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Connected Cars and Traffic Flow Control



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Abstract

Intelligent Transport Systems (ITS) services are very useful in surface transportation, since they have the purpose of improving the traffic conditions and public services. In particular, the connected cars paradigm plays a key role in the evolution of the smart city, offering improvement in several field such as safety and efficiency.

In this thesis we will focus on the preliminary stage of a possible implementation of an ITS application, based on connected cars. This preliminary stage consists in collecting data regarding the traffic flows in different scenarios and different assumptions like straight road single lane, straight road double lane, roundabouts. In particular, we study and analyze the traffic flow behaviour in a crowded road and how an extraordinary event can affect the traffic shape. Our goal is to verify if we can use a queueing network model to represent the road. In this way, using our queue theory knowledges, we are able to improve traffic efficiency, travel comfort and safety. For example, if a car accident happens, we can suggest the other drivers to perform a lane changing in advance, in order to get away with long queues behind the obstacle.

In this project, in order to carry out the simulations of the urban environment and the traffic flows, Simulation of Urban Mobility (SUMO) package is used; indeed this simulator allows to manually create or edit a single road or a network and create a proper traffic flow. Moreover, the post-processing phase on the data is done through MATrix LABoratory (MATLAB).

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Chapter 1

Introduction

In recent years, the development of computers and telecommunications technologies has guided the Information and Communications Technology (ICT) researchers to be interested in transport systems, one of the most important sectors concerning our society. Especially for surface transportation, due the evolution of the Smart City, there are some important fields to be improved such as convenience, efficiency and safety.

For this reasons the Intelligent Transport Systems (ITS) [1] plays a very important role and it is largely used in this sectors.

The main aims of the above mentioned ITS are to improve the traffic conditions and public services, to decrease the probability of car accidents, since road traffic injuries are the leading cause of death for children and young adults aged 5-29 years [2], and to increase, for both drivers and pedestrians, travel comfort and traffic efficiency.

Moreover, thanks to the introduction of 5G Networks, ITS services are widely developed and reliable. In particular this thesis will focus on the traffic efficiency and travel comfort sector of ITS, analyzing the traffic flow along different scenarios and different assumptions. In this thesis simple simulation roads will be presented, with different configurations and both single and double lanes. Other simulation topologies will be presented, such as a simulation road including an obstacle along the path and a roundabout. The project consists in the use of Simulation of Urban Mobility (SUMO) package to perform our simulation; indeed this simulator allows to manually create or edit a single road or a network and create a proper traffic flow.

The basic idea is to divide the road in several sectors and collect the data from the simulator, in particular the travel time of each car and the time interval between cars. The next step will be to handle this data. In particular, performing post-processing analysis we are able

to draw the PDF of the travel time and the PDF of the interval time between cars. Our goal is to find a mapping between data and queue theory, in order to apply the theory knowledge in the real situation, especially to improve traffic efficiency, traffic comfort avoiding long queues and cooperation in case of car accidents.

The thesis is organized as follows:

- In Chapter 2 framework and reference scenario are presented: fundamentals of queue theory, SUMO overview, traffic demand and concept of traffic flow.
- In Chapter 3 the simulation methodology is presented: after the description of the post-processing phase on the simulation logs, we introduce the first simulation settings and the general assumptions, concluding with the presentation of simulation results.
- In Chapter 4 a new simulation road is presented: after the introduction of the simulation settings and the general assumptions, we introduce the first set of results. Then, after a briefly description of TraCI tool, the second set of results is presented.
- In Chapter 5 a completely different topology is presented, providing the first simulation settings and the general assumptions to simulate a roundabout. Moreover, two different kind of roundabouts are presented, concluding with the presentation of simulation results.

Chapter 2

Framework and reference scenario

In this chapter the preliminary notion and the background simulation environment are presented: after a briefly introduction of queue theory in section 2.1, in section 2.2 will be provided a general overview of SUMO simulator. In section 2.3 the definition of traffic demand is presented, instead section 2.4 describes the reference simulation road and the arrival rate for traffic flows used to carry out simulations.

2.1 Elements of queueing theory

As already said in chapter 1, the basic idea is to divide the simulation road into several sectors and, for each of them, collect the data from SUMO output file. In order to study the simulated system, each sector is considered as a single queue.

A queue [3] is a system represented like in Fig.2.1, where it is possible to distinguish the clients arrival (representing by the vehicles in our simulations), a waiting queue, a service, and the clients departure. Customers arrive to the service facility, receive service and then depart.

2.1.1 Kendall's notation

The notation used to classify the queueing models is the one proposed by Kendall. It uses six indicators $A/B/c/d/e-f$ with the following meaning:

- A represents the stochastic process describing the client arrivals. In particular, we classify the kind of stochastic distribution of the time intervals between two consecutive arrivals. In our case A assume the value M - continuous time Markovian

arrival process, interarrival times with negative exponential probability density function, arrivals according to a Poisson process.

- B represents the stochastic process describing the service times. In our case B assume the value M; each client requires to the server a service whose duration is an independent random variable with negative exponential probability density function.
- c indicates the number of servers providing the service, in our case one.
- d describes the capacity of the waiting queue.
- e indicates the number of elements in the clients population.
- x indicates the queue discipline, that is the rule followed to choose the next client to be served among the ones in the waiting queue.

The parameters d and e are indicated only if they are different from ∞ . The parameter x is indicated only if the queue discipline is not FIFO - First In First Out. Consequently, we can model each sector of the simulation road as a $M/M/1$ queue.

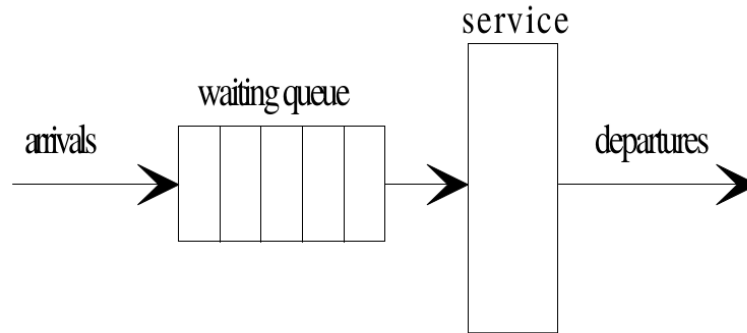


Figure 2.1. A queue

2.1.2 Poisson arrivals

The customer arrival process may be described by characterizing the number of arrivals per unit time or by characterizing the time between successive arrivals (the interarrival time). We use the variable λ to denote the mean arrival rate ($1/\lambda$ denotes the mean time between arrivals). If the arrival pattern is not deterministic, the input process is a stochastic

process, which means that we need its associated probability distribution. In stochastic modelling, a lot of random variables are frequently modelled as exponentials, such as interarrival time; reasons for the use of exponential distribution include:

- its memoryless property and resulting analytical tractability.
- its relationship to the Poisson process.

Indeed a Poisson process having a rate λ is a counting process with independent and stationary increments, and it is such that the number of events that occur in any time interval of length t has a Poisson distribution with mean λt . Moreover the interarrival times are independent and identically distributed. If the arrival process is a Poisson process, then the associated random variable defined as the time between successive arrivals (the interarrival time) has an exponential distribution.

2.2 SUMO overview

SUMO [4][5] is a free and open traffic simulation suite which is available since 2001. SUMO allows modelling of intermodal traffic systems including road vehicles, public transportation and pedestrians. It is a microscopic traffic simulator that can be enhanced with custom models and provides various APIs to remotely control the simulation.

In SUMO the road network is described in a proper file `.net.xml` that specifies all the roads belonging to the same network topology; each route is defined as edge, setting its length, shape, speed limits, number of lanes, and the connections between other roads. This file can be generated through NETEDIT tool, a visual editor within the SUMO package for street networks, traffic lights, and further network elements.

SUMO require also a so-called traffic demand to actually simulate traffic in the road; in other words we have to provide the description about vehicles behavior in the network. Modelling of the traffic demand can be done in a proper file `.rou.xml` that contains both the set of routes that each vehicles can go through and all the information about vehicle type and physical properties, such as vehicle ID, speed, acceleration, departure time, dimensions etc.

The simulation is started with the command `sumo` or `sumo-gui` to open the graphical user interface, providing as input the configuration file `.sumo.cfg`, that must be contain the network file `.net.xml`, the route file `.rou.xml`, and the time duration of the simulation.

SUMO, during the simulations, generate a huge number of different measures and collect

it into files triggered by command line options. One of the most common output file is the Floating Car Data output file (FCD), a vehicle-based information file in which we can read all the dynamics of vehicles, such as their position on the road, speed, heading, timestamp. All output file written by SUMO are in XML-format.

Moreover, SUMO has been continuously developed and it provides the user with a large number of tools such as Traffic Control Interface (TraCI) to control and interact with the simulation in an online way.

2.3 Vehicular demand for SUMO

Before starting, a vehicular demand in .rou.xml file must be defined, as already mentioned in 2.2, setting all the parameters usefull to carry out simulations. It is possible to define the demand file manually or to edit generated files with a text editor. A vehicle in SUMO consists of three parts: a vehicle type which describes the vehicle's physical properties, a route the vehicle shall take, and the vehicle itself. In this section we will focus on vehicle's physical properties.

A vehicle is defined using the <vType> attributes to write in .rou.xml file. There are huge available <vType> parameters and the most relevant ones have the following meanings:

- id, the name of the vehicle type.
- accel, the acceleration ability of vehicles of this type that in our case is fixed at 2.9 m/s^2 .
- decel, the deceleration ability of vehicles of this type that in our case is fixed at 7.5 m/s^2 .
- minGap, empty space in meters after leader that in our case is fixed at 1.0 m , as shown in Fig.2.2.
- tau, this parameter is intended to model a drivers desired time headway in seconds. Drivers attempt to maintain a minimum time gap of tau between the rear-bumper of their leader and their own front-bumper + minGap to assure the possibility to brake in time when their leader starts braking and they need tau seconds reaction time to start braking as well. In our case it is fixed at 0.05 s .

- length, the vehicle's length in meters that in our case is fixed at 4.0 *m*.
- width, the vehicle's width in meters that in our case is fixed at 1.8 *m*.

For other attributes not listed above a default value is applied.

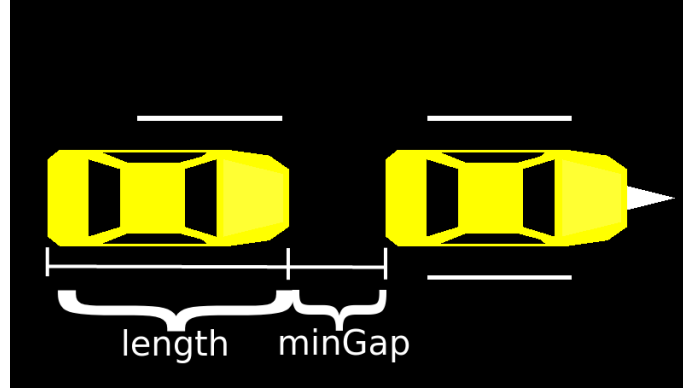


Figure 2.2. minGap parameter

2.3.1 Speed distributions

The desired driving speed, that we call v usually varies among the vehicle of a fleet. In SUMO this is modeled by a speed distribution using two parameters of `<vType>`:

- speedFactor f
- speedDev d

This two value are used to drawn a coefficient c from a normal distribution $c \in N(f, d)$.

In particular, the final value v is obtained multiplying the speed limit of the road, that in our case is fixed at 50 *Km/h*, by the coefficient c :

$$v = c \cdot speedLimit$$

Of course there are both upper and lower bound in the range of coefficient c in order to avoid vehicles too slow and vehicles too fast. Futhermore, the vehicle speed is also capped at the maximum speed declared by the manufacturer. Finally, in our simulations, we fix a speedFactor $f = 1$ and a speedDev $d = 0$ in order to have $c \in N(1, 0)$ that correspond to default value of SUMO. In this configuration it is clear that all vehicles try to reach the same driving speed.

2.4 Reference scenario

The reference topology we consider, depicted in Fig.2.3, is a straight urban road. It was created through the already mentioned NETEDIT tool, in order to generate the proper file .net.xml. It is 1200 meters long and the entities moving in the topology are vehicles, following a straight path. This urban topology is very simple but, at the same time, allows us to have representative scenario which closely mimics many real-world traffic flows behaviour.



Figure 2.3. Screenshot of the simulated scenario in SUMO

As said before, we have to define also the traffic flow behaviour inside the road in a .rou.xml file. In order to obtain such a flow description, several methods can be exploited, such as randomization; in our case it is generated through a Python script. An important features of the above mentioned file is that for each vehicle we can define its departure time in the simulation, having the possibility to create different traffic flows at different rate.

In our simulation vehicles arrive according to a Poisson process [6] with rate λ so the interarrival time between vehicles follow a negative exponential probability density function with mean $1/\lambda$. In order to have realistic mobility pattern and reliable results, we have to run the simulations with a proper value for the vehicular generation rate λ , choosing it in such a way that the simulated scenario is stable; in particular, the average number of vehicles should never start clogging the road. To properly individuate the

arrival rate values that guarantee stability in our simulation we have to look at the linear region; in other words, the region for which the average number of vehicles in the road grows linearly with the generation rate λ .

Fig.2.4 shows the dependence of the number of vehicles from λ , in which there is a saturation of the road for λ above 2.5. Consequently, for all the simulations, we must choose the vehicular generation rate λ below 2.5.

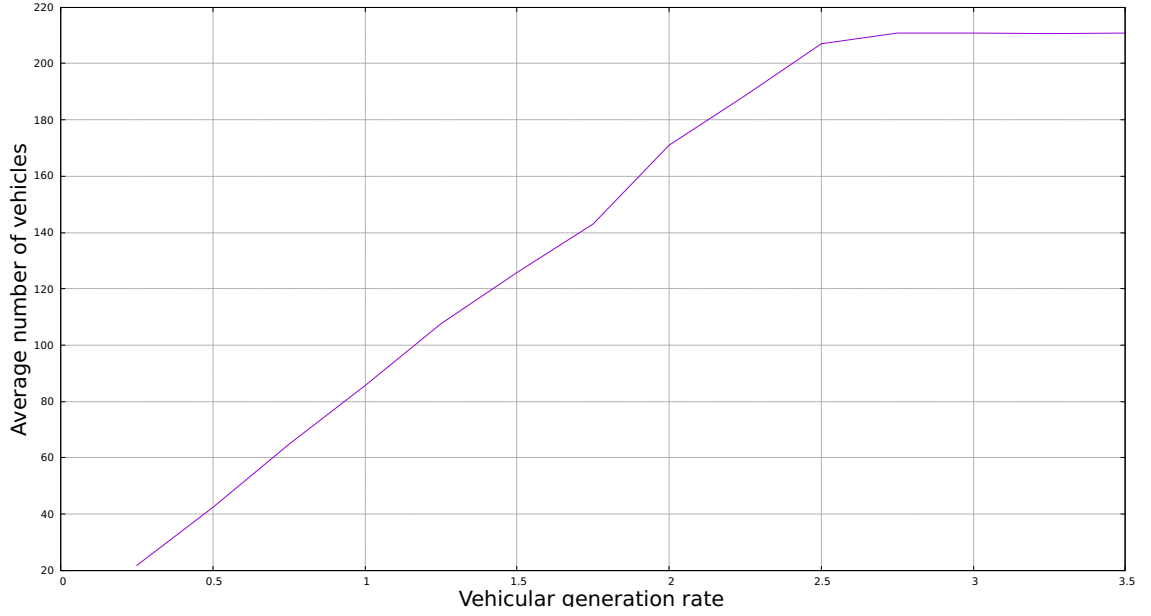


Figure 2.4. Evolution of the average number of vehicles in the road

Chapter 3

Simulation methodology

In this chapter, we first describe the approach we adopted to process the simulation logs in order to derive the main metrics of interest, introducing the concept of goodness-of-fit test. We then describe the simulation settings we used and the general assumptions to carry out the simulation runs. Finally, the simulation results are presented in three different scenarios, scenario A, B, and C.

3.1 Processing the simulation logs

During the simulations, SUMO generate the Floating Car Data (FCD) output file, triggered by command line option `--fcd-output<FILE>` where `<FILE>` is the file name. For each sector of the simulation road, that we will see later, we collect the dynamics of vehicles. In particular, the FCD export contains location and speed along with other information for every vehicle in the network at every time step. This output, XML-format, behaves somewhat like an accurate high-frequency Global Positioning System (GPS) for each vehicle. However, through python tool `xml2csv.py`, within SUMO, we convert the file to a flat-file (CSV) format which can be opened by any spread-sheet software.

In particular, performing post-processing analysis through python scripts and program in C language, we start by measuring the following information:

- travel time to cover a sector in seconds; this time is computed for each vehicle running the simulation.
- time interval between vehicles at each stopwatch in seconds; this time is computed for any general pair of vehicles running the simulation.

Moreover, we run our simulation for 700 seconds, in order to increase the number of vehicles running the simulation and the stored measurements as well.

3.1.1 Statistical analysis - Probability Density Function

This two measurements are two random variables and we can perform some statistical analysis by computing the Probability Density Function (PDF) [7]. Indeed, it is a statistical expression that defines a probability distribution for a random variable. When the PDF is graphically portrayed, the area under the curve will indicate the interval in which the variable fall. More precisely, since the absolute likelihood of a continuous random variable taking on any specific value is zero due to the infinite set of possible values available, the value of a PDF can be used to determine the likelihood of a random variable falling within a specific range of values. Furthermore the PDF is a positive function since the Cumulative Distribution Function (CDF) is an increasing function. Indeed, PDF is the derivative of CDF.

This is done through MATrix LABoratory (MATLAB) [8] environment in which we load the file containing all the already mentioned measurements. MATLAB is a multi-paradigm numerical computing environment that allows matrix manipulations, plotting of function and data, implementation of algorithms, creation of user interface, and interfacing with programs written in other languages. In particular, we use the specific command histogram in MATLAB. Histograms are a type of bar plot for numeric data that group the data into bins. Once we create the histogram object, it can be possible to modify aspects of the histogram by changing its property values. This is particularly useful for quickly modifying the properties of the bins or changing the display. There are different available syntax for the command histogram in MATLAB to control the appearance and behavior of the histogram. By changing property values, we can modify aspects of the histogram. We can specify, within the command, additional options with one or more <name,value> pair arguments, such as <'BinWidth',value> to adjust the width of the bins. In our particular case we use <'Normalization','pdf'> as pair argument in order to plot an estimate of the PDF input data, our measurements.

Indeed, 'pdf' normalization specifies the following meaning, for each bin i :

$$v_i = \frac{c_i}{N \cdot w_i}$$

where

- v_i is the bin value.

- c_i is the number of elements in the bin.
- w_i is the width of the bin.
- N is the number of elements in the input data.

The area of each bar is the relative number of observations. The sum of the bar areas is less than or equal to 1.

3.1.2 Goodness of Fit

As already mentioned in section 2.1, our goal is to estimate the PDF of the measurements and obtain an exponential distribution for the time interval between vehicles at each stopwatch. The reason is that exponential distribution it is very simple to manage, with some good properties such as memoryless. Indeed we can study its relationship to the Poisson arrival process, improving traffic efficiency and cooperation among vehicles. To verify that our set of measurements shares stochastic characteristics with a real PDF we use a goodness of fit test.

The Goodness of Fit (GOF) [9] of a statistical model describes how well it fits a set of observations. Measures of goodness of fit typically summarize the discrepancy between observed values and the values expected under the model in question, in our case the exponential distribution. In other words we test whether two samples are drawn from identical distributions. In particular, we perform the test through MATLAB, typing the command `lillietest`. Given a hypothesis H_0 (e.g., data comes from an exponential distribution), we define a level of significance α of the test as:

$$\alpha = P(\text{reject } H_0 \mid H_0 \text{ true})$$

where H_0 is called 'null hypothesis'.

The `lillietest` function returns a test decision for the null hypothesis H_0 that the input data comes from a distribution family, against the alternative that it does not come from such a distribution, using a Lilliefors test as goodness of fit. The result is 1 if the test rejects the null hypothesis at the α (%) significance level, and 0 otherwise. As in the previous command `histogram`, we can specify additional options within the command, in order to change the significance level or change the distribution family. For example, in our case we use `<'Distribution','exp'>` as pair argument.

3.2 Simulation settings and general assumptions

We build several scenarios with different settings and, for each of them, we run one 700s-long simulation. The simulation road, depicted in the following figures, is 1200 meters long, formed by 10 100-meter-long sectors (splits) plus a transient 200-meter-long sector at the entrance. The transient sector at the entrance assume a very important role for the simulation because it represent the transient phase of the traffic flow. In this sector, vehicles adjust their departure speed in order to have a cooperation with other driver that share the same road. Indeed, the departure speed for each vehicles is selected by drawing a random number between 30 Km/h and 40 Km/h following a uniform distribution. Then, vehicles will accelerate and will try to reach the desired driving speed v , as explained in section 2.3.1. At the end of each split, there is a stopwatch to measure both travel time for each sector and time interval between vehicles at each stopwatch. Moreover, vehicle arrivals follow a Poisson process with a rate λ , different for each scenario. Finally, this assumptions refer to all the following scenarios.

3.3 Simulation results

Below, several scenarios are presented, with different simulation settings and different veicular arrival rate. In scenario A we build the basic case, single lane; instead in scenario B and scenario C we simulate a double lane road with different routing policy among the lanes.

3.3.1 Scenario A

The first simulated scenario, namely scenario A and depicted in Fig. 3.1, is the very basic case. In this scenario, there are just a couple of parameters to highlight; the simulation road, descripted above, is formed by a single lane and vehicles arrive at a rate $\lambda = 1.0$.

Fig. 3.2 shows the PDF of the travel time to cover a single 100-meter-long sector. As already said, the simulation road is formed by 10 back to back sectors but, for simplicity, we plot only the relevant ones. Split 1 from 200 m to 300 m (top left), split 5 from 600 m to 700 m (top right), split 8 from 900 m to 1000 m (bottom left), and split 10 from 1100 m to 1200 m (bottom right). The important result that we highlight is that we obtain an almost "flat" PDF. It means that the driving speed is almost the same for all vehicles and they take almost the same time to cover a single 100-meter-long split. This is due to the fact that in

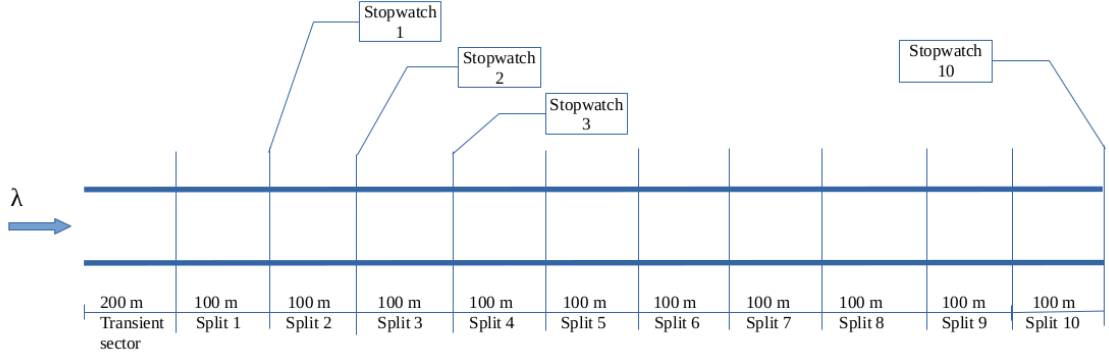


Figure 3.1. Scheme of scenario A

section 2.3.1 we set speedDev $d = 0$ so, travelling at 50 km/h they take circa 7 seconds to cover a 100-meter-long split. As a consequence the bin in the plot are very tight (5 ms).

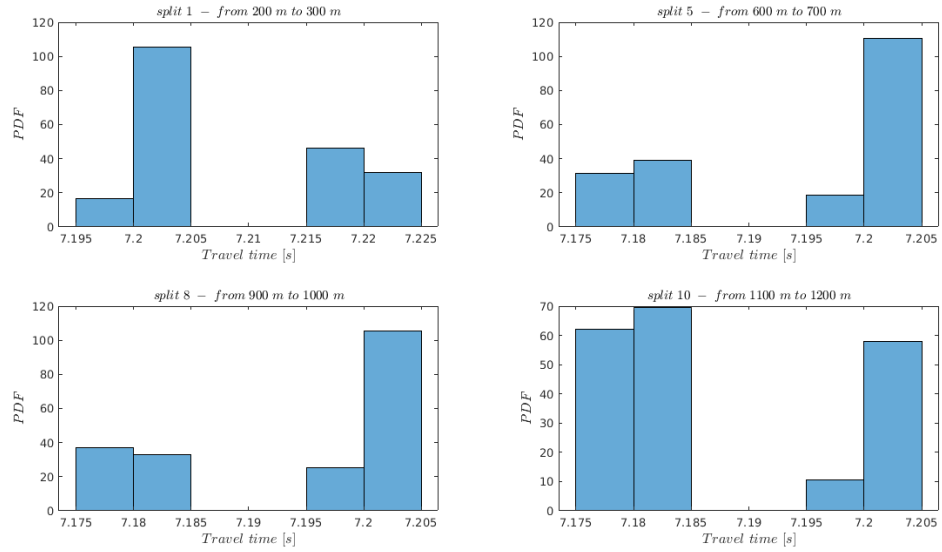


Figure 3.2. PDF of the travel time for scenario A

Instead, Fig. 3.3 shows the PDF of the time interval between vehicles at each stopwatch. As in the previous figure, for simplicity, we plot only 4 stopwatches, the most relevant ones. The most important result that we highlight is that, performing the goodness-of-fit test as explained in section 3.1.2, all of them "fit" an exponential distribution family at the

1% significance level. Indeed, we can notice that the exponential shape is held at each stopwatch, from the beginning of the road (stopwatch 1) till the end (stopwatch 10).

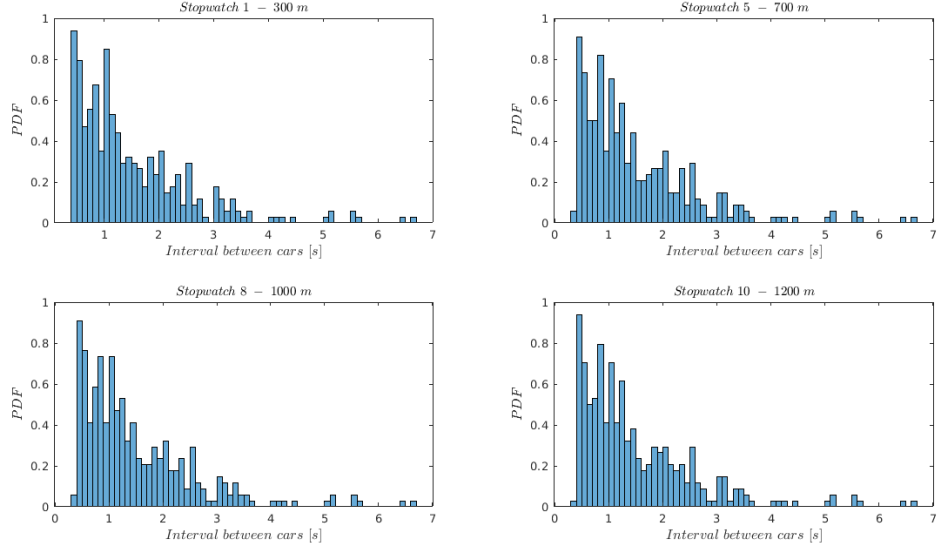


Figure 3.3. PDF of the interval time between cars for scenario A

3.3.2 Scenario B

In this scenario, namely scenario B and depicted in Fig. 3.4, we modify the physical characteristics of the road. Now the simulation road is a double lane road in which vehicles arrive at a rate $\lambda = 1.5$. Indeed, since now we have an additional lane, we increase the rate value but still in the stability region, below the value 2.5 as explained in section 2.4. Vehicles arrive at the beginning of the road and choose one of the two lanes. The routing policy among the two lanes follows the default setting in SUMO so vehicles may use the rightmost one.

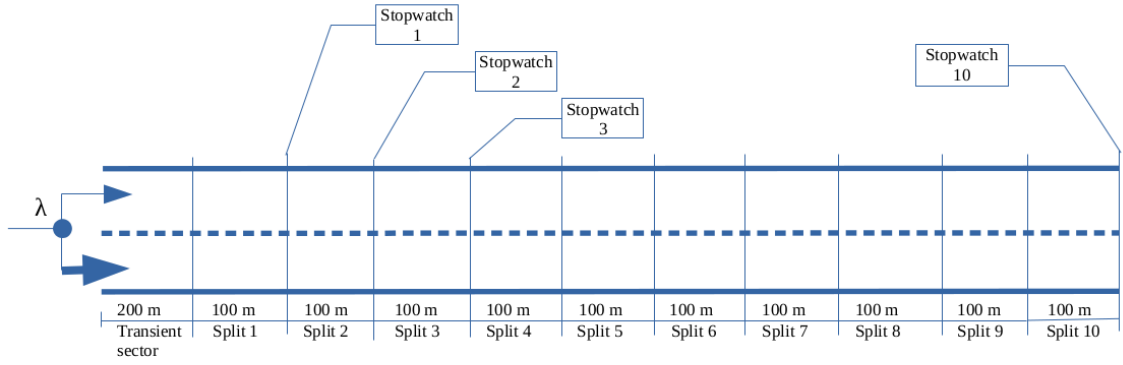


Figure 3.4. Scheme of scenario B

Again, Fig. 3.5 and Fig. 3.6 below, show the PDF of the travel time and the PDF of the time interval between vehicles, respectively. In this specific case, we do not have relevant variations with respect to scenario A. Indeed, the results have the same behaviour as before, with a goodness-of-fit positive test at the 1% significance level for the PDF in Fig. 3.6.

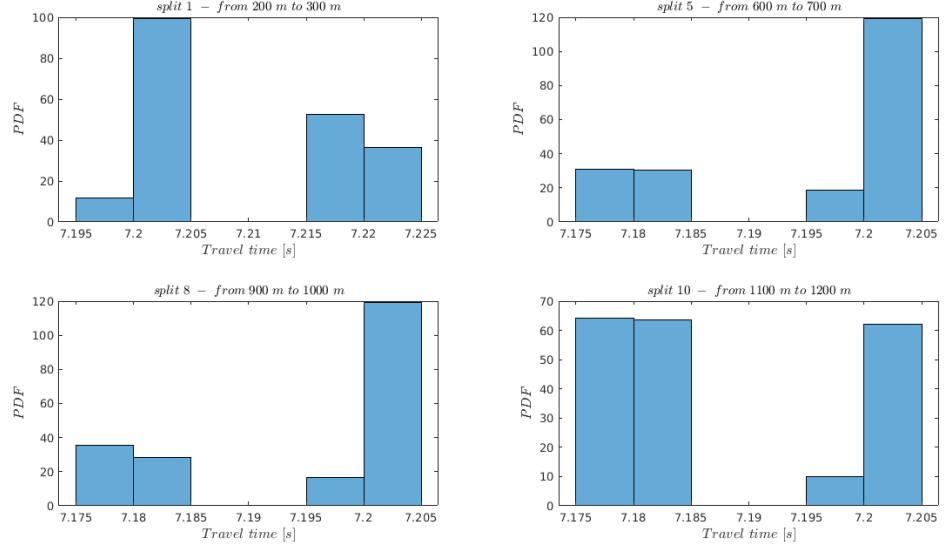


Figure 3.5. PDF of the travel time for scenario B

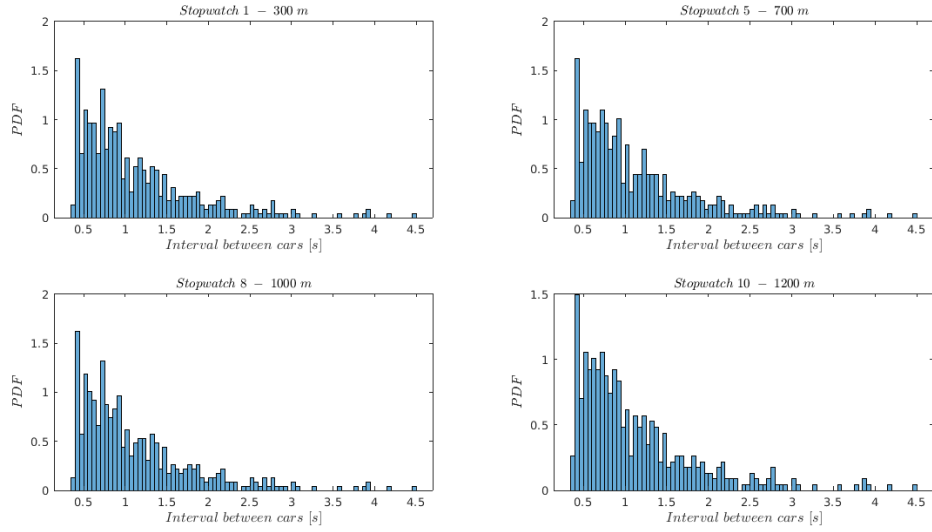


Figure 3.6. PDF of the interval time between cars for scenario B

3.3.3 Scenario C

In this third scenario, namely scenario C, we have still a double lane simulation road with a vehicular arrival rate $\lambda = 1.5$. The key point that we have to highlight is that now the routing policy, in order to choose the left or the right lane, is done with an equal probability of $1/2$, as depicted in Fig. 3.7.

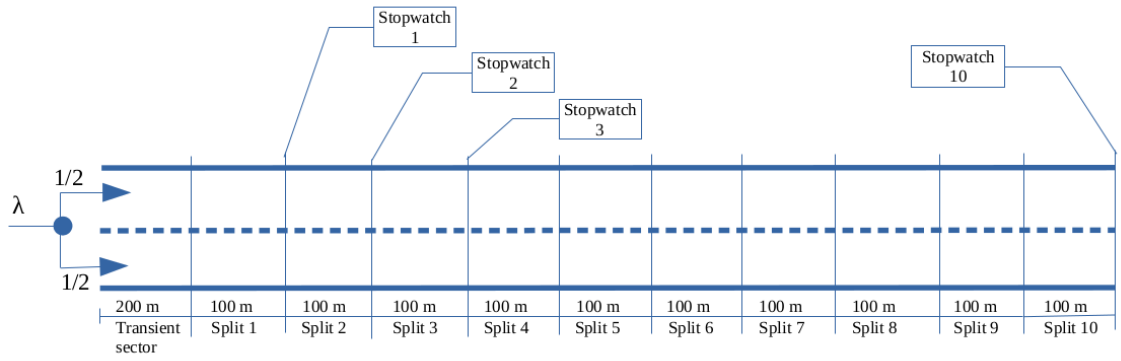


Figure 3.7. Scheme of scenario C

Once again, Fig. 3.8 and Fig. 3.9 show the PDF of our measurements. As we can see, in this specific case, the PDF of the travel time is pretty similar to the previous scenario.

Instead, there are some variation of shape for the PDF of time interval between vehicles. In particular, we can highlight a peak at around 0.5 seconds, for all the four PDF in Fig. 3.9. This is due to the fact that, since lane routing policy is done with an equal probability among the two lane, it is very likely that an incoming vehicle find both lane busy. If this happens, SUMO have to wait an amount of time before insert the vehicle in the simulation road, in order to keep the minimum distance from the leader, `minGap` parameter explained in section 2.3. As a consequence, in this configuration we obtain a negative goodness-of-fit test.

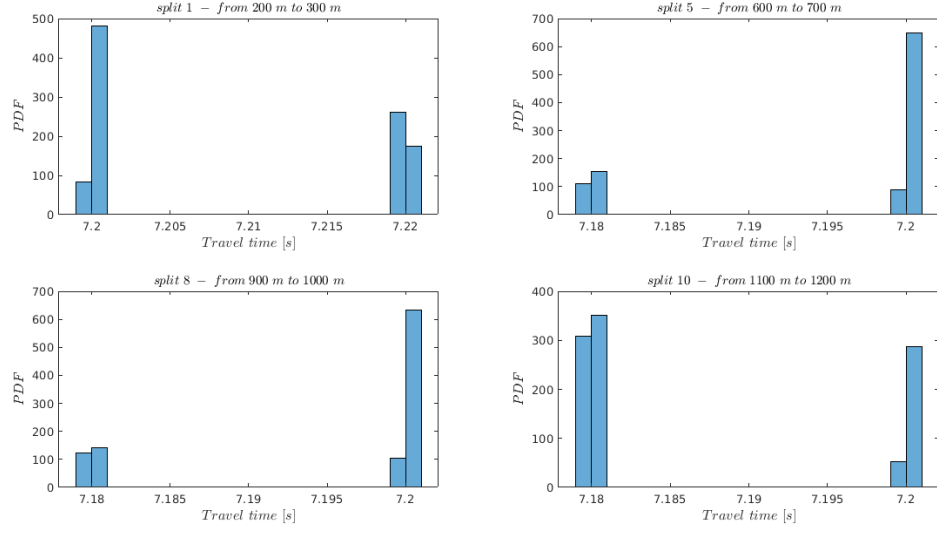


Figure 3.8. PDF of the travel time for scenario C

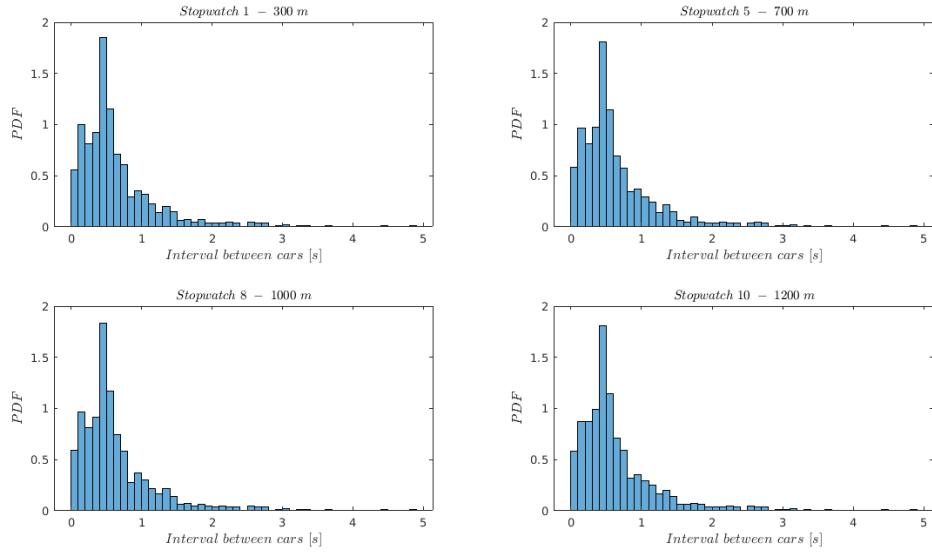


Figure 3.9. PDF of the interval time between cars for scenario C

Finally, in the following table 3.1 we summarize the obtained results.

| SCENARIO | RATE | N. OF LANE | LANE ROUTING | GOF (1%) |
|----------|------|------------|---------------------|----------|
| A | 1.0 | 1 | rightmost (default) | yes |
| B | 1.5 | 2 | rightmost (default) | yes |
| C | 1.5 | 2 | equal prob. (1/2) | no |

Table 3.1. Results overview - simulation road

Chapter 4

Simulation road with obstacle

In this chapter we deal with a particular case of simulation. We want to simulate the same piece of road as in chapter 3, but now with an obstacle along the path, in the right lane. Our goal is to study vehicle's behaviour both before and after the obstacle. Indeed, in proximity of the obstacle, vehicles have to brake to reduce their speed and then, once they pass the obstacle, they will perform a new acceleration. In this simulation runs, travel time and time interval between vehicles are collected, in order to verify if the exponential distribution in the PDF is hold for the total duration of the simulation, like in scenario A and scenario B in the previous sector 3.3.

4.1 Simulation settings and general assumptions

One more time, we build several scenarios with different settings, running one 700s-long simulation for each of them. The simulation road, depicted in Fig. 4.1, is still 1200 meters long, formed by 10 100-meter-long sectors (splits) plus a transient 200-meter-long sector at the entrance, in order to adjust the departure speed of each vehicle. Indeed, even in this case, the departure speed for each vehicles is selected by drawing a random number between 30 *Km/h* and 40 *Km/h* following a uniform distribution. Then, vehicles will accelerate and will try to reach the desired driving speed v , as explained in section 2.3.1. The difference with respect to the previous case is that now there are two disjointed arrivals in the simulation road. Vehicles arrive at right lane with rate λ_1 and at left lane with rate λ_2 ; both of them follow a Poisson process, so again the time between arrivals follows a negative exponential distribution. Moreover, in order to simulate our obstacle, we put a broken down vehicle at 640 meters blocking the passage, inside split 5, right lane.

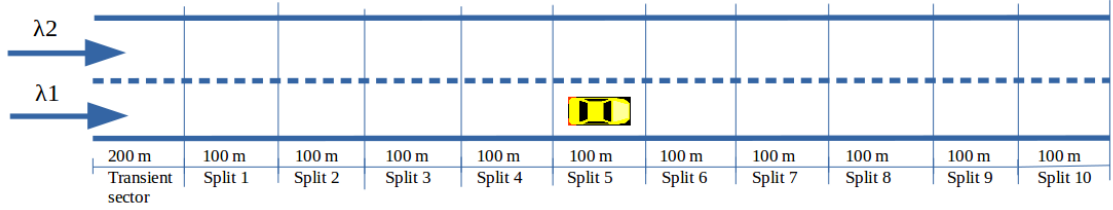


Figure 4.1. Scheme with obstacle

In the following simulations we will focus on the central part of the road, where there is a broken down vehicle inside split 5. In particular we analyze and collect data for those splits that are around it, in order to observe how traffic shape change to overtake the broken down vehicle. An additional diversification in the previous scheme 4.1 is done. Now we are able to measure the time interval between vehicles for each lane; indeed, for each split, we have two stopwatches. The first one is devoted to measure data from traffic flow in the right lane; the second one is devoted to measure the same data for the left lane. This further detailed layer is useful to better study the traffic behaviour behind the broken down vehicle, in particular to analyze lane changing performed by vehicles from right lane toward left lane, to overtake the obstacle.

Our goal is to monitoring where this lane changing happens, with default settings of SUMO; indeed, when the queue of cars behind the obstacle starts to grow up during the simulation, some vehicle will perform their lane changing within split 4 and some other will perform their lane changing within split 5. For what concerns the methodology to measure the travel time in each split, we have no difference with respect to the concept used in previous scenarios. Finally, the scheme described above is depicted in the following Fig. 4.2 where the sky blue circles represents the stopwatch ID and the yellow car represents the broken down vehicle within split 5.

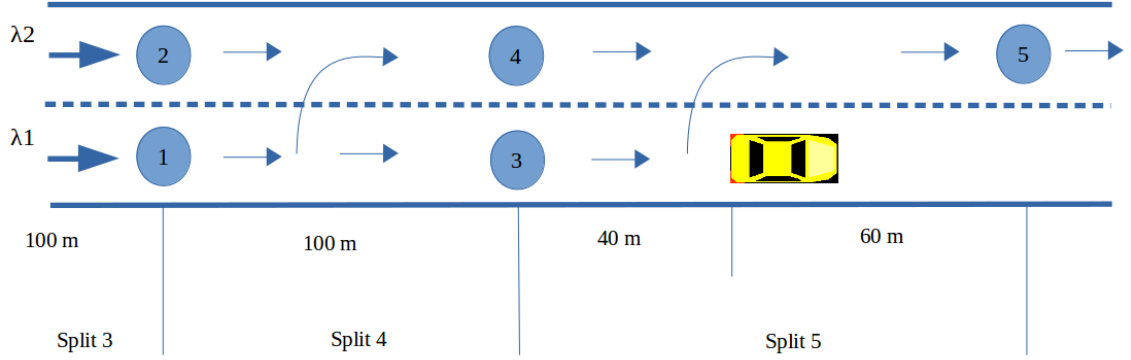


Figure 4.2. Detailed scheme with obstacle

4.1.1 Queueing networks

In this section we introduce the analytical model to describe the scheme of the simulation depicted in Fig. 4.2. This model is a queueing network and it is extremely simple, especially for what concerns the description of the general modeling methodology. A queueing network [10] is a system made by several queues connected in arbitrary way. In our case the model is made by five shunted $M/M/1$ queues in which customers of the queue represent vehicles, as shown in Fig. 4.3. From the model, it is clear that the arrival process at the successive queues cannot be described independently from the rest of the network. Then, we should more correctly identify such queues with the notation $\cdot/M/1$. These considerations show the importance of the correct characterization for the departure process of a queue in the queueing networks analysis; indeed, from the Burke's Theorem, the departure process for a $M/M/1$ queue at steady state is a Poisson process with the same rate of the arrival process. However, we have to build an acyclical queueing network model with no feedback among the queues. In other words, they do not allow any client to return in a queue already visited, without internal cycles. The absence of cycles is fundamental to maintain the Poisson characteristics of the arrival processes; indeed, also for a simple $M/M/1$ queue with feedback, such in Fig. 4.4, the departure process is not a

Poisson process anymore.

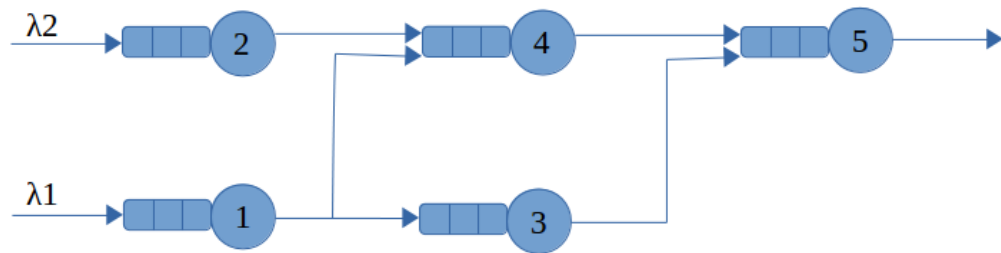


Figure 4.3. Acyclical queueing network model

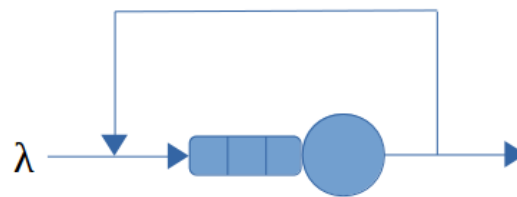


Figure 4.4. A queue with feedback

4.2 Simulation results

Below, several simulations are performed. In this first set of results, namely scenario D scenario E and scenario F, we simulate different scenarios with different value of arrival rate. The reference scheme is the one depicted in Fig. 4.1. As already said, we will focus on the central part of the road and, for simplicity, we plot the PDF of the travel time for the most relevant sectors; split 3 from 400m to 500m, split 4 from 500m to 600m, split 5, where there is the broken down vehicle, from 600m to 700m, and split 6 from 700m to 800m. Instead, regarding the PDF of the interval time between cars, we plot data for those stopwatches depicted with sky blue circle in Fig. 4.2. We set the arrival rate value at the beginning of the simulation, the same value for both right lane and left lane. Finally, it is important to highlight that simulation settings and the general assumptions are the one explained in section 4.1.

4.2.1 Scenario D

In this scenario, namely scenario D, vehicles arrive at a rate equal to 0.3 in both right and left lane. As a consequence,

$$\lambda_1 = \lambda_2 = 0.3$$

Fig. 4.5 shows the PDF of the travel time to cover a single 100-meter-long sector. This is a scenario in which there is a low load of traffic in the simulation road; indeed, vehicles in right lane will slow down, forming a short queue behind the obstacle but, once they arrive close the broken down vehicle, they will perform lane changing without any type of issue, since the traffic in the left lane is low. As a consequence, most of the vehicles will perform the lane changing just behind the obstacle, inside split 5. In particular, we can notice this behaviour looking at split 4 and split 5 in Fig. 4.5. The PDF is not "flat" anymore and vehicles take more time to go through those splits due to the presence of queues in right lane.

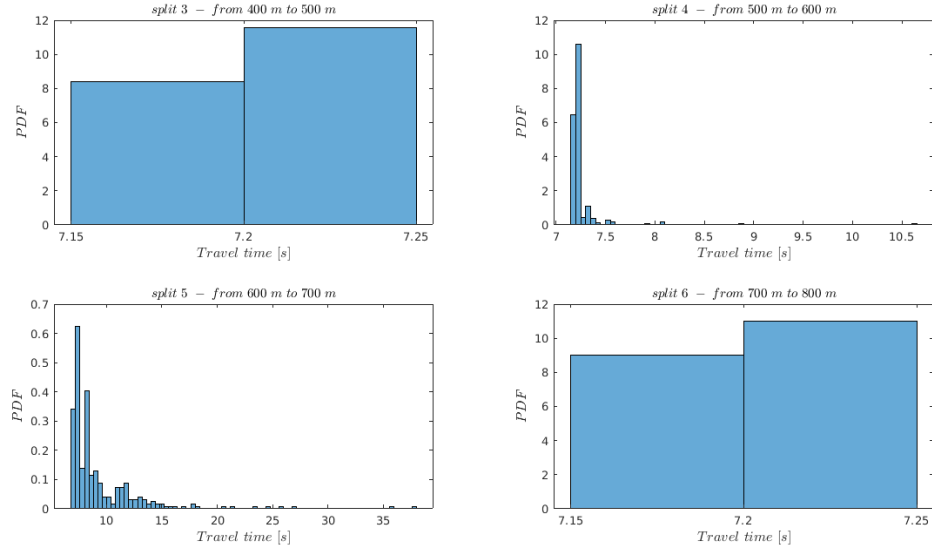


Figure 4.5. PDF of the travel time for scenario D

Instead, Fig. 4.6 shows the PDF of the time interval between vehicles at the stopwatches. The most relevant result that we highlight is that, performing the goodness-of-fit test already explained, there is a "match" with an exponential distribution family at the 1% significance level for those stopwatches that are behind the broken down vehicle. It means that at stopwatch 1, stopwatch 2, stopwatch 3, and stopwatch 4, the exponential distribution of the traffic is held even if there are some lane changing so the traffic is shuffled. This is due to the fact that an arrival rate of 0.3 generate low load of vehicles in the simulation road. Moreover, as we can see in Fig. 4.6, the PDF at stopwatch 5 has a completely different shape with respect to the previous one; indeed, since there is the obstacle, all vehicles are passing through the left lane so the vehicles are back to back forming a train of cars.

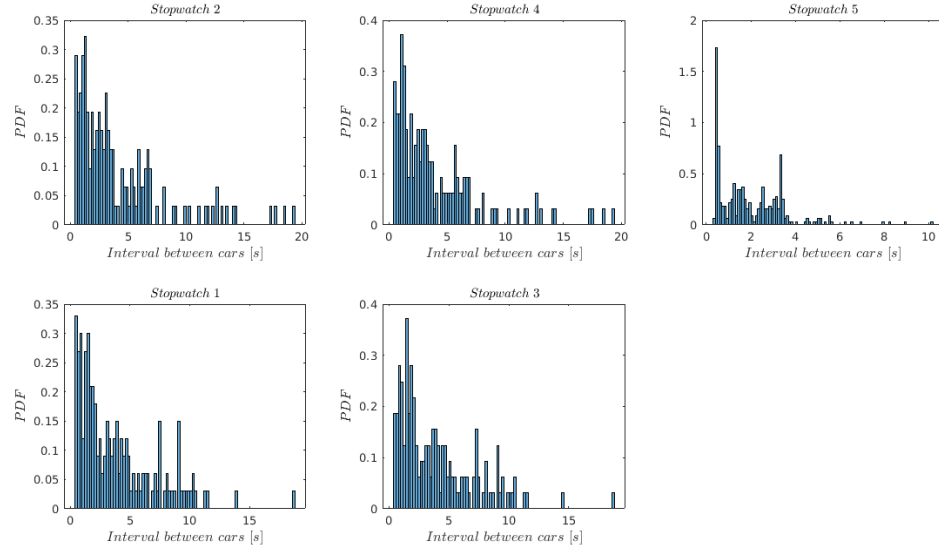


Figure 4.6. PDF of the interval time between cars for scenario D

4.2.2 Scenario E

In this scenario, namely scenario E, we increase the vehicle arrival rate up to 0.5 in both right and left lane. As a consequence,

$$\lambda_1 = \lambda_2 = 0.5$$

Again, Fig. 4.7 and Fig. 4.8 below, show the PDF of the travel time and the PDF of the time interval between cars, respectively. This is a scenario in which there is a medium load of traffic in the simulation road. Indeed, as we can notice from the figures, there is a longer queue behind the broken down vehicle because the PDF of the travel time in split 4 and split 5 are more spreaded with respect to scenario D.

Moreover, regarding the time interval between cars, we have a positive goodness-of-fit test at the 1% significance level only at stopwatch 1 and stopwatch 2. This is due to the fact that now there are a lot of vehicles that perform their lane changing before stopwatch 3, causing a more significant traffic shuffle.

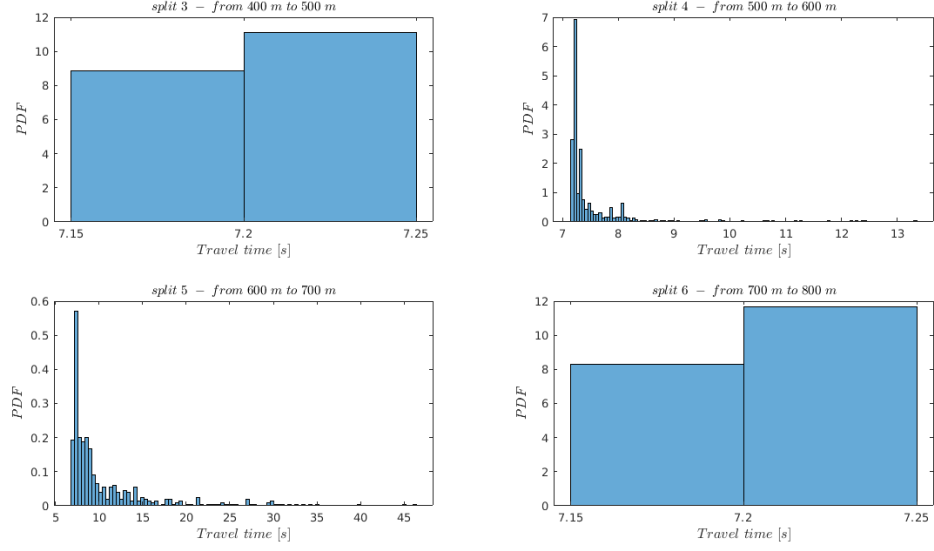


Figure 4.7. PDF of the travel time for scenario E

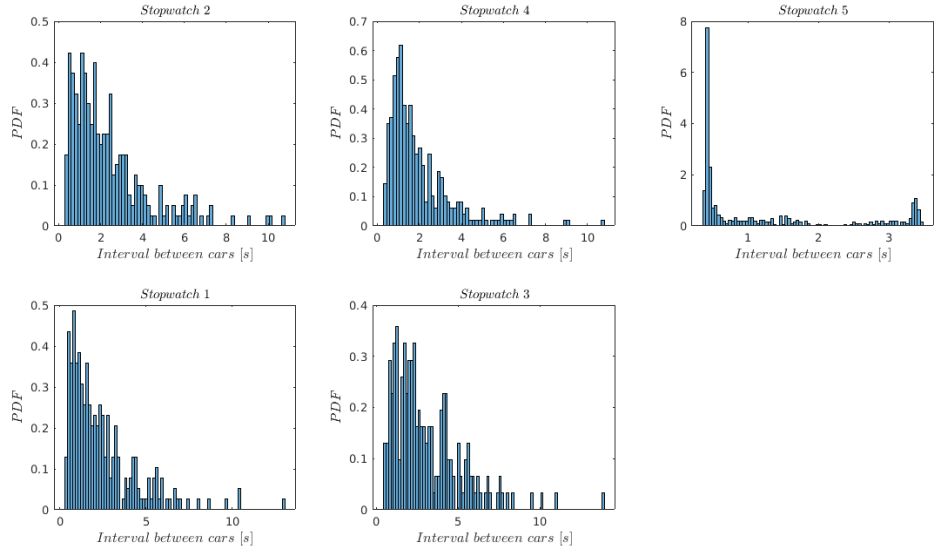


Figure 4.8. PDF of the interval time between cars for scenario E

4.2.3 Scenario F

In this third scenario, namely scenario F, we increase vehicle arrival rate up to 0.8 in both right and left lane. We set:

$$\lambda_1 = \lambda_2 = 0.8$$

It is a very extreme scenario in which the simulation road is crowded. Indeed we have a very congested road with a very long queue behind the obstacle. This is due to the fact that it is difficult to perform a lane changing because the left lane is very crowded as well. As a consequence, most of vehicles are stuck in the right lane, increasing the time to go through split 5 above 50 seconds depicted in Fig. 4.9.

Below, Fig. 4.9 and Fig. 4.10, show the PDF of the travel time and the PDF of the time interval between cars, respectively. Even in this case, due to the high level of traffic, we have a positive goodness-of-fit test at the 1% significance level only at stopwatch 1 and stopwatch 2.

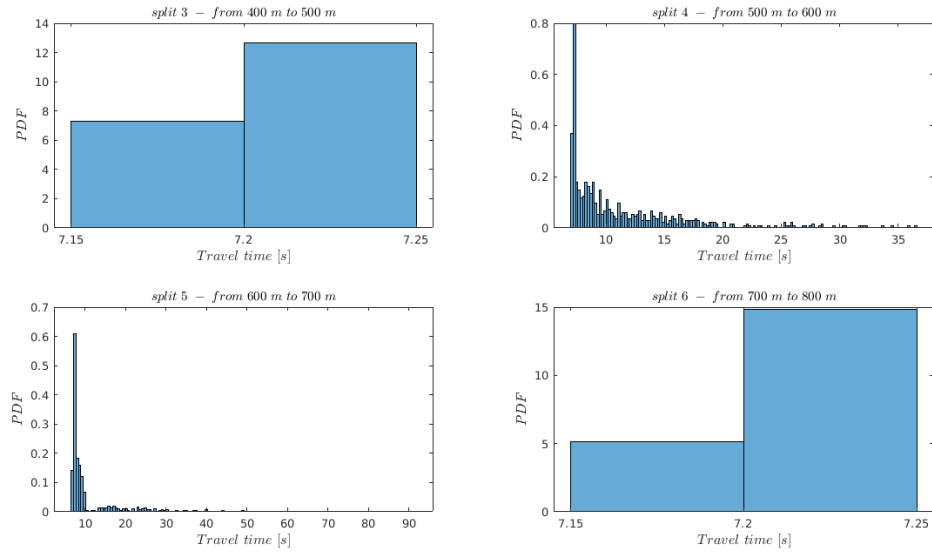


Figure 4.9. PDF of the travel time for scenario F

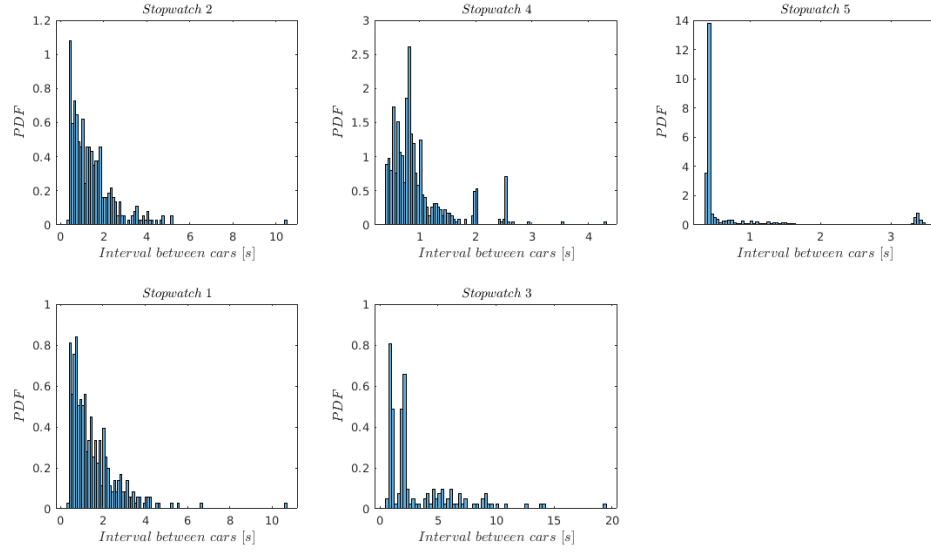


Figure 4.10. PDF of the interval time between cars for scenario F

4.3 TraCI tool

In this scenarios with obstacle in the right lane, at split 5, vehicles have to perform a lane changing toward left lane, to overtake the broken down vehicle. We have seen that, using the default settings of SUMO, the physical point in which vehicles perform their lane changing is strongly dependent on the arrival rate λ_1 and λ_2 . Indeed, higher values of arrival rate will generate more congestion with longer queue behind the obstacle, so most vehicles will perform their lane changing earlier, within split 4. On the contrary, lower values of arrival rate will generate shorter queue behind the broken down vehicle, so most vehicles will perform their lane changing later, just behind the obstacle within split 5.

The operation of lane changing performed by vehicles at the right lane toward the left lane can be divided in two main region. In the following scheme, depicted in Fig. 4.11, we define two interchange region, called deviations:

- Deviation 1 (Dev1): with this notation we characterize all those vehicles who perform lane changing within split 4, before stopwatch 3.
- Deviation 2 (Dev2): with this notation we characterize all those vehicles who perform lane changing within split 5, ranging from stopwatch 3 to the broken down vehicle.

In other words, even for fixed value of arrival rate and default settings of SUMO, we are

not able to control the amount of vehicles that perform lane changing through Dev1 or Dev2 as well. In the following simulations we want to control this lane changing policy by using an auxiliary SUMO tool called TraCI.

Traffic Control Interface (TraCI) [11] allows, giving access to a running road traffic simulation, to retrieve values of simulated objects and to manipulate their behaviour "on-line". TraCI uses a client/server architecture to provide access to SUMO. Indeed, SUMO acts as server that is started with additional command line options to create the connection with the client. SUMO only prepares the simulation and waits for all external applications to connect and take over the control. Instead, TraCI acts as client. The client application sends commands to SUMO to control the simulation run, to influence single vehicle's behaviour or ask for environmental details. In our case we use TraCI to impose a lane changing for a set of vehicles, wherever we want. SUMO answers with a status-response to each command and additional results that depend on the given command. In other words, TraCI is used to couple multiple processes; a SUMO server process and one or more TraCI client processes. Using TraCI slows down the simulation speed. The amount of slow-down depends on many factors like the number of TraCI function calls per simulation step and the computation within TraCI script.

Fig. 4.12 shows the connection between TraCI and SUMO.

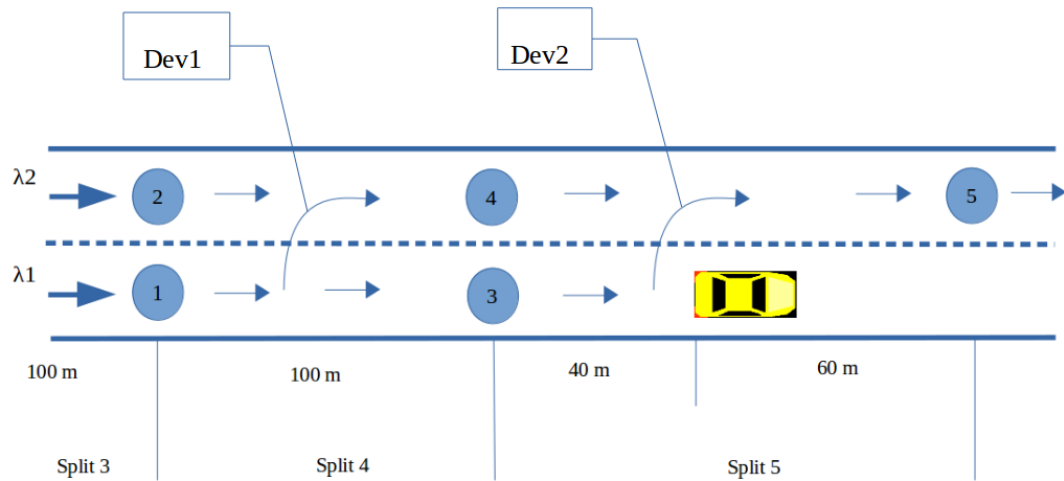


Figure 4.11. Detailed scheme with deviations

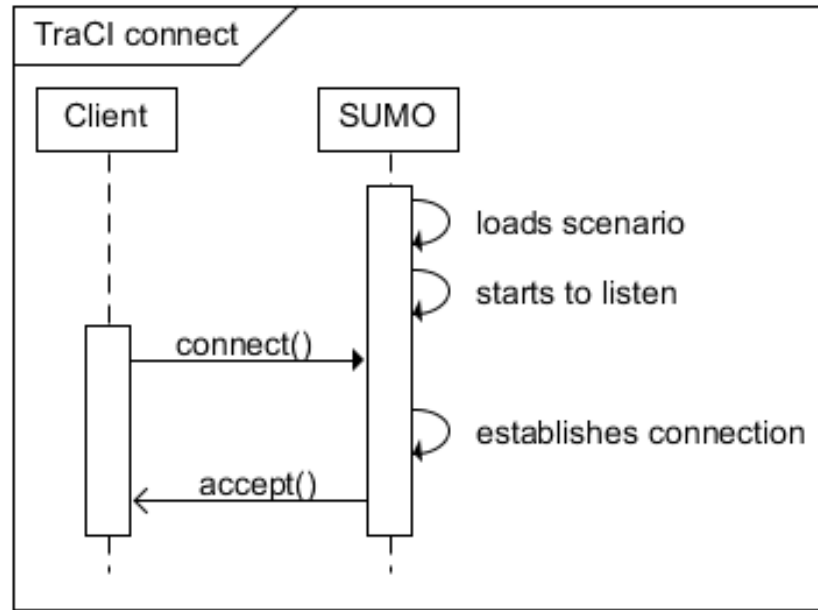


Figure 4.12. TraCI: establishing a connection to SUMO

4.4 Simulation results with TraCI tool

Below, another set of simulations is performed. In this second set of results, namely scenario G scenario H and scenario I, we have the same value for the arrival rate. In particular, for all of them, we have:

$$\lambda_1 = \lambda_2 = 0.5$$

As already said, now we can control the amount of vehicles that perform lane changing through Dev1 or Dev2. Taking into account the traffic flow in the right lane, we are going to manipulate this flow through TraCI, in order to impose a lane changing to vehicles according to a given probability. Moreover, reference scheme, simulation settings, and general assumptions are the one used also in the previous set of results.

4.4.1 Scenario G

In this scenario, namely scenario G, there is an equal subdivision of the traffic flow in the right lane. It means that, for vehicles in the right lane, 50% of them will perform lane changing within split 4, and the other 50% will perform lane changing within split 5. Indeed, we have:

- Dev1 - 50%
- Dev2 - 50%

As usual, Fig. 4.13 and Fig. 4.14 below, show the same measurements, the PDF of the travel time and the PDF of the time interval between cars, respectively. The most relevant result that we have to highlight is that, with respect to scenario E in section 4.2, now we have a positive goodness-of-fit test at the 1% significance level also at stopwatch 3. So, in summary, there is a positive test at stopwatch 1, stopwatch 2, and stopwatch 3. But on the other hand, the PDF of the travel time in split 5, where there is the broken down vehicle, is more spreaded toward the right.

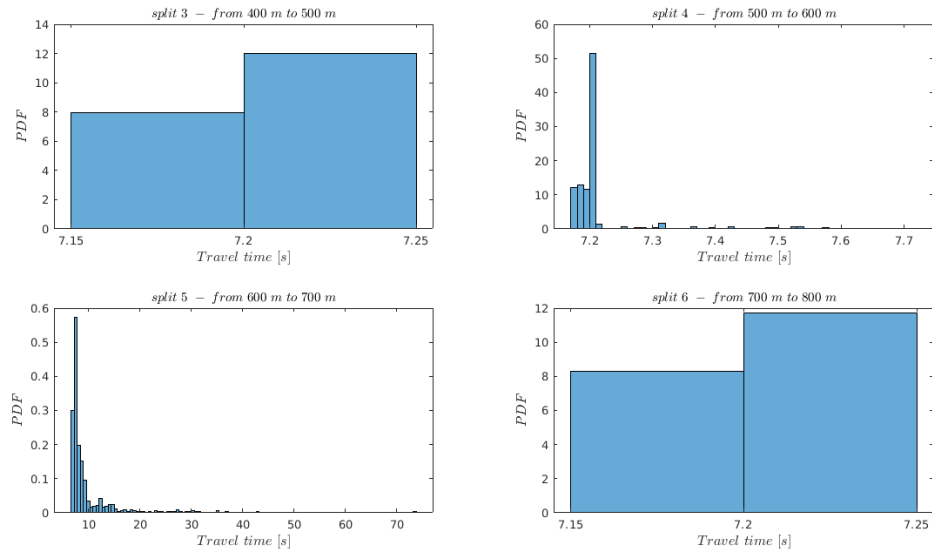


Figure 4.13. PDF of the travel time for scenario G

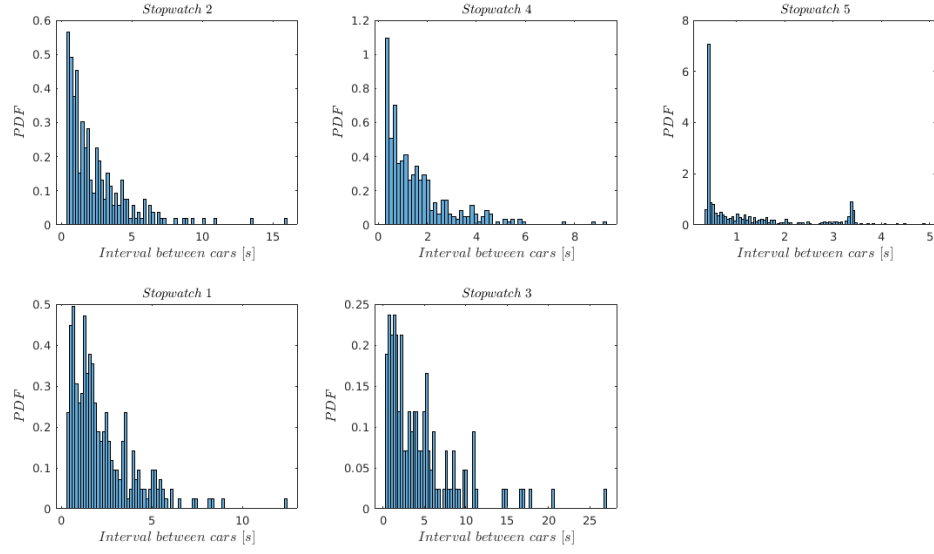


Figure 4.14. PDF of the interval time between cars for scenario G

4.4.2 Scenario H

In this scenario, namely scenario H, there is a different subdivision of the traffic flow in the right lane. In particular, for vehicles in the right lane, 70% of them will perform lane changing within split 4, and the other 30% will perform lane changing within split 5. Indeed, we have:

- Dev1 - 70%
- Dev2 - 30%

Again, Fig. 4.15 and Fig. 4.16 below, show the same measurements as before. In this case, as we can see from the PDF at split 5 in Fig. 4.15, there is a substantial improvement in the travel time.

Instead, regarding the time interval between cars, there is no difference with respect to the previous scenario G. It means that in the PDF of stopwatch 3, in Fig. 4.16, there are less "sample", due to 70% of lane changing, but still there is a positive goodness-of-fit test at the 1% significance level at stopwatch 1, stopwatch 2, and stopwatch 3.

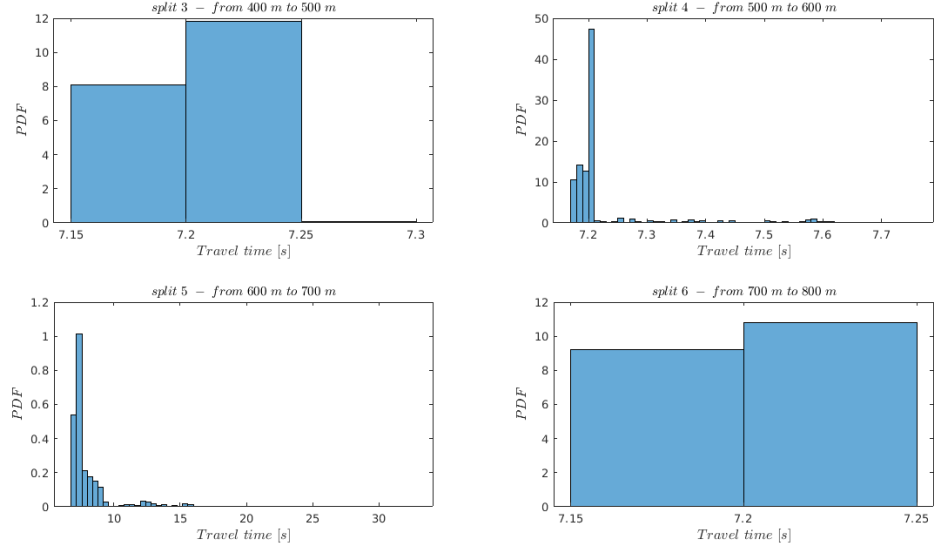


Figure 4.15. PDF of the travel time for scenario H

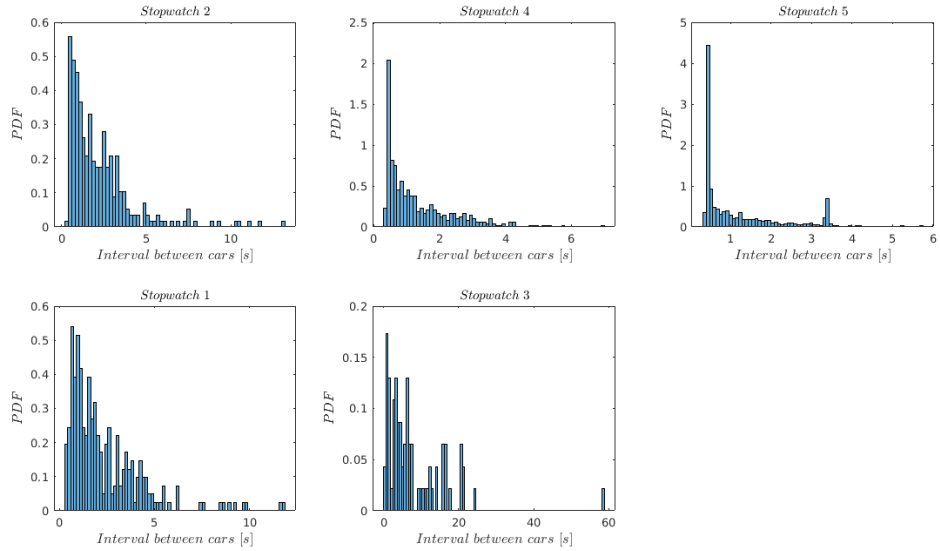


Figure 4.16. PDF of the interval time between cars for scenario H

4.4.3 Scenario I

Finally, in this last scenario namely scenario I, we change one more time the subdivision of the traffic flow in the right lane. In particular, for vehicles in the right lane, 30% of them will perform lane changing within split 4, and the other 70% will perform lane changing within split 5. Indeed, we have:

- Dev1 - 30%
- Dev2 - 70%

In this scenario, the most important result is that now we have a positive goodness-of-fit test at the 1% significance level for all those stopwatches that are behind the broken down vehicle, depicted in Fig. 4.18. This is due to the fact that, since most vehicles (70%) perform their lane changing at the second deviation (Dev2 within split 5), there is no substantial modification of the traffic shape for traffic flow in the left lane, passing through stopwatch 4. So, in summary, there is a positive test at stopwatch 1, stopwatch 2, stopwatch 3, and stopwatch 4. Lastly, for what concern the PDF of the travel time in Fig. 4.17, this scenario is very similar to scenario H.

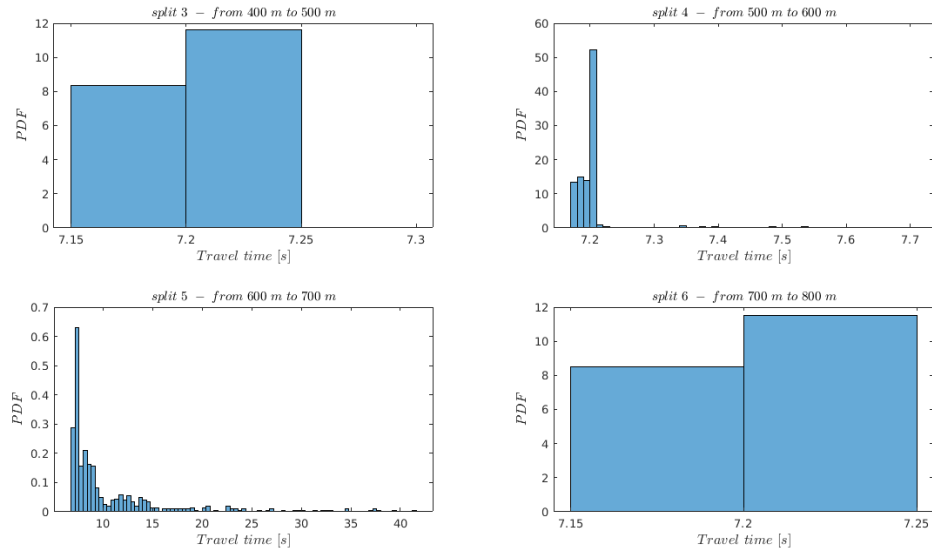


Figure 4.17. PDF of the travel time for scenario I

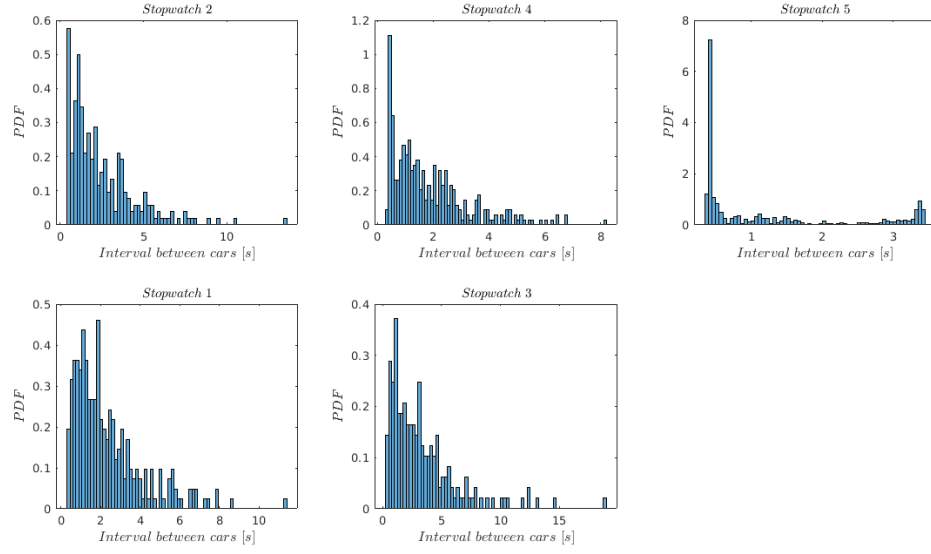


Figure 4.18. PDF of the interval time between cars for scenario I

Finally, in tables 4.1 and 4.2 we recap the obtained results.

| SCENARIO | RATE | STOPWATCH | GOF (1%) |
|----------|------|-----------|----------|
| D | 0.3 | 1 | yes |
| | | 2 | yes |
| | | 3 | yes |
| | | 4 | yes |
| | | 5 | no |
| E | 0.5 | 1 | yes |
| | | 2 | yes |
| | | 3 | no |
| | | 4 | no |
| | | 5 | no |
| F | 0.8 | 1 | yes |
| | | 2 | yes |
| | | 3 | no |
| | | 4 | no |
| | | 5 | no |

Table 4.1. Results overview - simulations with obstacle

| SCENARIO | RATE | TRACI: DEV1 - DEV2 | STOPWATCH | GOF (1%) |
|----------|------|--------------------|-----------|----------|
| G | 0.5 | 50% - 50% | 1 | yes |
| | | | 2 | yes |
| | | | 3 | yes |
| | | | 4 | no |
| | | | 5 | no |
| H | 0.5 | 70% - 30% | 1 | yes |
| | | | 2 | yes |
| | | | 3 | yes |
| | | | 4 | no |
| | | | 5 | no |
| I | 0.5 | 30% - 70% | 1 | yes |
| | | | 2 | yes |
| | | | 3 | yes |
| | | | 4 | yes |
| | | | 5 | no |

Table 4.2. Results overview - simulations with TraCI tool

Chapter 5

Roundabouts

In this final part of the thesis we deal with a completely different topology. We want to simulate a roundabout formed by four legs. As usual, we use SUMO to carry out the simulations and the topology was created through NETEDIT tool, as depicted in Fig. 5.1. Again, the entities moving in the topology are vehicles. This element is very simple but allows us to have representative scenario which closely mimics many real-world trafficflows behaviour. Indeed, in urban environment there are a huge number of roundabouts. Roundabout in a network influence the right of way and it is defined by its nodes and edges within .net.xml file. Moreover, lane-changing models may take roundabouts into account.

Our goal is to study the effect which the roundabout have on vehicle's behaviour. In particular, we will focus on the entrances and exits of the roundabout; indeed, at the entrances, the right of way policy may modify traffic shape. In this simulation runs, travel time and time interval between cars are collected.

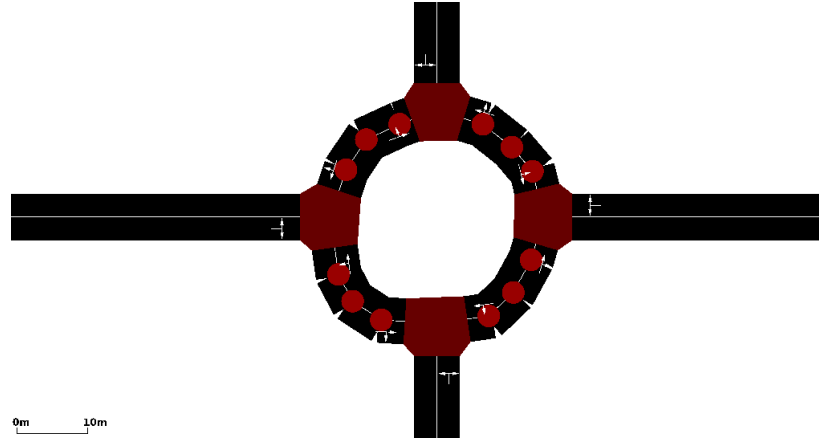


Figure 5.1. Screenshot of a roundabout in NETEDIT

5.1 Simulation settings and general assumptions

The simulation topology is a roundabout, formed by 4 legs of intersection. All the 4 legs are double lane. Vehicles arrive at the roundabout through 2 legs and leave the same roundabout through the other 2 legs. So, for each incoming vehicle from the two entrances, a random exit leg will be selected. Even in this case, the departure speed for each vehicle is selected by drawing a random number between 30 Km/h and 40 Km/h following a uniform distribution. Then, within the transient sector at the entrance, vehicles will accelerate and will try to reach the desired driving speed v . Vehicles arrive at the two entrance legs with rate $\lambda_{Leg\ i}$; both of them follow a Poisson process, so again the time between arrivals follows a negative exponential distribution.

As already said, we are interested in the entrances and exits of the roundabout. In particular, we analyze and collect data for those splits that are at the borders of the roundabout. There is a 100-meter-long split in each leg, with four stopwatches namely stopwatch 1 in leg 1, stopwatch 2 in leg 2, stopwatch 3 in leg 3, and stopwatch 4 in leg 4.

The following set of results that we deal with in this chapter can be divided into two main scenarios:

- Roundabout A, depicted in Fig. 5.2
- Roundabout B, depicted in Fig. 5.9

The difference among the two is the way in which vehicles arrive at the roundabout. Indeed, by changing the direction of arrivals, we obtain a different behaviour of the roundabout. As a consequence, there are variations also in our measurements.

5.2 Roundabout A

In this set of results, namely Roundabout A, the reference scheme is depicted in Fig. 5.2. In particular, vehicles arrive at the roundabout through leg 1 and leg 4 with rate $\lambda_{Leg\ 1}$ and $\lambda_{Leg\ 4}$ respectively. As we can see in the picture, leg 1 and leg 4 are represented with a yellow arrow. Leg 1 and leg 4 are on the West and North side respectively. Then, vehicles leave the roundabout through leg 2 or leg 3, choosing it according to an equal probability. Leg 2 and leg 3 are represented with a red arrow in the picture and they are on the South and East side respectively.

We simulate three scenarios with three different value of arrival rate $\lambda_{Leg\ i}$. As usual, we plot the PDF of the travel for the four cardinal points; split 1 west, split 2 south, split 3 east, and split 4 north. The same for stopwatches depicted with sky blue circle, plotting the PDF of the interval between cars; stopwatch 1 west, stopwatch 2 south, and so on and so forth.

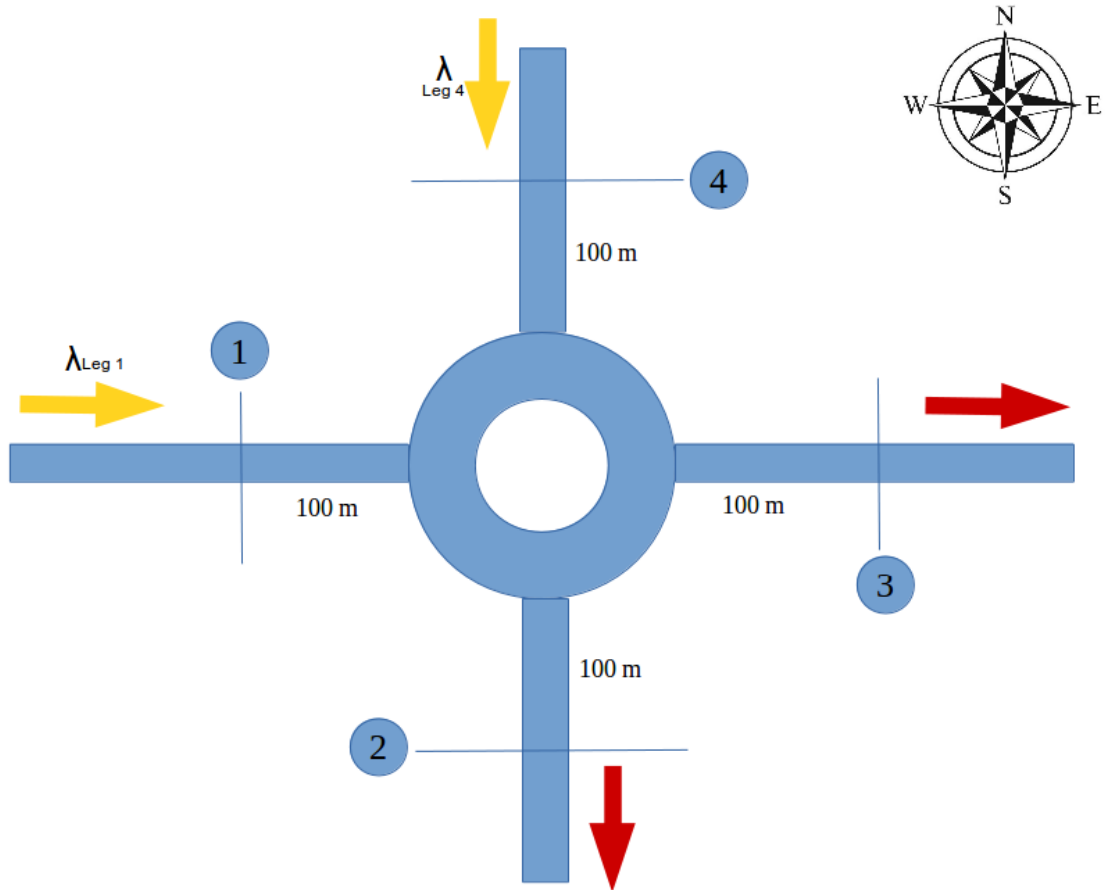


Figure 5.2. Scheme of Roundabout A

5.2.1 Scenario 1

In this scenario, namely scenario 1, vehicles arrive at the roundabout with a rate equal to 0.2 in both leg 1 and leg 4:

$$\lambda_{Leg\ 1} = \lambda_{Leg\ 4} = 0.2$$

Fig. 5.3 shows the PDF of the travel time to cover the 100-meter-long sector in each cardinal point. In this scenario we have a low load of traffic, since the rate is fixed at 0.2. Moreover, since the roundabout influence the right of way, vehicles that arrive from the north entrance, leg 4, shall give way to vehicles coming from west entrance, leg 1. Indeed, a variable queue of cars at the north entrance will be formed, in which every vehicle is waiting its eligibility to move forward. The queue length depends on the arrival rate $\lambda_{Leg\ 1}$ and $\lambda_{Leg\ 4}$. As a consequence, the above vehicles takes more time to cover its own split. This behaviour is visible looking at split 4 (north) in Fig. 5.3. Furthermore, split 2 (south) and split 3 (east) have a different shape with respect to split 1 (west) because in those sectors we have a combined traffic formed by incoming vehicles from both the entrance, split 1 and split 4.

Instead, Fig. 5.4 shows the PDF of time interval between vehicles at the four stopwatches. The most relevant result that we highlight is that, performing the goodness-of-fit test, there is a "match" with an exponential distribution family at the 1% significance level for all the four stopwatches, one for each legs. Again, this is due to the fact that an arrival rate of 0.2 generate low load of vehicles in the simulation topology and the roundabout does not modify the traffic shape.

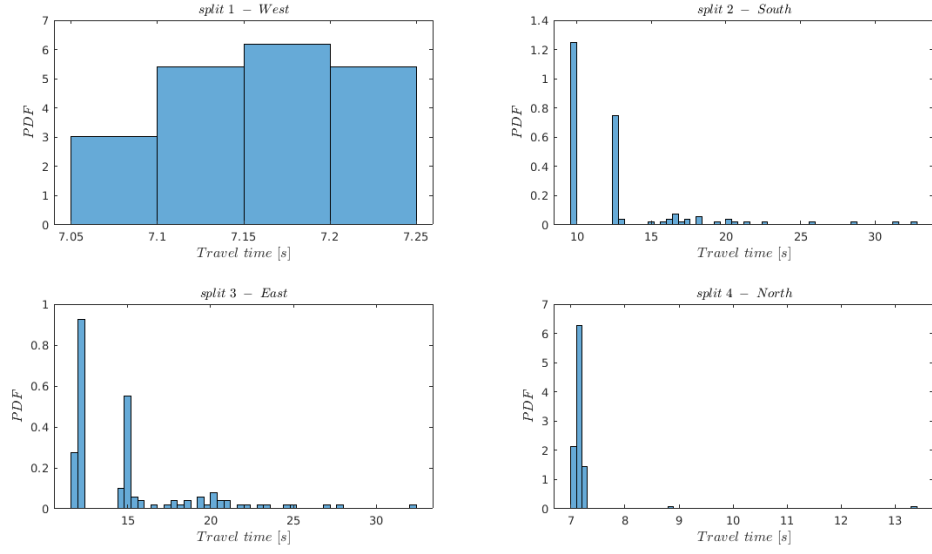


Figure 5.3. PDF of the travel time for scenario 1 of Roundabout A

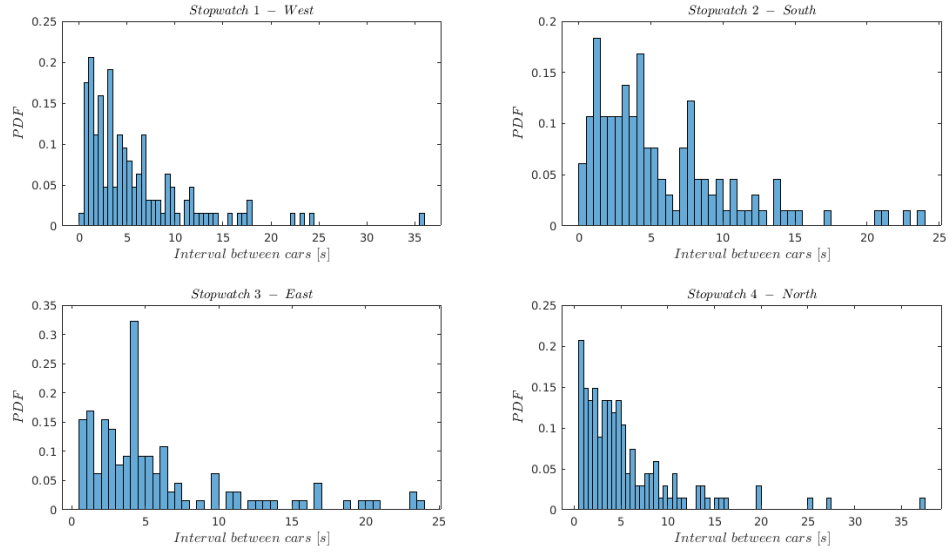


Figure 5.4. PDF of the interval time between cars for scenario 1 of Roundabout A

5.2.2 Scenario 2

In this scenario, namely scenario 2, we increase the vehicle arrival rate up to 0.3 in both leg 1 and leg 4. As a consequence:

$$\lambda_{Leg\ 1} = \lambda_{Leg\ 4} = 0.3$$

Again, Fig. 5.5 and Fig. 5.6 below, show the PDF of the travel time and the PDF of the time interval between cars, respectively. This is a scenario in which there is a medium load of traffic in the simulation topology. There is a longer queue at leg 4 with respect to scenario 1; indeed, as we can notice in the figure, there is an increasing time up to 45 seconds to cover the north split in leg 4.

Moreover, regarding the time interval between cars, we have a positive goodness-of-fit test at the 1% significance level at each stopwatch, like in the previous scenario. This is because, even if we increase the arrival rate up to 0.3, the load of traffic in the roundabout is pretty low and we have no changes of the traffic shape; in other words, the exponential shape is held at each stopwatch in the four cardinal points.

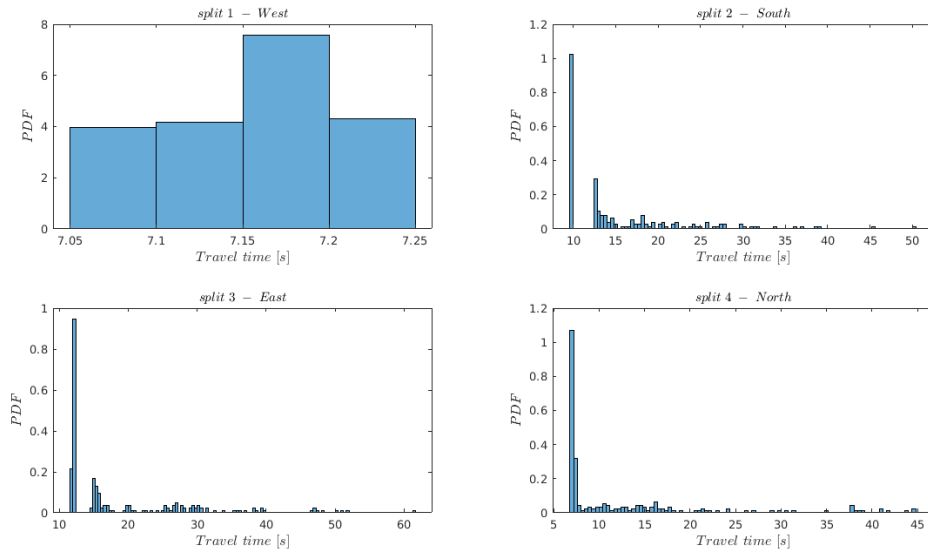


Figure 5.5. PDF of the travel time for scenario 2 of Roundabout A

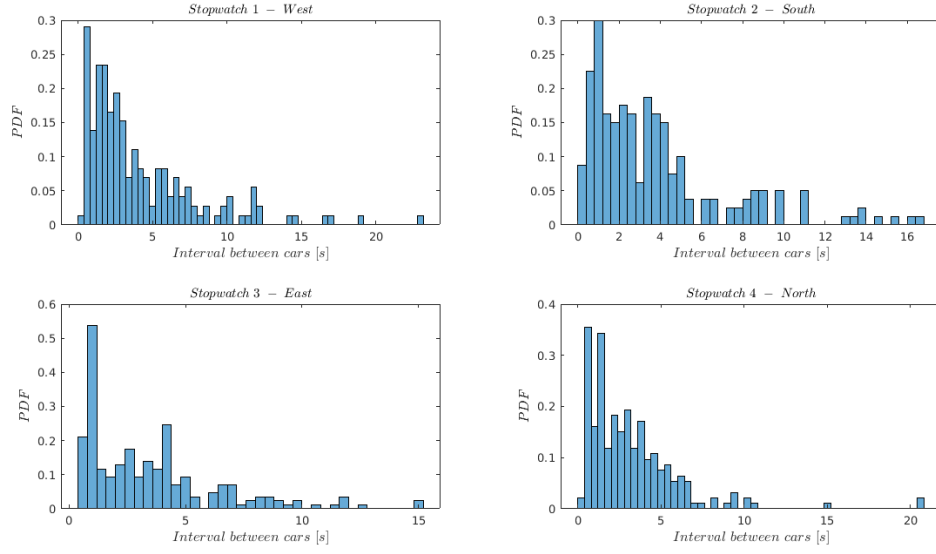


Figure 5.6. PDF of the interval time between cars for scenario 2 of Roundabout A

5.2.3 Scenario 3

In this third scenario, namely scenario 3, we increase vehicle arrival rate up to 0.4 in both leg 1 and leg 4. We set:

$$\lambda_{Leg\ 1} = \lambda_{Leg\ 4} = 0.4$$

In this case, the arrival rate is too high. The roundabout is crowded, especially leg 4 (north) in which vehicles are stuck in there for the same reasons seen before. Indeed, those vehicles increase its own time to go through split 4 within leg 4. As we can see in the PDF of travel time depicted in Fig. 5.7, there are huge values, up to 200 seconds, in split 4.

Instead, Fig. 5.8 show the PDF of the time interval between cars. Here we have that the roundabout modify the traffic shape indeed there is a positive goodness-of-fit test at the 1% significance level only at stopwatch 1 within leg 1 (west) and stopwatch 4 within leg 4 (north). We have a "match" in those stopwatches because they are at the entrance legs, before the roundabout element.

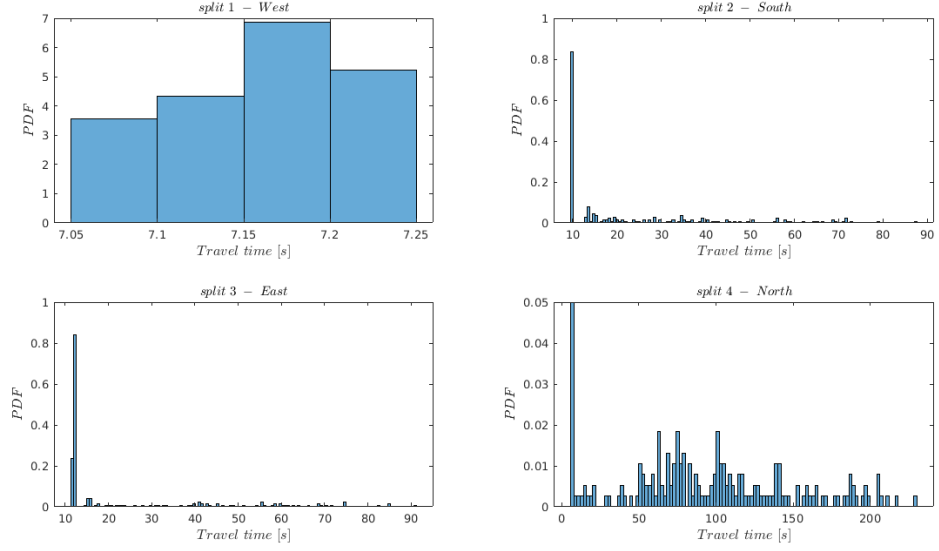


Figure 5.7. PDF of the travel time for scenario 3 of Roundabout A

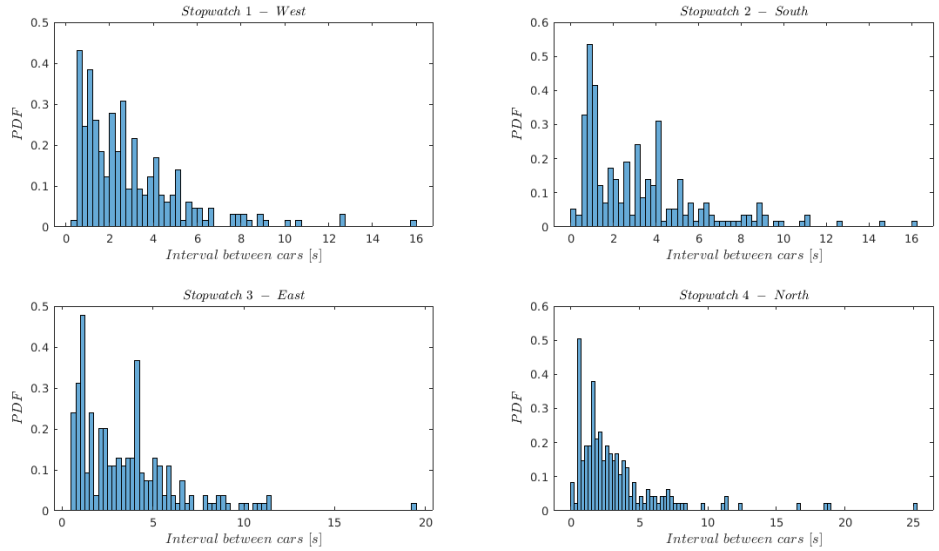


Figure 5.8. PDF of the interval time between cars for scenario 3 of Roundabout A

5.3 Roundabout B

In this second set of results, namely Roundabout B, the reference scenario is depicted in Fig. 5.9. First of all, it is important to highlight that we changed the name to legs. In this particular case we have another direction of arrivals; vehicles arrive at the roundabout through leg 1 and leg 3 with rate $\lambda_{Leg\ 1}$ and $\lambda_{Leg\ 3}$ respectively. The two entrance legs are placed directly opposite to each other, leg 1 at South side and leg 3 at North side. They are represented with a yellow arrow. Then, vehicles leave the roundabout through leg 2 or leg 4, choosing it according to an equal probability. The two exit legs, Leg 2 and leg 4, are represented with a red arrow in the picture and they are on the East and West side respectively. One more time, we simulate three scenarios with three different value of arrival rate $\lambda_{Leg\ i}$. As in the Roundabout A, we plot the PDF of the travel for the four cardinal points; split 1 south, split 2 east, split 3 north, and split 4 west. The same for stopwatches depicted with sky blue circle, plotting the PDF of the interval between cars; stopwatch 1 south, stopwatch 2 east, and so on and so forth.

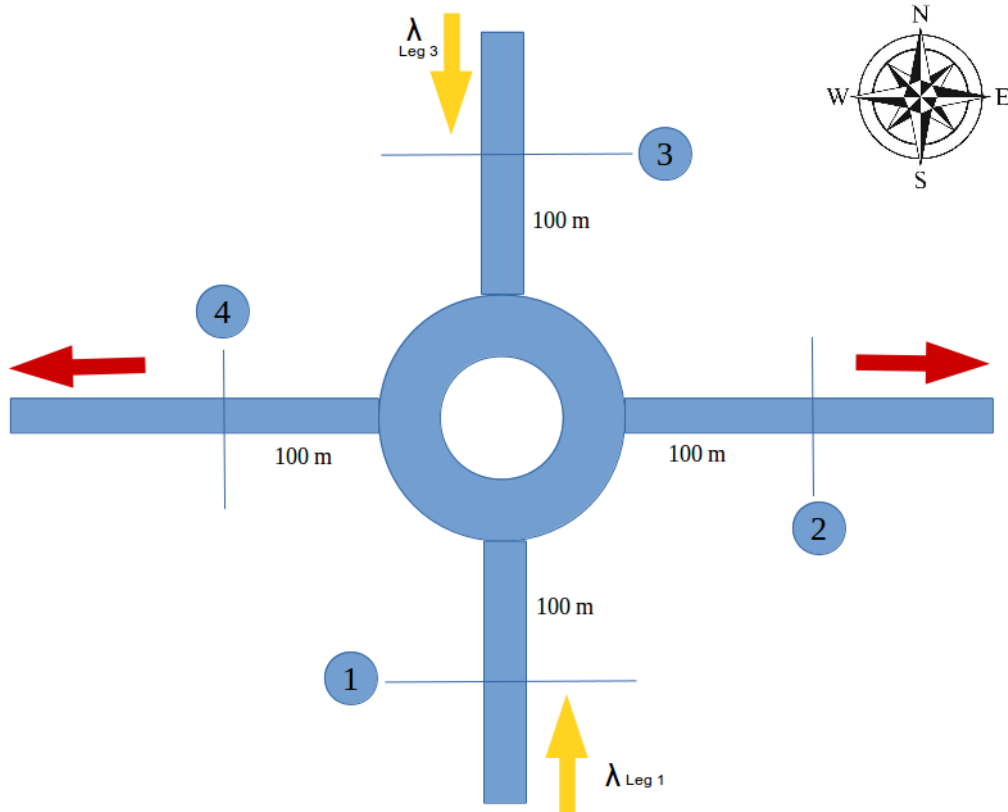


Figure 5.9. Scheme of Roundabout B

5.3.1 Scenario 4

In this scenario, namely scenario 4, vehicles arrive at the roundabout with a rate equal to 0.2 in both leg 1 and leg 3:

$$\lambda_{Leg\ 1} = \lambda_{Leg\ 3} = 0.2$$

Fig. 5.10 shows the PDF of the travel time to cover the 100-meter-long sector in each cardinal point. Even in this case, since the rate is fixed at 0.2, we have a low load of traffic. As already said above, the main difference with respect to Roundabout A is the new pattern for the direction of arrivals. For this reason, the roundabout element influence the right of way in a completely different manner with respect to Roundabout A in the previous set of results. Indeed, since the entrance legs are no adjacent anymore, traffic flow in leg 1 does not give-way to traffic flow in leg 3, since vehicles of leg 1 have "free right". As a consequence, now the PDFs of the travel time to cover the entrance split 1 (south) and split 3 (north) have the same behaviour.

Instead, Fig. 5.11 shows the PDF of time interval between vehicles at the four stopwatches. The most relevant result that we highlight is that, performing the goodness-of-fit test, there is a "match" with an exponential distribution family at the 1% significance level for all the four stopwatches, one for each legs.

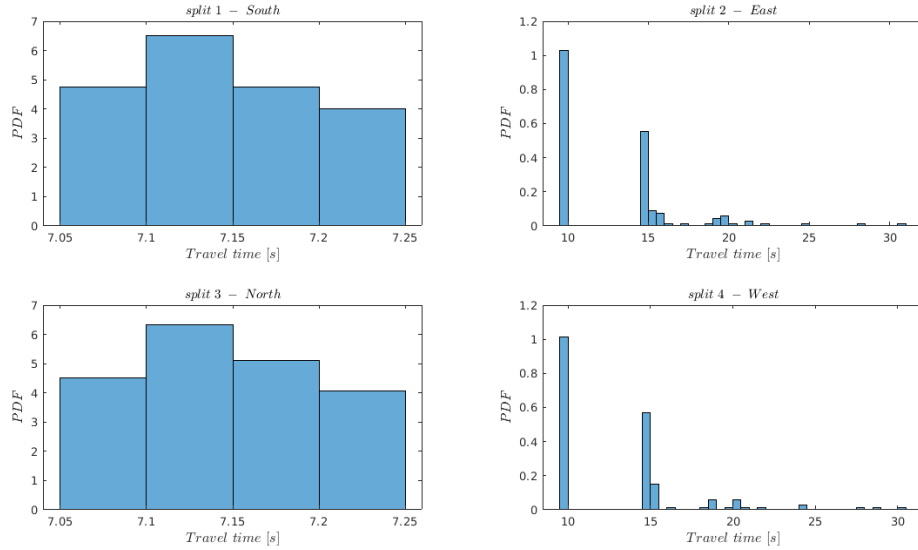


Figure 5.10. PDF of the travel time for scenario 4 of Roundabout B

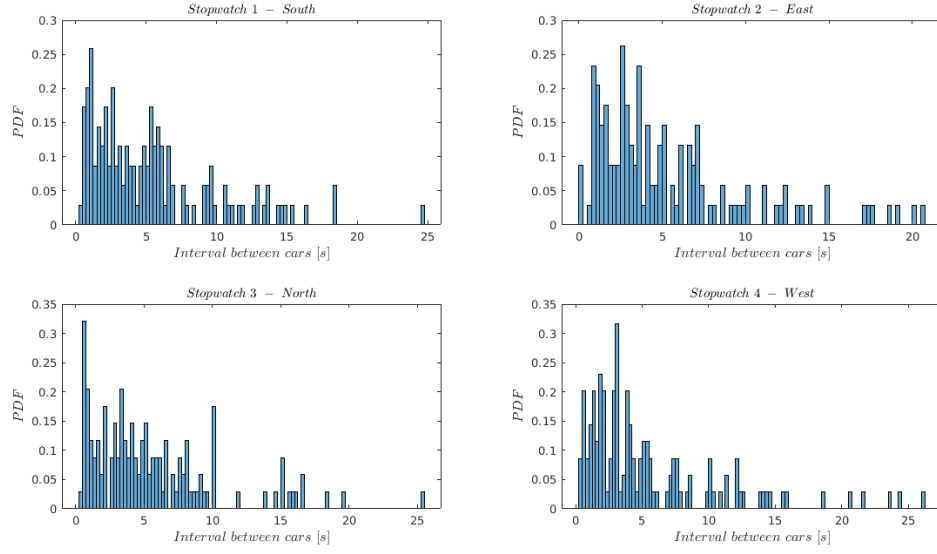


Figure 5.11. PDF of the interval time between cars for scenario 4 of Roundabout B

5.3.2 Scenario 5

In this scenario, namely scenario 5, we increase the vehicle arrival rate up to 0.3 in both leg 1 and leg 3, in order to obtain a medium load scenario. As a consequence:

$$\lambda_{Leg\ 1} = \lambda_{Leg\ 3} = 0.3$$

Fig. 5.12 and Fig. 5.13 below, show the PDF of the travel time and the PDF of the time interval between cars, respectively. As we can see in the figures, the results are pretty similar to the previous scenario 4. Of course, a higher arrival rate will increase the number of vehicles and the time to tackle the roundabout as well. Indeed, split 2 (east) and split 4 (west) have a more spreaded shape with respect to scenario 4.

Moreover, regarding the time interval between cars, we have a positive goodness-of-fit test at the 1% significance level at each stopwatch, except for stopwatch 2 (east).

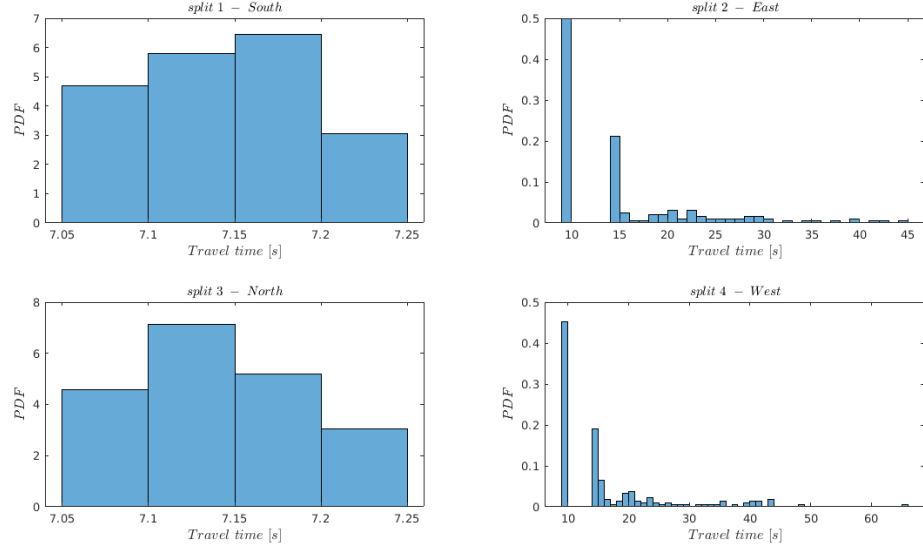


Figure 5.12. PDF of the travel time for scenario 5 of Roundabout B

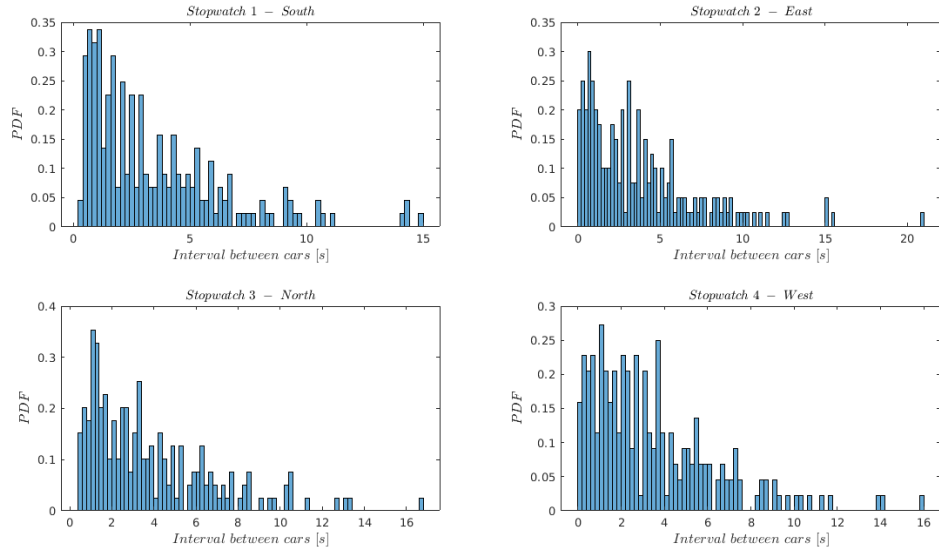


Figure 5.13. PDF of the interval time between cars for scenario 5 of Roundabout B

5.3.3 Scenario 6

In this last scenario, namely scenario 6, we increase vehicle arrival rate up to 0.4 in both leg 1 and leg 3, in order to obtain a high load scenario. We set:

$$\lambda_{Leg\ 1} = \lambda_{Leg\ 3} = 0.4$$

In this scenario the roundabout is very crowded. Fig. 5.14 and Fig. 5.15 below, show the PDF of the travel time and the PDF of the time interval between cars. Again, the results are pretty similar to the previous scenario 5 but there is an even higher travel time at split 2 (east) and split 4 (west).

Finally, regarding the time interval between cars, we have a positive goodness-of-fit test at the 1% significance level at stopwatch 1 (south) and stopwatch 3 (north). As a matter of fact, those stopwatches are within the entrance legs. So, in this case, the roundabout modify the traffic shape.

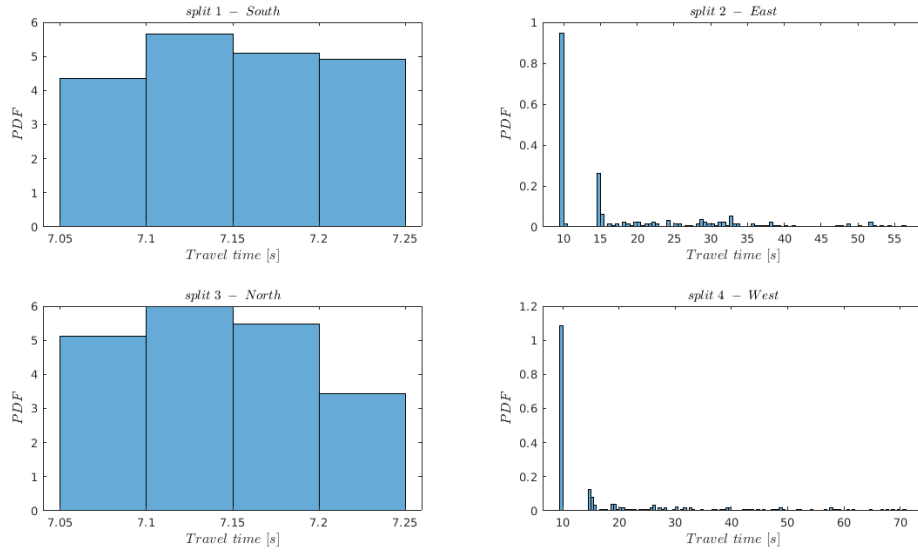


Figure 5.14. PDF of the travel time for scenario 6 of Roundabout B

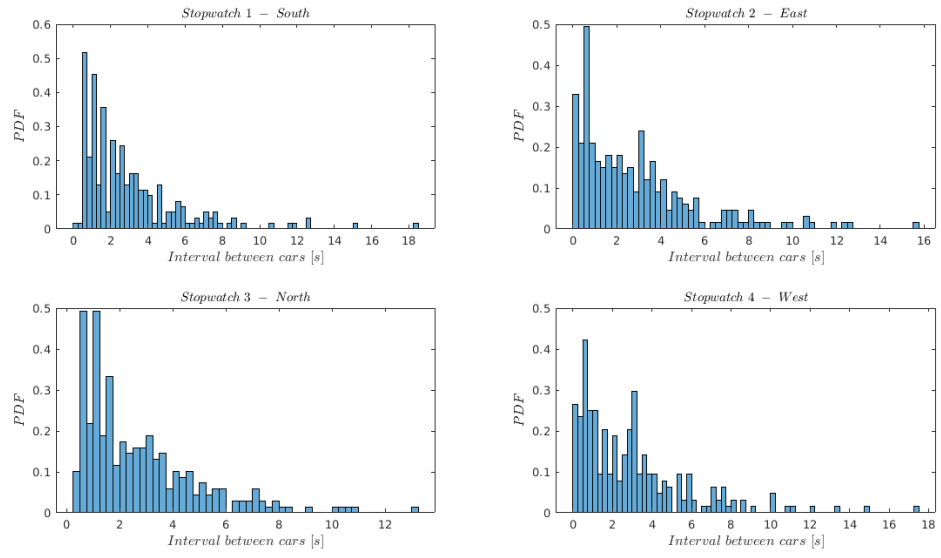


Figure 5.15. PDF of the interval time between cars for scenario 6 of Roundabout B

Fig. 5.16 is a screenshot of the simulated roundabout in SUMO.

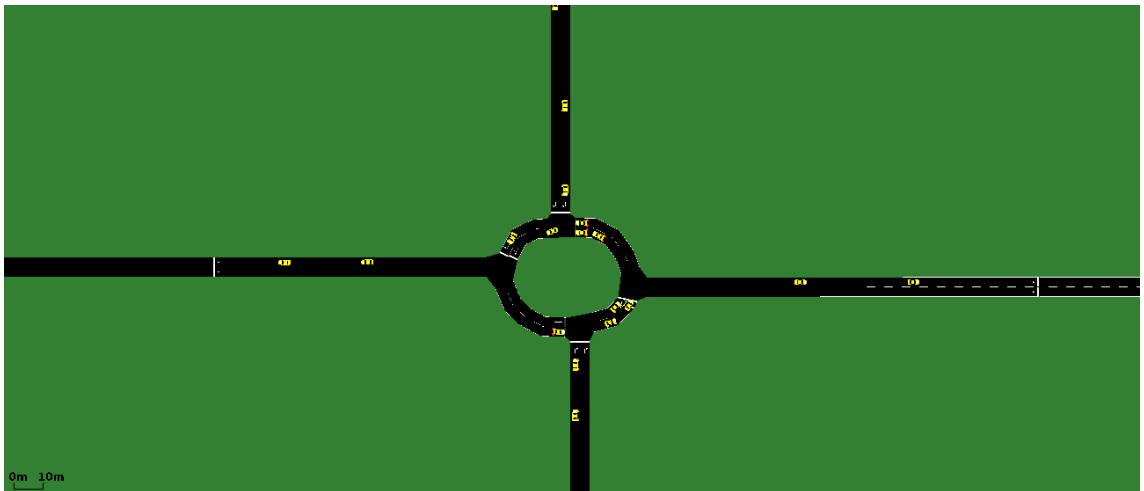


Figure 5.16. Screenshot of the simulated roundabout in SUMO

Finally, in tables 5.1 and 5.2 we recap the obtained results for Roundabout A and Roundabout B respectively.

| SCENARIO | RATE | STOPWATCH | GOF (1%) |
|----------|------|-----------|----------|
| 1 | 0.2 | 1 (west) | yes |
| | | 2 (south) | yes |
| | | 3 (east) | yes |
| | | 4 (north) | yes |
| 2 | 0.3 | 1 (west) | yes |
| | | 2 (south) | yes |
| | | 3 (east) | yes |
| | | 4 (north) | yes |
| 3 | 0.4 | 1 (west) | yes |
| | | 2 (south) | no |
| | | 3 (east) | no |
| | | 4 (north) | yes |

Table 5.1. Results overview - Roundabout A

| SCENARIO | RATE | STOPWATCH | GOF (1%) |
|----------|------|-----------|----------|
| 4 | 0.2 | 1 (south) | yes |
| | | 2 (east) | yes |
| | | 3 (north) | yes |
| | | 4 (west) | yes |
| 5 | 0.3 | 1 (south) | yes |
| | | 2 (east) | no |
| | | 3 (north) | yes |
| | | 4 (west) | yes |
| 6 | 0.4 | 1 (south) | yes |
| | | 2 (east) | no |
| | | 3 (north) | yes |
| | | 4 (west) | no |

Table 5.2. Results overview - Roundabout B

Chapter 6

Conclusion

This last chapter deals with a general summary and some conclusive remarks about the obtained results.

The conducted simulations in chapter 3 showed that in a general urban road with more than one lane, given an exponential distribution of the traffic shape, it is held during the whole simulation road. Moreover, when there are more than one lane, it is better a more natural redistribution of vehicles among the lanes. It means vehicles have to privilege the rightmost free lane, like in real situations.

In the second case study in chapter 4, we can deduce two things: In a situation like that, in which vehicles have to perform a lane changing to pass through the obstacle, once vehicles get past the obstacle traffic shape lose its exponential distribution, very useful characteristic to better create a mapping between our road and queue theory. Furthermore, in general, sectors before the obstacle still preserve the exponential distribution of the traffic shape; nevertheless, if the road get crowded, we can lose this exponential property, especially just behind the obstacle.

Moreover, an important role for those results is where vehicles perform their lane changing to pass through the obstacle. Indeed, in terms of travel time, it is better a policy like scenario H in which most cars perform their lane changing in advance in order to form a short queue behind the obstacle. On the contrary, in terms of GOF test, it is better a policy like scenario I in which most cars perform their lane changing later, just behind the obstacle.

In the third case study in chapter 5 we introduce an additional element, the roundabout. Even in this new element of the topology, by increasing the load of traffic, we will lose the above exponential distribution of the traffic shape.

Finally, an important role for those results is the physical topology. Roundabout B is better in terms of both travel time and GOF test. Indeed, this last topology allows a less congested operation of the roundabout element, even with pretty high arrival rate.

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