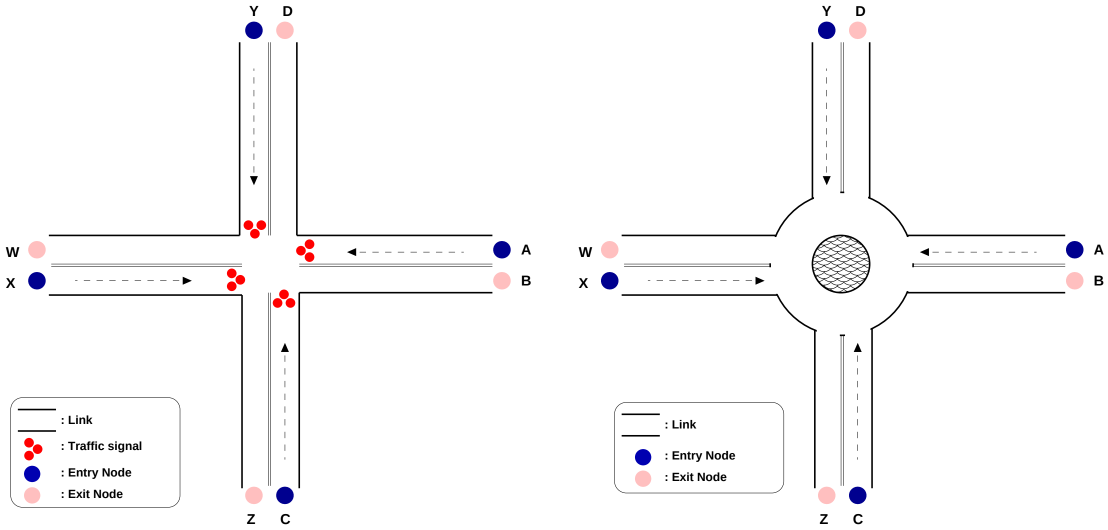
```
DECLARE $L_R$: list of individual roundabout travel times
DECLARE $L_I$: list of individual signalized intersection travel times

DECLARE $A_R$: list of average roundabout travel times
DECLARE $A_I$: list of average signalized intersection travel times

FOR network with j road junctions IN [1 .. 4] DO
   DECLARE $Rnetwork_j$: Network with j roundabouts
   DECLARE $Inetwork_j$: Network with j signalized intersections
   FOR vehicle demand v in [$v_0$ .. $v_n$] DO
      DECLARE $Raverage_v$: Average travel time when traffic volume is v
      $L_R$ $\leftarrow$ Simulate $Rnetwork_j$ at v
      $Raverage_v$ $\leftarrow$ Compute the average of $L_R$
      Add $Raverage_v$ to $A_R$
      DECLARE G: list of average signalized intersection travel times
      FOR green time interval T in [$t_0$ .. $t_z$] DO
         DECLARE $Iaverage_{v,T}$: Average travel time when traffic
                                   volume is v and green time interval is T
         $L_I$ $\leftarrow$ Simulate $Inetwork_j$ at v and T
         $Iaverage_{v,T}$ $\leftarrow$ Compute the average of $L_I$
         Add $Iaverage_{v,T}$ to G
      END FOR
      DECLARE $Iaverage_{v,T_{optimum}}$: Average travel time with optimum
                                   green interval time $T_{optimum}$
      $Iaverage_{v,T_{optimum}}$ $\leftarrow$ Pick the best average from G
      Add $Iaverage_{v,T_{optimum}}$ to $A_I$
      Do statistical comparison between $Raverage_v$ and $Iaverage_{v,T_{optimum}}$
   END FOR
   Do statistical comparison between $L_R$ and $L_I$
END FOR
```

**Figure 3.5**: The algorithm used to generate simulation experiments and analyze results.

## 3.3 Vehicle Demand

Vehicle demand represents the total number of vehicles per hour that will enter the simulation network from a given source node and travel through various links to designated destination nodes. For each pair of compatible networks, vehicle demand for all origin-destination node pairs is identical and equally distributed over all destination nodes. For example, in a comparison of both single roundabout and single signalized intersection that *Figure 3.6* depicts, vehicle demand for all source nodes is identical. That is, vehicle demand values at nodes C, A, Y, and X are identical. In addition, vehicles are equally distributed over all destination nodes such that each destination node receives the same number of vehicles. So, in *Figure 3.6*, the number of vehicles that will be received through destination nodes Z, B, D, and W will be identical.

We do not consider the U-turn movement, and this means that no vehicles will be traveling from, say, node C to node Z. We placed this restriction on the traffic we simulated due to a bug we discovered in MITSIMLab. At a traffic signal, we observed that in MITSIMLab vehicles wishing to make a U-turn through a red light were still able to proceed with their movement, as long as there were no vehicles waiting for the green light to move to another link, hence blocking the faulty U-turn movement.



(a) Vehicles demand of a single signalized intersection

(b) Vehicles demand of a single roundabout

**Figure 3.6**: Vehicle demand for a signalized intersection and a roundabout: Both networks are identical except for the control strategy of the junction (roundabout and signalized traffic signals). Vehicle demand is identical for all source nodes C, A, Y, and X, and vehicles are equally distributed over all destination nodes Z, B, D, and W. In addition, U-turns are not allowed.

## 3.4 Traffic Signal Phasing

A traffic signal phase is the part of the cycle given to an individual movement, or combination of non-conflicting movements during one or more intervals (MN/DOT, 2006). Traffic signal phasing reduces conflicts between traffic movements at signalized intersections. A phase may involve one or more vehicular movements.

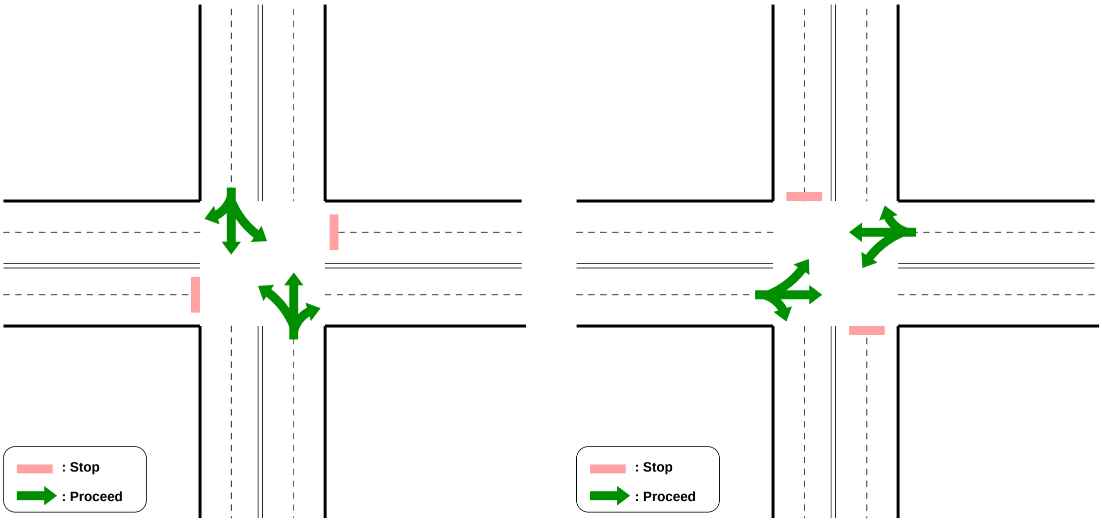
Traffic signal phase design involves the following:

- Determination the number of phases that we need to serve all incoming links at an intersection.
- Determination of the sequence of movements and stops.

Traffic signal phasing must be done according to the traffic conditions at corresponding intersections. Because of the equal distribution of vehicle density across our traffic networks and the limitations in MITSIMLab, we chose to use split 4-phase traffic signaling. This section describes the reasons behind this decision, as opposed to using 2-phase traffic signaling or typical 4-phase traffic signaling.

### 3.4.1 2-Phase Traffic Signaling

*Figure 3.7* illustrates 2-phase traffic signaling. 2-phase traffic signaling is usually applied if through traffic is significant compared to turning movements. 2-phase traffic signaling introduces conflicts, and *Figure 3.8* illustrates this behavior. Vehicles wishing to make left turns have to yield to vehicles in through traffic and wait for an acceptable gap to proceed (Mathew and Rao, 2007).



(a) Phase-1 (b) Phase-2

**Figure 3.7**: 2-Phase traffic signaling

Since we have a significant number of turn movements according to our traffic network setup, 2-phase traffic signaling is unsuitable to use, since such signaling would cause a high number of crossing conflicts between through traffic and turning traffic. *Figure 3.8* illustrates this type of conflict in 2-phase traffic signaling (Mathew and Rao, 2007).

If the number of vehicles wishing to make left turns is low compared to the number of vehicles wishing to go straight, then 2-phase signaling may be used, since the low number of vehicles wishing to turn left will likely find enough number of gaps in the through traffic in order to proceed. However, when the number of vehicles wishing to make left turns is high compared to the number of vehicles wishing to go straight, then vehicles wishing to turn will likely have to wait a long time before finding a gap in through traffic in order to proceed, hence defeating the purpose of 2-phase signaling.

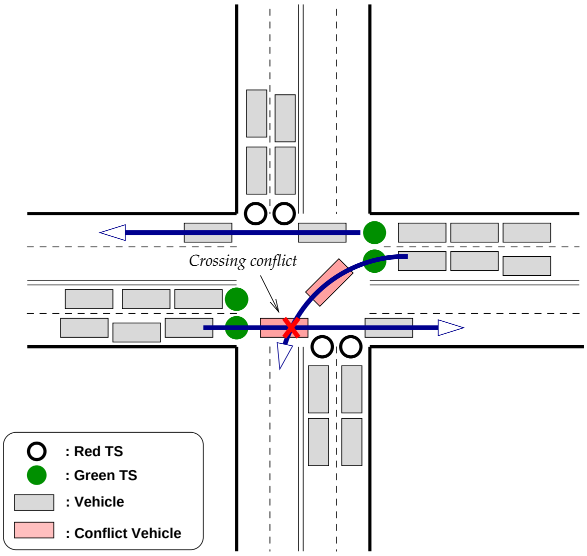
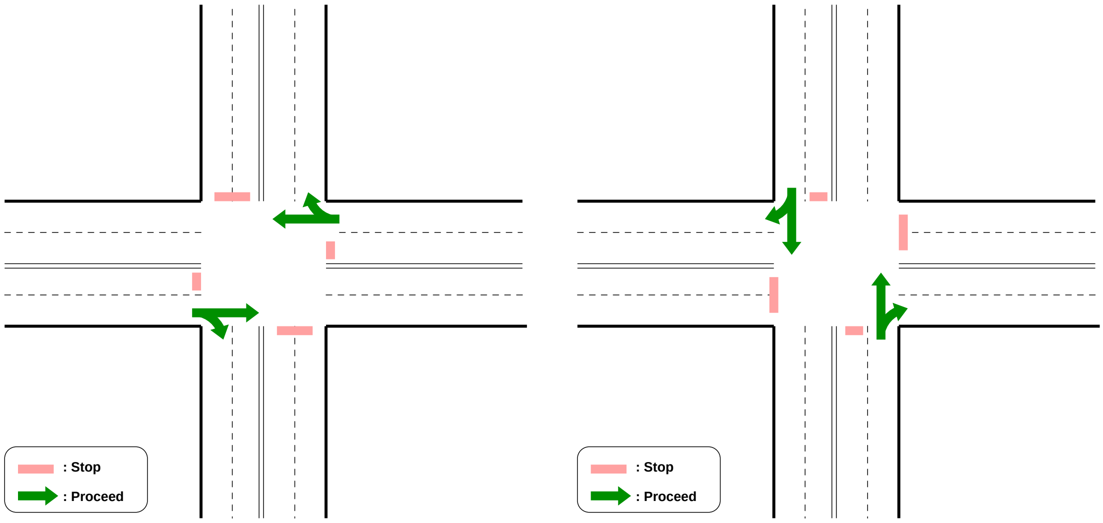


**Figure 3.8**: Conflicts in 2-phase traffic signaling: When the number of vehicles that wish to make left turns is relatively high compared to the number of vehicles that need to go straight, vehicles moving in the west-east direction wishing to make a left turn at the intersection will be in conflict with the vehicles moving straight across the signalized intersection.

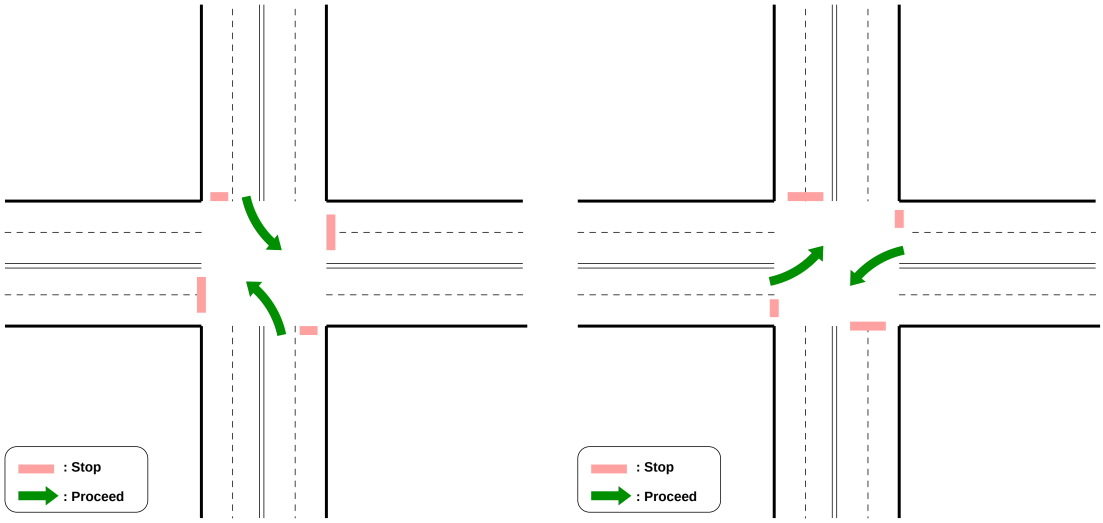
### 3.4.2 Typical 4-Phase Traffic Signaling

Typical 4-phase traffic signaling is usually adopted when turning movements are significant (Mathew and Rao, 2007). *Figure 3.9* illustrates 4-phase traffic signaling, where left-turning movements and through movements have separate phases (Mathew and Rao, 2007).

Traffic signals in the MITSIMLab environment are link-specific, and hence a set of traffic signals controls traffic in all lanes of a link (MIT-ITS, 2001), as *Figure 3.10(b)* and *Figure 3.10(c)* illustrate. Unfortunately, MITSIMLab does not directly support the implementation of lane-specific traffic signals as *Figure 3.10(a)* depicts, and, because of this lack of support, implementation of typical 4-phase signaling is difficult in MITSIMLab.



(a) Phase-1 (b) Phase-2

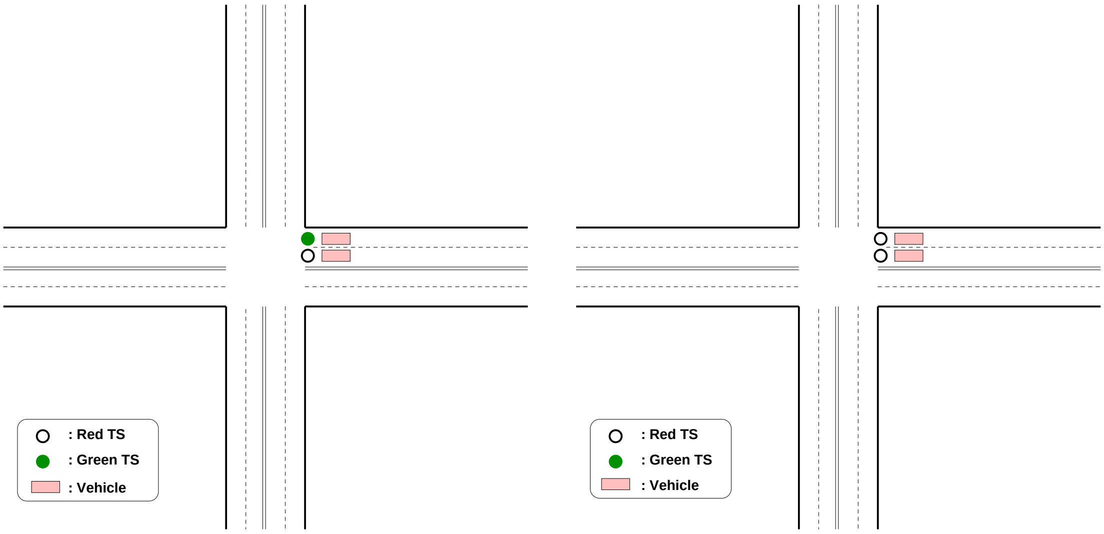


(c) Phase-3 (d) Phase-4

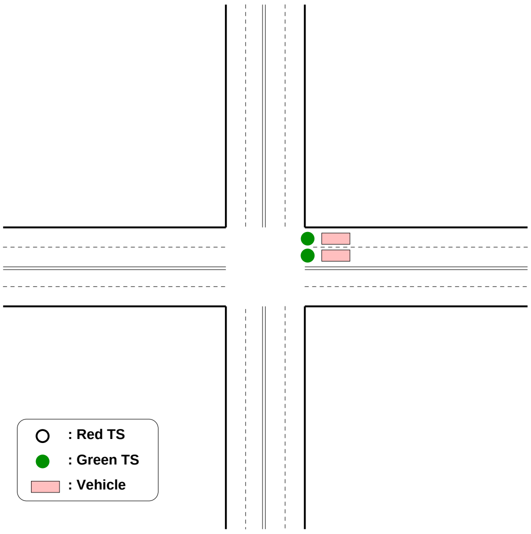
**Figure 3.9**: Typical 4-Phase traffic signaling

### 3.4.3 Split 4-Phase Traffic Signaling

Another alternative for controlling traffic at intersections is to use split 4-phase traffic signaling. *Figure 3.11* illustrates the phases of split 4-phase traffic signaling, where there is no need for separate phases for turning movements. Therefore, implementation of this type of signaling is straightforward in MITSIMLab.



(a) Lane specific traffic signal (b) Link specific traffic signal with red status



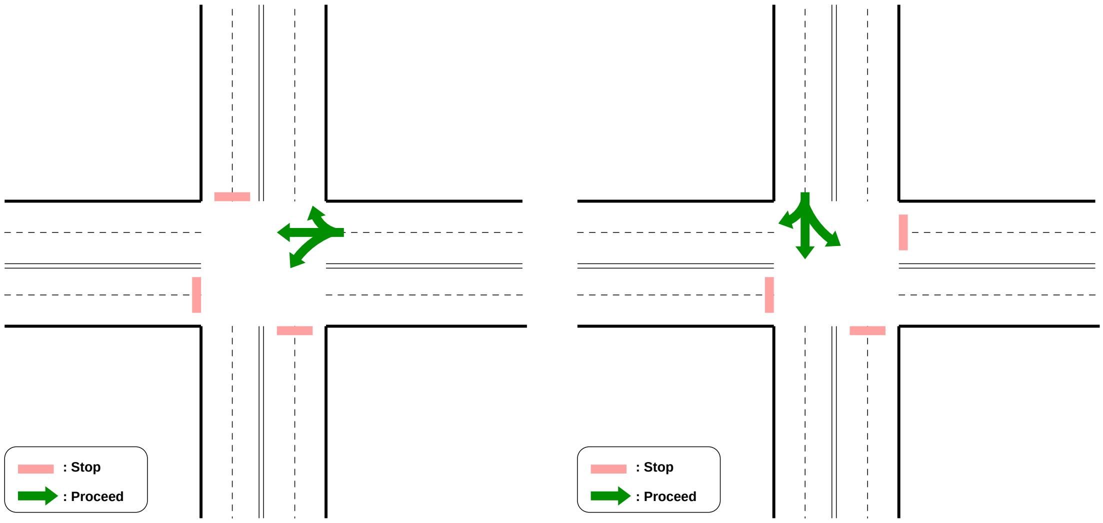
(c) Link specific traffic signal with green status

**Figure 3.10**: Link-specific traffic signals implemented in both (b) and (c) are directly supported by MITSIMLab, where all lanes within a link have the same traffic signal status. Lane-specific traffic signals implemented in (a) are not directly supported, where lanes in specific links have different traffic signal status.

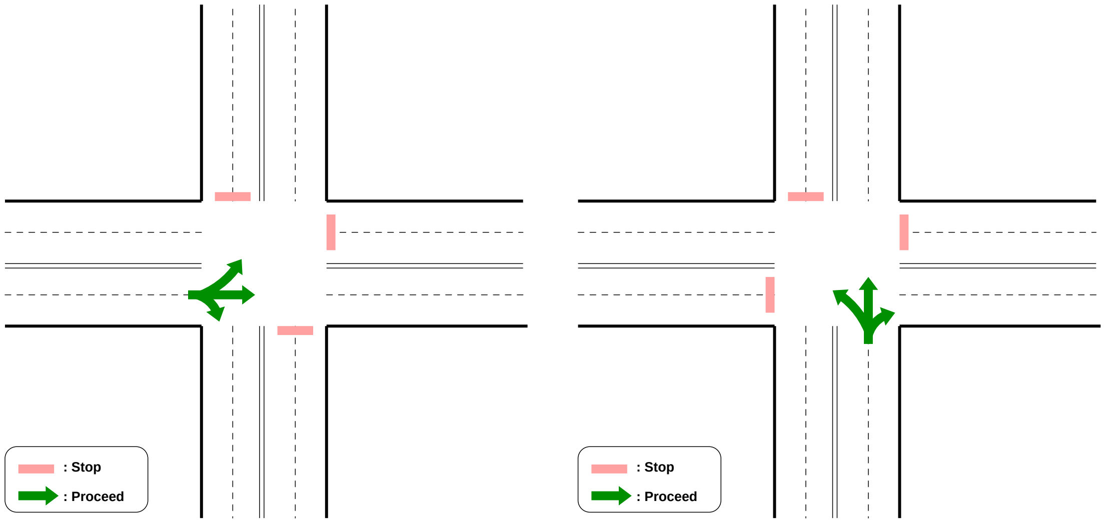
## 3.5 Non-optimized Split 4-Phase Traffic Signaling

When green time intervals are not optimized, then it is natural to use equal intervals, and this approach results in only four signal phases for each traffic signal, regardless of the number of junctions presents in a network.

*Figure 3.12* illustrates the traffic signal setup at a single intersection. *Figure 3.13* shows the signal timing plan for the single intersection given in *Figure 3.12*.



(a) Phase-1 (b) Phase-2



(c) Phase-3 (d) Phase-4

**Figure 3.11**: Split 4-Phase traffic signaling

*Figure 3.14* illustrates the traffic signal setup in a network with two signalized intersections.

*Figure 3.15* shows the signal timing plan for the network with two intersection given in *Figure 3.14*.

*Figure 3.16* illustrates the traffic signal setup in a network with three signalized intersections.

*Figure 3.17* shows the signal timing plan for the network with three intersection given in *Figure 3.16*.

*Figure 3.18* illustrates the traffic signal setup in a network with four signalized intersec-

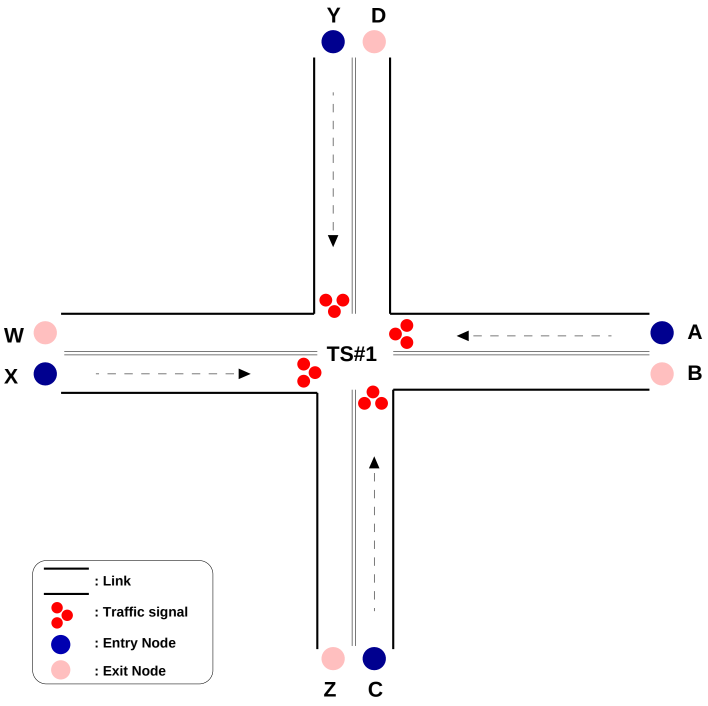


**Figure 3.12**: Traffic signals for a single intersection.

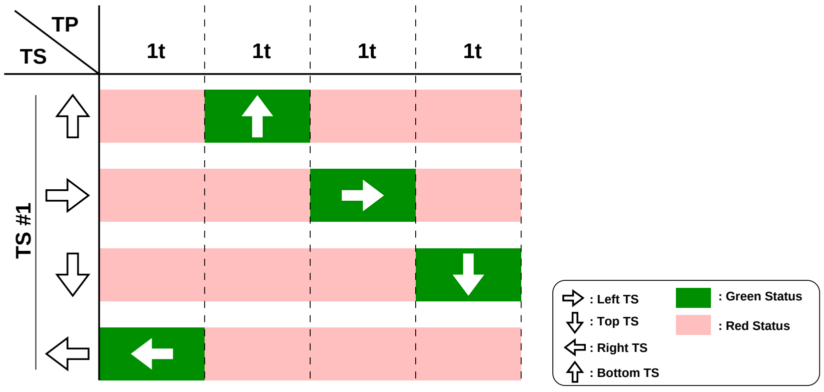


**Figure 3.13**: Traffic signal time plan table for a single intersection: Time interval for each traffic signal is equal, and there are no overlapping phases. So only one signal is green at a time.

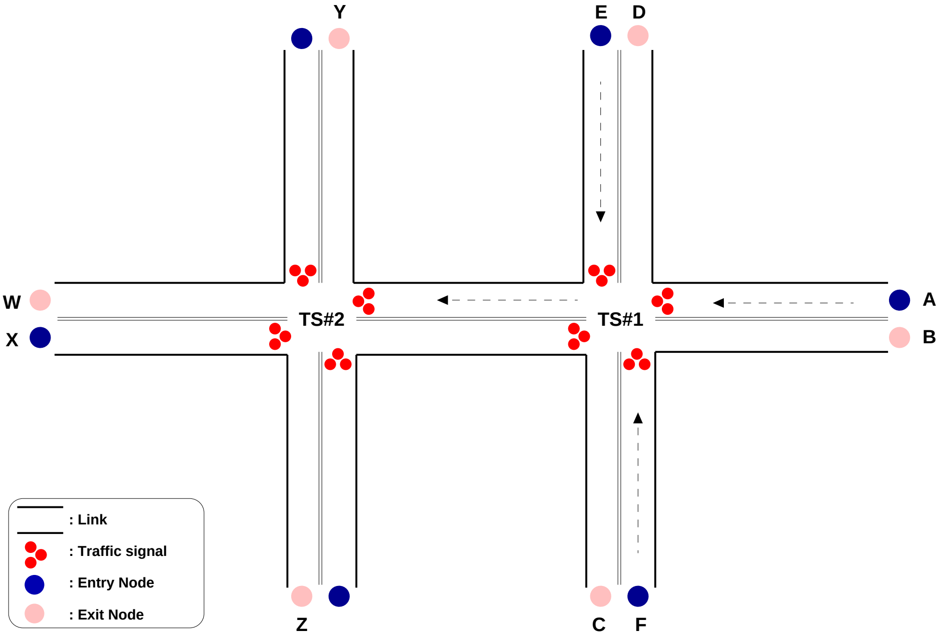


**Figure 3.14**: Traffic signal for two intersections: The network has two signalized intersections with eight traffic signals.

tions.

*Figure 3.18* illustrates the traffic signal setup in a network with four signalized intersections.

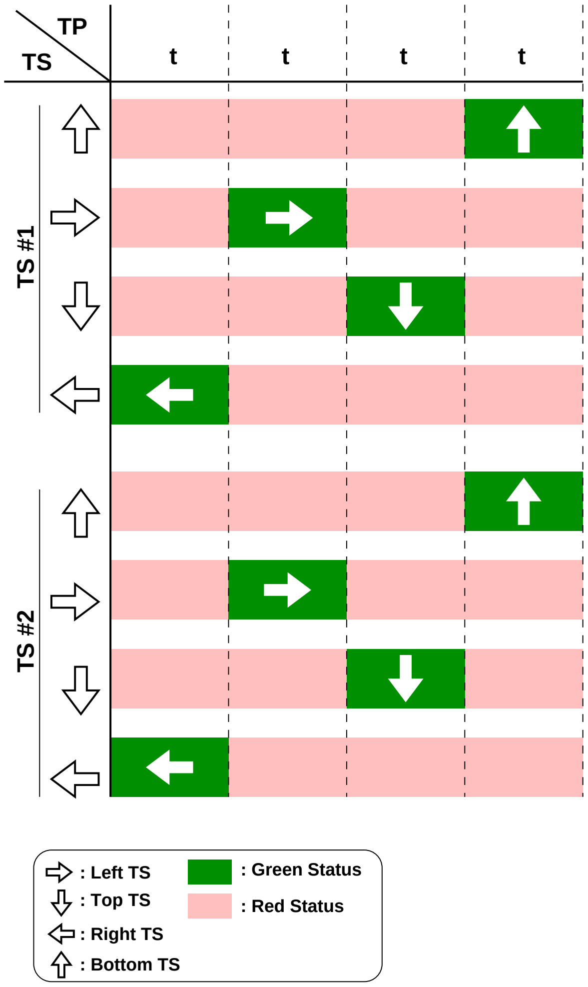
## 3.6 Optimization of Split 4-Phase Traffic Signaling

There are two key factors in optimizing green signal intervals:

- The order in which adjacent traffic signals will switch their status from green to red and from red to green within the same intersection and in coordination with other adjacent intersections.
- The time interval of each signal phase.

These key factors depend primarily on three variables: (1) traffic volume that is moving through each traffic signal, (2) distance between any two adjacent signalized intersections, and (3) speed limit on the link that joins the adjacent signalized intersections.

A good number of traffic signal optimization tools available are unfortunately proprietary. In our case, we could only implement split 4-phase signaling due to the limitation we placed upon our models by equally distributing traffic volume in each network. However,



| TS \ TP | | t | t | t | t |
|---|---|---|---|---|---|
| TS #1 | ⇧ | 🟥 | 🟥 | 🟥 | 🟩 ⇧ |
| | ⇨ | 🟥 | 🟩 ⇨ | 🟥 | 🟥 |
| | ⇩ | 🟥 | 🟥 | 🟩 ⇩ | 🟥 |
| | ⇦ | 🟩 ⇦ | 🟥 | 🟥 | 🟥 |
| TS #2 | ⇧ | 🟥 | 🟥 | 🟥 | 🟩 ⇧ |
| | ⇨ | 🟥 | 🟩 ⇨ | 🟥 | 🟥 |
| | ⇩ | 🟥 | 🟥 | 🟩 ⇩ | 🟥 |
| | ⇦ | 🟩 ⇦ | 🟥 | 🟥 | 🟥 |

⇨ : Left TS
⇩ : Top TS
⇦ : Right TS
⇧ : Bottom TS
🟩 : Green Status
🟥 : Red Status

**Figure 3.15**: Traffic signal time plan table for two intersections: Note that only one signal is green at a time, due to split four-phase signaling implemented in our work.

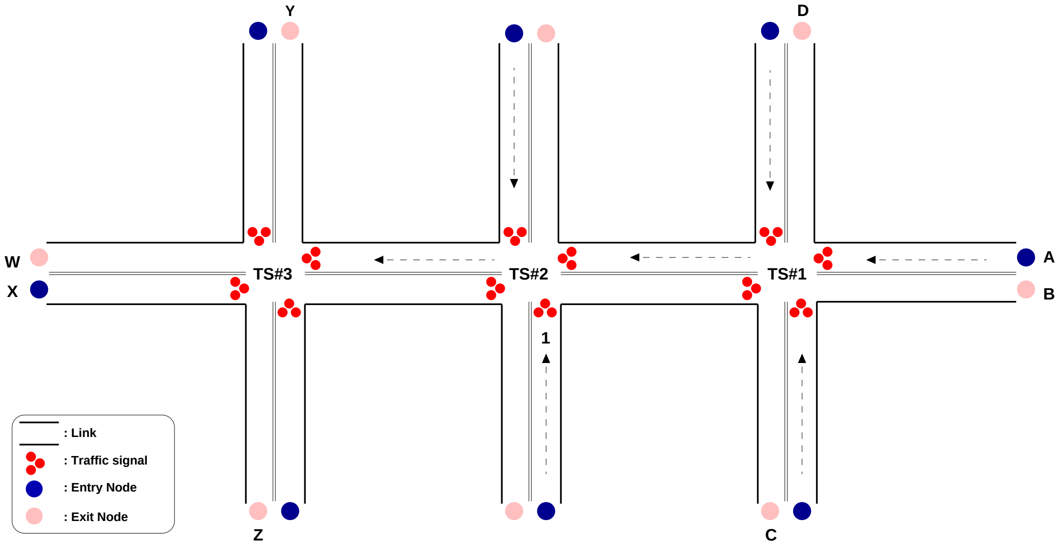


**Figure 3.16**: Traffic signal for three intersections: The network has three signalized intersections with twelve traffic signals.

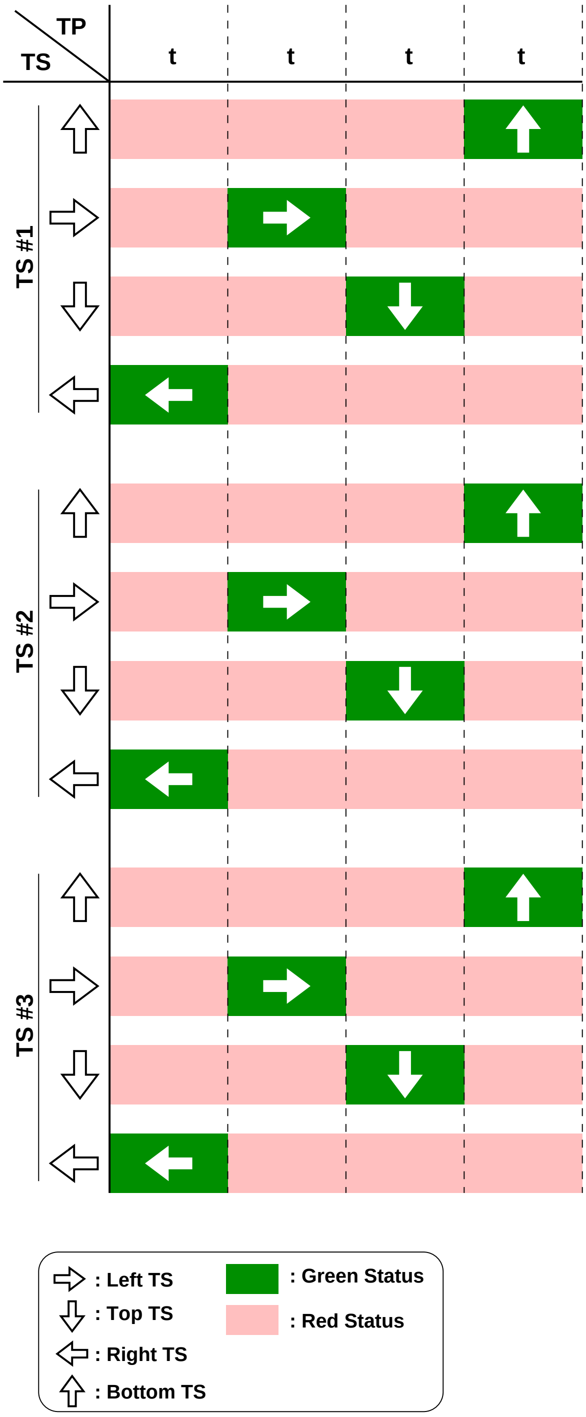


**Figure 3.17**: Traffic signal time plan table for three intersections: Note that only one signal is green at a time, due to split four-phase signaling implemented in our work.

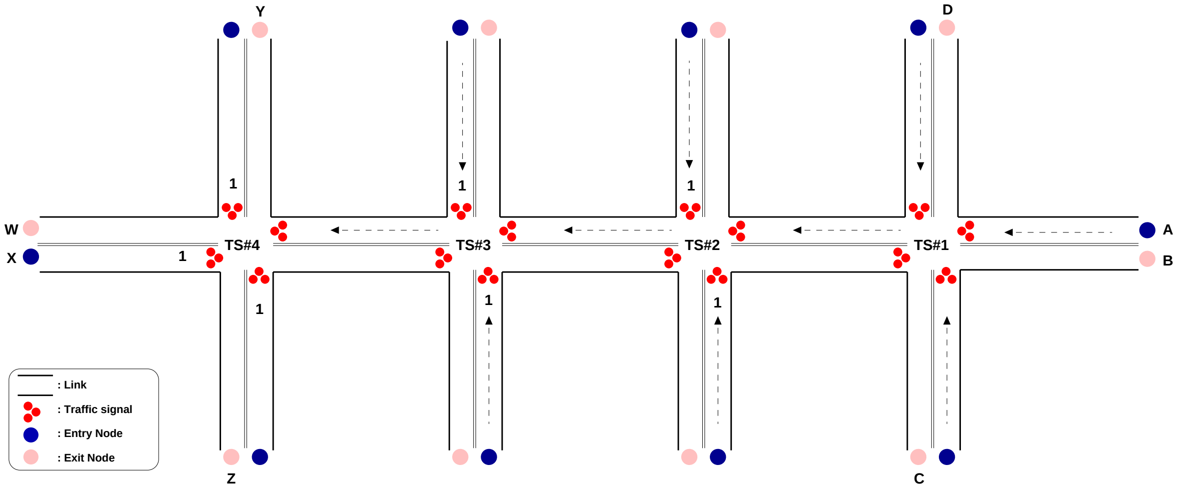
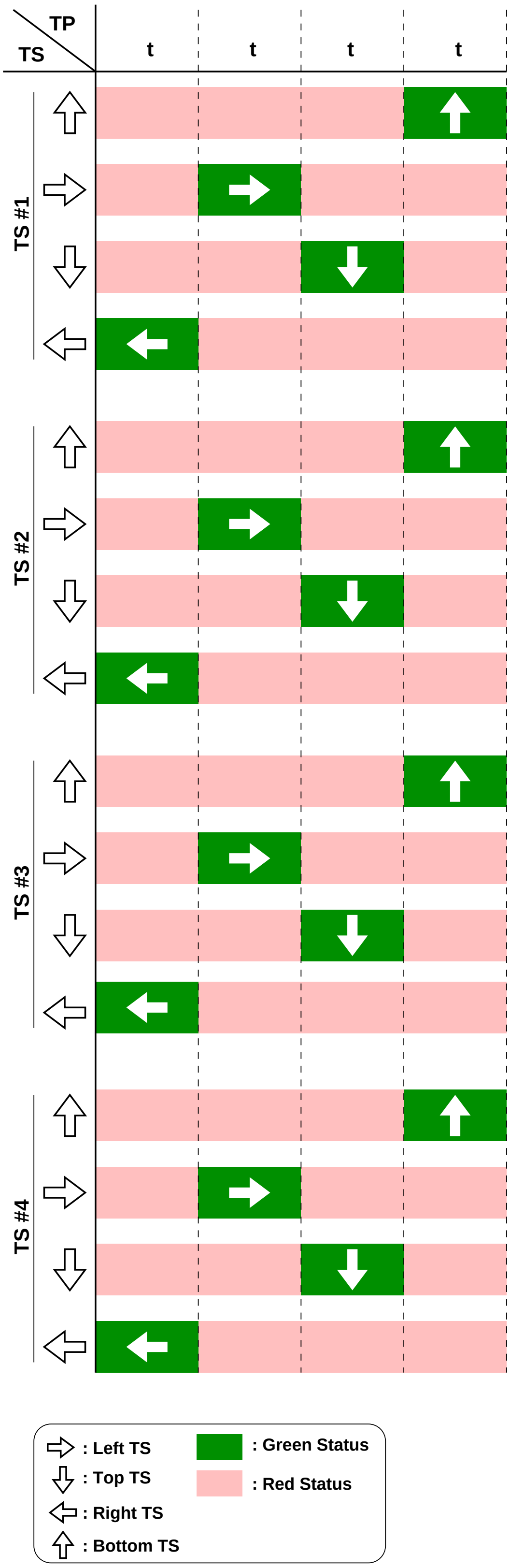


**Figure 3.18**: Traffic signal for four intersections: The network has four signalized intersections with sixteen traffic signals.

traffic signal optimization is usually based on two-phase signaling (Homburger et al., 2007). Thus we opted to construct our own approach for optimizing traffic signal timing by taking into consideration both switching sequences and status periods to achieve as much as throughput as possible through signalized intersections.

The optimization approach we devised comprises three phases:

1. **Assigning a factor for each traffic signal**: In this phase, a factor is assigned for each traffic signal based on the expected traffic volume through that traffic signal.
2. **Designing signal time plans**: In this phase, green status switching sequences among various traffic signals is assigned with the following restrictions in mind:
   - We consider green and red phases only. We eliminated the yellow phase, since our investigation of the simulator revealed that yellow phase is treated as the green phase in MITSIMLab. Vehicles proceed with their movements during yellow as they do during green.
   - Since we are restricted to split 4-phase traffic signals, we can only have one link at a 4-way intersection that can have the green signal at a time, and we cannot have more than one link to have green traffic signal at the same time.
   - Timing plan of traffic signals must exactly match the assigned factors. For example, a traffic signal with a factor of three must stay green three times as long as a traffic signal with a factor of one.



| TS | TP | t | t | t | t |
|---|---|---|---|---|---|
| TS #1 | ⇧ | 🟥 | 🟥 | 🟥 | 🟩 ⇧ |
| | ⇨ | 🟥 | 🟩 ⇨ | 🟥 | 🟥 |
| | ⇩ | 🟥 | 🟥 | 🟩 ⇩ | 🟥 |
| | ⇦ | 🟩 ⇦ | 🟥 | 🟥 | 🟥 |
| TS #2 | ⇧ | 🟥 | 🟥 | 🟥 | 🟩 ⇧ |
| | ⇨ | 🟥 | 🟩 ⇨ | 🟥 | 🟥 |
| | ⇩ | 🟥 | 🟥 | 🟩 ⇩ | 🟥 |
| | ⇦ | 🟩 ⇦ | 🟥 | 🟥 | 🟥 |
| TS #3 | ⇧ | 🟥 | 🟥 | 🟥 | 🟩 ⇧ |
| | ⇨ | 🟥 | 🟩 ⇨ | 🟥 | 🟥 |
| | ⇩ | 🟥 | 🟥 | 🟩 ⇩ | 🟥 |
| | ⇦ | 🟩 ⇦ | 🟥 | 🟥 | 🟥 |
| TS #4 | ⇧ | 🟥 | 🟥 | 🟥 | 🟩 ⇧ |
| | ⇨ | 🟥 | 🟩 ⇨ | 🟥 | 🟥 |
| | ⇩ | 🟥 | 🟥 | 🟩 ⇩ | 🟥 |
| | ⇦ | 🟩 ⇦ | 🟥 | 🟥 | 🟥 |

⇨ : Left TS
⇩ : Top TS
⇦ : Right TS
⇧ : Bottom TS
🟩 : Green Status
🟥 : Red Status

**Figure 3.19**: Traffic signal time plan table for four intersections: Note that only one signal is green at a time, due to split four-phase signaling implemented in our work.

  - As much as possible, consider the speed limits and distances between adjacent signalized intersections in order to reduce the delay experienced by vehicles traveling through streams with many traffic signals. This is similar to creating a *green wave* along a travel path. In our case, however, we do not consider implementing green waves since our hypothetical networks do not model scenarios with major paths that have high volume traffic and minor paths that have considerably low volume traffic.

3. **Determination of the optimal green time interval**: To find the optimal green time interval for a specific network, we simulate a number of base green time intervals. The time interval that leads to the lowest average vehicle travel time is chosen as the optimal green time for that network configuration.

   In our optimization approach, each phase does not have the same duration. However, each phase is governed by a factor that multiplies a base time interval. It is this base time interval that we vary.

### 3.6.1 Optimization of Single Signalized Intersections

This section explains the optimization process for a single signalized intersection that *Figure 3.20* depicts. As *Section 3.6* discusses, we require three phases for optimizing traffic signal intervals. These phases involve the determination of traffic signal factors, designing a time plan table, and picking the best green time interval to use in the comparison with a compatible roundabout network.

The network under consideration has only one intersection with four traffic signals placed at traffic signal station, TS#1. All straight links have identical length. Vehicle demand from all source nodes A, C, X and Y are identical and equally distributed for all destination nodes B, D, W and Z. U-turns are not allowed. If, for example, the vehicle demand for each source node (C, A, X, and Y) is set to 100 vehicles/hour, then we will have 100 vehicles will be arriving at each destination node B, D, W and Z per hour.

- **Determination of traffic signal factors**: The first step in determining traffic signal factors involves choosing a traffic volume at a traffic signal with a reference value of one. We choose the traffic volume at node C as reference for this network as *Figure 3.20*

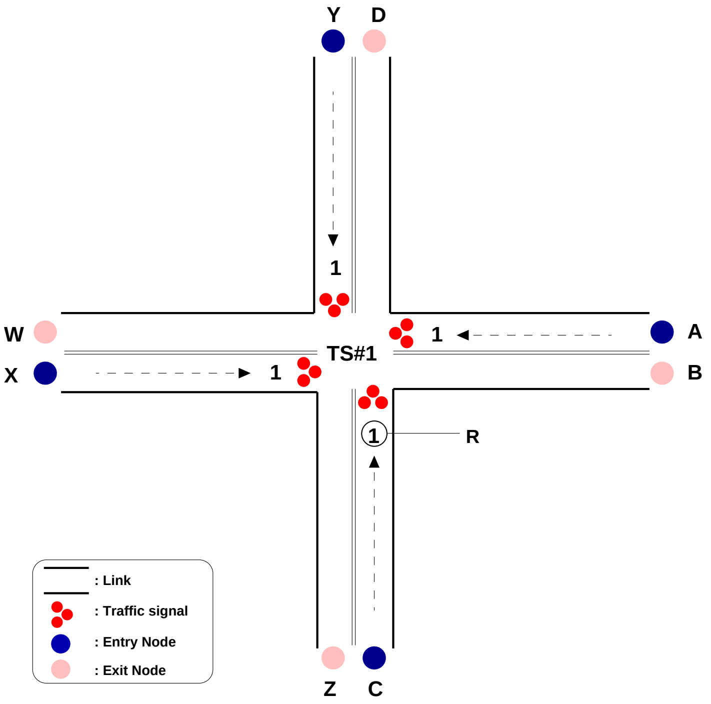


**Figure 3.20**: Traffic signals factors for a single intersection: All traffic signals have a factor of one.

illustrates. Since we have identical vehicle demand from all source nodes, traffic volume at all source links is identical. That is, the traffic volume passing through all traffic signals is identical, and it has a factor of one.

- **Design of a time plan table**: We need to know when and how traffic signals need to switch their status from red to green and vice versa. A single intersection poses the simplest case, since the network has only one station of traffic signals. *Figure 3.21* shows the time plan for a single signalized intersection.

- **Choosing the best green time interval**: For a specific travel demand, a range of green time intervals are applied to the time plan table shown in *Figure 3.21*. For example, if a set of ten green time intervals are applied in simulation, then this means that we have ten time plan tables. Then we decide on the best green time interval depending on which base green time interval lead to the average minimum travel time for a particular vehicle demand value.

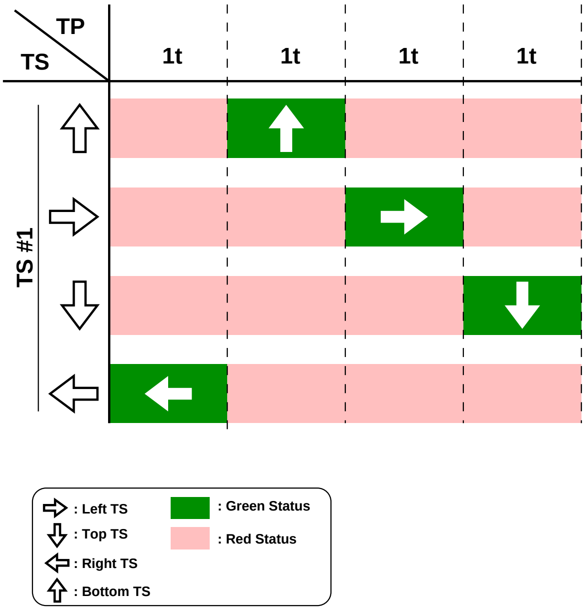


**Figure 3.21**: Traffic signal time plan table for a single intersection: Time interval for each traffic signal is equal, and there are no overlapping phases. So only one signal is green at a time.

### 3.6.2 Optimization of Two Signalized Intersections

Optimization becomes a more difficult task when the number of signalized intersections increases. A traffic network with two signalized intersections has eight traffic signals placed at two traffic signal stations (TS#1) and (TS#2) with four traffic signals for each as *Figure 3.22* illustrates. As in the previous case with a single signalized network, straight links have identical length, vehicle demand from all source nodes is identical and equally distributed over all destination nodes, and U-turn movements are not allowed.

- **Determination of traffic signal factors**: First, we choose a reference node that will have a factor of 1. As in the previous case, we choose node C as reference for the two-intersection network shown in *Figure 3.22*. Since we have identical vehicle demand from all source nodes, then traffic volume in all source links is identical in comparison with the traffic originating from the reference node. This means that all traffic signals near source links have the same traffic volume with a factor of 1.

  To determine the traffic signal factors for traffic signals implemented in non-source links such as the right traffic signal TS#1 and left traffic signal TS#2, we track the traffic volume in the stream from node A to node W. The link between TS#1 and TS#2 has traffic volume contributed from source nodes A, E, and F. Since we have identi-

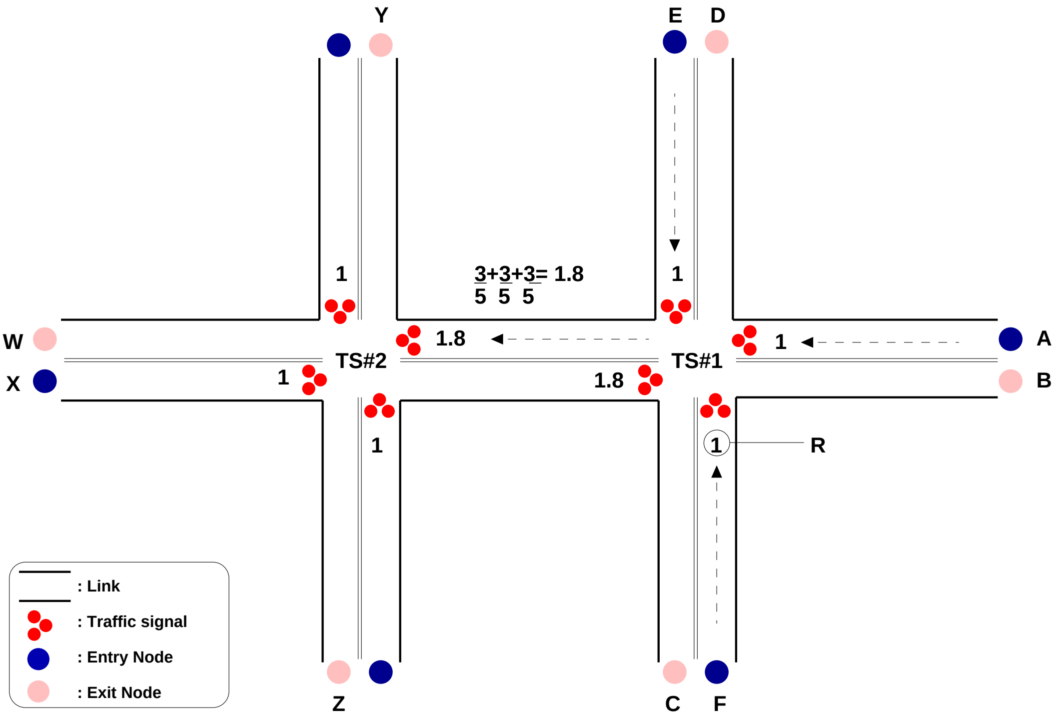


**Figure 3.22**: Traffic signal factors for two intersections: The network has two signalized intersections with eight traffic signals. Traffic signals adjacent to source links have a signal factor of 1 each, and traffic signals on non-source links have a signal factor of 1.8 each.

cal traffic demand from all six source nodes and equal distribution to all destination nodes, there are six possible destination nodes, and, since U-turns are not allowed, we have five destination nodes for each source node. Therefore, the traffic volume in each source link can be divided into five equal parts ($1/5$). Each destination node will then receive one-fifth of the vehicle demand from each source link. Then the link between TS#1 and TS#2 will receive three-fifths from each source links. This leads to a total factor of $1.8$. Due to symmetry, streams in the opposite direction, that from node X to node B, will have the same traffic volume and hence the same factor.

- **Design of a time plan table**: *Figure 3.23* depicts the phases of all traffic signals for a two-intersection network. A factor of 1.8 is used for the two traffic signals joining the two intersections, and remaining traffic signals will work with a factor of 1.

- **Choosing the best green time interval**: In order to pick the best green time interval, we simulate a series of green time intervals for each given vehicle demand value. Then the green time interval that leads to the lowest average travel time is the considered best.

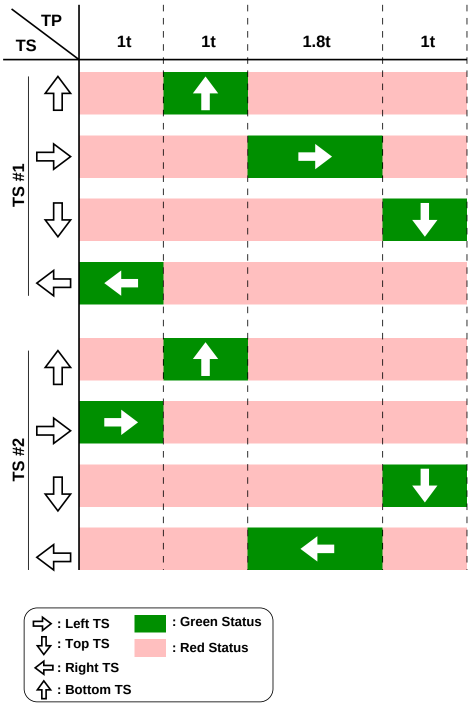


**Figure 3.23**: Traffic signal time plan table for two intersections: Note that only one signal is green at a time, due to split four-phase signaling implemented in our work.

### 3.6.3 Optimization of Three Signalized Intersections

Next, we consider a traffic network with three signalized intersections. *Figure 3.24* demonstrates this case. All the links have the same length. Vehicle demand from all source nodes are identical and equally distributed over all destination nodes.

- **Determination of traffic signals factors**: Vehicle demand at node C is the reference with a value of 1 as *Figure 3.24* depicts. Since we have identical vehicle demand from all source nodes, traffic volume in all source links is identical to that of the reference node. This means that all traffic signals connected to source links have the same traffic volume and hence a signal factor of 1. Since the three intersection network has eight destination nodes, the traffic volume at each source node is divided into seven equal parts (1/7), since U-turns are not allowed. Each destination node will then receive one-seventh of the total vehicle demand from each source node. The traffic volume of the stream from node A to node W is tracked in order to calculate the cumulative traffic volume that exists in non-source links between TS#1, TS#2, and TS#3. After accumulating factors, we get two similar traffic signal factors with a value of 2.14. Traffic signals between nodes X and B have the same traffic signal factors but in the

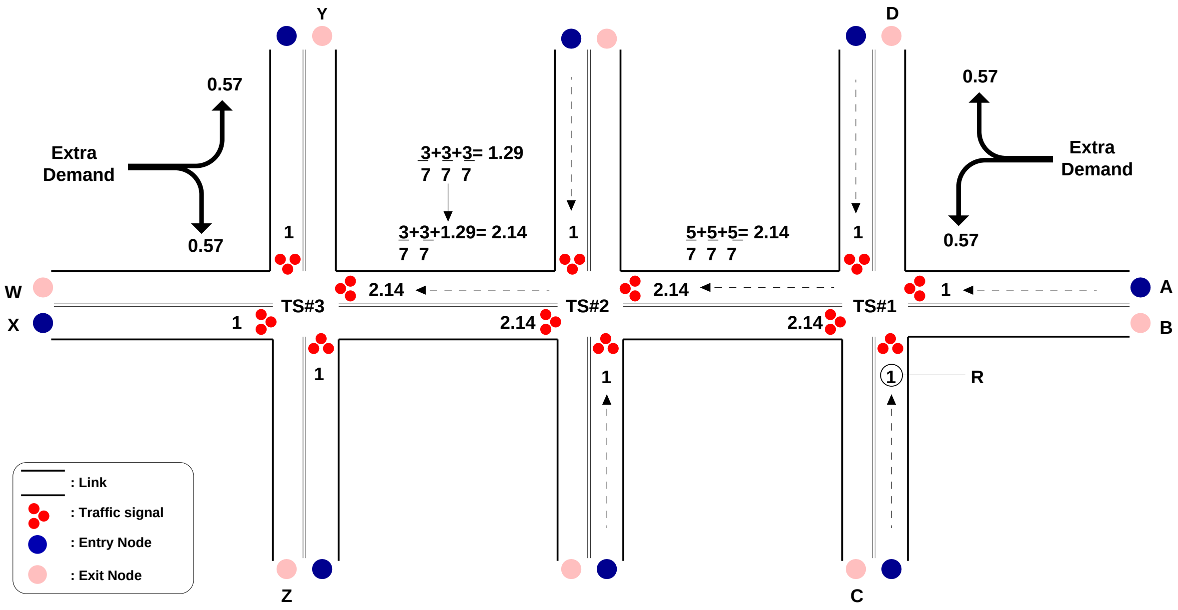
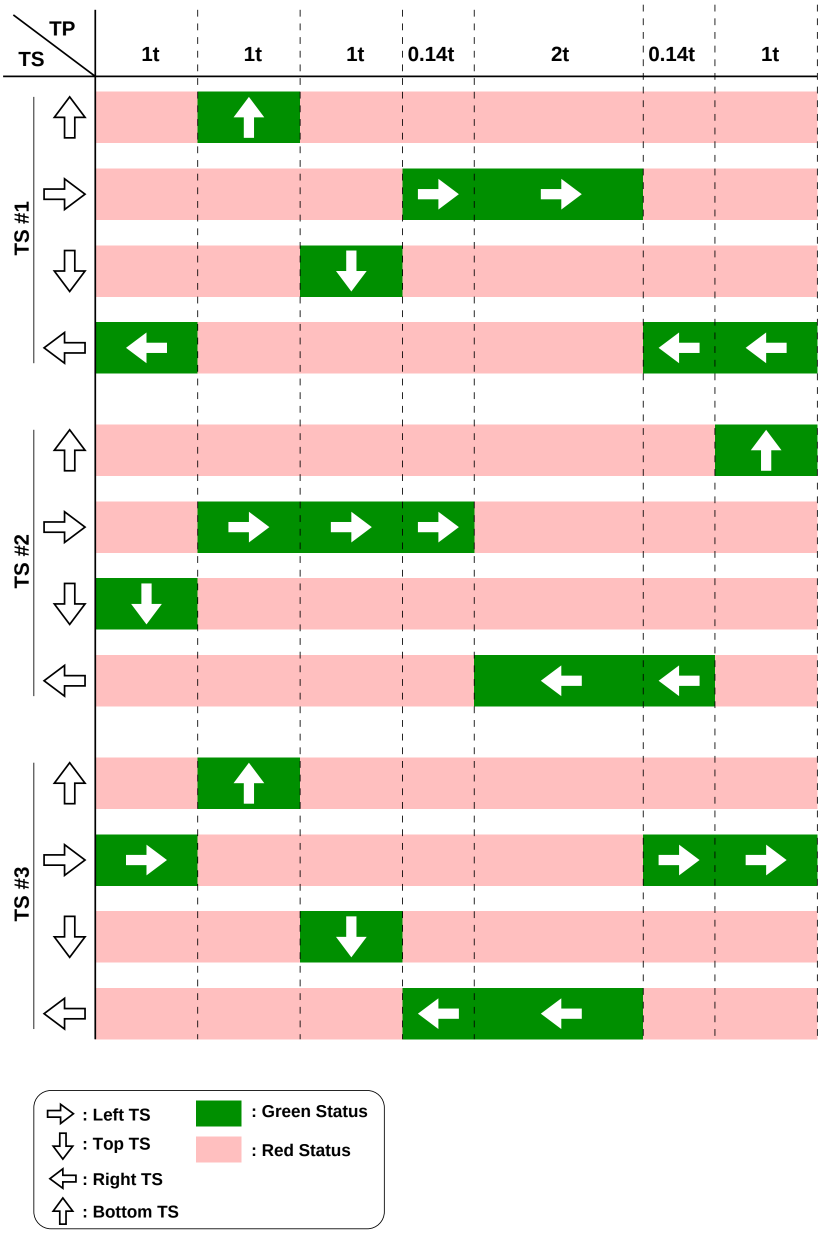


**Figure 3.24**: Traffic signal factors for three intersections: The network with three signalized intersections has 12 traffic signals. Links have identical type and length. Vehicle demand is identical at every single source node, and it is equally distributed over all destination nodes. An extra 114% vehicle demand for nodes A and W are considered and only distributed to non-signalized links that end at nodes C, D, Y and Z in order to optimize traffic signal factors (See *Figure 3.25*). In this case, traffic signals at links that are adjacent to source nodes have signal factors of 1 each. Traffic signals on non-source links have factors of 2.14 each.

opposite direction since both streams have the same traffic volume distribution.

- **Design of a time plan table**: *Figure 3.25* illustrates the time plan table of three signalized intersections. The time plan table is designed to exactly match the traffic signal factors computed. Only one green light at a time is allowed at the same intersection. Traffic lights on source links at nodes A and B have extra factors equal to 1.14 each. In order to optimize the traffic signal factors according to traffic volume, we add an extra vehicle demand factor of 1.14 at nodes A and B. The traffic that will result from this extra vehicle demand will travel through non-signalized links towards nodes such as D and C.

- **Choosing the best green time interval**: A set of green time intervals are tested for each traffic volume level in simulation, and the green time interval associated with the minimum average travel time is chosen as the best. Then, the vehicle trip times generated by the experiment with the best green time is used in the comparison with the trip times obtained from the three-roundabout experiment for the same traffic volume.



| TS | | TP: 1t | 1t | 1t | 0.14t | 2t | 0.14t | 1t |
|---|---|---|---|---|---|---|---|---|
| TS #1 | ⇧ | 🟥 | 🟩 ↑ | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 |
| | ⇨ | 🟥 | 🟥 | 🟥 | 🟩 → | 🟩 → | 🟥 | 🟥 |
| | ⇩ | 🟥 | 🟥 | 🟩 ↓ | 🟥 | 🟥 | 🟥 | 🟥 |
| | ⇦ | 🟩 ← | 🟥 | 🟥 | 🟥 | 🟥 | 🟩 ← | 🟩 ← |
| TS #2 | ⇧ | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟩 ↑ |
| | ⇨ | 🟥 | 🟩 → | 🟩 → | 🟩 → | 🟥 | 🟥 | 🟥 |
| | ⇩ | 🟩 ↓ | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 |
| | ⇦ | 🟥 | 🟥 | 🟥 | 🟥 | 🟩 ← | 🟩 ← | 🟥 |
| TS #3 | ⇧ | 🟥 | 🟩 ↑ | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 |
| | ⇨ | 🟩 → | 🟥 | 🟥 | 🟥 | 🟥 | 🟩 → | 🟩 → |
| | ⇩ | 🟥 | 🟥 | 🟩 ↓ | 🟥 | 🟥 | 🟥 | 🟥 |
| | ⇦ | 🟥 | 🟥 | 🟥 | 🟩 ← | 🟩 ← | 🟥 | 🟥 |

⇨ : Left TS
⇩ : Top TS
⇦ : Right TS
⇧ : Bottom TS
🟩 : Green Status
🟥 : Red Status

**Figure 3.25**: Traffic signal time plan table for three intersections: Time interval for each traffic signal matches its factor, and there is no overlapping between traffic signals within same intersection. For each intersection, only one traffic signal is green at a time.

### 3.6.4 Optimization of Four Signalized Intersections

Finally, we consider traffic networks with four signalized intersections. Each intersection has a traffic signal station containing four traffic signals. As *Figure 3.26* illustrates, a four-intersection network has a total of 16 traffic signals. The links in this network also have identical lengths. The vehicle demand from all source nodes is identical, and traffic volume is equally distributed among all destination nodes.

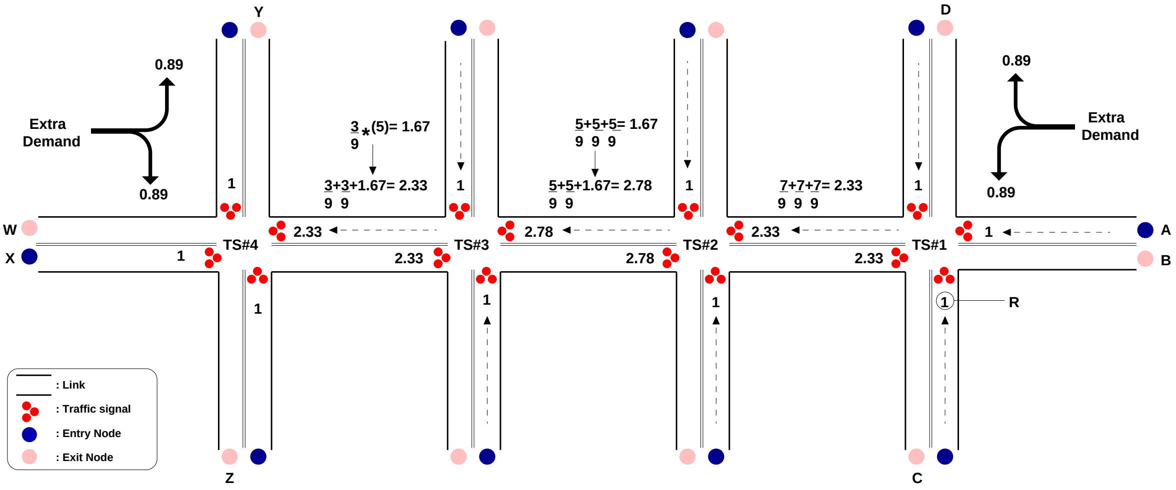


**Figure 3.26**: Traffic signal factors for four intersections: A network with four signalized intersections has 16 traffic signals. We add an extra 178% vehicle demand at nodes A and W. This traffic is distributed to non-signalized links that end at nodes C, D, Y, and Z to optimize traffic signal factors with respect to vehicle demand (See *Figure 3.27*). Traffic signals on source links have a factor of 1 each. Outermost traffic signals on non-source links have a signal factor of 2.33, and innermost traffic signals have a factor of 2.78.

- **Determination of traffic signal factors**: By following the same procedure as before, we get traffic signal factors for non-source links as 2.33, 2.78, and 2.33, from left to right.
- **Design of the time plan table**: The time plan table of traffic signals is shown in *Figure 3.27*.
- **Choosing the best green time interval**: Again, we choose the green time that leads to the lowest average travel time for each tested traffic volume. Then the results from this instance of the intersection experiment is compared to the corresponding roundabout experiment for the same traffic demand value.

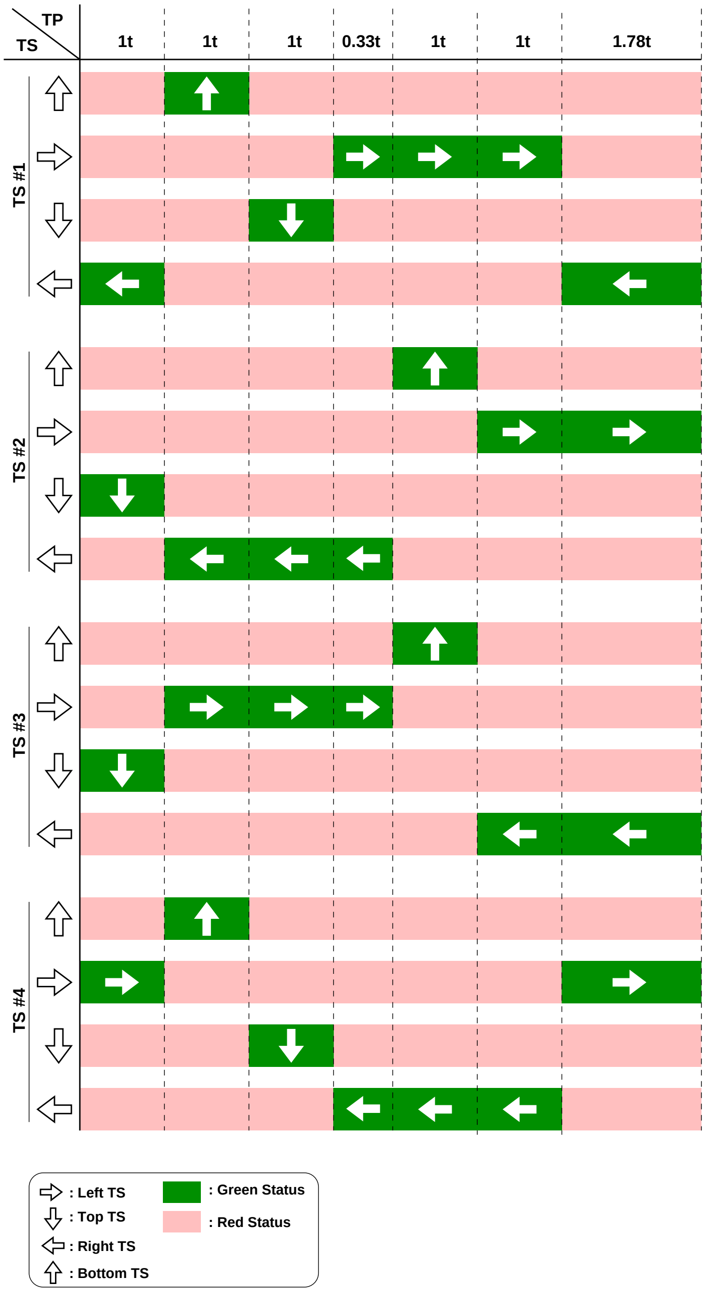


**Figure 3.27**: Traffic signal time plan table for four intersections

## 3.7 Summary

This chapter presents our approach for comparing traffic flow between roundabouts and signalized intersections. It discusses the hypothetical network models we used in simulating traffic and presents the statistical test procedures and parameters we used in our study. It also discusses our technique for optimizing green time intervals for traffic signals.

# CHAPTER 4

# IMPLEMENTATION

## 4.1 Overview

This chapter describes the implementation of the work reported in this thesis. This work ranges from implementing the roundabout and signalized intersection networks to be simulated in MITSIMLab to generating experiments and analyzing the results. In addition, this chapter discusses the practical problem we faced regarding the building of the MITSIMLab programs on latest GNU/Linux systems.

## 4.2 Networks

As described in *Chapter 3*, our work considers four major scenarios. These scenarios are one roundabout versus one signalized intersection, two roundabouts versus two signalized intersections, three roundabouts versus three signalized intersections, and four roundabouts versus four signalized intersections. For each scenario, compatible networks are simulated and statistical analysis of the vehicle travel times is performed to determine the impact of each type of network on vehicle travel time. Each pair of compatible networks have identical configuration, except for the structures at road junctions. Remaining parameters such as link length, link type, speed limits, source and destination nodes, and lane rules are identical. That is, the only difference is whether a roundabout or a signalized intersection is used in the implementation of a given junction.

Links, lanes, source and destination nodes have unique IDs that distinguish them from others. MITSIMLab allows IDs to be shared among various types components of network but not among components of the same type. For example, MITSIMLab allows a link, a lane, and a node to have ID=10 at the same time, but MITSIMLab does not allow either two links or two lanes to have the same ID.

All straight links in all networks have a length of 3280 feet. The links that implement roundabouts and small links added to the end of each straight link near each entry or exit node (in order to circumvent an operational error in MITSIMLab) do not follow this length setup.

### 4.2.1 Single Junction Networks

The first comparison involves roundabouts and signalized intersections with a single road junction in each. Both networks have identical link types (ramp link), link IDs, link lengths (3280 feet), link speed limits, number of lanes in each link, lanes IDs, lanes rules, and origin-destination sets. The only difference between the two networks has to do with the traffic management strategy used to control the junction, which is implemented with either a signalized intersection or a roundabout.

*Figure 4.1* depicts the design of the signalized intersection network, and *Figure 4.2* depicts that of the roundabout. These two figures demonstrate that link IDs, lane IDs, source and destination nodes IDs are identical for both networks, and that the only difference between the two is the junction control strategy.

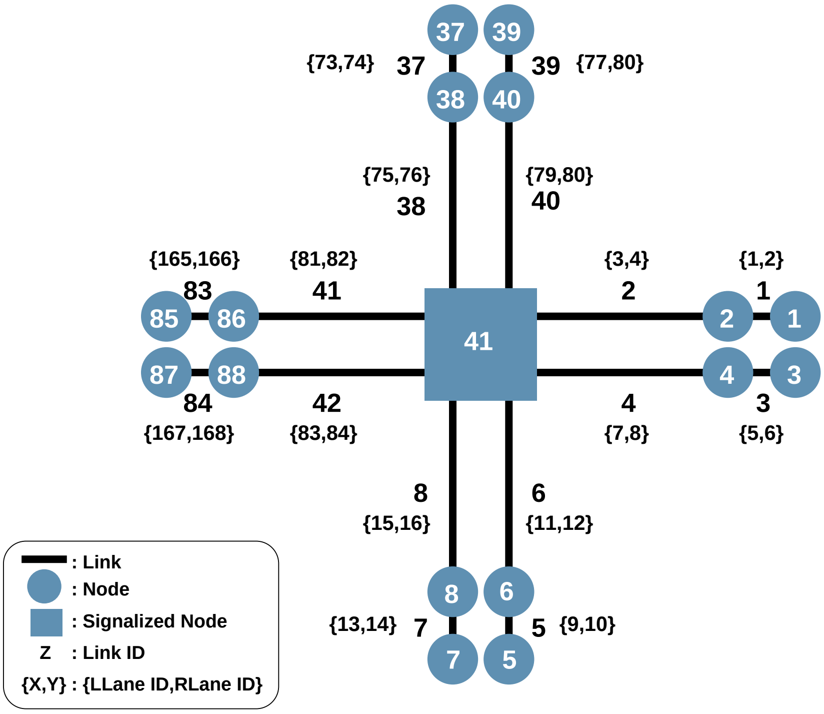


**Figure 4.1**: The design of the test network with one signalized intersection.

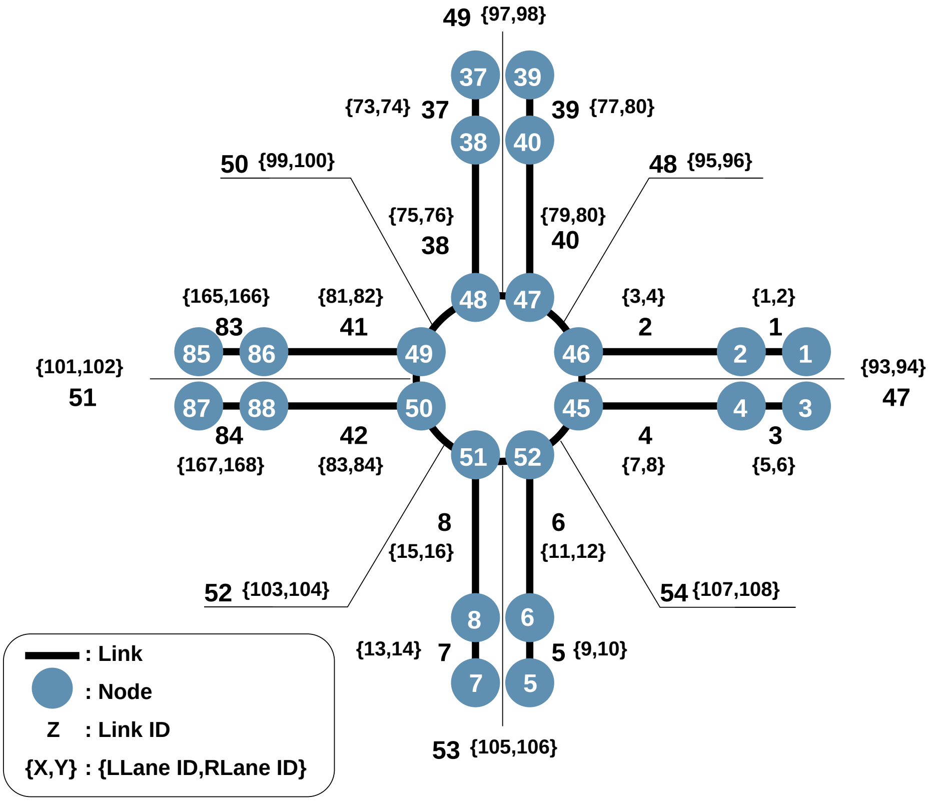


**Figure 4.2**: The design of the test network with a single roundabout.

### 4.2.2 Two-Junction Networks

The second comparison involves roundabouts and signalized intersections with two road junctions in each. As before, both networks have identical link types (ramp link), link IDs, link lengths (3280 feet), link speed limits, number of lanes in each link, lanes IDs, lanes rules, and origin-destination tables. Therefore, the only difference between the two networks has to do with the traffic management strategy used to control the junction.

*Figure 4.3* depicts the design of the signalized intersection network, and *Figure 4.4* depicts that of the roundabout. The link IDs, lane IDs, source and destination nodes IDs are identical in both networks, and the only difference between the two is the road junction control strategy.

### 4.2.3 Three-Junction Networks

The third comparison scenario involves roundabouts and signalized intersections with three junctions in each. *Figure 4.5* depicts the design of the signalized intersection network, and *Figure 4.6* depicts that of the roundabout. The link IDs, lane IDs, source and destination

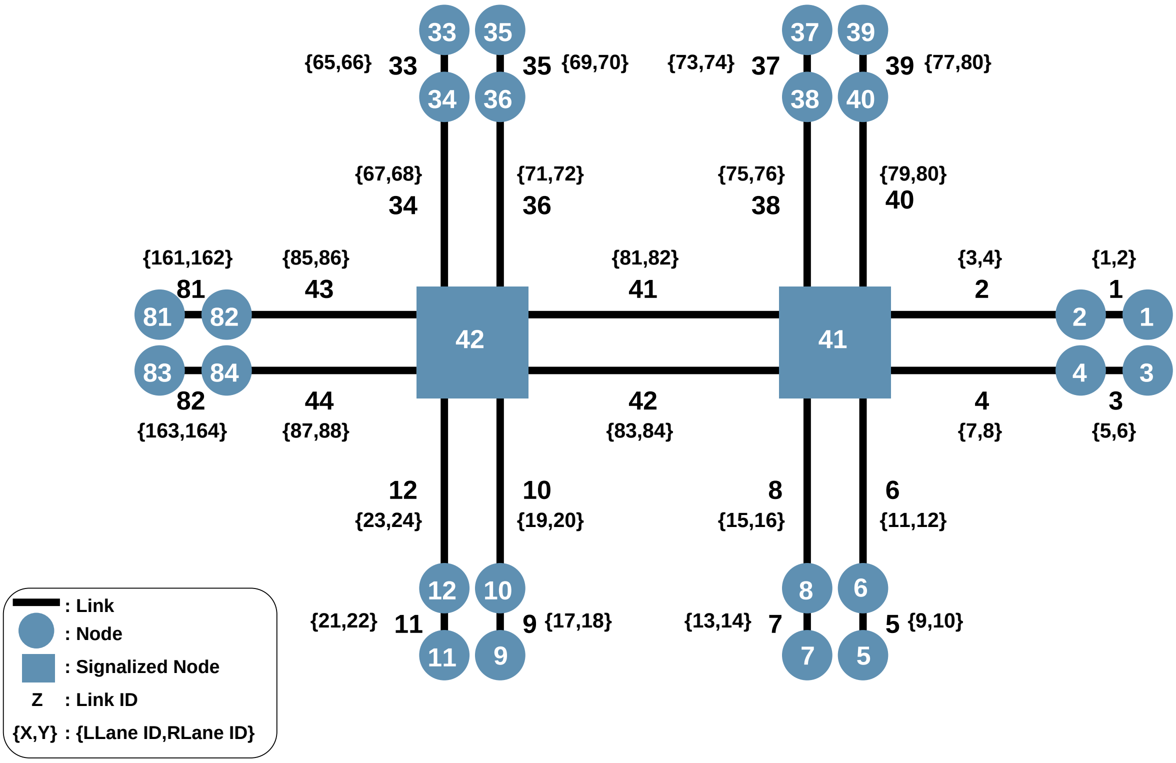


**Figure 4.3**: The design of the test network with two signalized intersections.

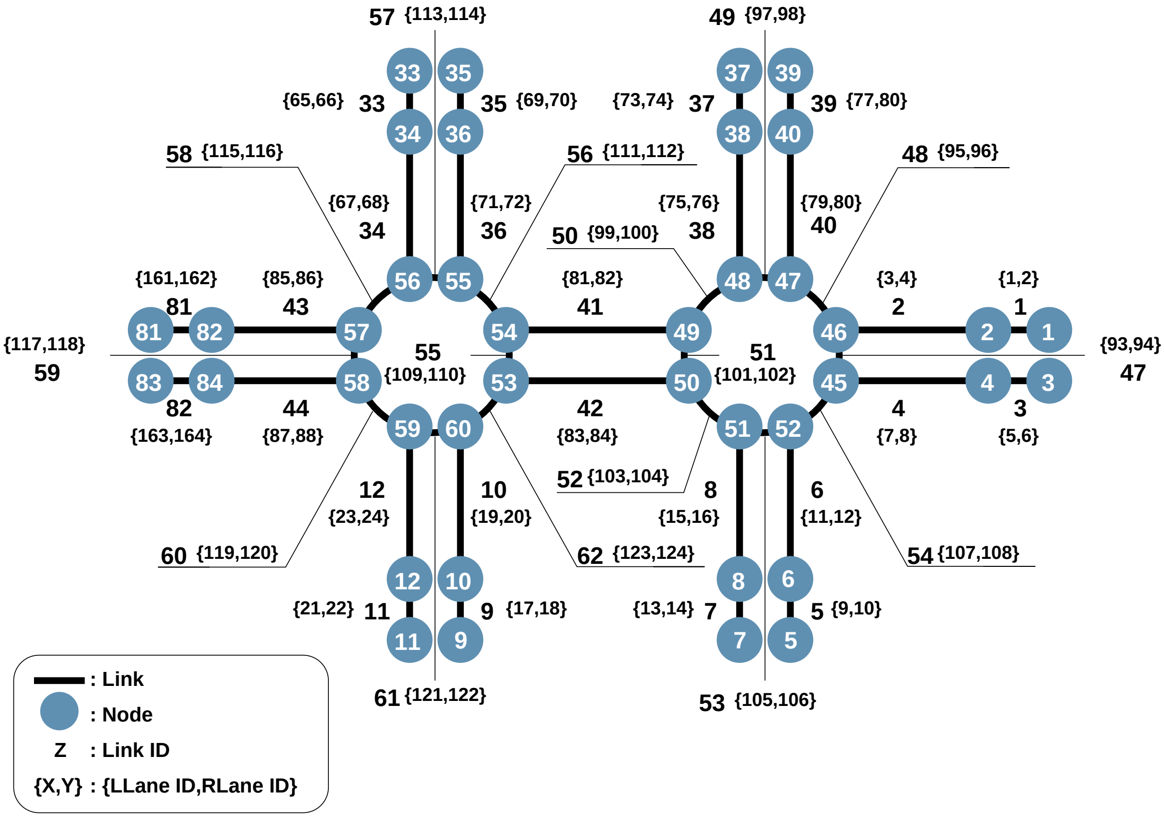


**Figure 4.4**: The design of the test network with two roundabouts.

nodes IDs are identical in both networks, and that the only difference between the two networks is the road junction control strategy.

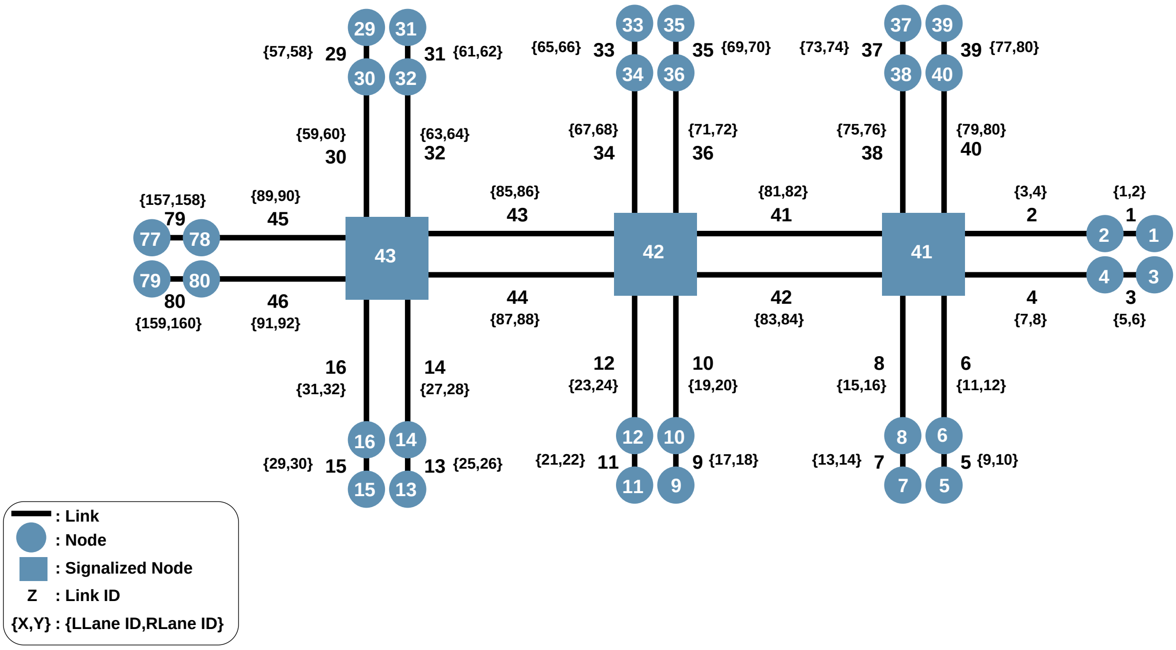


**Figure 4.5**: The design of the test network with three signalized intersections.

### 4.2.4 Four-Road Junctions

The final comparison scenario involves roundabouts and signalized intersections with four road junctions in each. *Figure 4.7* depicts the design of the signalized intersection network, and *Figure 4.8* depicts that of the roundabout.

## 4.3 Extra Links

During the development of the road networks we intended to study, we discovered that MITSIMLab does not report the total distance traveled correctly, since it fails to add the distance of the last traveled link. Unfortunately the simulator does not consider the traveled distance when vehicles reach their destination and therefore leave the network. Therefore, to circumvent this problem, we devised a method where we add very short links of relatively negligible length at the end of existing entry or exit nodes in order to force MITSIMLab to consider the distance traveled in the last main link. Each such extra link has a length of 1 foot, and each main link has a length of 3280 feet. Therefore, extra links are only 0.03% of

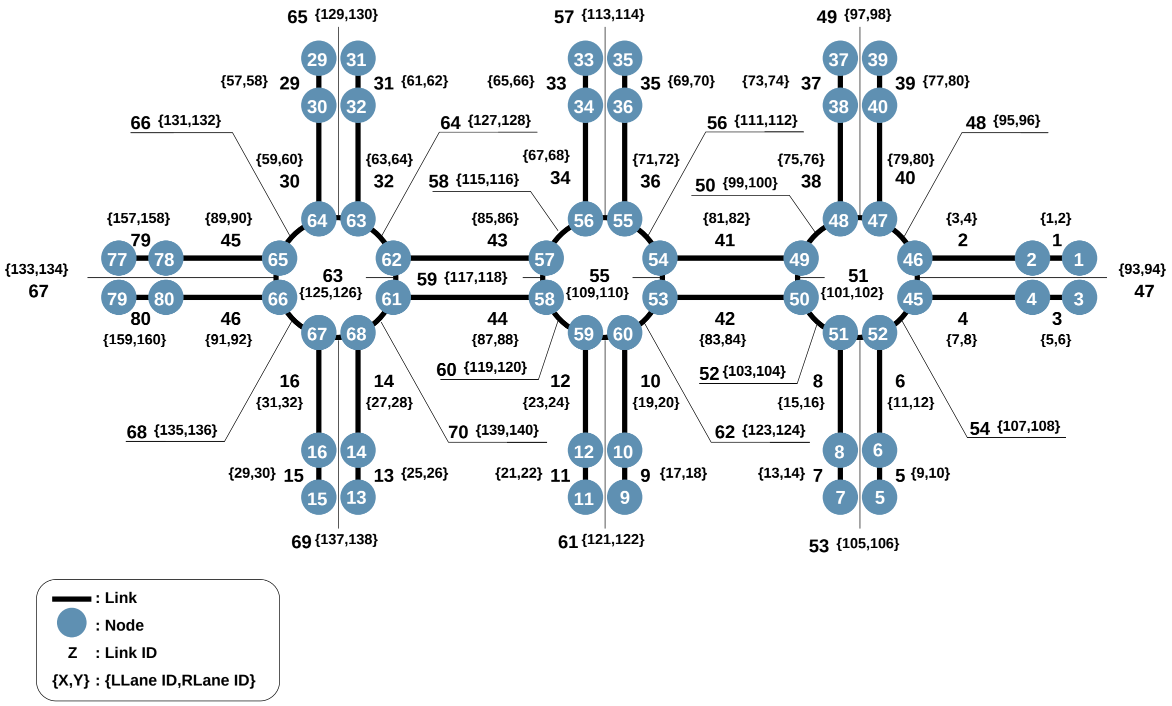


**Figure 4.6**: The design of the test network with three roundabouts.

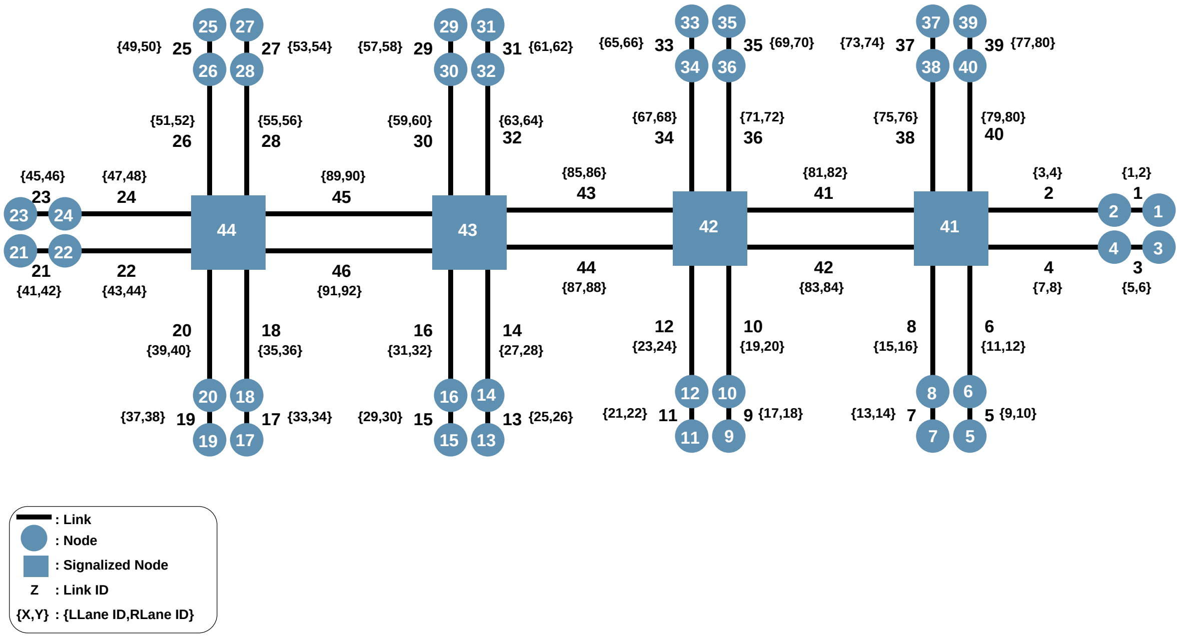


**Figure 4.7**: The design of the test network with four signalized intersections.

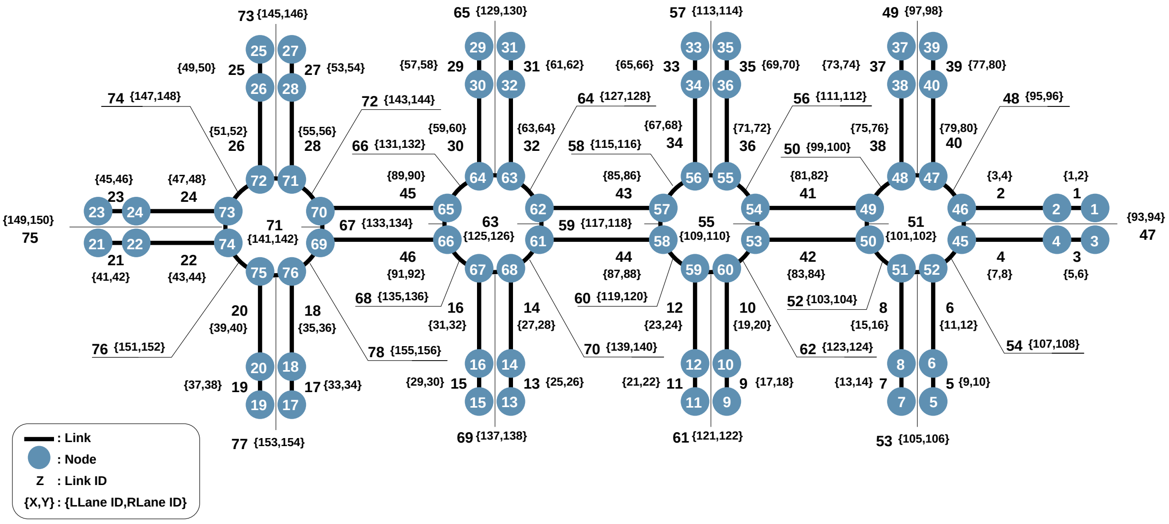


**Figure 4.8**: The design of the test network with four roundabouts.

the main links they extend. So, with this modification, vehicles have to cross a 1-foot link before they exit the simulation. So, with a tiny error, MITSIMLab reports distances traveled correctly.

As the network design in *Section 4.2* shows, we place extra nodes adjacent to all entry and exit nodes in all networks to implement this idea. For example, the network implemented in *Figure 4.2* has 8 extra nodes, namely nodes with IDs 2, 4, 6, 8, 88, 86, 38 and 40. These extra nodes are used to create small links to expand the main links by 1 foot. For example, the extra link with ID 1 joins nodes 1 and 2. This link is an expansion to the main link with ID 2, which joins nodes 2 and 46.

## 4.4 Implementation of Roundabouts

The implementation of roundabouts posed a set of difficulties since MITSIMLab does not have explicit support for the specification of rules regarding the right-of-way in roundabouts. On the other hand, MITSIMLab is not well documented, and the user guide available does not have sufficient information about a number of issues, including the design of roundabouts. We tested several ideas in order to represent the right-of-way rules for roundabouts as *Section 2.2* explains:

- Represent all links in all networks as urban links.
- Represent all links as freeway links.

- Represent all links as ramp links.
- Represent all links as ramp links excluding links which represent the roundabouts themselves, and represent links implementing the roundabouts as freeway links.

The first three attempts were unsuccessful, since the vehicles wishing to enter roundabouts did not give the right-of-way to the vehicles already inside the roundabouts when they should have yielded to them. The last attempt, which we implemented using ramp links for straight connections to junctions and freeway links for roundabout links, was successful. Hence, vehicles wishing to enter roundabouts yielded to vehicles inside the roundabouts. However, vehicles wishing to enter roundabouts still do not spend enough time waiting for vehicles approaching them in the roundabout before entering the roundabouts. Therefore, the yielding model did not work as realistically as it should have.

The parameters we had to adjust in our attempt to implement better roundabout behavior are as follows (MIT-ITS, 2001):

- **Parameters regarding the merging model**: The merging model parameters determine the behavior of each vehicle that is in the act of merging to a traffic stream. The parameters control the merging behavior of drivers within the merging region in the upstream link and the merging region in the downstream link, and the number of vehicles allowed to merge at one time.
- **Parameters related to nosing and yielding**: The nosing and yielding parameters control the probability of nosing vehicles to enter the next link on their destination path.
- **Parameters related to the probability of yielding to other vehicles**: These parameters control how drivers yield to other vehicles. We modified these parameters such that all vehicles yield to three vehicles instead of yielding at various probabilistic levels, i.e., yielding to no vehicles, yielding to one vehicle, yielding up to two vehicles, and yielding up to three vehicles.
- **Parameters for headway variance**: These parameters describe the aggressiveness of a driver for accepting a headway gap in changing lanes, merging, and car following.

*Figure 4.9* shows the set of parameters stored in `paralib.dat` files under each experiment directory that we modified. *Figure 4.10* shows the modified version of these parameters.

```
# MERGING
[Merging Model] = {
     100     # feet, upstream area
     200     # feet, downstream area
     8       # number of vehicles allowed
     0.2     # probability of aggressive merge from ramp
}
# PARAMETERS FOR NOSING AND YIELDING
[LC Nosing Model] = {
     1.0  \# max prob 2 in connection to next link
}
# PROBABILITY OF YIELDING TO OTHER VEHICLES
[MLC Yielding Probabilities] = {
     0.13    # None
     0.71    # Up to 1
     0.13    # 2
     0.03    # 3
}
# PARAMETERS FOR HEADWAY VARIANCE
[Headway Buffer Lower Bound] = 0.1  # seconds
[Headway Buffer Upper Bound] = 0.2  # seconds
```

**Figure 4.9**: Original set of parameters from the parameter configuration file, `paralib.dat`.

## 4.5 Roundabout Speed Limits and Roundabout Geometric Design

The speed limit and the geometrical dimensions of a roundabout affect both the operational performance and capacity of that roundabout. Therefore, speed limits and geometry should be chosen carefully. In our study, we based the values of these parameters on (W.Robinson et al., 2000). *Table 4.1* cites the values we used in this thesis.

**Table 4.1**: Parameters for the geometric design of roundabouts and speed limits in roundabouts.

| Parameter | Value |
|---|---|
| Number of roundabout lanes | 2 |
| Roundabout inscribed circle diameter | 180 ft |
| Roundabout speed limit range | 25–30 mph |
| Roundabout splitter island width | 20 ft |

```
# MERGING
[Merging Model] = {
     200   # feet, upstream area
     400   # feet, downstream area
     0     # number of vehicles allowed
     0.0   # probability of aggressive merge from ramp
}
# PARAMETERS FOR NOSING AND YIELDING
[LC Nosing Model] = {
     0.1  # max prob 2 in connection to next link
}
# PROBABILITY OF YIELDING TO OTHER VEHICLES
[MLC Yielding Probabilities] = {
     0.00    # None
     0.00    # Up to 1
     0.00    # 2
     1.00    # 3
}
# PARAMETERS FOR HEADWAY VARIANCE
[Headway Buffer Lower Bound] = 0.5  # seconds
[Headway Buffer Upper Bound] = 0.5  # seconds
```

**Figure 4.10**: The original set of parameters listed in *Figure 4.9* have been modified with the values given in this figure in order to help implement vehicle behavior in roundabouts.

*Figure 4.11* illustrates the geometric dimensions we used in our simulation models of roundabouts.

Please see *Appendix C*, *Appendix D*, and *Appendix E* for more details on the implementation of roundabouts in MITSIMLab.

## 4.6 Vehicle Demand, Green Time Interval, and Simulation Time

As *Section 3.2* discusses, in our work, each pair of compatible networks are simulated for a range of vehicle demand values $vd = [50..\,450]$ with an increment of 50 vehicles/hour and a range of green time intervals $ts = [10..\,120]$ with an increment of 10 seconds. So, we have 9 different $vd$ values and 12 different $ts$ values for a total of 108 experiments for each major intersection scenario. Since we considered 4 such major scenarios, the total number of individual intersection experiments were 432. Since roundabout experiments do not involve the $ts$ parameter, each major roundabout scenario only needed 9 individual experiments for a total of 36 roundabout experiments. Hence, we ran a total of 468 experiments. Every individual experiment simulates a 30-minute period.

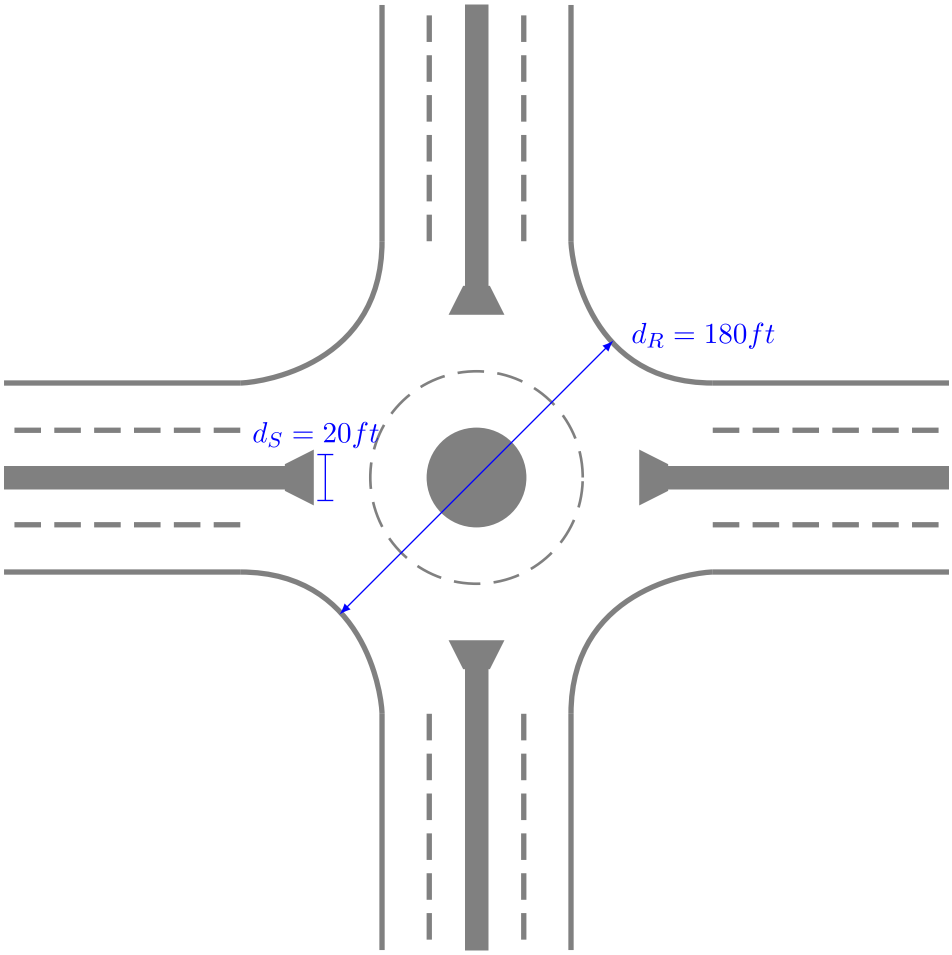


**Figure 4.11**: Roundabout dimensions: This figure shows geometric dimensions of a roundabout which it has 180 foot inscribed circle diameter ($d_R$) and 20-foot splitter island ($s_R$).

## 4.7 Updating of the MITSIMLab Source Code

MITSIMLab microscopic traffic simulator was developed circa 1999 and built last on the Redhat 7.3 GNU/Linux operating system. Due to advances in the GNU/Linux operating system in intervening years, the MITSIMLab source code became somewhat outdated. As a result of this, we were unable to build the MITSIMLab executables with the current state of the source code on latest GNU/Linux systems. In order to build the executables, we had to modify the source code by mostly making syntactic modifications to many source files. After succeeding in building the MITSIMLab system on the openSUSE 11.1 GNU/Linux operating system (openSUSE, 2009), we shared the modified MITSIMLab source code with the designers and maintainers of MITSIMLab at the MIT Civil Engineering Department. In turn, MIT researchers were able to build MITSIMLab on the Ubuntu 8.04 GNU/Linux operating system (Ubuntu, 2009). *Appendix F* provides detailed instructions on how to build

MITSIMLab on latest GNU/Linux systems using the modified source code (Sevay, 2009).

## 4.8 Automation of Experiment Generation and Result Analysis

Since we had to create different scenarios with varying parameters, we needed to automate the generation of experiments and the analysis of results. We organize each major scenario in a directory, which initially contains only a single directory with template files, from which all experiments for that major scenario are created with the help of scripts we implemented. Each individual experiment has a unique name that reflects the major parameters of that experiment. Each individual experiment is stored in a separate subdirectory under the major scenario directory along with its configuration files. When MITSIMLab runs the experiment configured in a given individual experiment directory, the output files are stored under the subdirectory belonging to that experiment. *Appendix A* lists some of the template files we created for generating experiments automatically.

For example, `intersection-3` is major scenario directory for all experiments with 3 signalized intersections. Under this directory, the `templates` directory stores the input template files that are used to generate the needed experiment directories (*Appendix A*), which are created under another subdirectory called `experiments`. For example, under `experiments`, a subdirectory named `intersection-3-vd-0350-ts-100` contains the setup for a 3-intersection experiment with a vehicle demand value of 350 vehicles/hour (per OD pair) and standard base green interval time of 100 seconds.

In the remainder of this section, we will briefly describe the main scripts that we created for these automation tasks.

- `genintersectionexperiments.sh` is a Bash shell script that generates intersection experiments in the given vehicle demand range `[vd_begin .. vd_end]` with an increment of `vd_inc` and green interval time range `[ts_begin .. ts_end]` with an increment of `ts_inc`.

```
Usage:  genintersectionexperiments.sh [options]
Options:
   -v vd_begin,vd_end
      Specifies the range of vehicle demand values to be used in
      generating experiments.
```

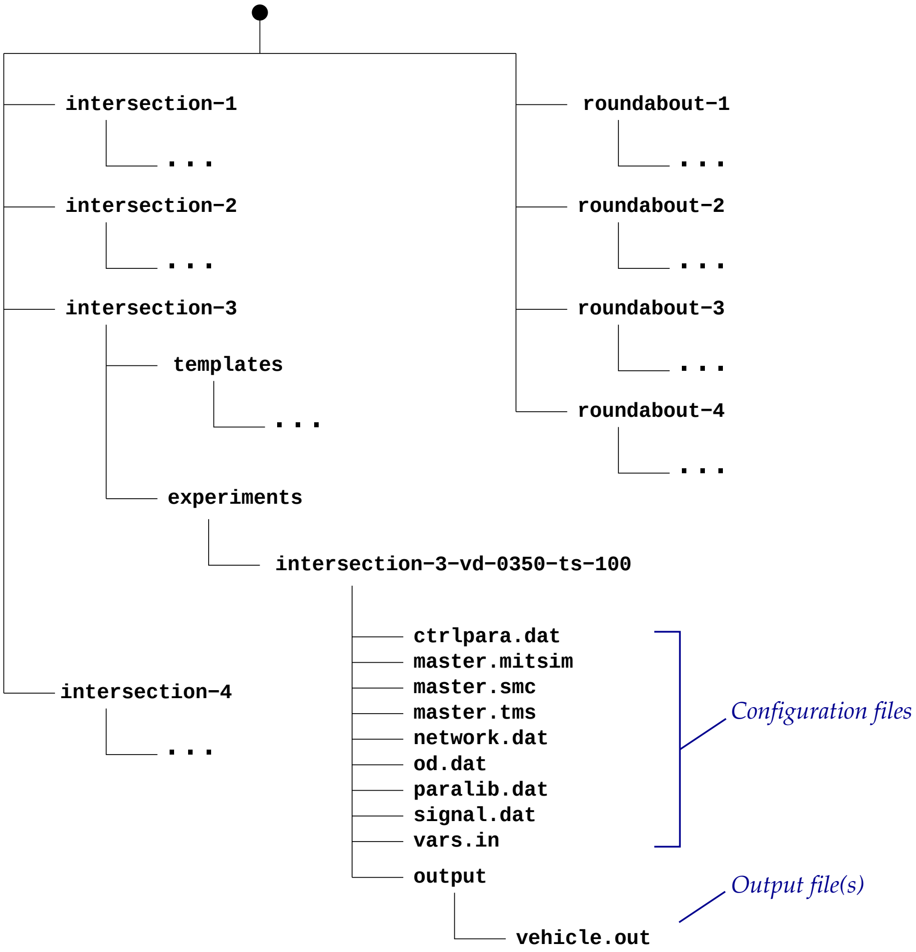


**Figure 4.12**: The directory structure of experiment directories where each major scenario is stored at the top level (`intersection-1`, `intersection-2`, `intersection-3`, `intersection-4`, `roundabout-1`, `roundabout-2`, `roundabout-3`, and `roundabout-4`). Each major scenario directory contains two main subdirectories, namely `templates` and `experiments`. The `templates` directory contains the template files for configuring each experiment with the given set of parameters, and the `experiments` directory contains all experiment subdirectories for that major scenario. The configuration files for each individual experiment directory is stored under a uniquely named directory, for example, `intersection-3-vd-0350-ts-100`, and each contains a subdirectory called `output`, where all output data that the simulator generates is stored, e.g., `vehicle.out`.

```
   -t ts_begin,ts_end
      Specifies the range of vehicle demand values to be used in
      generating experiments.
   -V vd_inc
      Vehicle demand increment
   -T ts_inc
      Signal timing increment
   -h
      Prints help and exists the script without doing anything.
```

- `genroundaboutexperiments.sh` is a Bash shell script that generates roundabout experiments in the given vehicle demand range `[vd_begin .. vd_end]` with an increment of `vd_inc`.

```
Usage:  genroundaboutexperiments.sh [options]
Options:
   -v vd_begin,vd_end
      Specifies the range of vehicle demand values to be used in
      generating experiments.
   -V vd_inc
      Vehicle demand increment
   -h
      Prints help and exists the script without doing anything.
```

- `runexperiments.sh` is a Bash shell script that runs experiments within a given vehicle demand range `[vd_begin .. vd_end]` in the current major experiment scenario.

```
Usage:  runexperiments.sh [options]
Options:
   -v vd_begin,vd_end
      Specifies the range of vehicle demand values to be used in
      generating experiments.
   -t
      Turns on TEST MODE. In test mode, no experiments are actually
      run, but the rest of the script operates. This mode can be used
      for testing the operation of this script.
   -P
      Turns on pausing before starting to execute experiments, so that
      the user can review the input parameters that will be used.
   -h
      Prints help and exists the script without doing anything.
```

- `analyze.sh` is a Bash shell script automates the collection of data from all experiment directories and generation of GNU Octave code that is used for statistical analysis. This generated GNU Octave code contains all necessary input data and call to statistical test functions.

## 4.9 Summary

This chapter presents our implementation of roundabouts and intersection networks and describes each network in detail to obviate that each pair of compatible networks are identical in terms of all aspects except for traffic management strategy used at junctions. Second, this chapter describes our modifications to the MITSIMLab source code to enable it to be installed under latest GNU/Linux operating systems. It discusses a number of deficiencies in MITSIMLab in regard to the operation in roundabouts. Finally, this chapter also describes the main software programs we designed and implemented for our work.

# CHAPTER 5

# RESULTS AND DISCUSSION

## 5.1 Overview

The major goal of this thesis is to study the impact of both roundabouts and signalized intersections on traffic flow performance based on individual vehicle travel times and average travel times for each traffic volume scenario. In order to measure the traffic flow performance in each situation, we analyze the data produced by the simulator from three perspectives. First, we statistically compare the individual vehicle travel times for all vehicles with completed trips in each compatible pair of roundabout-intersection experiment. Second, we statistically compare the average travel times between compatible roundabout and intersection experiments for each traffic volume value. Since the sequence of vehicles is identical for each pair of roundabout-intersection experiments, we do the analysis using a paired Student's t-test. Third, to get a wider perspective on each comparison, we compare the total number of vehicles that complete their trips between each compatible roundabout and intersection experiment.

## 5.2 Non-optimized and Optimized Traffic Signaling

This section presents the average travel times that result from non-optimized and optimized traffic signaling for different traffic volumes ([50 . . 450] vehicles/hour) and for all four network types with intersections that we used in our study.

*Table 5.1* presents the average travel times for a single intersection. The average travel times are very close in both the non-optimized and optimized case for all vehicle demand values.

*Table 5.2* presents the average travel times for the two-intersection scenario. The average travel times in the non-optimized case are consistently lower than those in the optimized case for all vehicle demand values, even though the difference between individual average

**Table 5.1**: Non-optimized and optimized average travel times for a single intersection

| vd | Non-optimized Average Travel Time | Optimized Average Travel Time |
|---|---|---|
| 0050 | 132.15 | 132.43 |
| 0100 | 133.97 | 133.64 |
| 0150 | 138.71 | 137.34 |
| 0200 | 141.74 | 142.84 |
| 0250 | 150.47 | 154.41 |
| 0300 | 204.27 | 204.64 |
| 0350 | 256.71 | 257.59 |
| 0400 | 312.67 | 307.69 |
| 0450 | 359.77 | 349.06 |

travel times is not high with respect to the magnitude of either average travel time.

**Table 5.2**: Non-optimized and optimized average travel times for 2 intersections

| vd | Non-optimized Average Travel Time | Optimized Average Travel Time |
|---|---|---|
| 0050 | 181.66 | 185.84 |
| 0100 | 238.24 | 294.01 |
| 0150 | 348.50 | 407.55 |
| 0200 | 447.07 | 471.80 |
| 0250 | 511.83 | 530.88 |
| 0300 | 564.47 | 582.91 |
| 0350 | 603.80 | 617.69 |
| 0400 | 644.62 | 648.32 |
| 0450 | 672.41 | 676.44 |

*Table 5.3* presents the average travel times for the three-intersection scenario. Except for the case when $vd$=50 (vehicles/hour), average travel times in the optimized case are consistently lower than those in the non-optimized case.

*Table 5.4* presents the average travel times for the four-intersection scenario. The average travel times in the optimized case are consistently lower than those in the non-optimized case for all vehicle demand values.

*Table 5.5* presents the statistical comparison of the values in the previous four tables, *Table 5.1*, *Table 5.2*, *Table 5.3*, and *Table 5.4*. The Student's t-test tells us that, in the single-intersection scenario, optimization does not produce an advantage. In the case of the two-intersection scenario, however, non-optimized traffic signaling produced statistically better results than optimized traffic signaling. However, as networks became more complex with 3 and 4 intersections, our optimization approach resulted in lower average travel times.

**Table 5.3**: Non-optimized and optimized average travel times for 3 intersections

| vd | Non-optimized Average Travel Time | Optimized Average Travel Time |
|---|---|---|
| 0050 | 238.47 | 249.08 |
| 0100 | 437.65 | 414.49 |
| 0150 | 565.41 | 531.07 |
| 0200 | 651.55 | 616.86 |
| 0250 | 688.27 | 680.64 |
| 0300 | 744.56 | 721.11 |
| 0350 | 769.20 | 751.27 |
| 0400 | 792.35 | 779.72 |
| 0450 | 816.44 | 797.19 |

**Table 5.4**: Non-optimized and optimized average travel times for 4 intersections

| vd | Non-optimized Average Travel Time | Optimized Average Travel Time |
|---|---|---|
| 0050 | 398.54 | 382.44 |
| 0100 | 622.37 | 601.67 |
| 0150 | 719.45 | 691.33 |
| 0200 | 780.01 | 765.45 |
| 0250 | 813.53 | 794.33 |
| 0300 | 853.24 | 842.16 |
| 0350 | 868.97 | 859.32 |
| 0400 | 884.41 | 885.94 |
| 0450 | 898.46 | 880.70 |

## 5.3 Best Green Time Intervals

This section presents the best green time intervals for all four intersection scenarios for each vehicle demand value that we simulated. The green intervals we simulated range from 10 seconds to 120 seconds. *Table 5.6* presents the best green time intervals for single-intersection experiments.

*Table 5.7* presents the best green time intervals for each of the simulated vehicle demand values in the two-intersection experiments. We note that only small green time interval

**Table 5.5**: t-test comparison of optimized and non-optimized traffic signaling: Negative values indicate a confidence result in favor of non-optimized traffic signaling, and positive values indicate a confidence result in favor of optimized traffic signaling.

| 1 Intersection | 2 Intersections | 3 Intersections | 4 Intersections |
|---|---|---|---|
| — | -95% | 99% | 99% |

**Table 5.6**: Best green interval time optimized based on average travel time for a single signalized intersection for different vehicle demand (vd) values.

| vd (#vehicles/hr) | Green Interval Time (sec) |
|---|---|
| 0050 | 010 |
| 0100 | 010 |
| 0150 | 010 |
| 0200 | 010 |
| 0250 | 010 |
| 0300 | 030 |
| 0350 | 060 |
| 0400 | 050 |
| 0450 | 060 |

values lead to the best average trip times.

**Table 5.7**: Best green interval time optimized based on average travel time for 2 signalized intersections for different vehicle demand (vd) values.

| vd (#vehicles/hr) | Green Interval Time (sec) |
|---|---|
| 0050 | 010 |
| 0100 | 020 |
| 0150 | 010 |
| 0200 | 020 |
| 0250 | 020 |
| 0300 | 030 |
| 0350 | 040 |
| 0400 | 060 |
| 0450 | 040 |

*Table 5.8* presents the best green time interval for each of the simulated vehicle demand values in the three-intersection experiments. We note that, compared to the two-intersection case, even smaller green time interval values lead to the best average trip times, except for the vehicle demand value of 450 vehicles/hour, for which the best green interval time interval was 100 seconds. As it turns out, the best three green interval times for $vd$=450 were within 5 seconds of each other, and the second best green time interval was 10 seconds, followed by the third best that was 20 seconds.

*Table 5.9* presents the best green time intervals for each of the simulated vehicle demand values in the four-intersection experiments. As networks grow in complexity, the best green time intervals become consistently small.

**Table 5.8**: Best green interval time optimized based on average travel time for 3 signalized intersections for different vehicle demand (vd) values.

| vd (#vehicles/hr) | Green Interval Time (sec) |
|---|---|
| 0050 | 010 |
| 0100 | 010 |
| 0150 | 010 |
| 0200 | 020 |
| 0250 | 020 |
| 0300 | 010 |
| 0350 | 020 |
| 0400 | 020 |
| 0450 | 100 |

**Table 5.9**: Best green interval time optimized based on average travel time for 4 signalized intersections for different vehicle demand (vd) values.

| vd (#vehicles/hr) | Green Interval Time (sec) |
|---|---|
| 0050 | 010 |
| 0100 | 010 |
| 0150 | 010 |
| 0200 | 010 |
| 0250 | 010 |
| 0300 | 020 |
| 0350 | 030 |
| 0400 | 010 |
| 0450 | 030 |

## 5.4 Statistical Comparison of Individual Vehicle Travel Times

In order to study the impact of roundabouts and signalized intersections on every single vehicle traveling through networks, we track individual vehicle travel times of all compatible networks, and we compare those vehicles one-to-one and analyze their travel times using the paired two-tailed Student's t-test.

*Table 5.10* demonstrates the statistical comparison of individual vehicle trip times between roundabouts and signalized intersections over various traffic volumes. The comparison involves four scenarios with 9 vehicle demand values for each scenario, where the vehicle demand varies in the range [50 . . 450] vehicles/hour with 50 vehicles/hour increments. The table presents the confidence level of t-test results for each scenario.

As *Table 5.10* indicates, roundabouts outperform signalized intersections with a statistical 99% confidence under all conditions considered.

**Table 5.10**: Individual t-test comparison of roundabouts versus signalized intersections: This table presents the statistical two-tailed paired t-test results of comparing individual vehicle trip times in 4 scenarios where the traffic volume varies between 50 vehicles/hour to 450 vehicles/hour. Each table cell indicates the confidence level of the performed t-test.

| vd | 1 Roundabout vs 1 Intersection | 2 Roundabouts vs 2 Intersections | 3 Roundabouts vs 3 Intersections | 4 Roundabouts vs 4 Intersections |
|---|---|---|---|---|
| 050 | 99% | 99% | 99% | 99% |
| 100 | 99% | 99% | 99% | 99% |
| 150 | 99% | 99% | 99% | 99% |
| 200 | 99% | 99% | 99% | 99% |
| 250 | 99% | 99% | 99% | 99% |
| 300 | 99% | 99% | 99% | 99% |
| 350 | 99% | 99% | 99% | 99% |
| 400 | 99% | 99% | 99% | 99% |
| 450 | 99% | 99% | 99% | 99% |

## 5.5 Statistical Comparison of Average Vehicle Travel Times

Besides comparing individual travel times of identical vehicles for each pair of compatible networks, we compare the performance of the same networks based on their average vehicle travel time performance.

*Figure 5.1* shows the average vehicle travel times for each type of general network and set of traffic volumes that we considered in our work. Note that roundabouts lead to consistently smaller average vehicle travel times than signalized intersections over all vehicle volumes we considered for all four major scenarios.

*Table 5.11* presents the statistical comparison of average vehicle travel times between roundabouts and signalized intersections. The t-test results show that roundabouts outperform signalized intersections with a statistical 99% confidence in 2, 3, and 4 road junctions. In the case of a single road junction, traffic flow was better through a roundabout than through a signalized intersections with a statistical 95% confidence. Therefore, when average travel times are considered, roundabouts outperformed signalized intersections in all cases.

## 5.6 Total Number of Completed Trips

In addition to statistical comparisons based on individual trip times and average trip times, we may gain additional perspective on the operational performance of roundabouts and

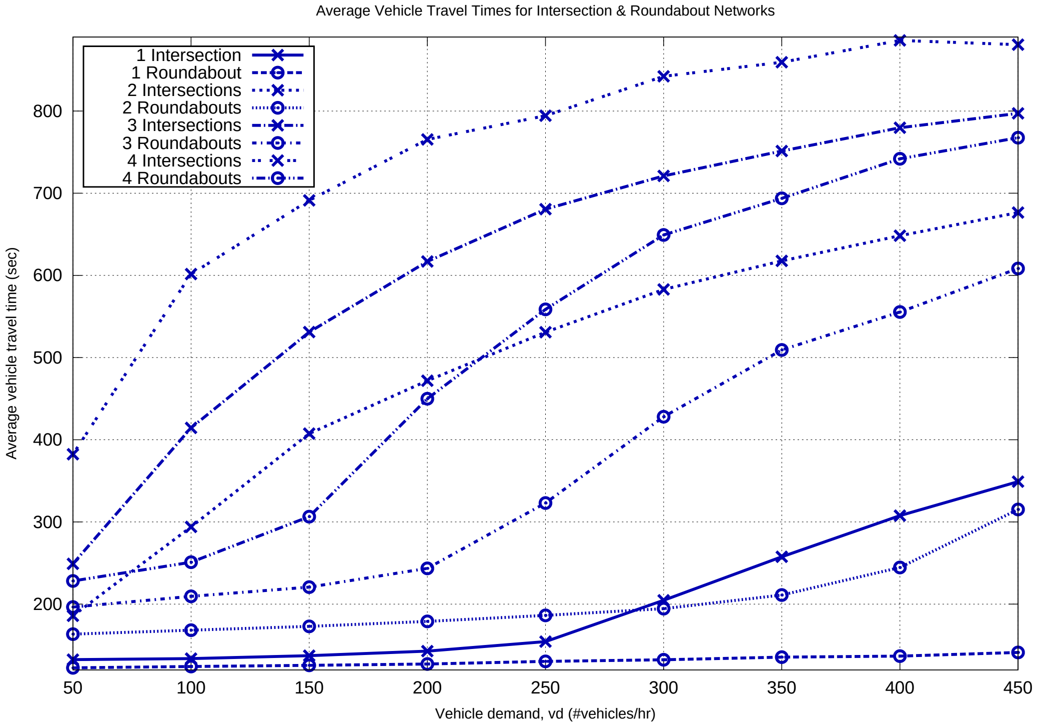


**Figure 5.1**: Average vehicle travel times for each general type of roundabout and signalized intersection scenario. The averages were computed over all tested vehicle volumes for each case.

**Table 5.11**: The confidence level of statistical two-tailed paired t-test comparisons of the four main network scenarios considered in this study, where travel times were averaged over all traffic volumes in each case as opposed to considering individual trip times for each traffic volume.

| 1 Roundabout vs 1 Intersection | 2 Roundabouts vs 2 Intersections | 3 Roundabouts vs 3 Intersections | 4 Roundabouts vs 4 Intersections |
|---|---|---|---|
| 95% | 99% | 99% | 99% |

signalized intersections by comparing the total number of trips completed in each pair of compatible scenarios. Since statistical comparisons only consider the intersection of vehicles that completed their trips in a pair of compatible roundabout-intersection experiments, vehicles not in the intersection are discarded. However, there is additional information in comparing the total number vehicles that completed their trips between a roundabout and an intersection experiment. All networks were simulated over vehicle demand values in the range [50 . . 450] as discussed in *Section 4.6*.

The first scenario compares a single roundabout network and a single signalized intersection network. *Table 5.12* lists the total number of vehicles with completed trips for each

**Table 5.12**: Number of vehicles with completed trips in 1-intersection and 1-roundabout experiments.

| vd | Intersection (I) | Roundabout (R) | Ratio $\frac{R}{I}$ |
|---|---|---|---|
| 50 | 261 | 267 | 1.02 |
| 100 | 541 | 544 | 1.01 |
| 150 | 820 | 821 | 1.00 |
| 200 | 1095 | 1104 | 1.01 |
| 250 | 1350 | 1375 | 1.02 |
| 300 | 1571 | 1656 | 1.05 |
| 350 | 1748 | 1924 | 1.10 |
| 400 | 1855 | 2198 | 1.18 |
| 450 | 1987 | 2469 | 1.24 |

type of network and the ratio of the number of completed trips in the roundabout to that of the intersection. From *Table 5.12*, we can conclude that the roundabout network enables only a slightly higher number of vehicles to reach their destinations compared to the signalized intersection.

**Table 5.13**: Number of vehicles with completed trips in 2-intersection and 2-roundabout experiments.

| vd | Intersection (I) | Roundabout (R) | Ratio $\frac{R}{I}$ |
|---|---|---|---|
| 50 | 650 | 656 | 1.01 |
| 100 | 1176 | 1341 | 1.14 |
| 150 | 1479 | 2010 | 1.36 |
| 200 | 1770 | 2678 | 1.51 |
| 250 | 1821 | 3341 | 1.83 |
| 300 | 1839 | 3980 | 2.16 |
| 350 | 1859 | 4602 | 2.48 |
| 400 | 1841 | 5064 | 2.75 |
| 450 | 1858 | 5129 | 2.76 |

The second scenario compares a two-roundabout network versus a two signalized intersection network. *Table 5.13* lists the total number of vehicles with completed trips for each type of network and the ratio of the number of completed trips in the roundabout to that of the intersection. The ratio of total number of vehicles with completed trips increases from almost 1 when traffic volume is relatively low to above 2 when traffic volume is 300 vehicles/hour and above. In addition, the ratio steadily increases in this case as traffic volume increases.

The third scenario compares a three-roundabout network versus a three signalized intersection network. *Table 5.14* lists the total number of vehicles with completed trips for each

**Table 5.14**: Number of vehicles with completed trips in 3-intersection and 3-roundabout experiments.

| vd | Intersection (I) | Roundabout (R) | Ratio $\frac{R}{I}$ |
|---|---|---|---|
| 50 | 1116 | 1205 | 1.08 |
| 100 | 1747 | 2455 | 1.41 |
| 150 | 2038 | 3665 | 1.80 |
| 200 | 2246 | 4800 | 2.14 |
| 250 | 2312 | 5338 | 2.31 |
| 300 | 2285 | 5352 | 2.34 |
| 350 | 2335 | 5387 | 2.31 |
| 400 | 2276 | 5483 | 2.41 |
| 450 | 1864 | 5413 | 2.90 |

type of network and the ratio of the number of completed trips in the roundabout to that of the intersection. The ratio of the total number of vehicles with completed trips increases from almost 1 when traffic volume is relatively low to above 2 when traffic volume is 200 vehicles/hour and above as *Table 5.14* indicates. Therefore, compared to the two-junction scenario, this ratio grew over 2 quicker, i.e., with less traffic volume than in the two-junction case. When the traffic volume is 450 vehicles/hour, almost 3 times as many vehicles complete their trips in the roundabout network compared to the intersection network. The ratio values are relatively steady for traffic volumes between 200 vehicles/hour and 400 vehicles/hour.

**Table 5.15**: Number of vehicles with completed trips in 4-intersection and 4-roundabout experiments.

| vd | Intersection (I) | Roundabout (R) | Ratio $\frac{R}{I}$ |
|---|---|---|---|
| 50 | 1549 | 1925 | 1.24 |
| 100 | 2099 | 3857 | 1.84 |
| 150 | 2406 | 5461 | 2.27 |
| 200 | 2448 | 5510 | 2.25 |
| 250 | 2465 | 5452 | 2.21 |
| 300 | 2501 | 5557 | 2.22 |
| 350 | 2382 | 5627 | 2.36 |
| 400 | 2363 | 5632 | 2.38 |
| 450 | 2274 | 5531 | 2.43 |

The final scenario compares a four-roundabout network versus a four signalized intersection network. *Table 5.15* lists the total number of vehicles with completed trips for each type of network and the ratio of the number of completed trips in the roundabout to that of the intersection. The ratio of the total number of vehicles with completed trips increases from almost 1.25 when traffic volume is relatively low to above 2 when traffic volume is only 150 vehicles/hour and above as *Table 5.15* indicates. Therefore, compared to the three-junction scenario, this ratio grew over 2 quicker. However, the ratio does not reach as high as 3 as in the three-roundabout case in *Table 5.14*. In addition, we note that the ratio of the number of completed in roundabouts to that in intersections in the four-junction networks remains relatively steady for all traffic volumes above 100 vehicles/hour.

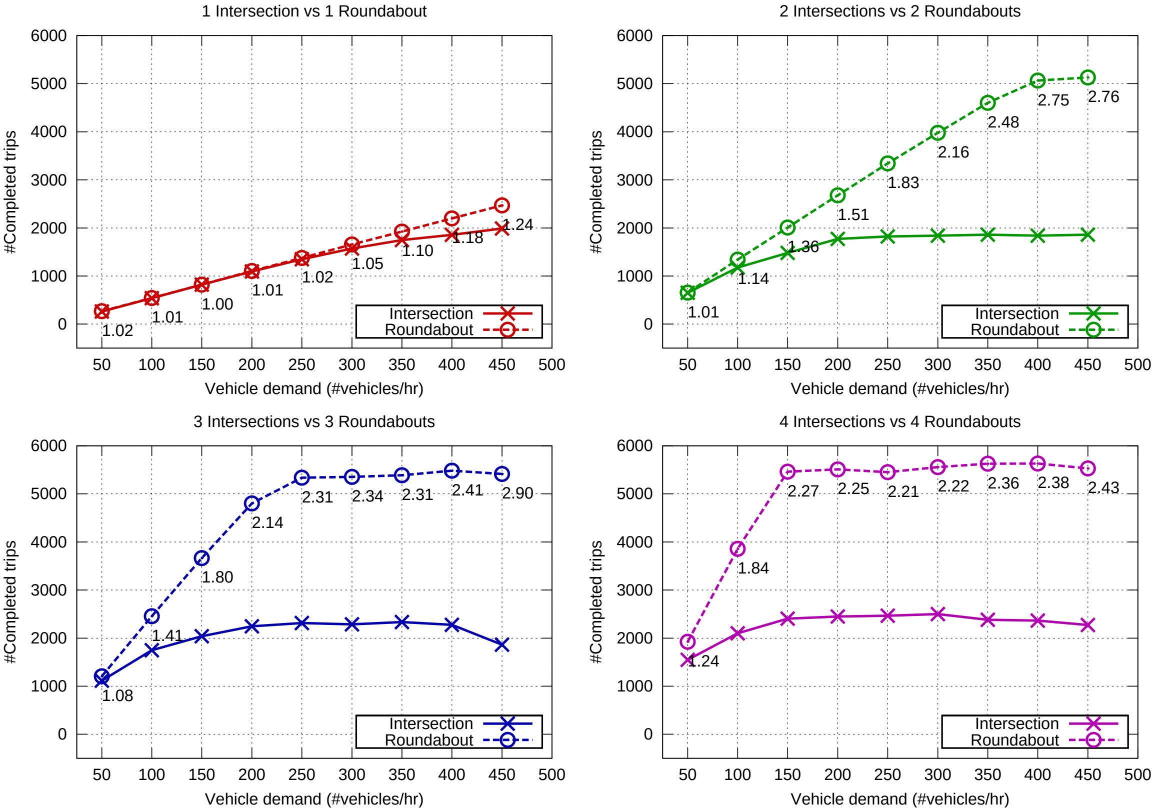


**Figure 5.2**: The graphs in this figure depict how the total number of trips vary as vehicle volume increases for each roundabout and intersection network. Traffic flow through a single roundabout is not drastically higher than the traffic flow through a single intersection. However, as the network has more junctions (two, three, or four), the ratio of the the total number of completed trips becomes more noticeable.

*Figure 5.2* summarizes the results presented in *Table 5.12*, *Table 5.13*, *Table 5.14*, and *Table 5.15* graphically.

## 5.7 Summary

This chapter presents the results of our work reported in this thesis and the evaluation done using statistical analysis. The chapter outlines two sets of results. First it presents the results of the Student's t-test that compared individual vehicle travel times one-to-one and average travel times one-to-one. The chapter shows that individual vehicles in roundabout networks had shorter trip times with 99% confidence, and that, in 2-, 3-, and 4-roundabout experiments, vehicles completing their trips had shorter average trip times than vehicles in intersection experiments with 99% confidence. The average trip times in single roundabout experiments were better than that in single intersection experiments with 95% confidence. In addition, this chapter presents simulation results that demonstrated that roundabouts enable a considerably higher number of vehicles to complete their trips than intersections. Hence, both sets of results show that roundabouts outperformed signalized intersections under all conditions.

# CHAPTER 6

# CONCLUSIONS

In this thesis, we compared the impact of roundabouts and pre-timed signalized intersections on traffic flow performance based on travel times of vehicles that complete their trips in a simulated environment. Using simulation in traffic research is a powerful method for studying the potential performance of new traffic infrastructures and traffic management approaches. In our work, we studied four fundamental networks with one, two, three, or four road junctions where junctions were implemented with either roundabouts or pre-timed signalized intersections. We used MITSIMLab for conducting our simulations (MIT-ITS, 2001).

We compared each compatible pair of networks with identical geometrical infrastructure except for the implementation of junctions. All corresponding networks had identical vehicle demand values, origin-destination pairs, link length, link ID, lane ID, lane usage rules, and speed limits. All links had two lanes in all experiments. We also modified the source code of the simulator so that an identical sequence of vehicles are created for each major scenario such that it would be possible to compare the performance of roundabouts to signalized intersections on a vehicle-to-vehicle basis.

Due to the limitation of the simulator, for signalized intersections, we created a basic method for optimizing the split 4-phase traffic signal timing plan used in the simulation models so that the best traffic flow in an intersection scenario could be compared to the corresponding roundabout experiment. The optimizing approach of traffic signals is based on assigning a factor for every traffic signal according to traffic volume that is expected to pass through that signal. We then use these factors in designing the green time plans for all traffic signals in each given scenario. We only considered green and red durations, since yellow behaved just as green in the MITSIMLab environment.

We faced difficulties in implementing roundabouts since MITSIMLab does not support explicit specification of right-of-way rules. On the other hand, we were able to successfully implement roundabouts using highway links and right-of-way rules for ramps in addition to modifications on default simulation parameters.

In order to study the impact of roundabouts and signalized intersections on traffic flow performance based on travel time, we varied the traffic volume through all networks in the range [50 . . 450] vehicles per hour for each origin-destination pair in each given network, and, we incremented this traffic volume by 50 vehicles per hour for each origin-destination pair.

We simulated the networks using the MITSIMLab microscopic traffic simulator (MIT-ITS, 2001). We also designed and implemented a set of special software programs to automate the generation of experiments and analysis of the data produced by simulation runs. We chose the MITSIMLab simulator due to it being an open source software with the set of features that were required for our study. Having access to the source code of the simulator enabled us to study its source code and modify it according to our needs. We ran a total of 468 simulation experiments, each of which simulated 30 minutes of traffic. Completion of all experiments took two days on a Pentium-4 PC with 1GB of RAM.

We compared each pair of roundabout-intersection networks with one, two, three, and four junctions using the Student's t-test statistic in two-tailed paired mode. With help from the MIT Civil Engineering Department, we modified the source of MITSIMLab so that vehicles entered into each type of simulation (one, two, three, or four junction) were generated randomly but using a fixed seed such that we could guarantee that each identical vehicle entered into two compatible networks would be identical in all aspects. For example, if vehicle 456 enters the simulation at node 32 and has as its destination node 56 at simulation clock time 10:05:05 in a one-roundabout experiment, then, in a one-intersection experiment, the same exact vehicle would be entered into the simulation with identical parameters. This approach allowed us to eliminate parameters regarding vehicles as a source of variation between any pair of compatible intersection and roundabout experiments.

We compared the traffic flow performance of intersections and roundabouts at two levels. First, we compared the travel time of each vehicle in an intersection experiment to that of the same vehicle in a compatible roundabout experiment. For this comparison we used vehicles that completed their trips in both experiments and discarded the vehicles not in the intersection set of both experiments. Therefore, these comparisons were one-to-one at vehicle level. Second, we compared, one-to-one the average travel times of all vehicles with completed trips from an intersection experiment to that from the corresponding roundabout experiment at all traffic volume levels we simulated.

The results of our statistical analysis show that, at individual vehicle level, the traffic flow based on travel times in roundabouts was always better than than in intersections for all types of networks tested with a statistical confidence of 99%. The comparison based on average travel times, on the other hand, revealed that roundabouts outperformed signalized intersections with a statistical 99% confidence in two-, three- and four-junction networks. In the case of single junction networks, the one roundabout network enabled better traffic flow than a single signalized intersection with 95% statistical confidence.

In addition to this statistical comparison of individual trip travel times and average travel times, we compared the total number of completed trips between any two pair of compatible intersection and roundabout experiments. The results show the number of completed trips in a roundabout network is always higher than the number of completed trips in the corresponding signalized intersection network. Moreover, our results indicated that, with road networks with multiple junctions, roundabouts can carry up to almost 3 times as many vehicles as in the case of signalized intersection networks with relatively high traffic volumes.

In summary, our work demonstrated that, with statistical confidence, roundabout networks that carry low-speed traffic outperform networks with signalized intersections.

## 6.1 Future Work

In this thesis, we studied the impact of roundabouts and pre-timed signalized intersections on vehicle travel times using hypothetical networks. This work can be expanded and improved to implement and study realistic traffic networks with real information about traffic volumes and traffic conditions.

The networks we compared had either roundabouts or signalized intersections. In the future, we can study a mixture networks including both roundabouts and signalized intersections within the same traffic system and hence study their impact on traffic flow performance.

Due to the limitations of the MITSIMLab simulator, the implementation of right-of-way rules in roundabouts was difficult. In addition, we could not create a better traffic timing plan, i.e., a 4-phase traffic signal timing plan, since MITSIMLab does not directly support lane-specific traffic signals. So, we can improve MITSIMLab to provide explicit high-level right-of-way rules and lane-specific traffic signals, which will enable the creation of 4-phase signal timing plans.

Parallelization in MITSIMLab is based on the Parallel Virtual Machine (PVM) interface. On the other hand, our local supercomputing facilities have support for Message Passing Interface (MPI). Therefore, implementing the MPI interface in MITSIMLab would provide great benefits for simulating more complicated networks and studying a variety of issues regarding traffic.

In our study, we compared roundabouts and intersections based on vehicles travel time as evaluation metric. In the future, we can expand our work to study the following issues:

- Study the impact of roundabouts and intersections on fuel consumption.
- Study the impact of roundabouts and adaptive traffic signals instead of pre-timed traffic signals.
- Study the impact of accidents in roundabouts and signalized intersections.
- Study the operational performance between existing roundabouts and signalized roundabouts based on vehicle travel time and fuel consumption in real settings.
- Study the impact of roundabout dimensions on traffic flow performance.
- Study the impact of the vehicle dimensions on the operational performance of roundabouts and signalized intersections.

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# APPENDICES

# APPENDIX A

# Example Input Template Files for MITSIMLab

This appendix lists the input files for MITSIMLab that we parameterized in order to be able to generate different experiments. Each such file serves as a template for a set of experiments.

A variable is of the form `__<variable-name>__` where `<variable-name>` is the name of the variable, e.g., `__DISPLAY__`. Then, in generating each experiment, we automatically replace each such variable with a specific value.

## A.1 Master SMC File (`master.smc`) Template

```
[Title] = "__TITLE__"

[Input Directory]                 = "__MAIN_DIR__"
[Output Directory]                = "__MAIN_DIR__/output"

[MITSIM] = {
        "master.mitsim" # master file
        "$HOST"         # host
        "__DISPLAY__"   # display
}

[TMS] = {
        "master.tms"    # master file
        "$HOST"         # host
        ""              # display
}

[Break Points] = {}
```

## A.2 Master TMS File (`master.tms`) Template

```
[Title] = "__TITLE__"

[Default Parameter Directory]     = "__MAIN_DIR__"
[Input Directory]                 = "__MAIN_DIR__"
[Output Directory]                = "__MAIN_DIR__/output"
[Working Directory]               = "__MAIN_DIR__/output"

[Network Database File]           = "network.dat"
[GDS Files]                       = {}
[Parameter File]                  = "ctrlpara.dat"
[Control Logic File]              = ""
[Signal Plan File]                = ""
[Control Logic]                   = 0
[Information]                     = 0
[Start Time]                      = __SIMULATION_START_TIME__
[Stop Time]                       = __SIMULATION_STOP_TIME__
[Step Size]                       = 0.1

[Console Message Step Size] = 60
[Segments] = 4 % Flow
[Signals]  = 0x01 % Traffic signals
[Sensor Types] = 0x2 % AVI sensors
[Sensor Color Code] = 3 % Occupancy
```

## A.3 Origin-Destination File (`od.dat`) Template

```
__SIMULATION_START_TIME__ 0 1.0
{
   /*--------Demand to node #3---------*/
   { 5 3 __VEHICLE_DEMAND_1__ }
   { 9 3 __VEHICLE_DEMAND_1__ }
   { 13 3 __VEHICLE_DEMAND_1__ }
   { 17 3 __VEHICLE_DEMAND_1__ }
   { 21 3 __VEHICLE_DEMAND_1__ }
   { 25 3 __VEHICLE_DEMAND_1__ }
   { 29 3 __VEHICLE_DEMAND_1__ }
   { 33 3 __VEHICLE_DEMAND_1__ }
   { 37 3 __VEHICLE_DEMAND_1__ }

   /*--------Demand to node #7---------*/
   { 1 7 __VEHICLE_DEMAND_2__ }
   { 9 7 __VEHICLE_DEMAND_1__ }
   { 13 7 __VEHICLE_DEMAND_1__ }
   { 17 7 __VEHICLE_DEMAND_1__ }
   { 21 7 __VEHICLE_DEMAND_1__ }
   { 25 7 __VEHICLE_DEMAND_1__ }
   { 29 7 __VEHICLE_DEMAND_1__ }
   { 33 7 __VEHICLE_DEMAND_1__ }
   { 37 7 __VEHICLE_DEMAND_1__ }

   /*--------Demand to node #11---------*/
   { 1 11 __VEHICLE_DEMAND_1__ }
   { 5 11 __VEHICLE_DEMAND_1__ }
   { 13 11 __VEHICLE_DEMAND_1__ }
   { 17 11 __VEHICLE_DEMAND_1__ }
   { 21 11 __VEHICLE_DEMAND_1__ }
   { 25 11 __VEHICLE_DEMAND_1__ }
   { 29 11 __VEHICLE_DEMAND_1__ }
   { 33 11 __VEHICLE_DEMAND_1__ }
   { 37 11 __VEHICLE_DEMAND_1__ }

   /*--------Demand to node #15---------*/
   { 1 15 __VEHICLE_DEMAND_1__ }
   { 5 15 __VEHICLE_DEMAND_1__ }
   { 9 15 __VEHICLE_DEMAND_1__ }
   { 17 15 __VEHICLE_DEMAND_1__ }
   { 21 15 __VEHICLE_DEMAND_1__ }
   { 25 15 __VEHICLE_DEMAND_1__ }
   { 29 15 __VEHICLE_DEMAND_1__ }
   { 33 15 __VEHICLE_DEMAND_1__ }
```

```
{ 37 15 __VEHICLE_DEMAND_1__ }

/*--------Demand to node #19---------*/
{ 1 19 __VEHICLE_DEMAND_1__ }
{ 5 19 __VEHICLE_DEMAND_1__ }
{ 9 19 __VEHICLE_DEMAND_1__ }
{ 13 19 __VEHICLE_DEMAND_1__ }
{ 21 19 __VEHICLE_DEMAND_2__ }
{ 25 19 __VEHICLE_DEMAND_1__ }
{ 29 19 __VEHICLE_DEMAND_1__ }
{ 33 19 __VEHICLE_DEMAND_1__ }
{ 37 19 __VEHICLE_DEMAND_1__ }

/*--------Demand to node #23---------*/
{ 1 23 __VEHICLE_DEMAND_1__ }
{ 5 23 __VEHICLE_DEMAND_1__ }
{ 9 23 __VEHICLE_DEMAND_1__ }
{ 13 23 __VEHICLE_DEMAND_1__ }
{ 17 23 __VEHICLE_DEMAND_1__ }
{ 25 23 __VEHICLE_DEMAND_1__ }
{ 29 23 __VEHICLE_DEMAND_1__ }
{ 33 23 __VEHICLE_DEMAND_1__ }
{ 37 23 __VEHICLE_DEMAND_1__ }

/*--------Demand to node #27---------*/
{ 1 27 __VEHICLE_DEMAND_1__ }
{ 5 27 __VEHICLE_DEMAND_1__ }
{ 9 27 __VEHICLE_DEMAND_1__ }
{ 13 27 __VEHICLE_DEMAND_1__ }
{ 17 27 __VEHICLE_DEMAND_1__ }
{ 21 27 __VEHICLE_DEMAND_2__ }
{ 29 27 __VEHICLE_DEMAND_1__ }
{ 33 27 __VEHICLE_DEMAND_1__ }
{ 37 27 __VEHICLE_DEMAND_1__ }

/*--------Demand to node #31---------*/
{ 1 31 __VEHICLE_DEMAND_1__ }
{ 5 31 __VEHICLE_DEMAND_1__ }
{ 9 31 __VEHICLE_DEMAND_1__ }
{ 13 31 __VEHICLE_DEMAND_1__ }
{ 17 31 __VEHICLE_DEMAND_1__ }
{ 21 31 __VEHICLE_DEMAND_1__ }
{ 25 31 __VEHICLE_DEMAND_1__ }
{ 33 31 __VEHICLE_DEMAND_1__ }
{ 37 31 __VEHICLE_DEMAND_1__ }

/*--------Demand to node #35---------*/
```

```
   { 1 35 __VEHICLE_DEMAND_1__ }
   { 5 35 __VEHICLE_DEMAND_1__ }
   { 9 35 __VEHICLE_DEMAND_1__ }
   { 13 35 __VEHICLE_DEMAND_1__ }
   { 17 35 __VEHICLE_DEMAND_1__ }
   { 21 35 __VEHICLE_DEMAND_1__ }
   { 25 35 __VEHICLE_DEMAND_1__ }
   { 29 35 __VEHICLE_DEMAND_1__ }
   { 37 35 __VEHICLE_DEMAND_1__ }

   /*--------Demand to node #39---------*/
   { 1 39 __VEHICLE_DEMAND_2__ }
   { 5 39 __VEHICLE_DEMAND_1__ }
   { 9 39 __VEHICLE_DEMAND_1__ }
   { 13 39 __VEHICLE_DEMAND_1__ }
   { 17 39 __VEHICLE_DEMAND_1__ }
   { 21 39 __VEHICLE_DEMAND_1__ }
   { 25 39 __VEHICLE_DEMAND_1__ }
   { 29 39 __VEHICLE_DEMAND_1__ }
   { 33 39 __VEHICLE_DEMAND_1__ }
}

<END>
```

## A.4 Signal File (`signal.dat`) Template

```
__SIMULATION_START_TIME__
{
   1 1 1 4 { # ID ControllerType SignalType NumEgresses
      16 { # {SignalIDs}
         /*------Traffic Lights Region #4------*/
                 26      // UP side
                 18      // Down side
                 22      // Left side
                 45      // Right side
         /*------Traffic Lights Region #3------*/
                 30      // UP side
                 14      // Down side
                 46      // Left side
                 43      // Right side
         /*------Traffic Lights Region #2------*/
                 34      // UP side
                 10      // Down side
                 44      // Left side
                 41      // Right side
         /*------Traffic Lights Region #1------*/
                 38      // UP side
                 06      // Down side
                 42      // Left side
                 02      // Right side
      }
      0 1 { # Offset NumPhases
      { 7 # NumIntervals
//                    Region#4         Region#3         Region#2         Region#1
//                ---------------  ---------------  ---------------  ---------------
__GREEN_TIME_1__{ 111 111 111 333  111 333 111 111  111 333 111 111  111 111 333 111 }
__GREEN_TIME_1__{ 333 111 111 111  111 111 111 333  111 111 333 111  333 111 111 111 }
__GREEN_TIME_1__{ 111 333 111 111  111 111 111 333  111 111 333 111  111 333 111 111 }
__GREEN_TIME_2__{ 111 111 333 111  111 111 111 333  111 111 333 111  111 111 111 333 }
__GREEN_TIME_1__{ 111 111 333 111  333 111 111 111  333 111 111 111  111 111 111 333 }
__GREEN_TIME_1__{ 111 111 333 111  111 111 333 111  111 111 111 333  111 111 111 333 }
__GREEN_TIME_3__{ 111 111 111 333  111 111 333 111  111 111 111 333  111 111 333 111 }

      }
      }
   }  # End of controller
}
```

## A.5 Variable File (`vars.in`) Template

```
__SIMULATION_START_TIME__       10:00:00
__SIMULATION_STOP_TIME__        10:30:00
__DISPLAY__                     ""
__TITLE__                       NEU–Roundabout-4
```

# APPENDIX B

# Fixed-Seed Randomization Code

This appendix lists the C++ source code that we used to generate random sequences with a fixed seed, such that each experiment is identically reproducible. This is a feature needed in comparing compatible intersection and roundabout experiments.

This code has been contributed to us by the researchers at MIT Civil Engineering Department, and we only made a few additional modifications to the code. Please see the source code below for specific acknowledgments.

```
#ifdef USE_FIXED_SEED
// Based on Samuil Hasan's (MIT Civil Engineering) modification suggestion (17mar2009)
//
long int Random::randomize()
{
   unsigned int s = 0xFF << (signature_ * 8);
   if (!(seed_ = (flags_ & s))) {
      const int MY_OTHER_FIX_SEED=257;
      seed_=MY_OTHER_FIX_SEED;
   }
   return seed_;
}

#else

long int Random::randomize()
{
  unsigned int s = 0xFF << (signature_ * 8);
  if (!(seed_ = (flags_ & s))) {
        seed_ = time(0);
  }
  return seed_;
}

#endif // USE_FIXED_SEED
```

# APPENDIX C

## Computation of a Link's Bulge

In MITSIMLab microscopic traffic simulator, the implementation of non-straight links are described using an angle called the bulge. *Figure C.1* illustrates a positive bulge, and *Figure C.2* illustrates a negative bulge. The angle of the bulge must be in radians.

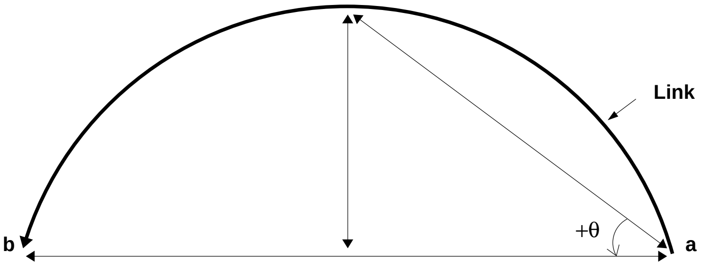

**Figure C.1**: Link with a positive bulge, A link that joins node a to node b with a positive bulge, where the angle $\theta$ is counterclockwise.

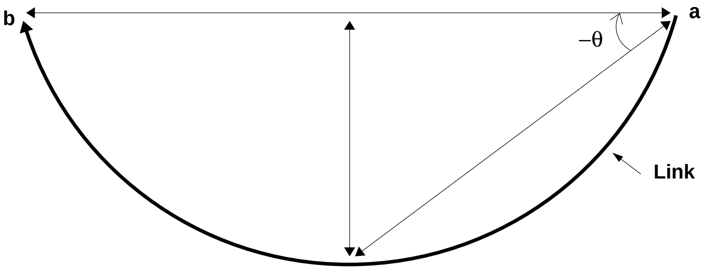

**Figure C.2**: Link with a negative bulge, a link that joins node a to node b with a negative bulge, where the angle $\theta$ is clockwise.

The angle of the bulge, $\theta$, varies according to the length of the link and the direction of that link. We compute the angle of the bulge for a roundabout link and splitter island according to both the diameter of that that roundabout and the width of the splitter island.

We derived equations to compute the bulge of roundabout links and splitter islands and to determine the offset of each link and splitter island from the center of the roundabout. *Figure C.3* illustrates the geometrical design of a roundabout, where $r$ is the radius of the roundabout, $\overbrace{bc}$ is the length of each roundabout link, and $\overbrace{ab}$ . is the width of the splitter islands.

The following equations determine step by step the bulge angle $\theta$ of the link $\overbrace{bd}$ in a roundabout. We use the same procedure for all roundabout links. From the sector $\overbrace{ab}$ in the circle:

$$\overbrace{ab} = 2\alpha * r \tag{C.1}$$

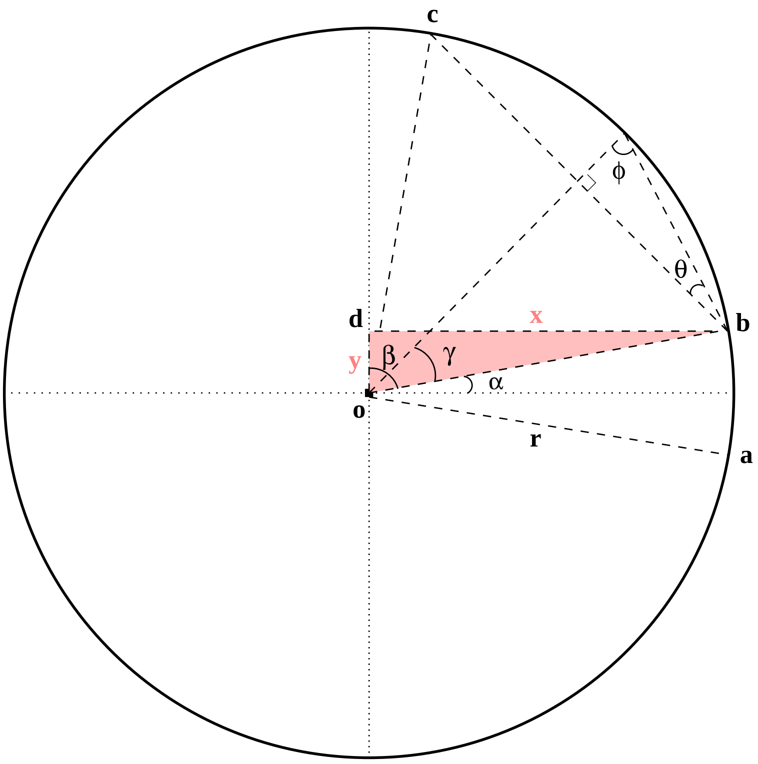

**Figure C.3**: Dimensions of roundabout design, $\overbrace{bc}$ is a link of the roundabout, $\overbrace{ab}$ is a splitter island, *r* is the radius of the roundabout, and $\theta$ is the bulge of the link $\overbrace{bc}$.

$$\Rightarrow \alpha = \frac{\overbrace{ab}}{2r} \tag{C.2}$$

$$\beta = \frac{\pi}{2} - \alpha \tag{C.3}$$

By substituting *Equation C.2* in *Equation C.3* we get:

$$\Rightarrow \beta = \frac{\pi r - \overbrace{ab}}{2r} \tag{C.4}$$

$$\gamma = \frac{\frac{\pi}{2} - 2\alpha}{2} \tag{C.5}$$

By substituting *Equation C.2* in *Equation C.5* we get:

$$\gamma = \frac{\frac{\pi}{2} - \frac{\overbrace{ab}}{r}}{2} \tag{C.6}$$

$$\gamma = \frac{\pi r - 2\overbrace{ab}}{4r} \tag{C.7}$$

$$\phi = \frac{\pi - \alpha}{2} \tag{C.8}$$

By substituting *Equation C.7* in *Equation C.8* we get:

$$\Rightarrow \phi = \frac{\pi - \frac{\pi r - 2\overbrace{ab}}{4r}}{2} \tag{C.9}$$

$$\phi = \frac{4\pi r - \pi r + 2\overbrace{ab}}{8r} \tag{C.10}$$

$$\phi = \frac{3\pi r + 2\overbrace{ab}}{8r} \tag{C.11}$$

$$\theta = \frac{\pi}{2} - \phi \tag{C.12}$$

By substituting *Equation C.11* in *Equation C.12* we get:

$$\theta = \frac{\pi}{2} - \frac{3\pi r + 2\overbrace{ab}}{8r} \tag{C.13}$$

$$\boxed{\theta = \frac{\pi r - 2\overbrace{ab}}{8r} \qquad \text{(C.14)}}$$

# APPENDIX D

# Computation of a Splitter Island Bulge

*Figure D.1* shows the expanded version of the sector $\overbrace{ab}$ in *Figure C.3* page 88, where $\sigma$ represents the bulge angle of the splitter island $\overbrace{ab}$.

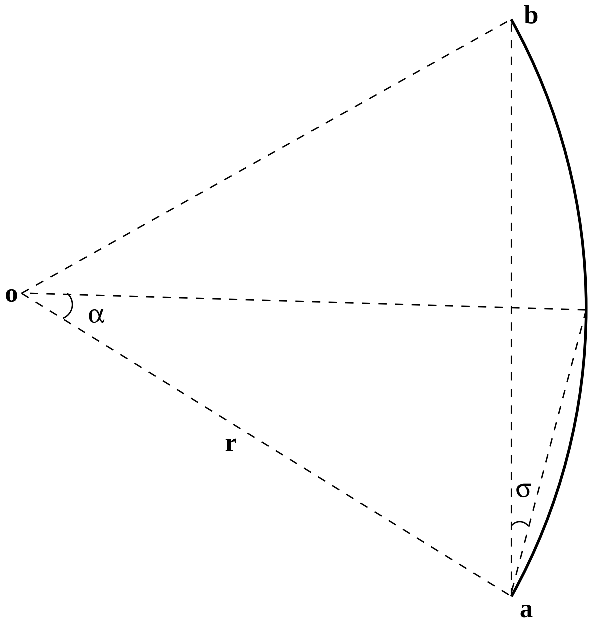

**Figure D.1**: Splitter island sector, $\overbrace{ab}$ is the splitter island, $r$ is the roundabout radius, and $\sigma$ is the bulge angle of the splitter island.

$$\sigma = \frac{\pi}{2} - \frac{\pi - \alpha}{2} \tag{D.1}$$

By substituting *Equation C.2* in *Equation D.1* we get:

$$\sigma = \frac{\pi}{2} - (\frac{\pi}{2} - \frac{\overbrace{ab}}{4r}) \tag{D.2}$$

$$\boxed{\sigma = \frac{\overbrace{ab}}{4r}} \tag{D.3}$$

# APPENDIX E

# Computation of the Coordinates of Links and Splitter Islands

To implement a link in MITSIMLab, one needs to determine the coordinates of the start and end points of each link. When one considers the design of roundabouts with splitter islands, the task of determining the coordinates of the start and end points of links and splitter islands in roundabouts becomes a more difficult task.

In this appendix, we derive the formulas that determine the offset of the start and end points of each link and splitter island from the center of a roundabout. Please refer back to *Figure C.3* on page 88 for the illustration of the dimensions used here.

By substituting *Equation C.2* in *Equation C.3* we get:

The x and y offset of the start and end points of links and splitter islands are:

From $\triangle \mathrm{obd}$,

$$\sin\beta = \frac{x}{r} \tag{E.1}$$

By substituting *Equation C.4* in *Equation E.1* we get:

$$\sin(\frac{\pi r - \overbrace{ab}}{2r}) = \frac{x}{r} \tag{E.2}$$

$$\boxed{x = r * \sin(\frac{\pi r - \overbrace{ab}}{2r})} \tag{E.3}$$

$$\cos\beta = \frac{y}{r} \tag{E.4}$$

By substituting *Equation C.4* in *Equation E.4* we get:

$$\cos(\frac{\pi r - \overbrace{ab}}{2r}) = \frac{y}{r} \tag{E.5}$$

$$\boxed{y = r * \cos(\frac{\pi r - \overbrace{ab}}{2r})} \tag{E.6}$$

# APPENDIX F

## How to Build MITSIMLab on GNU/Linux

This chapter provides a list of steps that are required to build and run MITSIMLab on a current GNU/Linux operating system such as openSUSE 11.1 or equivalent.

```
--------------------------------------------------------------------------------
A - Install Parser and Scanner Generators (FLEX++, BISON++)
--------------------------------------------------------------------------------

- Install BISON++

        Use bison++-1.21.11

        Download site:

           http://dir.filewatcher.com/d/Debian/Other/bison++_1.21.11.orig.tar.gz.543332.html

        Instructions:

           - You must be root to do 'make install' below

           tar zxvf bison++_1.21.11.orig.tar.gz
           cd bison++-1.21.11
           ./configure
           make
           make install

- Install FLEX++

        Use flex-2.5.35

        Download site:

           http://flex.sourceforge.net/

        Instructions:

           - You must be root to do 'make install' below

           ./configure
           make
```

```
make check
make install
```

- You must create a symbolic link named flex++:

```
ln -s /usr/local/bin/flex /usr/local/bin/flex++
```

## B - Install Graphics Libraries

- Install Xmt Motif Tools (XMT 4.00)

Use xmt400 (Provided with the distributed archive)

*** DO NOT USE Xmt310, which is part of the distributed archive!!!

Download site:

http://sourceforge.net/project/showfiles.php?group_id=13298

Instructions:

- No need to modify Xmt.tmpl

```
xmkmf
cd Xmt; xmkmf; make
```

- Do the following

```
cd clients; xmkmf; make
```

- However, do not worry if you get the following error message.

```
make[1]: *** No rule to make target ‘mockup.man’, needed by ‘mockup._man’. Stop.
```

- You must be root to do 'make install' below

```
make install
```

- You can type the following to run the demo.

```
cd clients; ./mockup demo
```

- Install XBAE 4.8.4

```
        Use Xbae-4.8.4 (Provided with the distributed archive)

        Instructions:

           - You must be root to do 'make install' below

           ./configure
           make
           make install

- Install ComboBox 1.32

        Use ComboBox-1.32 (Provided with the distributed archive)

           - You must be root to do 'make install' below

           make
           make install

- Install SciPlot 1.36-Qi

        Use SciPlot 1.36-Qi (Provided with the distributed archive)

           - You must be root to do 'make install' below

           make
           make install


- Install Motif Libraries from your GNU/Linux distribution

        openmotif               (OpenMotif executables, etc.)
        openmotif-devel         (OpenMotif development files)
        openmotif-libs          (OpenMotif libraries)

- Install PVM from your GNU/Linux distribution

        pvm                     (PVM executables, etc.)
        pvm-devel               (PVM development files)

- Install Xorg Development from your GNU/Linux distribution

        xorg-x11-devel
        xorg-x11-*-devel

        NOTE: * means all needed Xorg/X11 libraries
```

- Setting up the Motif Resource Files

  Create a symbolic link to Motif Resource Files

  ```
  ln -s <mitsim_install_dir>/lib/ad $HOME/lib/ad
  ```

- Build MITSIM executables

  First you must set up the Makefile variables in

  ```
     MITSIMLab/src/general.tmpl
  ```

  BASE_DIR: directory where you installed MITSIM

  INSTALL_DIR: directory where the binaries should be installed
  INSTALL_AD_DIR: directory where the Motif resource files will be installed

  ```
  cd MITSIMLab/src
  sh copy.working.sh
  make
  ```

- Create Symbolic Links to MITSIM Executables for PVM

  First create $HOME/pvm3/bin/LINUX
  PVM architecture is given under the third column in response to the

  ```
     conf
  ```

  command in PVM (i.e., after running PVM with the command, pvm).

  Then type the following commands at the command prompt:

  ```
     export PVM_EXPORT=$DISPLAY
     export PVM_ROOT=$HOME/pvm3

     PVM_BIN_HOME=$HOME/pvm3/bin/LINUX

     ln -s <mitsim-install-dir>/bin/linux $PVM_BIN_HOME
  ```

  where <mitsim-install-dir> is the directory where MITSIM main has been built, e.g., $HOME/MITSIMLab.

- Add $HOME/bin/linux to PATH in .bashrc

  ```
  export PATH=$PATH:$HOME/bin/linux
  ```

- Run PVM v3

```
pvm
```

At PVM prompt, type

```
conf
quit
```

- Run MITSIM Executable(s)

If your path variable is set up correctly, then you should be able to call any MITSIM executable with its name.

■