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A microsimulation study to assess re-design options and bus priority measures for a multi-junction area

Master's Thesis
Master in industrial engineering

Work conducted under guidance of
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October 2019

ACKNOWLEDGMENTS

I would take this opportunity to thank my professor and guide during this dissertation, Prof. José Manuel Henriques Telhada, who provided proper guidance and his expertise throughout the project. I am grateful to the Department of Production and Systems (DPS) of the EEUM (Escola de Engenharia da Universidade do Minho) for providing me complete access to the LabMob (Mobility Laboratory) facilities at the University of Minho during the project.

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

RESUMO

O congestionamento do trânsito em cidades de média dimensão, como Braga, está aumentando e levou já, em muitos casos, à deterioração das condições das viagens, ao aumento dos níveis de poluição e dos riscos de acidentes. Os indicadores de desempenho, como tempo de viagem, emissões de poluentes, velocidade do veículo, tempos de paragem em filas, etc., pioraram com o tempo. Este estudo visa reduzir o congestionamento, simulando projetos alternativos (adições de infraestruturas) sugeridos pelo Município de Braga e algumas estratégias alternativas de gestão do tráfego.

A área de estudo inclui a região em torno da rotunda de Infias e de duas escolas, Dom Diogo de Sousa e Escola Secundária de Sá de Miranda, e o cruzamento que liga a rodovia N101 à rodovia A11 e os subúrbios de Braga. Existem duas questões principais: a primeira é grande afluxo de veículos na rotunda de Infias, e a segunda é que todo o tráfego flui para uma zona da rede viária composta por múltiplas interseções de fluxos conflituantes. Como resultado, esta rede não consegue servir o seu propósito de servir adequadamente a procura nas horas de pico da manhã e da tarde.

Para melhor avaliar as condições atuais, é usado a componente de microssimulação do software de simulação de tráfego Aimsun. O software requer a definição precisa da área de estudo e simula diferentes tipos de comportamento do veículo que variam durante o tempo de execução. A coleta de dados envolve a previsão de dados de procura (estimativa de matrizes OD), recolhendo dados de fluxo de veículos e contagens no local. A validação do modelo de microssimulação é realizada mediante a simulação do modelo representativo da situação atual (com os dados recolhidos *in loco*).

Os resultados da simulação sugerem que as opções de alterar infrastruturalmente a zona de estudo permitirão uma melhoria significativa da maioria dos indicadores de desempenho, em comparação com os valores relativos à situação atual. Em particular, os resultados sugerem que a construção de novas pontes para facilitar significativamente o fluxo de tráfego entre a rotunda de Infias e a extremidade oposta da área de estudo. Recomenda-se que esta estratégia infrastutural seja implementada para resolver, ou, pelo menos, minorar o problema de congestionamento atual and the implementation of public transport priority plans.

PALAVRAS-CHAVE

Aimsun, Avaliação de estratégias infrastuturais, Estimação de matrizes OD, Simulação de tráfego rodoviário

ABSTRACT

Traffic congestion in medium-sized cities such as Braga is increasing and have led to worsened travel conditions for the commuters and a rise in pollution levels that lead to life-threatening conditions. Performance indicators, such as travel time, pollutant emissions, vehicle speed, stop times, etc., have worsened over time. This study aims at reducing congestion by simulating alternative designs (infrastructure additions) suggested by the Municipality of Braga and some traffic management strategies.

The study area includes the region around Infias roundabout, the two schools Dom Diogo de Sousa and Escola Secundária de Sá de Miranda and the multi-junction that lies connects the highways N101 with highway A11 and the suburbs of Braga. There are two main issues: first is the heavy input to the Infias roundabout and second is that all the traffic flow towards the multi-junction from all directions thus not being able to serve its purpose.

To evaluate the conditions, traffic simulation software Aimsun is used. We use microsimulation process that requires accurate study area definition and simulates different types of vehicle behavior that varies during runtime. Data collection involves demand data prediction (estimation of OD matrices) by collecting vehicle flow data by site visits and counts. System model validation is done by verifying the simulation of real-world model with the data collected from site visits.

Simulation results suggest that the re-design options led to a significant improvement of most of the performance indicators as compared to the values obtained for the real-world model. Results suggest addition of bridges to facilitate traffic flow from the connected areas towards the open end of the study area. It is recommended that the re-design route must be taken to solve the issue and the implementation of public transport priority plans.

KEYWORDS

Aimsun, Infrastructural strategies evaluation, OD matrix estimation, Traffic simulation

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LIST OF ABBREVIATIONS AND ACRONYMS

BI – Bayesian Inference

CAD – Computer Aided Design

CO – Carbon Monoxide

EM – Entropy Minimization

EU – European Union

GIS – Geographic Information System

GLS – Generalized Least Squares

GO – Gravity Opportunity

GR - Gravity

IBL – Intermittent Bus Lanes

ICSP – Initial Cost Shortest Path

IM – Information Maximization

KPI – Key Performance Indicator

ML – Maximum Likelihood

NO_x – Nitrous Oxides

OD – Origin Destination

ODM – Origin Destination Matrix

OSM – Open Street Maps

PM – Particulate Matter

PT – Public Transport

RFID – Radio Frequency Identification

SO_2 – Sulphur Dioxide

TUB – Transportes Urbanos de Braga

WHO – World Health Organization

1 CHAPTER 1: INTRODUCTION

1.1 Context and motivation

This dissertation is a part of the final year of the master's course in Industrial Engineering. This topic was chosen because of the motivation to pursue a research topic that involves helping the environment by reducing emissions due to burning of fossil fuels in any way. Upon conclusion of this study, we will have gained knowledge about the key factors while planning and managing traffic in a medium-sized city, reduction in atmospheric pollution (both air and noise) by solving the congestion problems. Major cities all over the world face this challenge due to increase in vehicle population. Traffic congestion not only leads to longer travel time or longer queues, but also deteriorates the environment and human/animal health daily causing an overall bigger impact over time.

The main purpose of this dissertation is to study the status of the traffic conditions in and around the Infias region that is a part of Braga. Braga is located in the northern part of Portugal and has mountainous terrains. The traffic conditions in a medium sized city such as Braga worsen in such narrow areas due internationalization because of international universities and new job opportunities, Study here refers to the evaluation of Key Performance Indicators (KPIs) such as harmful emissions from vehicles, travel time, stop time, queue length etc. The final objective is to suggest re-design options or certain traffic management techniques (installation of traffic signals). Vehicles pile up during peak hours and it appears that the nodes are being used at full capacities. But, on the contrary, just a few tactical changes could lead to smooth flow for the same vehicle demand.

A city or traffic planner aims at solving these issues by using up minimal resources (time and money). So, naturally the purpose of this study is to evaluate solution options as we keep in mind the havoc created along the problem solving process. For example, if there is a bridge to be built in an already narrow street, the current traffic will be even slower until the construction finishes. So the trade-off in terms of the different factors in play and the decision-making abilities of the concerned officials are crucial. A city engineer faces challenges such as understanding the dynamics of traffic flow, vehicle behaviour patterns etc. that must be evaluated accurately to obtain better solutions using modern traffic simulation software.

The purpose of public transport in such congested areas is understandably compromised as the travel times for people dependent on them increases substantially. Priority for such transport is another way of clearing up traffic in highly congested nodes and we will take a look at some such scenarios. With the advent of environment friendly initiatives all around the world, this study aims at the reduction of traffic related emissions, which in turn will help lead the way to healthy living for living beings and a better quality of commute for vehicle owners.

1.2 Objectives

- Improve general functionality of the junction area capacity to reduce delays and queues for a long-term re-design period;
- Improve safety by reducing traffic conflicts, and maintaining or improving crossing for pedestrians and cyclists;
- Improve environmental conditions, reducing site specific pollution;
- Evaluation assessment, determining the best possible solution based on the results from simulations;
- Implementation of bus priority measures to improve efficiency of public transport.

1.3 Methodology of the study

This report is a case study of a specific region and will include the following stages:

- Survey of the study area.
- Primary data collection from site visits
- Secondary data collection from official statistical databases such as Pordata and INE and literature reviews
- System modelling in Aimsun software, recording results and data analysis

The initial survey of the site includes tasks such as observing the patterns in traffic flow, problems faced by the commuters, vehicle behaviours in different situations, driver raections, pedestrian behaviour and so on. During heavy congestions, driver behaviour changes drastically. These observations are made over a duration of 2 weeks so that all the variations are properly recorded.

Data collection phase, just like the survey, is divided over a duration of several weeks so that different traffic patterns and counts are observed. Data collected from literature reviews (researchs and reports) will facilitate verification of the survey and data collections by understanding the studies conducted by other researchers.

Final phase of the study involves the simulation of the model developed in the software and analysing the data collected from the model runs.

1.4 Structure of the document

This document is structured as follows:

Chapter 1: Introduces the problem and motivation to conduct the research, along with its objectives and general methodology.

Chapter 2: Presents a brief literature review, covering the past research and projects in the area of traffic simulation and atmospheric effect of traffic congestions.

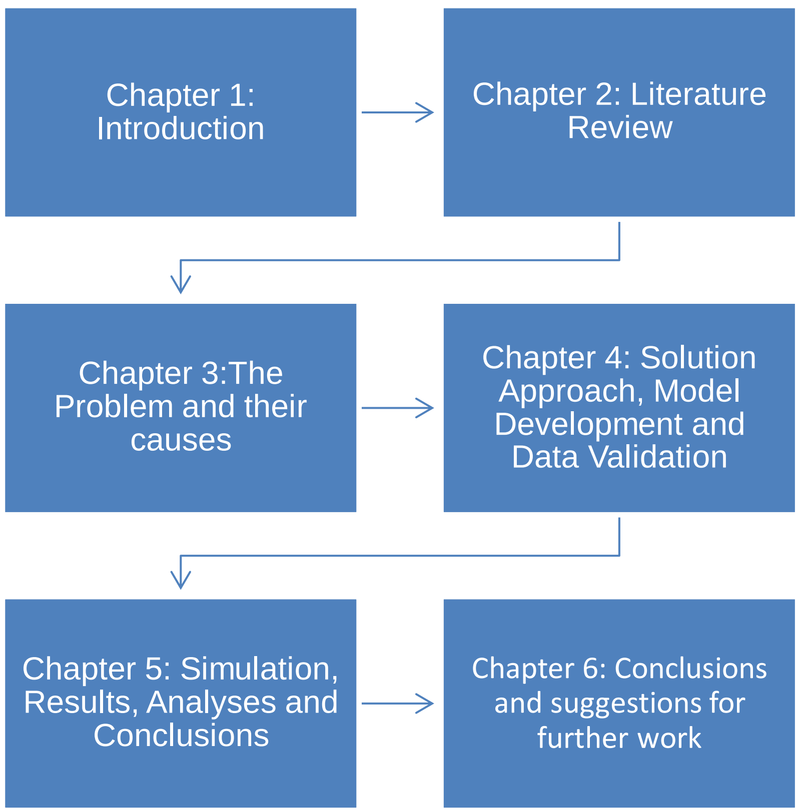
Chapter 3: Describes the problem under study in detail and their causes. Further, it describes the strategies that will be used to solve the problem.

Chapter 4: Discusses in detail the proposed solution approach and validates the simulation model.

Chapter 5: Reports and discusses the simulation results of the alternative strategies. Furthermore, the chapter presents the main conclusions and recommendations based on the results.

Chapter 6: Presents the main conclusions of the research, along with some suggestions for further work.

Table 1: Flow chart depicting the structure of the document



2 CHAPTER 2: LITERATURE REVIEW

2.1 Chapter overview

This chapter discusses the literature and research in the field of traffic simulation. Topics such as the different traffic simulation software, methodologies, etc., are discussed here. The aim of the chapter is to present and discuss the concepts relevant to our study and alternative methods available. This will allow us to understand the problems much better in chapter 3 and the solution approach section of our study in chapter 4.

2.2 Motor vehicle emissions and its health affects

Cars, buses and trucks powered by fossil fuels are major contributors to air pollution. The World Health Organization (WHO) conducts regular studies to determine the effects of human exposure to traffic emissions. Information about these exposures is collected by quantifying exposures. In many cases, information is gathered as part of an epidemiological study. One of the largest and most comprehensive study was the EU-funded study of air pollution exposure distributions within adult urban population in Europe (EXPOLIS), which involved measurements in 10 different cities in the EU in the 1990s (Matti, J. Jantunen, 1996). Following are some of the major components of air pollution:

- Particulate Matter (PM): One type of PM is the most seen in vehicle exhaust. Fine particles – less than one-tenth the diameter of a human hair – pose a serious threat to human health, as they can penetrate deep into the lungs.
- Nitrogen Oxides (NOx): These pollutants form ground level ozone and PM (secondary). Also harmful as a primary pollutant, NOx can cause lung irritation and weaken the body's defenses against respiratory infections such as pneumonia and influenza.
- Carbon Monoxide (CO): This odorless, colorless and poisonous gas is formed by the combustion of fossil fuels such as gasoline and is emitted primarily from cars and trucks. When inhaled, CO blocks oxygen from the brain, heart and other vital organs.
- Sulfur Dioxide (SO_2): Motor vehicles create this pollutant by burning sulfur-containing fuels, especially diesel and coal. SO_2 can react in the atmosphere to form fine particles and, as other air pollutants, poses the largest health risk to young children and asthmatics.

Population explosion is contributing heavily to global warming and pollution. Almost every living being has been exposed to polluted atmosphere. Passenger vehicles are major pollution contributors, producing significant amounts of nitrogen oxides (NOx), carbon monoxides (CO) and other pollutants. In 2013, transportation contributed more than half of the CO and NOx and almost a quarter of the hydrocarbons (HCs) emitted into the atmosphere. There are fewer number of heavy weight vehicles as compared to small (passenger) vehicles but the contribution towards pollutants is significant.

In developing nations in South East Asia, heavy air pollution contributes to congestion and accidents due to the formation of smog (smoke + fog). The health risks of air pollution are extremely serious. Particulate Matter (PM) is singlehandedly responsible for up to 30,000 premature deaths every year (US). Poor air quality increases respiratory ailments like asthma and bronchitis, heightens the risk of life-threatening conditions like cancer, and burdens our healthcare system with substantial medical costs.

2.3 Fuel efficiency vs vehicle emissions

The use of diesel vehicles is believed to be economical. But diesel engines produce more emissions as compared to its counterparts. Heavy duty vehicles such as trailers and buses use diesel as fuel that account for most of the emissions. But in their case, in order to power the high capacity engines, diesel is necessary.

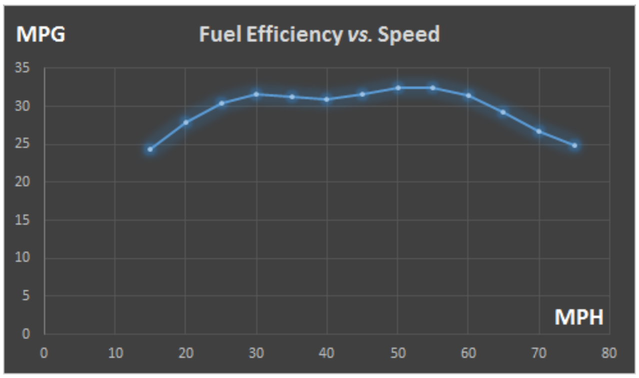


Figure 1: Relation between vehicle speed and fuel efficiency; Source: datagenetics.com

Vehicle speed and fuel efficiency are closely related. This implies that vehicle speed and emissions are related too. Congestion usually occurs in local roads. On highways it happens only due to some incident or some repair/renovation work. A study by the international Transport Forum discusses the reasons for differences in the real-world emissions and the legislative limits in EU (Ligterink, Norbert, 2017). This study also concludes that the driving conditions effect the vehicle emissions. By constantly stopping, the fuel efficiency takes a hit and leads to more and more emissions. This holds for all vehicles regardless of the size of engine, model etc. This happens because of two reasons:

- Air resistance increases as the speed increases: Pushing air around the vehicle takes up about 40% of a car’s energy at highway speeds. Traveling faster makes the job even harder. The increase is exponential, meaning wind resistance rises much more steeply between 70 mph an 80 mph that it does between 50 mph and 60 mph.
- Engines are designed for specific speed, temperature and RPM ranges. Driving out of these ranges goes against the fundamental design of the engine.

2.4 Kiss and Go

In localities with schools, roads usually have a speed limit and "Kiss n Go" areas to facilitate the pick-up and drop-off of children. Near pre-primary and primary schools, it is a must because the younger students need attention of their parents as well as the fellow drivers. So, a controlled speed is a must, and this leads to congestions in some cases but on the other hand it is very important to ensure student safety. There are a few factors that cause congestion around these areas:

- Younger students are not usually able to recognize their parents' cars. This leads to chaos amongst the parents waiting in queue, as well as the students waiting to be picked up (during home time).
- With narrow lanes, the usual traffic and the school-bound traffic mix up and lead to confusion.

2.5 Traffic simulation

Over the years there has been advancements in every field including simulation. A variety of traffic simulation software are available with some differences, but the basic features are the same. In this section we discuss some of these features and then compare a few simulation packages. Currently the city planning committee of Paris are trying to solve the congestion around the Eiffel tower. They are planning on redesigning the area by 2023. It is a microscopic model-based study and it contains the busiest sections and nodes of the world (Aimsun, 2018).

At the US-Mexico border, there are studies being conducted to examine the international land port entries. One such study modelled the study area in three different traffic simulation packages (Aimsun, VISSIM and Trans Modeller) and compared their advantages and disadvantages (David Salgado, 2016). So, we can say that traffic simulation is not limited to city (road and highway) management but also to complex study areas, as the previous example suggests. We now enlist some of the features available in the traffic software packages such as VISSIM, CarSim, Aimsun etc.

2.5.1 System modelling approaches

Traffic simulation is basically classified as microscopic, mesoscopic and macroscopic. A study describes the classification of previous researches done based on the type of simulation approach used with the majority of them being done using microscopic simulation (Nurul Nasuha Nor Azlan, Munzilah Md Rohani2, 2018). The basic difference between the three is that the size of the study area varies. As the name suggests, microsimulation is concerned with the study of smaller areas, macroscopic with large study areas and mesoscopic is a combination of the two types. Let us take a look at these types a bit in detail. They can deal with different traffic networks namely highways, urban networks, freeways etc.

2.5.1.1 Micro-simulation

A microsimulator follows a microscopic simulation approach. This means that the behavior of each vehicle in the network is dynamically modelled throughout the duration of the simulation as the vehicle travels through the traffic network. This is done according to different vehicle behavior models such as car following, lane changing etc. A microscopic simulator is a combination of both continuous and discrete elements. This means that there are some features like vehicles or detectors whose states change continuously over time (split into short fixed time intervals called cycles or steps) and on the other hand there some elements such as traffic signals whose state changes at specific discrete intervals. Here we can model a wide range of features such as different vehicle types, driver behavior, infrastructure geometries etc. It can also model incidents such as lane closure, accidents, speed variations etc.

2.5.1.2 Macro-simulation

Macro simulation has a slightly lower attention to detail when it comes to intersections. Since the study area is large as compared to microscopic simulation, an overall model for the traffic flow is defined (aggregated model). Characteristics such as speed, flow and density are the main parameters. Researchers have attempted to develop the speed-flow-density descriptions to develop models for uninterrupted traffic flow (Nurul Nasuha Nor Azlan, Munzilah Md Rohani2, 2018). City traffic planning on a large scale requires macro modelling.

2.5.1.3 Meso-simulation

A mesoscopic simulation approach involves the vehicles being modelled as individual entities, same as microscopic, but the behavioral models are simplified with a slight loss of realism in order to have a simulation event oriented. Meso-simulation can be used to study bigger and complex models as compared to micro models. For example a study can be conducted for a whole city (macro or meso) rather than just a small part of it (micro). Meso-simulation models require the definition of aspects at the lowest of levels as well because the different regions of the study area depend on each other for dynamic flow data.

2.5.2 View modes

Visualization can be two-dimensional (2D), three-dimensional (3D) or both. Some features that are not differentiable in 2D are better visualized in 3D mode. For example, the lane changing maneuvers, reaction time etc. are better understood while viewing in 3D.

2.5.3 Basic statistical outputs

All traffic simulators provide the following data outputs. These outputs are common to all the simulators with addition of others depending upon the package:

- Delay Time: Average delay per vehicle per kilometer. This is the difference between the expected travel time (the time it would take to traverse the system under ideal conditions) and the travel time. It is calculated as the average of all vehicles and then converted into time per kilometer.
- Stop Time: Average time at standstill per vehicle per kilometer.
- Queue Length: Average queue in the network during the simulation period. It is measured in number of vehicles.
- Total Travel: Average time a vehicle needs to travel one kilometer inside the network. This is the mean of all the single travel times (exit time – entrance time) for every vehicle that has crossed the network, converted into time per kilometer.
- Fuel Consumption: Total liters of fuel consumed by all vehicles that have crossed the network. This is only provided when the Fuel Consumption model is enabled.
- Pollutant Emission: For each pollutant, total kilograms of pollution emitted by all the vehicles that have crossed the network.
- Average Speed: Average speed for all vehicles that have left the system. This is calculated using mean journey speed for each vehicle.
- Missed Turns: total number of missed turns.
- Vehicles Lost outside: if the route-based mode is being used, the number of lost vehicles that have left the network during the simulation period.
- Harmonic Speed: harmonic mean speed for all vehicles that have traversed the section.

2.5.4 Infrastructure

Highways, local roads, freeways, pedestrian crossings, ramps, roundabouts, surroundings etc. comprise the infrastructure in a traffic simulation software. With proper specifications during data input, the model can replicate the real-world with high accuracy. Also during the evaluation of KPIs for alternate models by addition of bridges, extra lanes etc. is facilitated in these packages.

2.5.5 Vehicles and pedestrians

Different types of vehicles such as cars, buses, trucks, small trucks etc. as well as pedestrians can be simulated in these software. Pedestrians form an integral part of system modelling in study areas that are situated in city centers or around some touristic monuments or around public transport hubs as the flow is heavy during all times. Manhattan Traffic Model (MTM) is an example of such complex projects that has been undertaken (Aimsun, 2018). Vehicles can also be modelled according to their specs such as fuel consumption, emissions, size, shape etc. Vehicle behavior during peak hours in congested areas is also possible to model. One such study shows the different driving patterns in different traffic conditions such as weak lane discipline etc. and try to model them using microscopic, mesoscopic a macroscopic approaches (Caleb Ronald Munigety, Tom V. Mathew, 2016).

2.5.6 Demand Modelling

Demand estimation is one of the most important inputs for traffic simulators. Questions such as "how many vehicles are flowing in a network?" or "which type of vehicle (car, bus etc.)?" take up majority of the user's time. These packages basically provide two types of traffic modelling: OD matrices and flow counts. OD matrices require the input of flow data between two or more extreme points (origin /destination) in a system and the software assigns the flow of vehicles according to the preferences. On the other hand, traffic flow counts requires the user to input flow counts in each of the sections in the model. The second method has a drawback that the flow count do not help the simulator to assign the vehicles a particular destination. The vehicles are flowing along the sections to fulfill the counts input by the user. For this reason the use of OD matrices is preferred. We will study some ODM estimation methods in a later section.

2.5.7 Detectors, control plans and VMS

Achieving traffic management is the main purpose of system modelling in a simulation software. Detectors are an important feature that help in system validations. Variable Message Screens (VMS) can also be simulated depicting travel time, revised routes etc. in cases of congestions (just like it is already being used these days). Control plans involve activities such as installation of traffic lights, bus priority linked to traffic lights, node formation. Also random events such as accidents, lane closures, or vehicle speed reduction due to poor weather conditions and how they affect the KPIs can also be simulated using traffic management features.

2.5.8 File export/import

System modelling becomes easier with the facility of importing/exporting the files across different platforms. OSM and GIS are two platforms for exporting maps that are accepted by the traffic simulation software. Even though it requires further modelling, it helps in reducing the time substantially. These package allow importing files across themselves too. For example Aimsun allows file types from CONTRAM, Open Street Maps, CUBE, and Paramics amongst many more.

2.5.9 Data analysis and presentation

Data analysis tools are available built-in in all traffic simulator packages. Analysis of KPIs in well decorated time series graphs, map based outputs, path assignment or section analysis is made easy by the tools available. Comparison of two or more KPIs and how they are related (correlation) is also possible. Outputs of simulation are in the form of statistical outputs and map based outputs that depict the path or section usage according to color codes.

2.5.10 Further software development

Further development of such programs is possible so that more features can be added by the users to use the software as per their needs. Popular programming languages such as Python are generally used for such purposes.

2.6 Origin-destination matrix (ODM) estimation

ODM estimation is one of the most challenging aspects of traffic management planning. Vehicles go from one place to another at a certain velocity via a certain route (which might not be the same every day). Due to congestions or accidents or construction work along a route, the vehicle might take a different path. The estimation of ODM is tricky and once achieved, does not ensure that the simulation will be executed exactly as desired. Traffic planners need accurate data so solve the issues. There are many studies over the years constantly investigating the methods to estimate ODM. One such study classifies the different ODM estimation methods based on categories such as application, complexity etc. as well as it discusses the problems associated with ODM estimation (Timms, Paul, 2001).

Different approaches to ODM estimation have been taken up over time. Some researchers suggest considering the traffic networks as a graph and have achieved high accuracy of traffic estimation (Zhidan Liu, Pengfei Zhou, Zhenjiang Li, Mo Li, 2018). Smart data estimation through cellular data collection have also been performed in the past for the purpose of collecting traffic flow data (Noelia Caceres, Luis M. Romero ,Francisco G. Benitez ,Jose M. del Castillo, 2012).

Demographic data collection is a tedious task and might take up months. But studies have been conducted to distinguish the traffic estimation process by using demographic data and traffic counts (Subha Nair, Nisha Radhakrishnan, Samson Mathew, 2013). Some municipalities and government have made such data available on national statistics websites but data such as which vehicle is moving towards from which point in the system from which origin.

A study discusses the different ODM estimation mathematical models with classification on the lines of static and dynamic traffic conditions (Sharmindra Bera, K.V. Krishna Rao, 2011). Let us take a look at some of these methods as explained in the paper:

2.6.1 Static OD Matrix estimation from traffic counts

A static OD matrix estimation problem does not consider the time-dependent traffic flows and is assumed to represent a steady state situation over a period. The average traffic counts are collected for a longer duration to determine the average O-D trips.

2.6.1.1 Travel Demand Model Based Methods

Initially the researchers tried to relate the trip matrix as a function of models with related parameters. Some researchers used Gravity (GR) model-based approaches and some use Gravity-Opportunity (GO) based models for estimating ODM. These techniques require zonal data for calibrating the parameters of the demand models. The main drawback of the gravity model is that it cannot handle with accuracy external trips.

2.6.1.2 Information Minimization (IM) and Entropy Maximization (EM) approach

EM and IM techniques are use as model building tools in transportation, urban and regional planning context. The EM procedure analyzes the available information to obtain a unique probability distribution.

2.6.2 Statistical Approaches

Several models have been presented in order to estimate or to update ODM from traffic counts for the networks without congestion and with congestion effects via parametric estimation techniques such as Maximum Likelihood (ML), Generalized Least Squares (GLS) and Bayesian Inference (BI).

ML is one of the oldest and most important in estimation history. The ML estimates are the set of parameters that will generate the observed sample most often. In ODM estimation, ML approach maximizes the likelihood of observing the target ODM and the observed traffic counts conditional on the true trip matrix.

The method of GLS estimation based on the well-known Gauss-Markov theory plays an important role in many theoretical and practical aspects of statistical inference-based models. The advantage of this model is that no distributional assumptions are made on the sets of data and it allows the combination of the survey data relating directly to O-D movements with traffic count data, while considering the relative accuracy of these data.

The BI method has also been applied in various transportation planning problems where prior beliefs are combined with the observations to produce the posterior beliefs.

2.6.3 Bi-Level Programming Approach

Bi-level programming approach has been used for the problem of ODM estimation is case of congested networks. In this approach, the upper-level problem is the trip matrix estimation problem and the lower-level problem represents a network equilibrium assignment problem.

The travel demand in a study area might depend on many factors that influence the number of trips generated from a region. In the state-of-art, it is assumed that the trips are originating and terminating at the zone center. The zonal characteristics such as demographic data thus play an important role in such studies (Subha Nair, Nisha Radhakrishnan, Samson Mathew, 2013).

2.7 Previous research

The issue of traffic congestion is present all over the world. The roads and other infrastructure present all around the world had not anticipated such a significant rise in traffic demand. So researchers and traffic management officials have been constantly occupied with congestion issues arising in medium-sized and large cities. A study conducted in Portugal based on one such study to determine the compatibility of simulation software SUMO in simulating traffic in larger cities. The study shows that the simulation was successful for the test city of Coimbra and concludes that SUMO can be used for other (larger) study areas (Jose Capela Dias, Pedro Henriques Abreu, Daniel Castro Silva, Gustavo Fernades, Penousal Machado, Antonio Leitao, 2008). Another study that was conducted in Portugal (again using SUMO) that built an integrated framework for multi-paradigm traffic simulation to control the effects of traffic demand increase. This study shows the implementation of electric bus powertrain for the purpose of mobility and its performance in cases of traffic obstruction using microsimulation. Results of the project validated the integration approaches for the powertrain (Macedo, José Luís Pereira, 2013). For the purposes of simulation related projects, the availability of accurate traffic flow data is important. There have been studies about the generation of synthetic passenger data in the city of Porto using a technology that combines traffic –passenger data modelling and simulation (Rongye Shi, Peter Steenkiste, Manuela Veloso, 2018). Since the data available is not always complete, this study helps create complete data using simulation and the real-world data collected by Automated Fare Collection (AFC).

2.8 Concluding remarks

The ill effects of traffic congestion are suffered by both the commuters and the residents equally. It is important to maintain the average vehicle velocity between 50-60 kmph to keep the emissions at minimum. So, we can say the congestion is directly proportional to higher pollutants due to the behavioral changes amongst different drivers. To combat high pollution levels or longer travel time, the answer is ultimately reducing congestions. Macro-simulation and meso-simulations have their advantages but in our case, we stick to microsimulation. Infrastructure cost is another factor that we will revisit in chapter 5 while performing the cost analysis of the models. The major concept related to traffic simulation, that is the OD matrix estimation is crucial and in Chapter 4 we discuss in detail how the OD matrix for our project is determined.

3 CHAPTER 3: THE PROBLEM AND POSSIBLE SOLUTIONS

3.1 Chapter overview

In this chapter, we explain in detail the specific problems that contribute to the congestion. First, we define the study area in terms of a map and define the names for different sections for future reference. Moving on, we then explain the current situation, the causes that gave rise to them and multiple possible solutions that can be implemented to solve them. Numerous studies in Portugal have been conducted in the previous years. Projects in Lisbon and Porto metropolitan areas are on a bigger scale. Studies in Lisbon determine pedestrian flow towards the train station to assess the use of certain gates to avoid delays, walking times and so forth. This study was concluded using microscopic pedestrian flow simulation. In Lisbon, another concept of Intermittent Bus Lane (IBL) was introduced as an innovative approach to achieve bus priority (Jose Manuel Viegas, 2007).

3.2 The study area

The Municipality of Braga commenced the study of the Infias region in Braga due to the heavy traffic flow and congestion in and around the surrounding areas. Shown below is a snapshot of the area in Google maps that we are going to study in our project. As we can see there are four labels made and the other important landmarks across the area have been labelled by Google maps. The topmost in the north is the Taberna Belga roundabout. The one in the center is the multi-junction that joins the highway N101 from the North with the N101 in the direction East-West. The bottom most is the Infias roundabout. This area includes roads, both highways and local transit roads, of around 5 kilometers in length. Near the Infias roundabout, we can see the school Colegio Dom Diogo da Sousa of the right of the roundabout and on the left, is the other school Escola Secundaria de Sa de Miranda. On the left of our area is the city center and, on the right, we have the city hospital, highway A11 (that connects to Guimaraes) and the University of Minho.

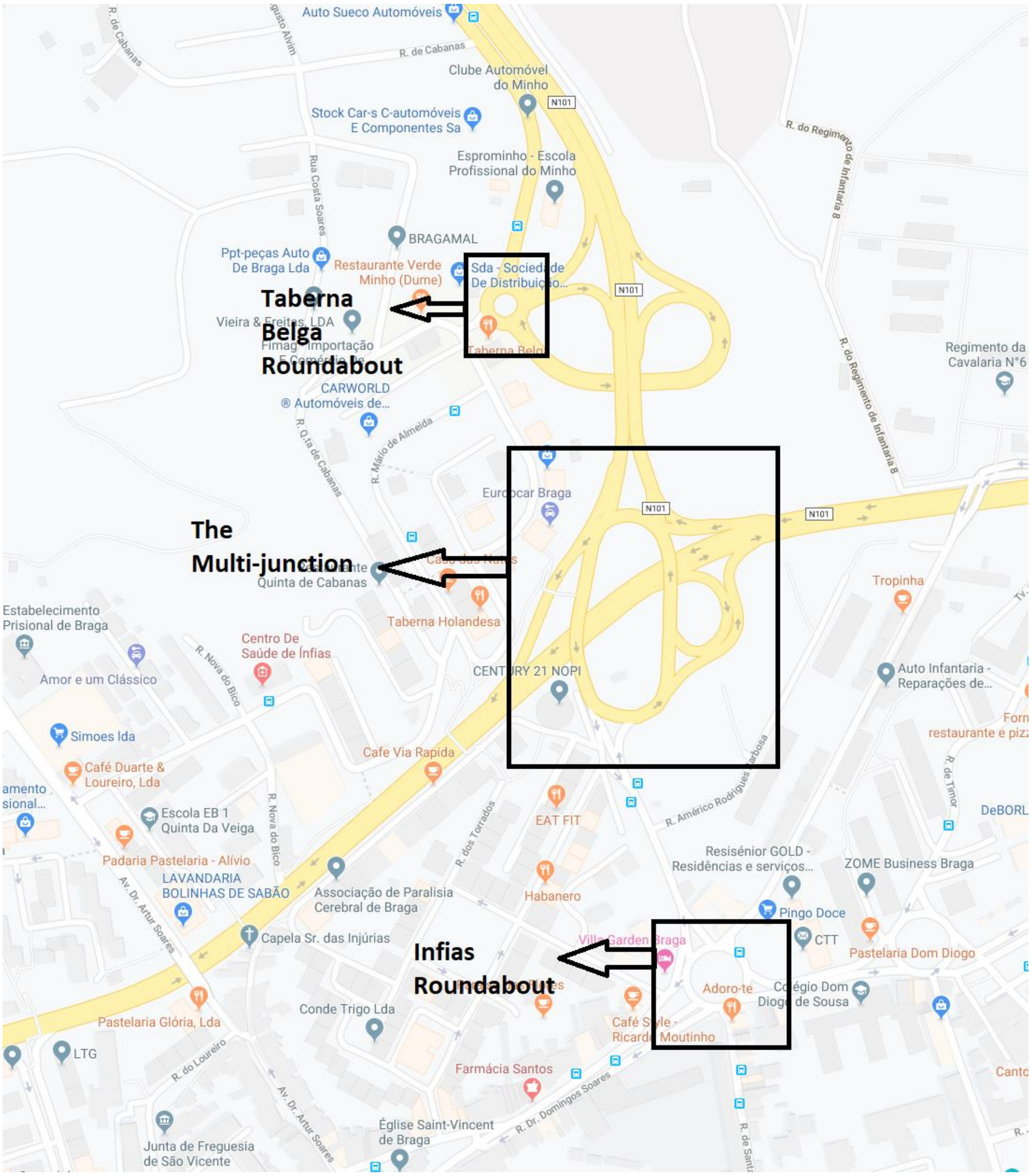


Figure 2: The study area with indications of major junctions

3.3 The status-quo

Upon visually analyzing the subject area, following are the observations made:

- Long vehicle queues along the sections adjoining the Infias roundabout.
- Vehicles trying to enter the Multi-junction from the section coming in from Infias roundabout have lower priority at the junction.
- During the evening peak, the vehicles coming in from the direction of Braga train station form long queues while entering the multi-junction.

- In front of the school, Colégio D. Diogo de Sousa, pedestrian crossings cause some congestion during the morning peak during school drop-off hours. The other school, Escola Secundária de Sá de Miranda, does not affect the traffic flow too much because of the presence of a service road.
- The traffic input flow from the East on N101, the vehicles attempting to join the Multi-junction cause long queues along the highway that extends up to a kilometer long on occasions.
- Another important observation is the driver behavior becomes more and more errant when the congestion increases. This includes not respecting the priorities at the roundabout, give way signs etc.
- During evening peak hours, the traffic coming in from the East (from Braga Parque direction), due to the large number of vehicles wanting to use the multi-junction, lead to huge queues and sequentially lead to delay for vehicles that want to go straight ahead towards the Baga train station. Even the vehicles that want to go towards the North must wait until the queue at the multi-junction is reduced.
- There are around 10 Transportes Urbanos de Braga (TUB) buses that run along the Infias region towards the north direction. People dependent on public transport are getting discouraged to use the buses because of increasing travel time during peak hours (a journey that must last 1 minute ends up being of 10 minutes in some cases).

The multi junction roundabout was built to facilitate smooth connectivity for the vehicles. But in recent years the traffic during peak hours has been so high that at times smooth traffic flow. Total input flow of the system is over 25,000 vehicles during morning peak hours (07h30 to 09h30) and around 30,000 during evening peak hours (17h30 to 19h30) (data collected via site visits and inspections). During regular school days, the schools - Colegio Dom Diogo de Sousa and Escola Secundaria de Sa de Miranda, present in the Infias area attract most of the traffic from the Multi Junction. Due to the “Kiss n Go” facility available in front of the schools, parents can stop in the narrow two-lane road, thus interfering with the otherwise (except school opening and closing hour) smooth traffic flow in that area.

3.4 The problems and their causes

Traffic demand expansion is an issue know to humans for decades now. Every big city (in terms of traffic demand) was once subject to fewer vehicles. The engineering teams in-charge of the highway projects that were concluded 50 years ago, did not forecast such a high increase in population and urbanization of small and medium sized cities. According to Pordata, the number of motorized vehicles per 1000 habitants in Portugal has risen from 584.7 in 2010 to 626.5 in 2017. (Instituto Nacional de Estatistica - Statistics Portugal, n.d.)

The highways A11, N101 and N103 that run through Braga, have seen a significant rise in the number of vehicles they handle since its construction concluded. During peak hours the waiting time in order to cross a road section 100 meters long is over 2 minutes in some cases. Our study area has a road network of around 7 kilometers. Including National highways and local roads.

Current traffic flow involves over 25000 vehicles operating in and out of the area chosen for the study. This study area is at the centre of the major traffic flow through Braga with commuters travelling in all directions from all direction through this section. Commuters, at times, must wait in queues for as long as 3 minutes to cover 100 meters. The study aims at reducing the congestion and thus reducing the KPIs under study. This will lead to better travelling conditions, lower hassle for the residents and finally lower negative impact on the environment and living beings. In this was there will be positive or less negative effects.

The problem area stretches from Lugar de Cabanas which is a service road alongside the N101 from the North (coming from Amares, Ponte de Lima etc.) until the Rua de Santa Margarida (street that runs between Colégio Dom Diogo de Sousa and Escola Secundária de Sa de Miranda). In the west, the national highway N101 goes in the direction of Porto, Barcelos, Póvoa de Varzim etc. Likewise, on the east, N101 joins N103 that runs towards Guimarães and other surrounding regions. The highway running in the East-West direction is named as Av. Antonio Machado.

Now let us look at the main sections with heavy congestion and their causes and their causes:

3.4.1 Infias roundabout

Infias roundabout manages input/output traffic flow from 5 directions. A huge amount of flow coming in from all 5 directions but maximum from the direction of Colégio D. Diogo de Sousa and from the direction of City Center. With all the traffic preferring the exit towards the Multi-junction, the Infias roundabout is constantly choked thus contributing to the delay and queue length factors heavily. So basically, delayed entrance to the multi-junction leads to the congestion. Furthermore, the surroundings include major residential areas and two schools that are exposed to high levels of pollution.

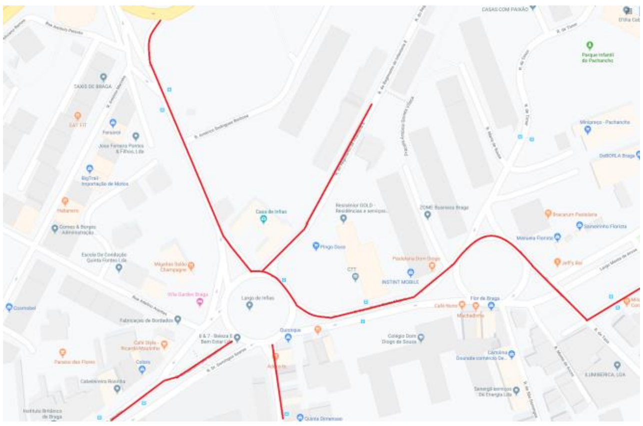


Figure 3: Traffic around the Infias roundabout – red marking indicate congestion

3.4.2 Multi-junction entrance

The Multi-junction facilitates the distribution of almost all the vehicles in the system. So, at every input to this junction, there are some delays due to the priority for the vehicles coming in from the left, as is in the case of a conventional roundabout.

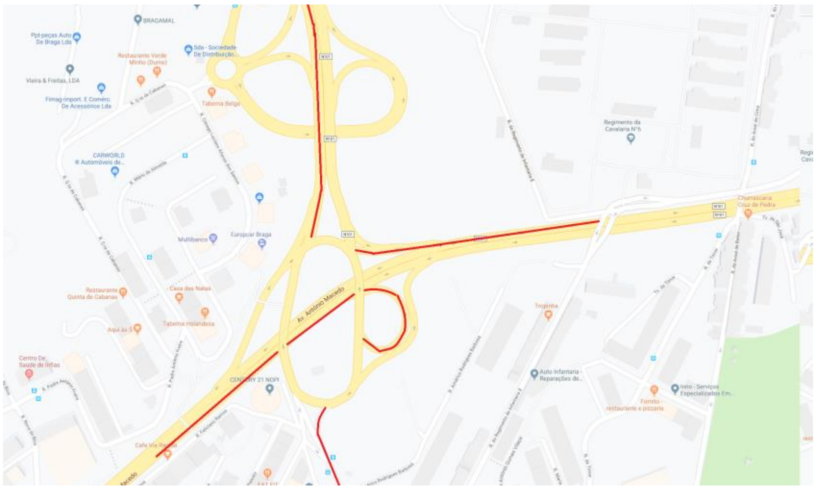


Figure 4: Traffic around Multi-junction - red marking indicate congestion

3.4.3 Taberna Belga Roundabout

The traffic coming in from the North are basically divided in to two main flows. The highway N101 is the major carrier of traffic and a service road running parallel to N101 is the other. Compared to N101 the flow is quite low but eventually they converge onto N101 at the Taberna Belga roundabout. Thus, leading to congestion along both sections.

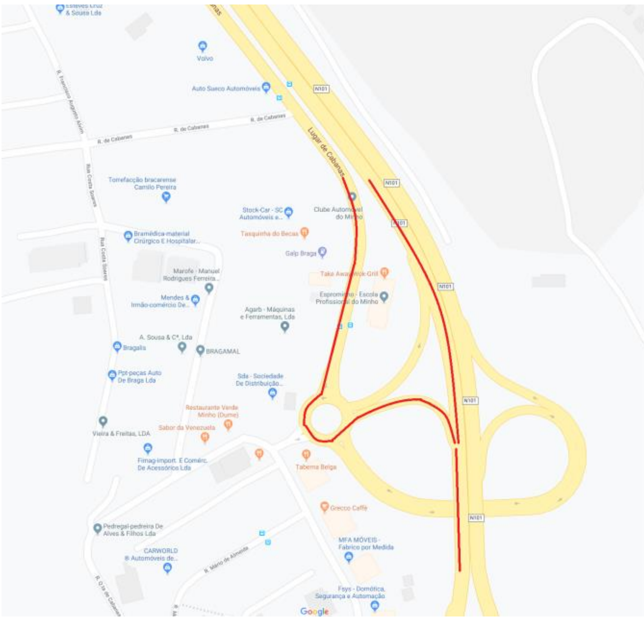


Figure 5: Traffic around the Taberna Belga roundabout

3.4.4 Pedestrian crossings

Near the schools Colegio Dom Diogo de Sousa and Escola Secundaria de Sa de Miranda congestion is imminent during morning school hours because of the heavy pedestrian counts. This results in cars stopping increased number of times and thus leading to longer queues, elevated pollutant levels, travel time surge and so on.

3.5 Parameters to be monitored

In our project we will monitor parameters such as average speed, emissions, delay time, stop time, fuel consumption for the real-world model and the model solutions as well. Apart from the statistical data outputs, we will look at map-based outputs such as section density (in terms of flow) as well. The quality of a model will directly depend on the values of these parameters. For example, higher emissions value than the real-world model will imply deterioration of the environment as a result of the changes made in the model.

3.6 Possible solutions

Traffic management and constructing new infrastructure are the ways in which traffic congestions can be solved. Traffic management comprises of actions such as controlling the speed limit, limited access to heavy weight vehicles, installation of traffic signals etc. Whereas building new infrastructure involves new bridges or underpasses to decongest the sections.

Traffic management, if it works, is the preferred solution for any city engineer because it does not involve new infrastructure cost. Furthermore, these new additions will need regular maintenance. During construction there will be delays and obstruction along the construction site which would lead to longer travel time and longer queues.

3.6.1 Traffic Management

In the study area selected, there is a possibility of installation of traffic signals at two locations: at the Infias roundabout and at the entrance to the Multi Junction node from the Infias roundabout section. As the traffic from all directions tend to flow towards the multi-junction, an experiment showing the effects of installation of traffic signals to facilitate flow to clear the traffic at Infias roundabout.

3.6.2 Solutions Recommended by Municipality of Braga

The Municipality of Braga currently has been working on this situation and have three modified models for the network. All three of them involve construction of infrastructure. Since these models have been suggested after careful surveying by civil engineers, the construction and implementation are sure provided they produce feasible results during the simulation.

3.6.2.1 Alternative 1

Description: The first scenario involves the construction of two sections explained below.

- First, a two-way flyover connecting the national highway from the north, N101, until the section just before the Infias roundabout (shown below in blue and green paint).
- Second, a diversion from the usual input section in the multi-junction, eliminating the existing section (shown in red paint).

Figure 6: Proposed infrastructure additions Alternative 1

3.6.2.2 Alternative 2

Description: This scenario is the same as the first one with some additions to the infrastructure. The two-lane flyover from the north and the diversion in the remains the same with two other additions.

- Firstly, the two-lane flyover takes a diversion to join the exit on the multi-junction towards the east, hence facilitating unobstructed flow of vehicles between the North and East directions (blue and green sections that diverge in two directions).
- Secondly, the section coming in from the Infias roundabout into the multi-junction towards the North and East directions (pink sections in the picture below).

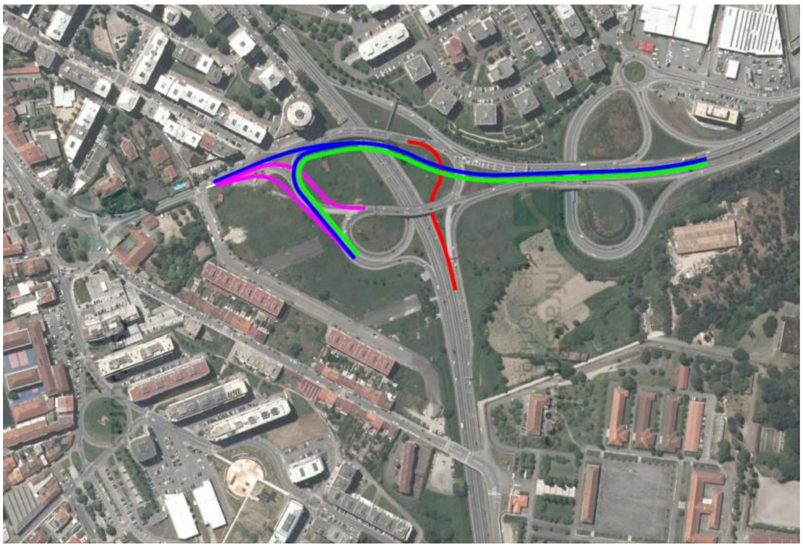


Figure 7: Proposed infrastructure additions Alternative 2

3.6.2.3 Alternative 3

Description: This scenario involves the construction of maximum infrastructure and is a bit complicated too. There are 5 major modifications:

- The first one is common to all the scenarios, i.e. the diversion from the East coming into the multi-junction (shown in pink).
- The second section involves the construction of an extra lane coming from the Infias roundabout into the multi-junction going towards the East direction (shown in red).
- Next one is just an addition of a lane in the section coming in from the West joining into the multi-junction (shown in yellow).
- Next one is the construction of a flyover bridge connecting the traffic coming from the North joining into the section going to East.
- The final addition is the construction of a flyover bridge that connects the traffic input flow from the West with the output towards the North.

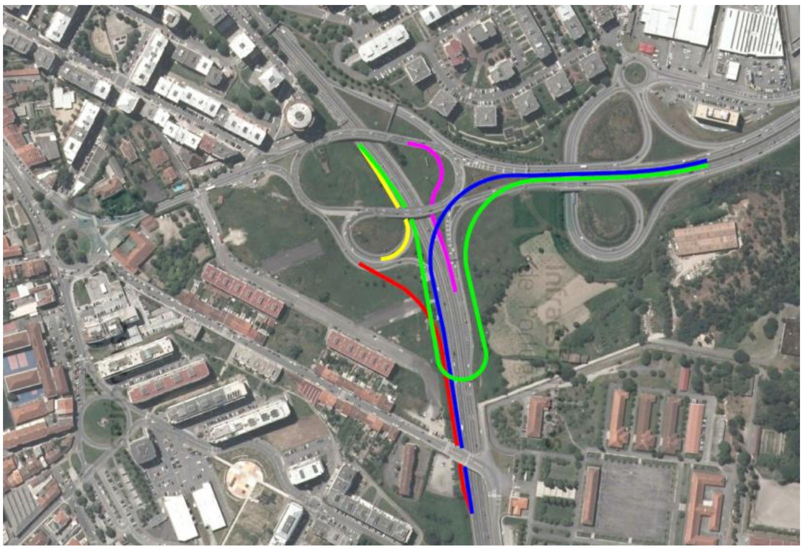


Figure 8: Proposed infrastructure additions Alternative 3

3.6.3 Bus priority options

Public transport run by TUB requires prioritization to serve its purpose and combined with traffic signals and detectors, it can be achieved. For example, in the figure shown below, once a TUB bus reaches the detector *D*, the traffic lights for that section at the Infias roundabout turns green. This serves the purpose of giving way to public transport and also clearing the traffic in front of the schools. But one drawback is that during heavy congestion, the time taken for the bus to reach the detector could take longer. Nevertheless this solution approach is interesting and worth evaluating.

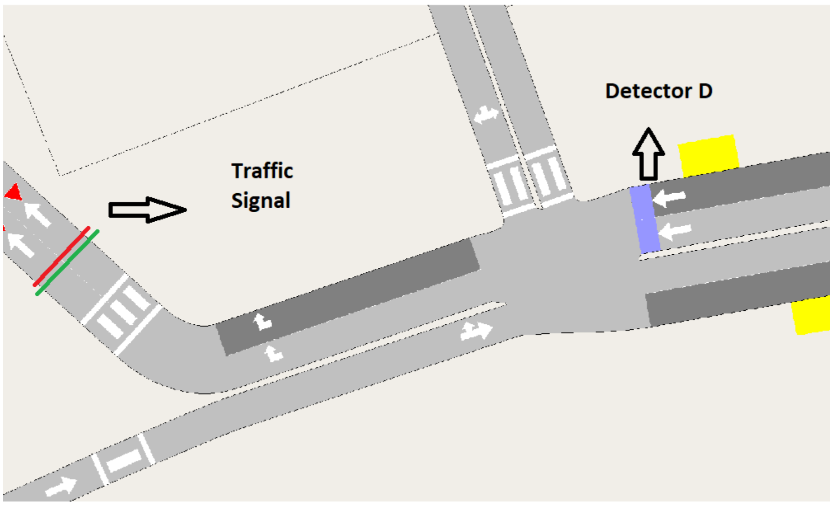


Figure 9: An example of working of the bus priority traffic management

The main expectation of this approach is to reduce the time taken by the TUB buses to travel the given route in the time that they must. In this project we depict the basic concept of how this works and suggest some ideas of further applications.

3.7 Concluding remarks

Understanding the problems and their causes helps us attain the vision to solve them better. In the next chapter we discuss the solution approach for the problems and model development of the study area in Aimsun simulator. Having understood the causes, we can design some models of our own, even though they won't be backed up by civil engineers' approvals, it will be interesting to have a look at the results.

4 Chapter 4: Model development and validation

4.1 Chapter overview

This chapter discusses the implementation of the problems and their suggested solutions as discussed in the previous chapter. We look at the step by step solution approach from data collection until the final output comparisons that will be done in chapter 5. Another important section of this chapter is the system validation which will be done by simulating the real-world model and verifying the results obtained with the data collected from site visits which was used in system modelling.

4.2 Solution approach

The solution to this problem requires the use of a professional traffic simulation software, in our case we used Aimsun 8.1. We will discuss the features of Aimsun in the next chapter. Here we describe the role of the software in better understanding and analyzing the problem and the parameters in different scenarios.

4.2.1 Step 1: Data collection

The number of vehicles that enter the system (input flow) through various entry points (Origin), flow along each section of the system and the vehicle counts for exit data (Destination) – all these data are crucial for accurate modeling of the real-world situation in Aimsun. The model is only as good as the data that we feed the software. So, this data accumulation process was accomplished by site visits over multiple days. 15-minute intervals were chosen to facilitate better imitation of the real world by accounting for varying traffic flow during each interval.

All data have been collected by site visits and observing the traffic flows at different points in the network on different days of the week during different 15-minute intervals within the peak periods.

First, we describe the OD pair names:

N: The northernmost OD pair.

NW: To the left of N, a bit towards the west (North-West). It has 2 input and output flow sections.

SW1, SW2 and SW3: Are the three OD pairs in the South-West.

S: Southernmost OD pair with 4 input and output flow sections.

C: Center of the network and has 4 input and output flow sections.

SE1: In the South and towards the East.

E: The Easternmost OD pair.

Having collected the input flow, the next challenge was to determine the OD Matrix for the model. As discussed in the literature review, there are several mathematical models to estimate the OD matrix with different sets of data. Due to lack of data about the census and the lack of smart technologies (vehicles fitted with trackers and RFID readers), the OD matrix estimation was achieved by using weighted ratios. Following is an illustration of the method of estimating the OD matrix.

Assume three OD pairs X, Y and Z. Say x vehicles come into the system from X, y from Y and Z from Z. So,

Total number of vehicles incoming = x+y+z

Similarly, assuming the outgoing vehicles from each of these centroids is a, b and c,

Total number of vehicles outgoing = a+b+c

Weight of each centroid in terms of outgoing traffic,

For X, a/ (a+b+c)

For Y, b/ (a+b+c)

For Z, c/ (a+b+c)

Now we use these weights to determine what portion of the incoming traffic (x, y & z) the three destinations attract.

Number of vehicles going from X to Y = x (a/ (a+b+c))

Similarly, the values for each OD pair is calculated.

Here is an example of the data collected during the time interval 17h30 to 17h45:

Table 1: Traffic counts with their weights for the time period 1730 to 1745

1730-1745				
Centroid	**Vehicles coming IN**	**Weights**	**Vehicles going OUT**	**Weights**
5571: SW1	856	0,27003	547	0,206259427
5574: E1	763	0,24069	394	0,148567119
5595: N	649	0,20473	724	0,273001508
5596: NW1	65	0,0205	30	0,011312217
5597: SW3	268	0,08454	275	0,103695324
5598: SW2	50	0,01577	97	0,036576169
5599: S	428	0,13502	347	0,130844646
5600: SE1	63	0,01987	208	0,078431373
5601: C	28	0,00883	30	0,011312217
TOTAL	3170	1	2652	1

In the table above, “Vehicles coming IN” holds the counts for number of vehicles entering the system through the corresponding centroid. Similarly, “Vehicles going OUT” holds the count for vehicles exiting the system through the corresponding centroid.

The Aimsun 8.1 version does not allow simulation of pedestrians so this data was used just for analysis purposes. It could not be simulated in the model. Lane width, driver reaction time (response in case of stopping a car or starting from a stopped state), average queue lengths – these data were also collected by site visit and have been summarized below.

Tabela 2: Summary of data during site visits

Characteristic	Specifications
Lane width: Highways	3 meters
Lane width: Local Roads	2 meters
Pedestrian counts (every 15 minutes)	50 (peak during school hours)
Driver reaction time	1 to 2 seconds
Average queue length	30 vehicles/100 meters

4.2.2 Step 2: Modelling the Network in Aimsun

Area selection: To obtain best results, appropriate area selection with respect to incoming and outgoing (Origin and Destination, OD) selection is important. In our situation, we decided to include 9 O-D pairs with 15 incoming and outgoing sections related to them.

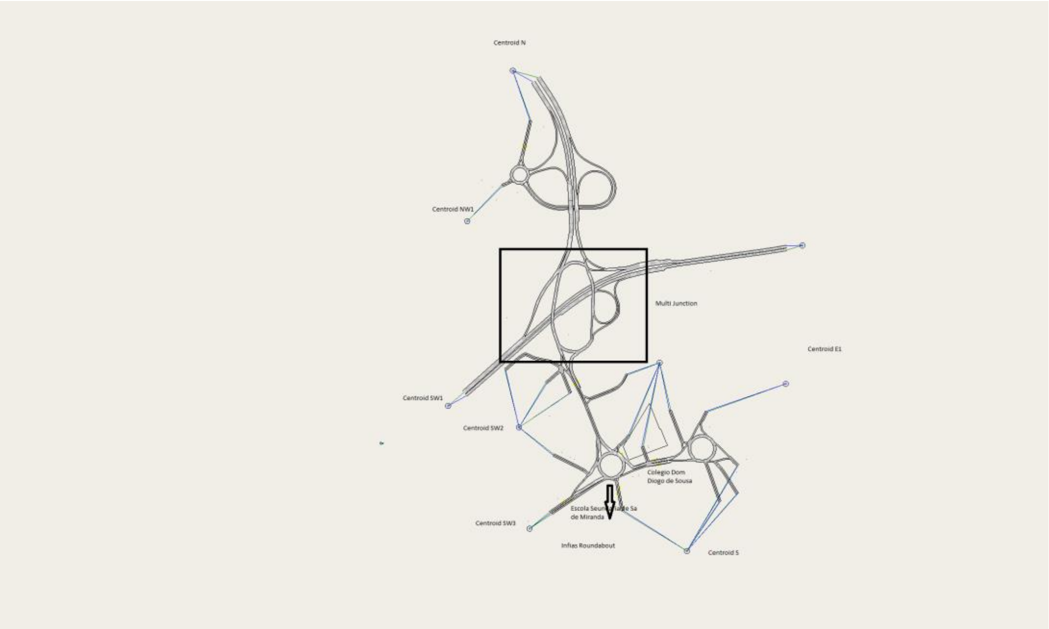


Figure 10: Indication of centroids, multi-junction and the Infias roundabout in the system model.

Road Lane Width: On the National Highways, the lane width is 3 meters and in the local streets/roads it is around 2 meters.

- Pedestrian Crossings: In Aimsun 8.1 we don't have the access to model pedestrian data.
- Section Parameters: Modelling the sections (roads) involves three main inputs: section length, section type and slope. The length is inputted in meters, and the slope requires the initial and final altitudes. In the case of varying altitudes in between, we input the intermediate altitudes too. This information is available for public use via Google Earth. The section type is either "reserved for public transport" or "for all vehicles". In our area selection, we have 3 lanes (in separate sections) in the category "reserved for public transport".
- Public Transport: Public transport in Braga is operated by TUB (Transportes Urbanos de Braga). In the area selected for our model, we have 6 public bus stops, with two of them having reserved lanes for this purpose.
- Data Inputs: Firstly, and most importantly, the traffic demand data. The data collected in Step 1 feeds the Traffic Demands via OD matrices. We have divided the two-hour time intervals in the morning and evening are divided into four 15-minute intervals to best imitate the real-world scenario. Second are the vehicle specifications: vehicle type, dimensions and emission model. Vehicle type include cars, trucks, buses etc. Vehicle dimensions can be changed according to different mix of vehicles in Braga.

These data parameters are set for the real world and the future scenarios as suggested by the Municipality of Braga and some other scenarios with control plans.

4.2.3 Step 3: Running the Simulation

After data input, Aimsun can simulate the model displaying the 2D and 3D views as per our requirement during the simulation. And the output data is recorded according to the analyses to be done.

4.2.4 Step 4: Simulation, Recording the Data and its Analyses

With Aimsun providing detailed statistical and map/graph-based outputs of all the major parameters, proper interpretation and conclusions are drawn using correlation between different KPIs.

4.3 About Aimsun 8.1 and model development

Aimsun 8.1 is a traffic simulator software that offers all necessary tools that a transportation professional would need. Major city municipalities all over the world employ professionals who use Aimsun to study and facilitate city management in terms of traffic. Paris, Shanghai, Sydney are some cities with ongoing projects that involve the use of Aimsun. In this section, we will take a brief look at the features of Aimsun used for the purpose of our study and how we have used them for developing the model. The software is extensible which means that developer can add new functionalities using the platformSDK. Aimsun stores the files in the formats .ang (uncompressed) and .anz (compressed; used for large sized files).

File Importers

Aimsun allows direct import of files from other environments such as Computer Aided Designing (CAD), Geographical Information Systems (GIS), and Open Street Maps (OSM). It also allows third party traffic and transportation software importing such as from Vissim and Paramics. In our project we have used the OSM file and imported it into Aimsun.

4.3.1 Traffic Network Editing

4.3.1.1 Sections, nodes and roundabouts

While modelling a network in Aimsun, there are some important components that are used such as sections, nodes, pedestrian crossings, traffic signals, give way signs and many more. Section refers to a road that can be a local road or a part of the highway. To connect two or more sections, we require nodes. Sections need these inputs to be defined: length, slopes, number of lanes and their widths. A node, once created, stores information about the turns and their priorities. Traffic signals are used at nodes by defining proper signal groups (using control plans) for each turn in the node.

Another important feature is the combination of section and nodes, the roundabout. Aimsun automatically creates a roundabout just by selecting all the output and input sections.

4.3.1.2 Vehicle Demand: Vehicle type, OD matrices and OD routes

Vehicle demand is modelled in Aimsun using the three important definitions: the type of vehicle such as car, bus, truck etc., the demand data which means the number of vehicles in the system, going out/in (defined using OD matrices) and finally defining if the vehicles follow any specific routes (defined by OD routes). In our models, we use only one vehicle type (car). The demand is modified accordingly in terms of vehicle dimensions, fuel consumption and emission models.

OD matrices and OD routes are a major section of our model development. The calculation of OD matrices has been explained thoroughly in section 4.2.1 under data collection. Aimsun uses two methods of path assignment namely Initial Cost Shortest Path (ICSP) and OD routes. ICSP is used by default if no OD routes are defined. OD routes are usually used when there is new infrastructure in the model, and we want the vehicles to use a path to commute between the centroids. So, we define the path between those two centroids and activate them in the OD matrices.

4.3.2 Control Plans

Control plans refers to traffic signals at nodes or roundabouts and are used to regulate vehicle flow. In Aimsun, it can be achieved by defining time durations during which a part of the node will allow the flow (green light) and the others will be red.

After a control plan is defined, it is activated by adding it into a Master Control Plan which contains a collection of different control plans for a model.

4.3.3 Traffic management

Traffic management involves the implementation of some scenarios such as lane closure due to an incident, reduction of speed, etc. These can be implemented in Aimsun using the traffic management tools such as *Problems* and can be overcome using *Strategies and Policies.*

4.3.4 Outputs and Data Analysis

Aimsun provides several facilities for comparing results from different simulation runs with the software. There is no need to export the data to another software to perform data analysis. Statistical outputs, map-based outputs and graphical outputs are some of the ways that we will perform our data analysis. Map based outputs depict the flow in every section by color coding them as shown in the image below. In our project we will analyze the main sections in the study area that experience congestions.

4.4 System validation

We look at the physical and data specific aspects of the real world and the real-world model in Aimsun. The objective is to verify that the model reflects and behaves exactly like the real world. Following is a step-by-step list of the aspects and the observations about their comparisons in the two cases:

- The physical appearance of the model is to scale as the Open Street Map file was imported in Aimsun. Upon looking in 3D view, the model represents the real world. The stop signals and the markings on the road are accurate. Lane widths, pedestrian crossings, road slope gradients are all verified using the altitudes from Google Earth.
- The centroids are correctly linked with their respective input and output sections.
- Following are the results of the simulation of the real-world model during morning and evening peak hours. After this we verify the results for parameters such as queue length, stop time etc.

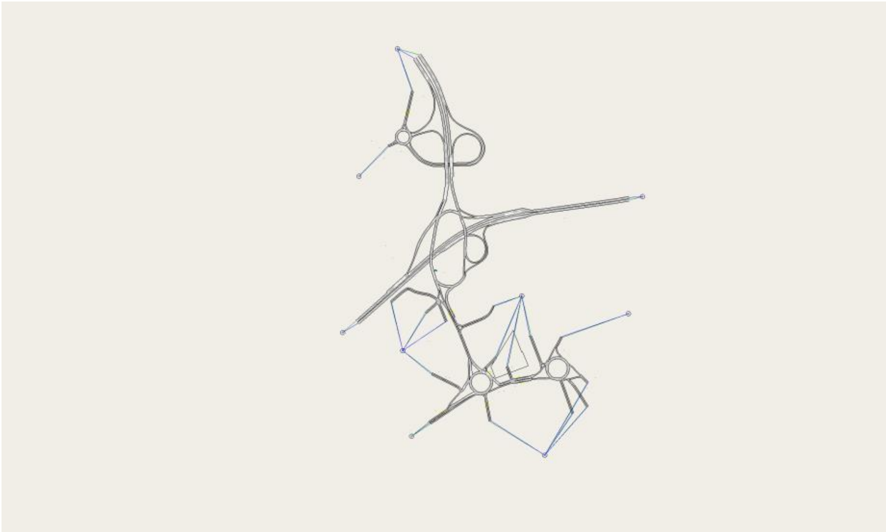


Figure 11: Aimsun model for the real-world model

4.4.1.1 Morning Peak

Figure 12: Simulation snapshot at the multi-junction and the Infias roundabout area

As we can see in the snapshot of the multi-junction, vehicles are queued up at the entrance from North the and at the entrance from the direction of train station that want to go towards the Infias roundabout. In the case of Infias region, the vehicles in front of the school Dom Diogo da Sousa have a very slow average speed because of the pedestrian crossing and the kiss and go facility. Also the vehicles from the center of the city go towards the multi-junction thus preventing the smooth flow of the traffic in front of the school.

4.4.1.1.1 Statistical Outputs

Table 3: Statistical Outputs for real=world model during morning peak.

Parameters	Value	Standard Deviation	Units
Fuel Consumption - Carro	2909,04	N/A	l
IEM Emission - CO2 - Carro	4892732	N/A	g
IEM Emission - NOx - Carro	8042,4	N/A	g
IEM Emission - PM - Carro	1279,94	N/A	g
IEM Emission - VOC - Carro	25369,06	N/A	g
Mean Queue - Carro	159,35	N/A	veh

Number of Stops - Carro	0,11	N/A	#/veh/km
Speed - Carro	39,51	23,6	km/h
Stop Time - Carro	82,05	149,15	sec/km
Travel Time - Carro	154,18	154,61	sec/km

4.4.1.1.2 Graphical Analyses

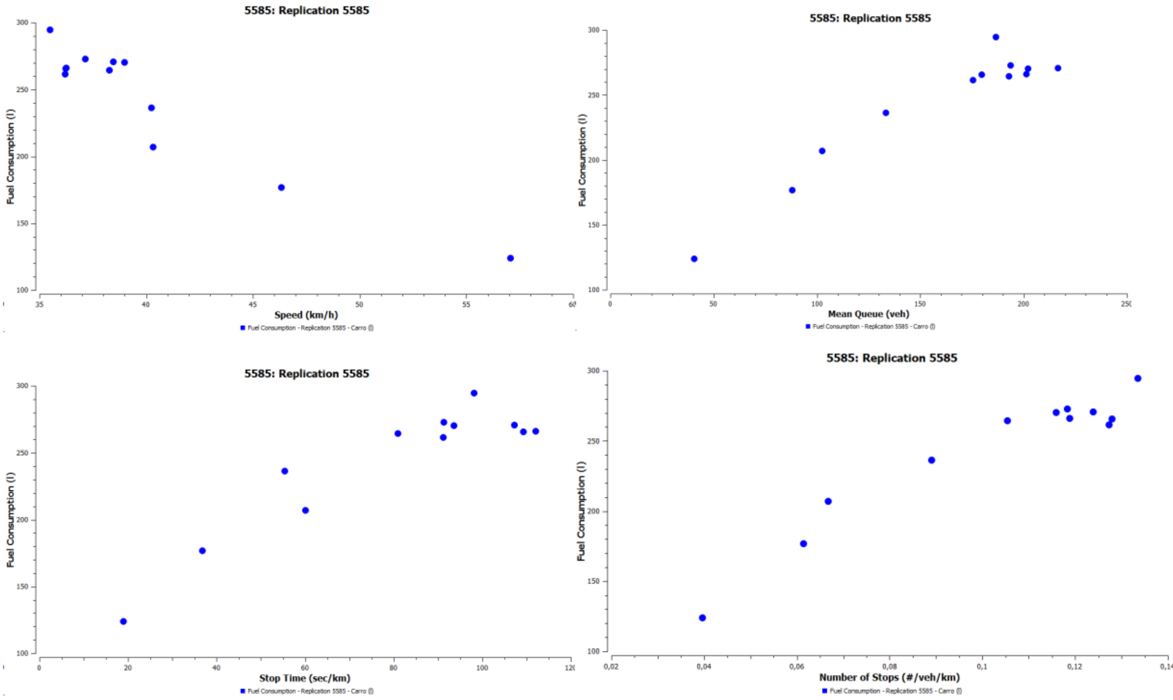


Figure 13: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively.

The graphical analyses of the simulations is done by focusing on the fuel consumption factor against other KPIs. In this case we can see the relationships are justified. Fuel consumed is proportional to KPIs such as stop time, number of stops etc. On the other hand it is inversely proportional to vehicle speed. We can see from the graph that as the speed approaches 50-60 kmph mark, the consumption is at the lowest.

4.4.1.1.3 Map based Outputs

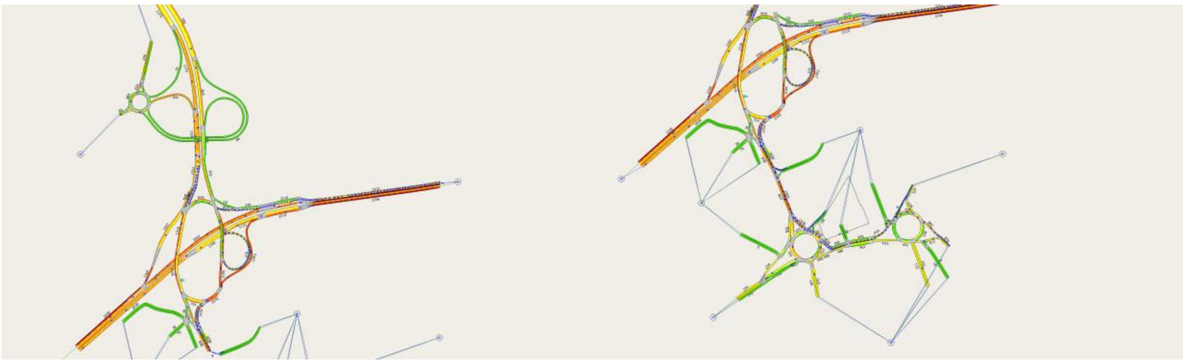


Figure 14: Map based outputs showing flow density in different sections

These outputs show the comparative vehicle flows in different sections of the system. The highway nodes of N101 from the North have less flow as compared to the nodes between the East and the train station direction because of the priority at the multi-junction which interrupts the flow. Whereas the flow is smooth and uninterrupted on the other node.

4.4.1.2 Evening Peak

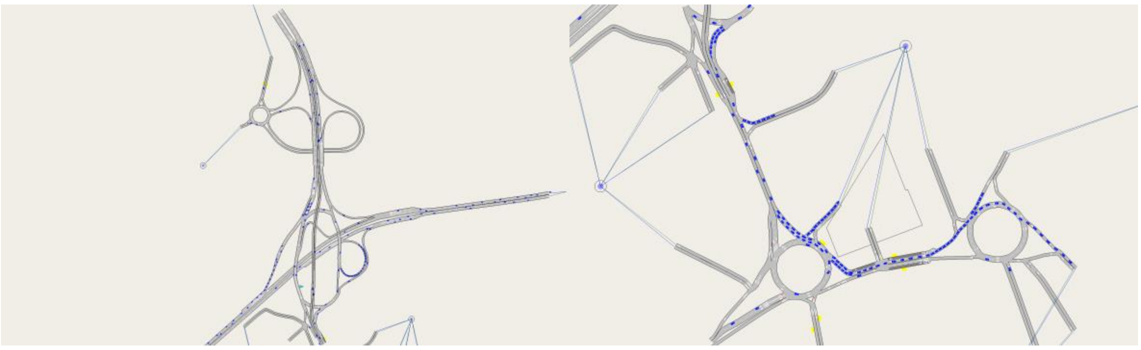


Figure 15: Simulation snapshot at the multi-junction and the Infias roundabout area

During the evening peak hours, the problematic part is the Infias roundabout and the multi-junction as well. The flow from all directions are very high and the vehicle flow is almost static for most parts of the simulation.

4.4.1.2.1 Statistical Outputs

Table 4: Statistical Outputs for real=world model during evening peak.

Parameters	Value	Standard Deviation	Units
Fuel Consumption - Carro	3219,59	N/A	l
IEM Emission - CO2 - Carro	6679741,5	N/A	g
IEM Emission - NOx - Carro	11353,77	N/A	g
IEM Emission - PM - Carro	1414,49	N/A	g
IEM Emission - VOC - Carro	59298,92	N/A	g
Mean Queue - Carro	525,59	N/A	veh

Number of Stops - Carro	0,14	N/A	#/veh/km
Speed - Carro	29,12	18,57	km/h
Stop Time - Carro	182,46	374,5	sec/km
Travel Time - Carro	266,13	372,87	sec/km

4.4.1.2.2 Graphical Analyses

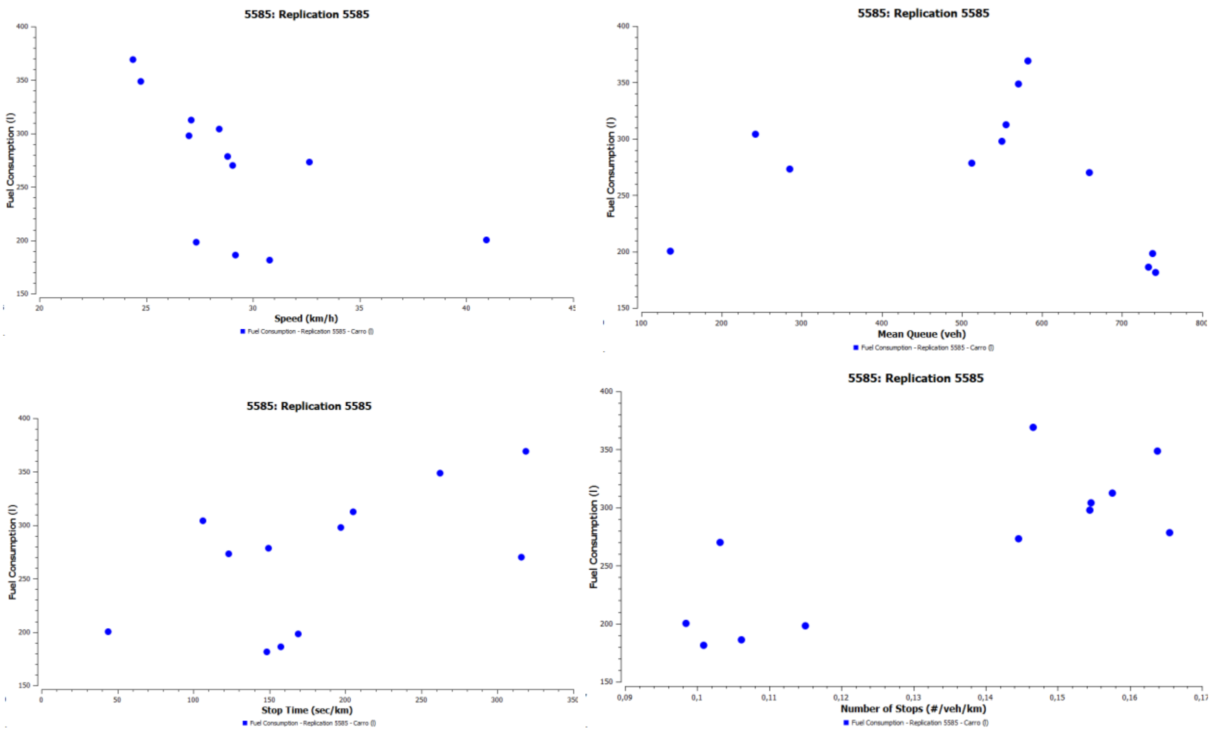
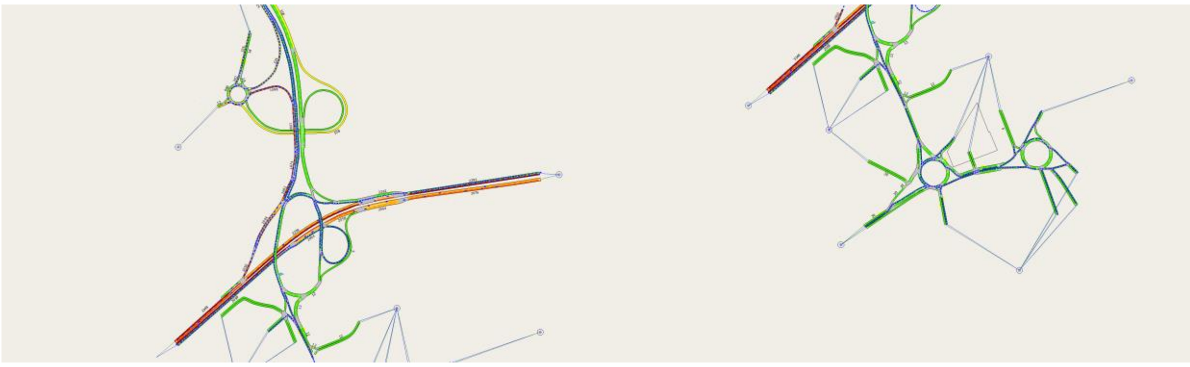


Figure 16: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

In this case the relationships are not too straight forward. Even though the expected trend is being followed, the values are a bit scattered. Also the fuel consumption vs queue length relation is erratic maybe because of the fact that the simulation was running at capacity vehicles in then nodes with almost zero velocity (in some instances the high input flow led to the flow being stuck with vehicles at zero velocity).

4.4.1.2.3 Map based Outputs



We can see from the maps that heavy flow is registered only on N101 between the East and train station directions. Rest all the sections are almost green because the flow is very less even though the input flow is high.

Figure 17: Map based outputs showing flow density in different sections with color coding

Statistical outputs during both morning and evening hours are consistent with what we expected.

- The system is fed with the information collected and we must verify and calibrate it against the data collected from simulation of the real-world model. As we have chosen the OD matrix method for defining the traffic demand, we can verify the accuracy of vehicle routing assigned by Aimsun by cross validating the flow amongst different sections. We install detectors in the sections that we wish to verify the counts of. Another way of achieving it is by directly referring to the flow data. Below are some of those counts and the errors in their values.

Table 5: Validation data for morning peak

Street and direction	Real-world counts	Simulation counts	% Error
Infias to multi-junction	1890	1750	7,41
Multi-junction to infias	948	839	11,50

Table 6: Validation data for evening peak

Street and direction	Real-world counts	Simulation counts	% Error
Infias to multi-junction	2364	1921	18,74
Multi-junction to infias	560	719	-28,39

We have chosen the street between Infias roundabout and the multi-junction because the functioning of ODM is determined from these values. All other flows amongst the ODs are direct.

- Similarly, the data for other statistics such as queue length, delay time etc. are verified.

4.5 Concluding remarks

The main objectives of the chapter, that were to understand the solution approach and the model development techniques, have been covered along with extra details about the features of Aimsun that have been used to achieve them have also been summarized. The final part of the chapter verifies that the data collected from site visits concur with the results obtained from the simulation of the real-world model. In the next chapter, we will use the original model to add the infrastructure or modify the existing ones to create the Municipality suggested changes. Also, we will look at some models with traffic management techniques and how they affect the original (real-world) simulation.

5 Chapter 5: Simulation Results and Analyses

5.1 Chapter overview

In this chapter, we simulate the alternative solution models by modelling them in Aimsun and record the outputs. In the last section, we compare the results from all the simulations and decide on the best model, if any of them are better than the real-world model results. Just like system validation performed in the last chapter, we will record the results in three parts: statistical, map based and graph-based outputs.

5.2 Outputs and results of simulation of suggested solutions

5.2.1 Alternative 1

Figure 18: Aimsun model for Alternative 1

5.2.1.1 Morning Peak

Figure 19: Simulation snapshot at the multi-junction and the Infias roundabout area

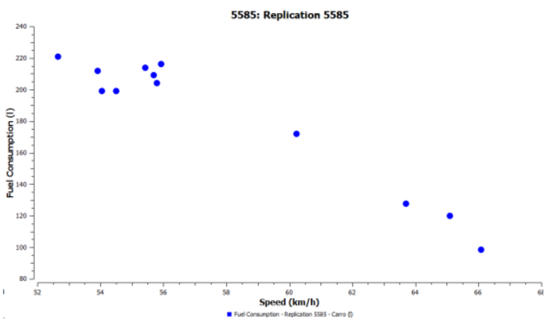
Even though the additions in this case are improving the flow between North and the Infias roundabout, the queues in front of the school do not decrease because of the better flow from the North making the roundabout more congested.

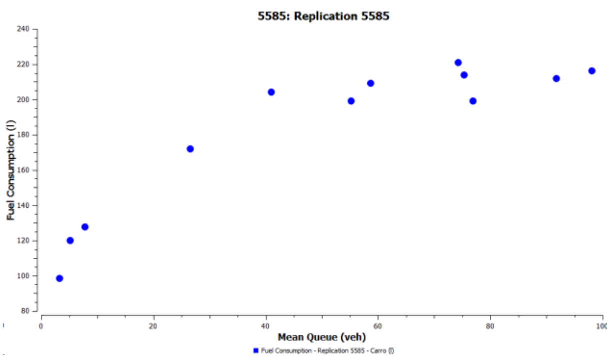
5.2.1.1.1 S0tatistical outputs

Table 7: Statistical Outputs for Alternate solution model during morning peak.

Parameters	Value	Standard Deviation	Units
Fuel Consumption - Carro	2191,76	N/A	l
IEM Emission - CO2 - Carro	3657345,99	N/A	g
IEM Emission - NOx - Carro	6539,54	N/A	g
IEM Emission - PM - Carro	943,37	N/A	g
IEM Emission - VOC - Carro	13554,15	N/A	g
Mean Queue - Carro	51,18	N/A	veh
Number of Stops - Carro	0,06	N/A	#/veh/km
Speed - Carro	57,19	21,7	km/h
Stop Time - Carro	28,36	228,77	sec/km
Travel Time - Carro	90,57	232,68	sec/km

5.2.1.1.2 Graphical analyses





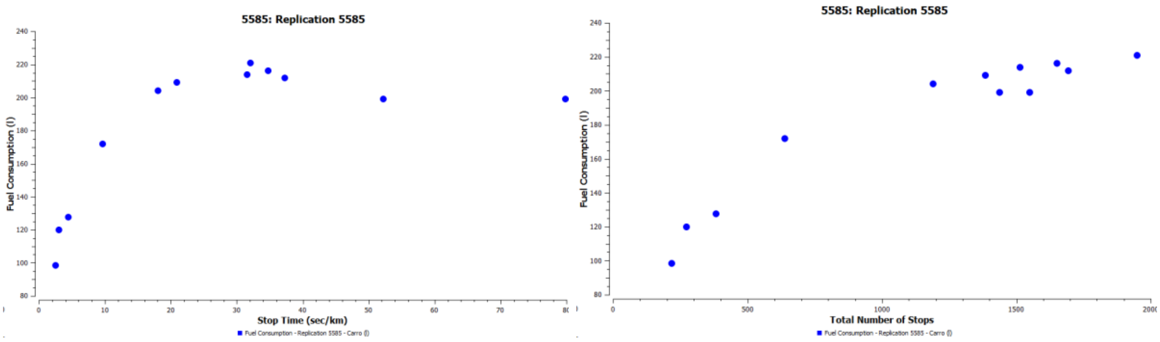


Figure 20: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

Here again the relationships between fuel consumption and other KPIs are justified. Fuel consumption increases proportionally with stop times, number of stops and queue length.

5.2.1.1.3 Map based outputs

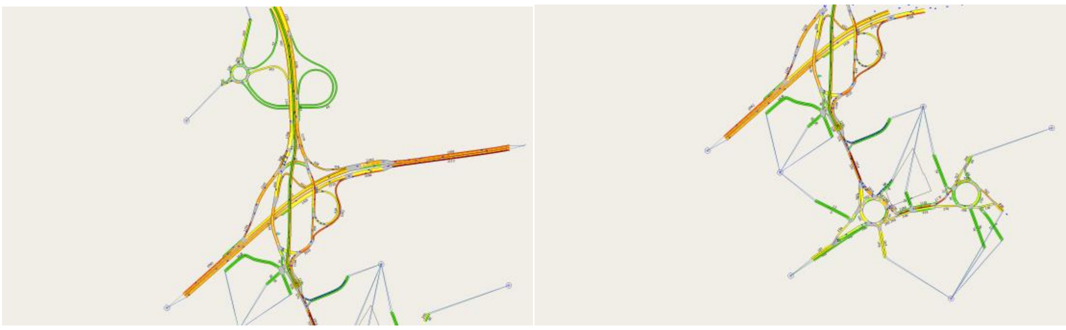


Figure 21: Map based outputs showing flow density in different sections with color coding

We can see that the flows are high on N101 and in the Infias region it is less because of the queue formation. Due to the queues in that area, the new bridge cannot be utilized as much as they must be.

5.2.1.2 Evening peak

Figure 22: Simulation snapshot at the multi-junction and the Infias roundabout area

We can see that the flow from the North is high and leads to some congestion at the multi-junction entrance. In the Infias region, the flow towards the multi-junction is facilitated by the bridge but at the roundabout the flow is based on priority that leads to some congestions.

5.2.1.2.1 Statistical outputs

Table 8: Statistical Outputs for Alternate solution model during morning peak.

Parameters	Value	Standard Deviation	Units
Fuel Consumption - Carro	4125,05	N/A	l
IEM Emission - CO2 - Carro	6999656,61	N/A	g
IEM Emission - NOx - Carro	10768,91	N/A	g
IEM Emission - PM - Carro	1884,38	N/A	g
IEM Emission - VOC - Carro	36524,38	N/A	g
Mean Queue - Carro	235,84	N/A	veh
Number of Stops - Carro	0,13	N/A	#/veh/km
Speed - Carro	37,48	25,49	km/h
Stop Time - Carro	97,75	179,35	sec/km
Travel Time - Carro	185,88	188,03	sec/km

5.2.1.2.2 Graphical analyses

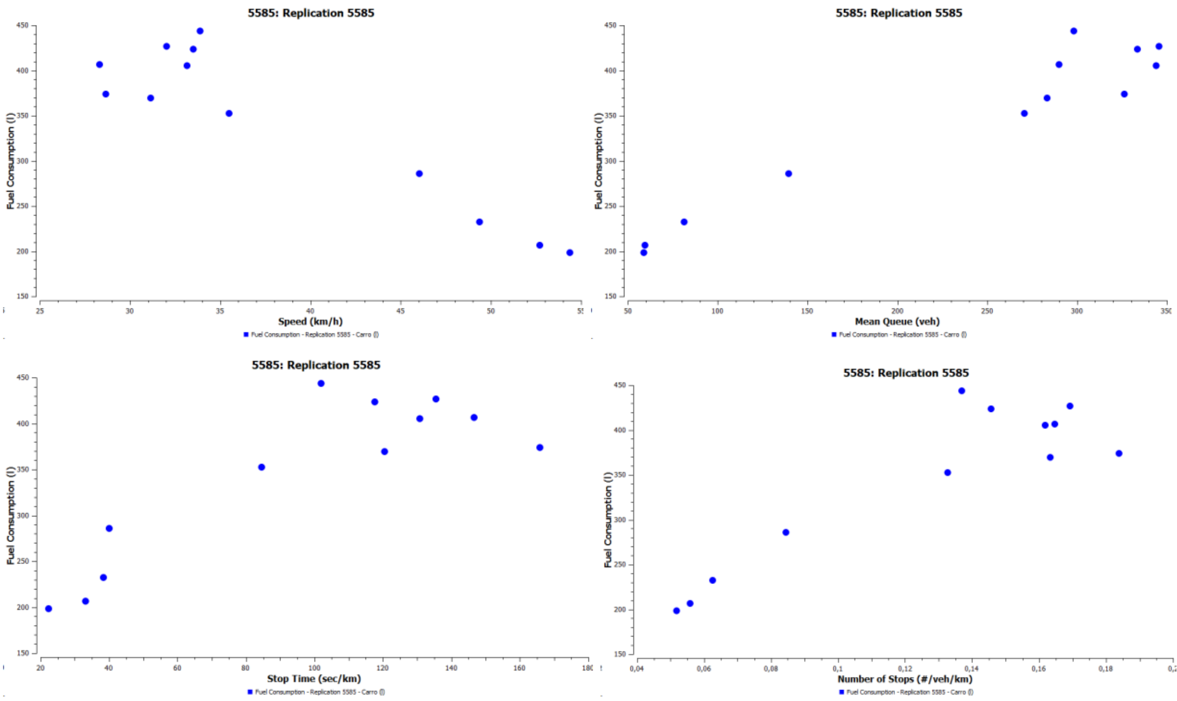


Figure 23: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

These outputs verify the relation between the KPIs.

5.2.1.2.3 Map based outputs

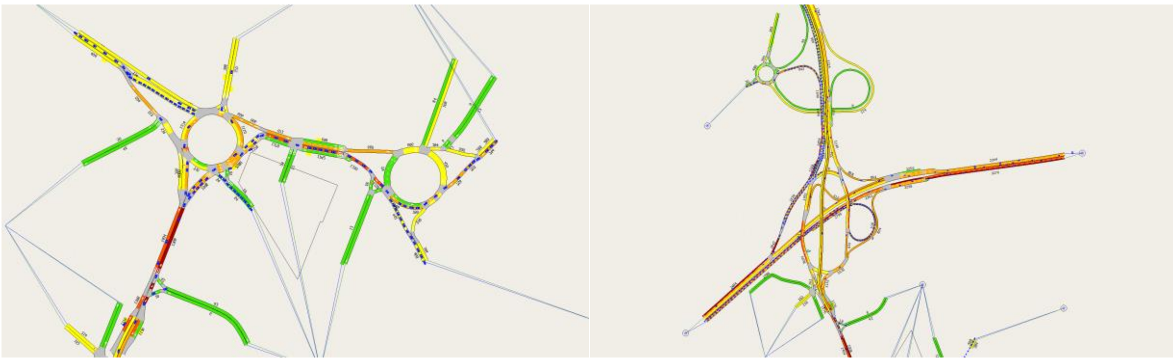


Figure 24: Map based outputs showing flow density in different sections with color coding

In this case we can see that there is more flow between the Infias roundabout and the multi-junction proving the functionality of the bridge.

5.2.1.3 Observations during simulation

The alternative 1 model facilitates the flow of traffic directly from the north to the Infias roundabout and vice versa. In some instances, heavy flow towards the south led to congestion at the roundabout. The opposite flow is improved because the bridge bypasses the multi-junction for the vehicles that wish to go north. The conditions at the roundabout are better as compared to the real-world model but not in the case of heavy flow from all other entrance to the roundabout.

5.2.2 Alternative 2

Figure 25: Aimsun model for Alternative 1

5.2.2.1 Morning peak

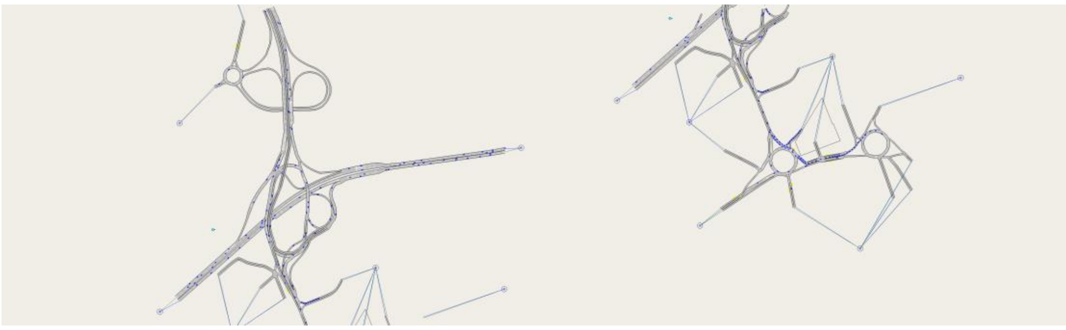


Figure 26: Simulation snapshot at the multi-junction and the Infias roundabout area

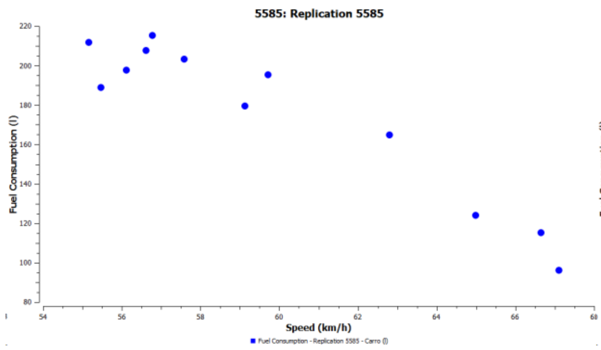
Near the Infias region because of the priority at the roundabout, there is some queueing up in all directions. But because of the options at the multi-junction towards all directions, the traffic is moving continuously.

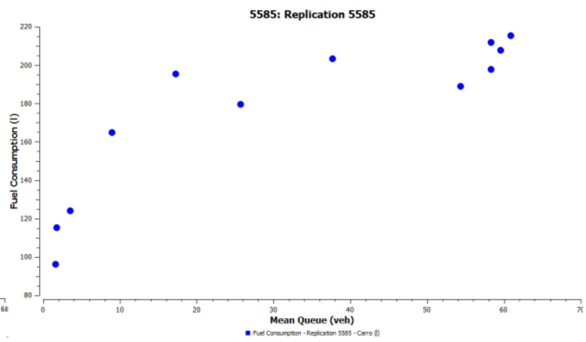
5.2.2.1.1 Statistical outputs

Table 9: Statistical Outputs for Alternate solution model during morning peak.

Parameters	Value	Standard Deviation	Units
Fuel Consumption - Carro	2099,58	N/A	l
IEM Emission - CO2 - Carro	3521261,14	N/A	g
IEM Emission - NOx - Carro	6370,18	N/A	g
IEM Emission - PM - Carro	899,43	N/A	g
IEM Emission - VOC - Carro	12231,37	N/A	g
Mean Queue - Carro	32,32	N/A	veh
Number of Stops - Carro	0,04	N/A	#/veh/km
Speed - Carro	59,32	20,26	km/h
Stop Time - Carro	20,14	163,21	sec/km
Travel Time - Carro	81,22	167,57	sec/km

5.2.2.1.2 Graphical Analyses





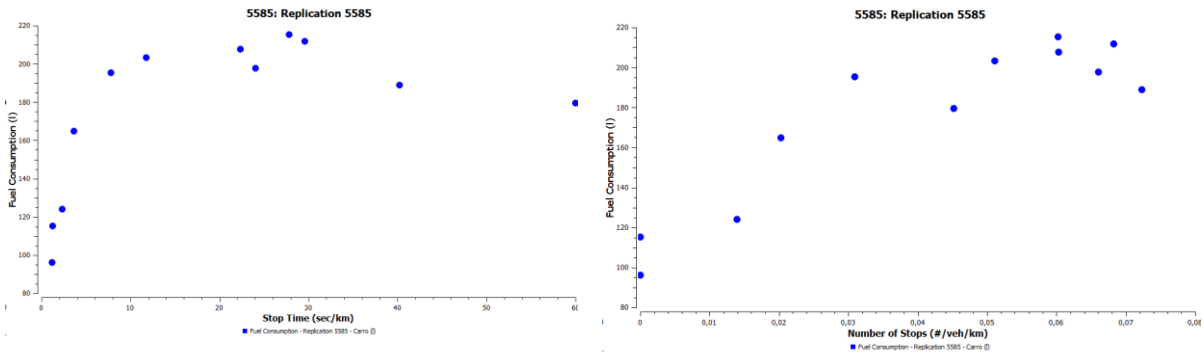


Figure 27: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

Graphical data in this model is as we expected. Since the average speed data is in the range 50-60 kmph, the fuel consumption is minimum. Also, the relationship between fuel consumption with other variabes is proportional.

5.2.2.1.3 Map based outputs

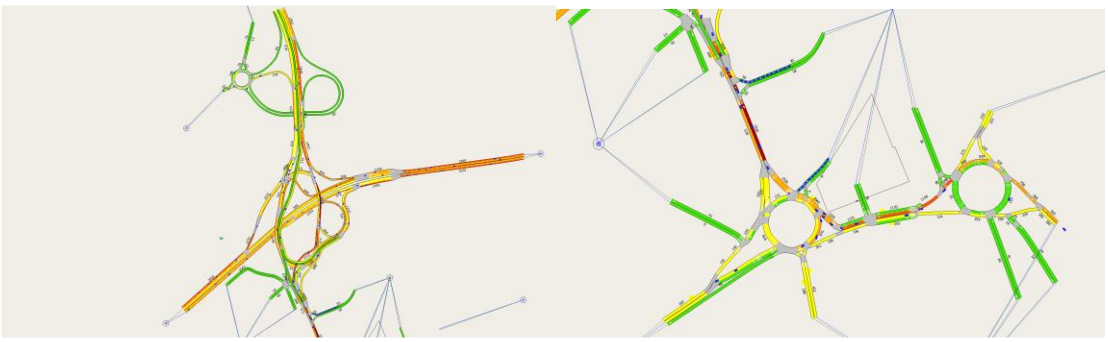


Figure 28: Map based outputs showing flow density in different sections with color coding

There is comparatively more flow amongst the sections because of the additions. The flow from the Infias region towards other directions is direct and without any priority definitions.

5.2.2.2 Evening peak

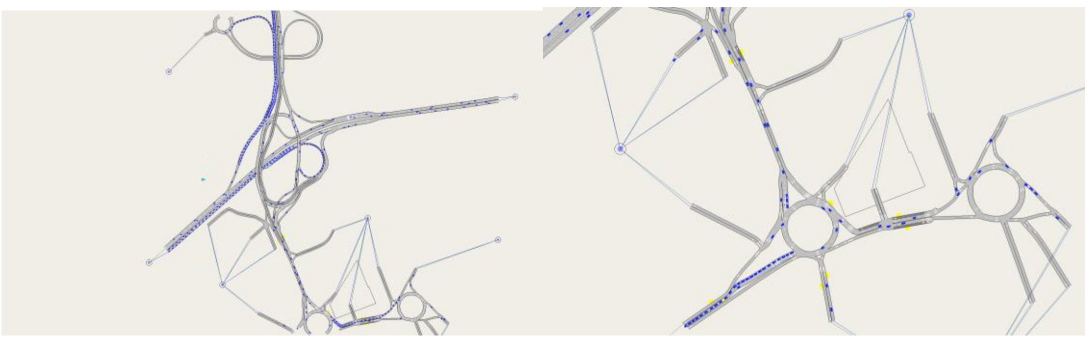


Figure 29: Simulation snapshot at the multi-junction and the Infias roundabout area

High input flows from the train station and the North directions lead to queuing at the multi-junction. Most of the traffic during this interval use the multi-junction to exit in the North and the East directions. Due to the priorities, there is queuing up at the entry to the multi-junction from the North. The usage of the new bridge that connects train the station to North is limited because the vehicles that want to go towards the Infias have to wait and thus conflicting with the free movement of traffic towards the North (from the train station direction).

5.2.2.2.1 Statistical outputs

Table 10: Statistical Outputs for Alternate solution model during morning peak.

Parameters	Value	Standard Deviation	Units
Fuel Consumption - Carro	3724,88	N/A	l
IEM Emission - CO2 - Carro	6458851,08	N/A	g
IEM Emission - NOx - Carro	10410,05	N/A	g
IEM Emission - PM - Carro	1597,68	N/A	g
IEM Emission - VOC - Carro	37332,06	N/A	g
Mean Queue - Carro	243,29	N/A	veh
Number of Stops - Carro	0,1	N/A	#/veh/km
Speed - Carro	40,35	25,81	km/h
Stop Time - Carro	95,53	291,9	sec/km
Travel Time - Carro	183,75	295,74	sec/km

5.2.2.2.2 Graphical analyses

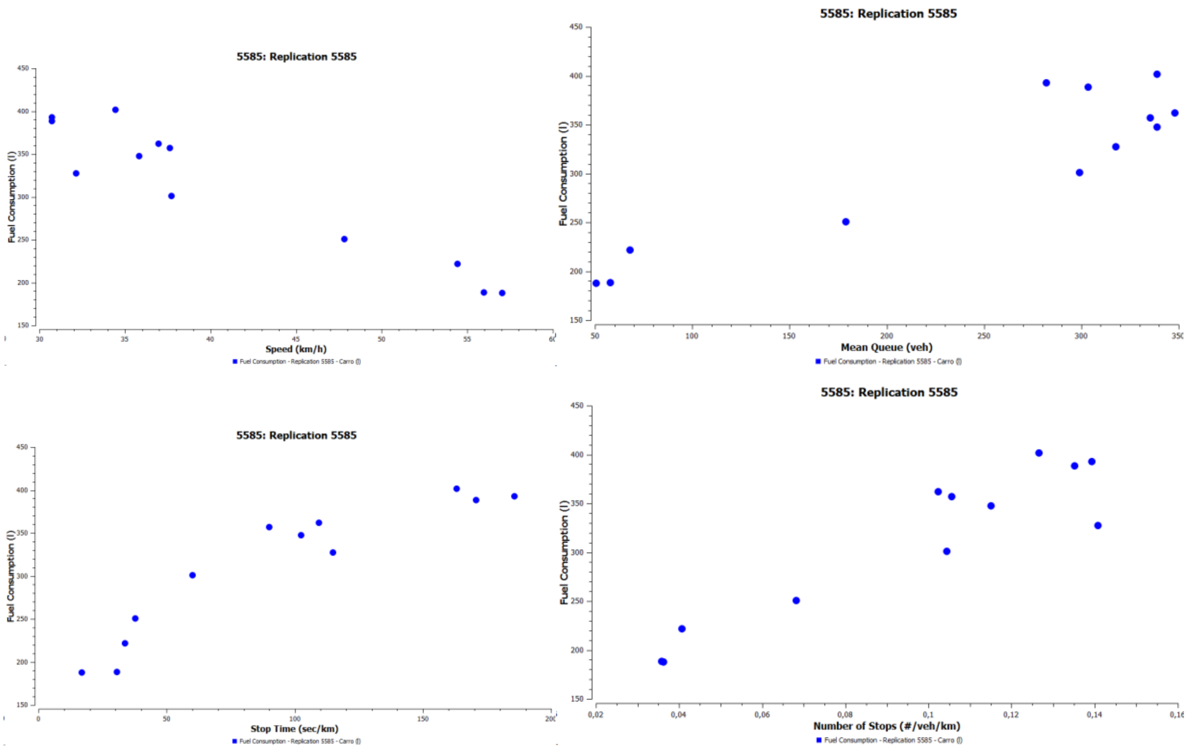


Figure 30: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

We can see that the relationships between KPIs are as expected.

5.2.2.2.3 Map based outputs

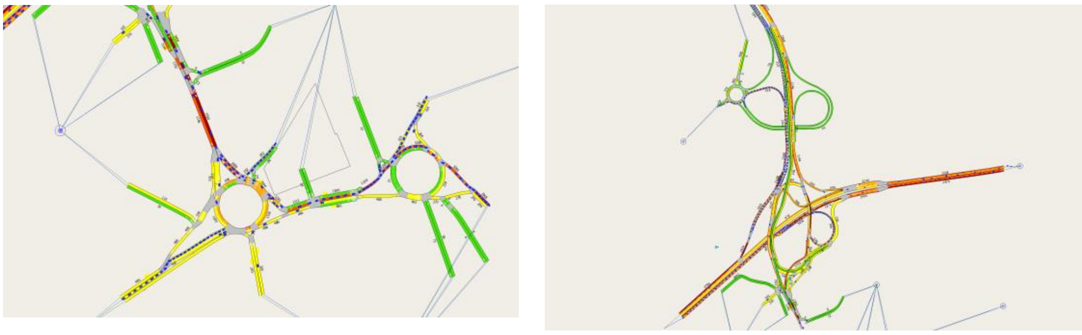


Figure 31: Map based outputs showing flow density in different sections with color coding

5.2.2.3 Observations during simulation

This model showed promising results because of the construction of major infrastructures. The expectancy in this case is to observe decrease in congestion at the infias roundabout because the flow towards multi-junction have distinct exits (3 new additions) for each direction. This fluid flow led to decongestion at the roundabout and better flow from all entrances. In the data comparison section, we will notice how good the numbers are in this case.

The other three additions are helpful too as they facilitate the flow for specific OD pairs. The usage of the multi-junction is reduced significantly which led to better flow. Reduced use of multi-junction means the input from the direction of Infias is no longer a problem for the other flows on the multi-junction.

5.2.3 Alternative 3

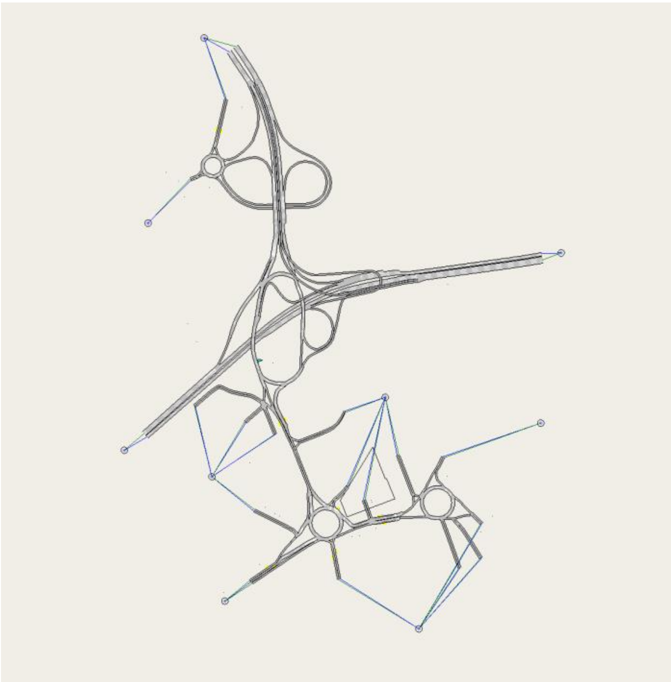


Figure 32: Aimsun model for Aternative 3

5.2.3.1 Morning peak

Figure 33: Simulation snapshot at the multi-junction and the Infias roundabout area

Just like the Alternative 2, here the use of the bridge for Porto-North direction is limited because of the queue for the Inifas direction.

5.2.3.1.1 Statistical outputs

Tabela 11: Statistical Outputs for Alternate solution model during morning peak

Parameters	Value	Standard Deviation	Units
Fuel Consumption - Carro	2059,67	N/A	l
IEM Emission - CO2 - Carro	3631905,04	N/A	g
IEM Emission - NOx - Carro	6471,94	N/A	g
IEM Emission - PM - Carro	842,01	N/A	g
IEM Emission - VOC - Carro	17925,22	N/A	g
Mean Queue - Carro	89,74	N/A	veh
Number of Stops - Carro	0,07	N/A	#/veh/km
Speed - Carro	55,8	24,31	km/h
Stop Time - Carro	51,79	257,76	sec/km
Travel Time - Carro	113,21	264,1	sec/km

5.2.3.1.2 Graphical analyses

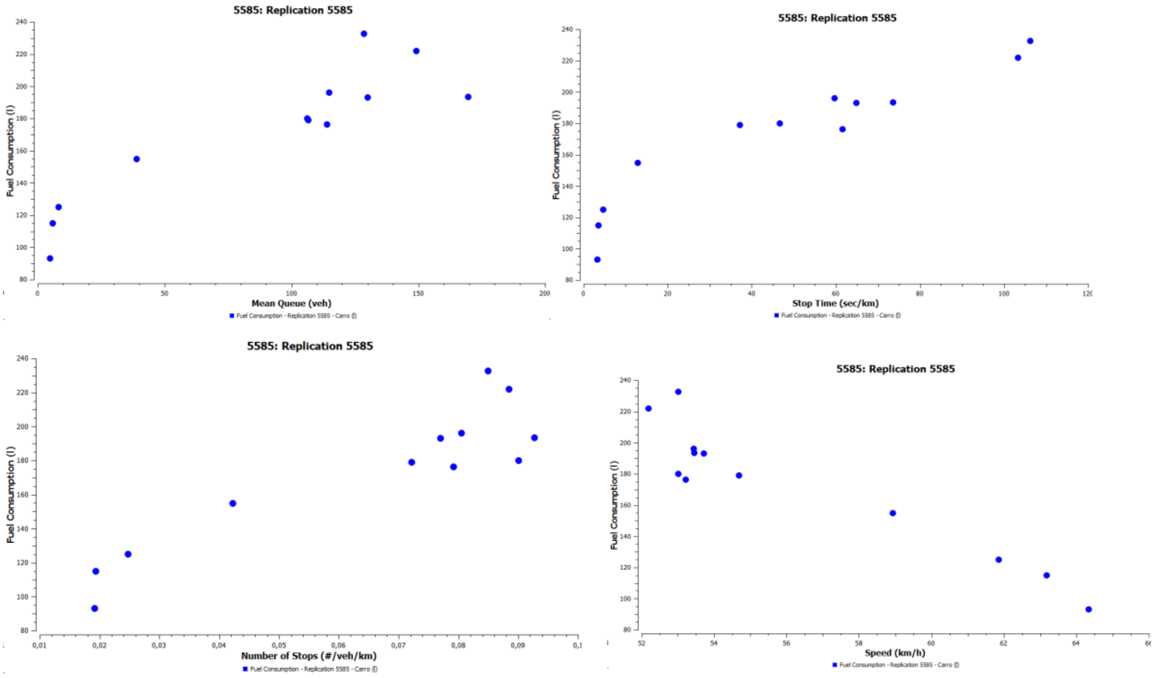


Figure 34: Simulation snapshot at the multi-junction and the Infias roundabout area

Here again the KPIs behave well and have an expected relationship with fuel consumption.

5.2.3.1.3 Map based outputs

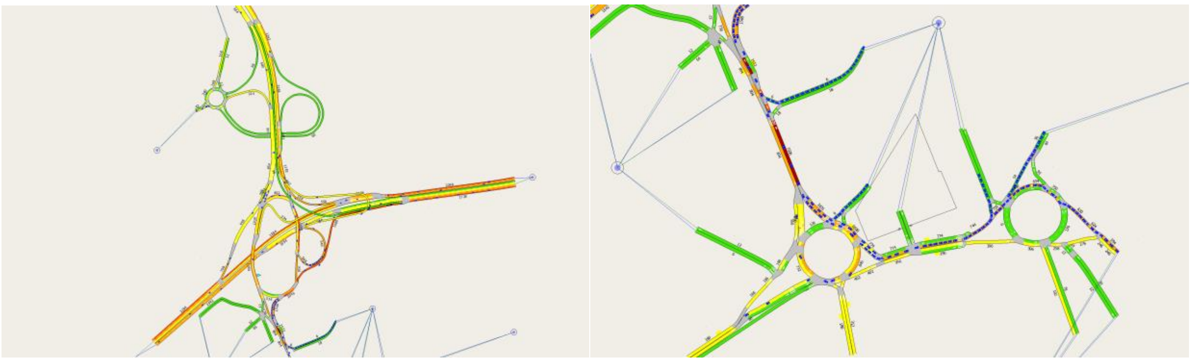


Figure 35: Map based outputs showing flow density in different sections with color coding

5.2.3.2 Evening peak

Figure 36: Simulation snapshot at the multi-junction and the Infias roundabout area

5.2.3.2.1 Statistical outputs

Table 12: Statistical Outputs for Alternate solution model during evening peak.

Parameters	Value	Standard Deviation	Units
Fuel Consumption - Carro	3846,84	N/A	l
IEM Emission - CO2 - Carro	6729672,72	N/A	g
IEM Emission - NOx - Carro	11113,79	N/A	g
IEM Emission - PM - Carro	1583,38	N/A	g
IEM Emission - VOC - Carro	43313,94	N/A	g
Mean Queue - Carro	302,69	N/A	veh
Number of Stops - Carro	0,1	N/A	#/veh/km
Speed - Carro	42,51	26,3	km/h
Stop Time - Carro	131,53	336,8	sec/km
Travel Time - Carro	205,42	345,28	sec/km

5.2.3.2.2 Graphical analyses

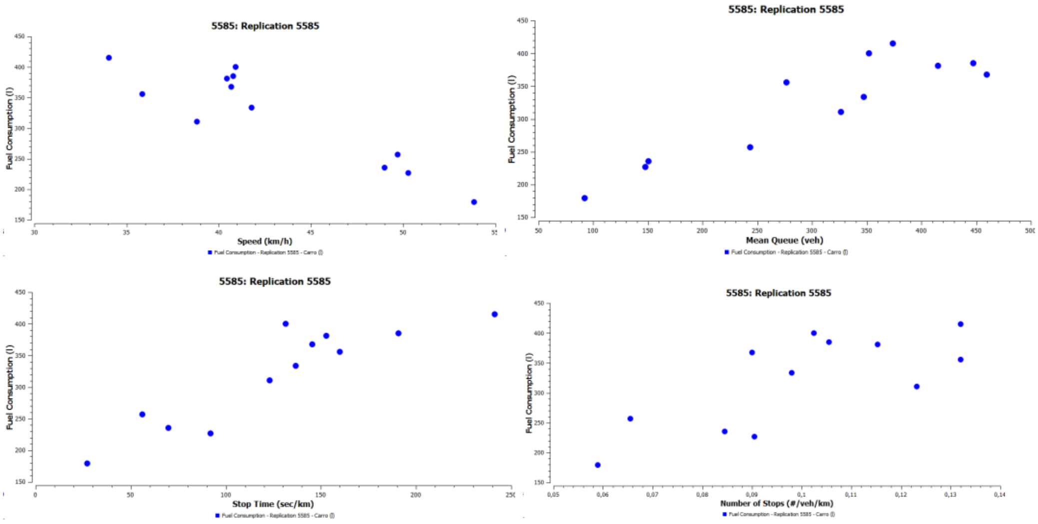


Figure 37: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

Here again the KPI graphs behave as expected but with some more scattering as compared to the real-world model.

5.2.3.2.3 Map based outputs

Figure 38: Map based outputs showing flow density in different sections with color coding

There was comparatively more flow amongst the sections as compared to the real-world model because of the bridges that serve the flows in specific directions.

5.2.3.3 Observations during simulation

In this case the infrastructural additions did not take care of the main source of congestion, the flow from Infias towards the multi-junction. The bridges facilitate the flows of vehicles going from the north to the east and the vehicles from the direction of train station towards the north too. Congestion in the infias region and subsequently in the multi-junction.

5.2.4 Traffic Signal at Multi-Junction

This is a model developed to attempt the congestion reduction with the help of traffic signals. At the Multi-junction we will simulate a traffic signal at the entrance from the direction of Infias roundabout as shown below. The flow from the roundabout and from the other direction are heavy during both morning and evening peaks. So it will be interesting to simulate controlled traffic flow. We have developed a cycle of 120 seconds during which for 55 seconds each of the directions will be allowed to flow (green) and for 5 seconds each at the end of each period the signal will turn yellow.

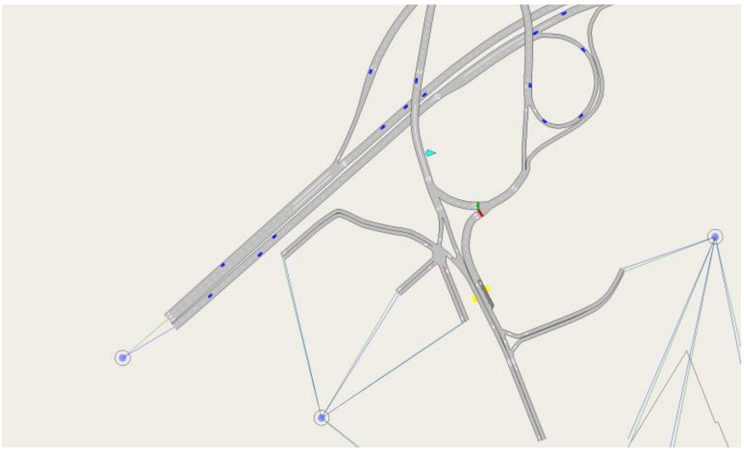


Figure 39: Traffic lights at the entrance of multi-junction

5.2.4.1 Morning peak

Figure 40: Simulation snapshot at the multi-junction and the Infias roundabout area

The “green” duration of 55 seconds is not enough at this junction because of the high flow. The vehicles queue up and makes it worse than the real world performance.

5.2.4.1.1 Statistical outputs

Table 13: Statistical Outputs for Alternate solution model during morning peak.

Time Series	Value	Standard Deviation	Units
Fuel Consumption - Carro	2875,36	N/A	l
IEM Emission - CO2 - Carro	4817760,63	N/A	g
IEM Emission - NOx - Carro	8139,25	N/A	g
IEM Emission - PM - Carro	1250,45	N/A	g
IEM Emission - VOC - Carro	26003,16	N/A	g
Mean Queue - Carro	165,27	N/A	veh
Number of Stops - Carro	0,1	N/A	#/veh/km
Speed - Carro	38,97	23,46	km/h
Stop Time - Carro	90,12	191,2	sec/km
Travel Time - Carro	161,82	196,94	sec/km

5.2.4.1.2 Graphical analyses

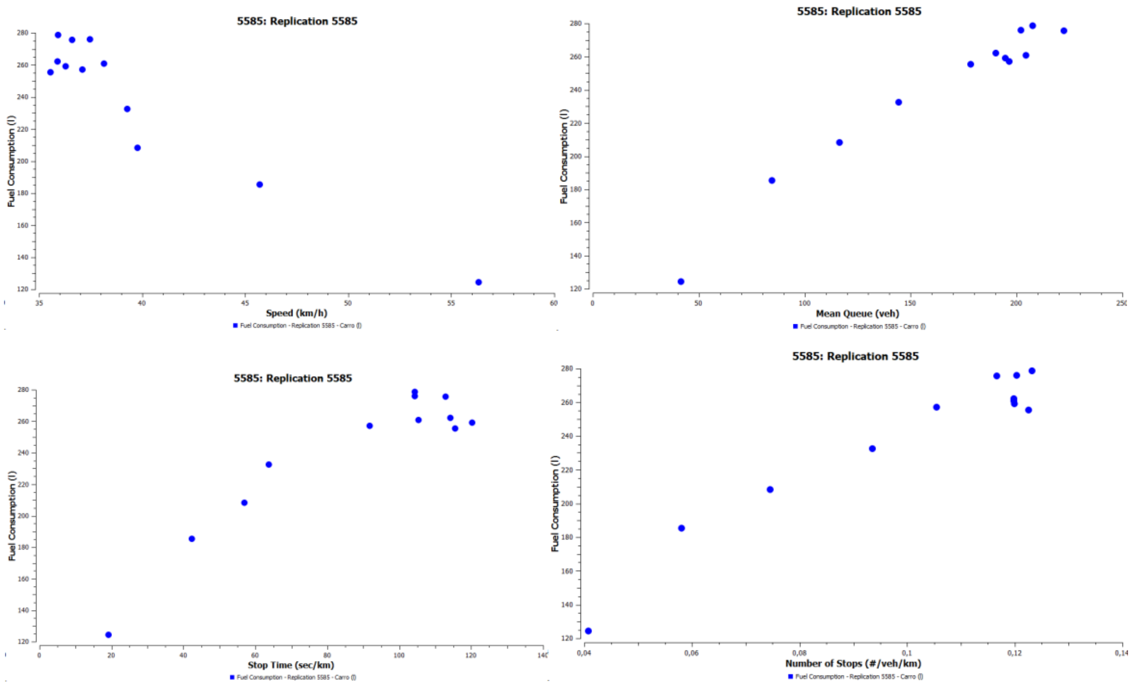


Figure 41: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

The KPis are correlated very well in this case.

5.2.4.1.3 Map based outputs

Figure 42: Map based outputs showing flow density in different sections with color coding

There was less flow because of the queuing up at the signal. Therefore we see many green and yellow sections.

5.2.4.2 *Evening peak*

Figure 43: Simulation snapshot at the multi-junction and the Infias roundabout area

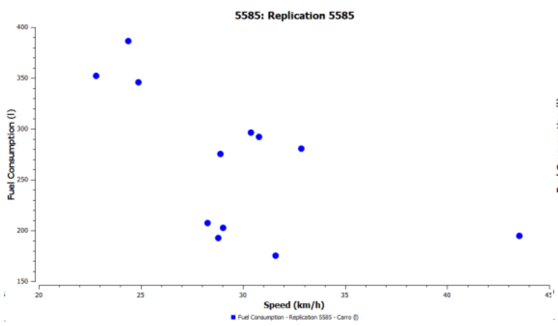
From the image we can see that the area around Infias roundabout is all choked up due to the signal at the multi-junction.

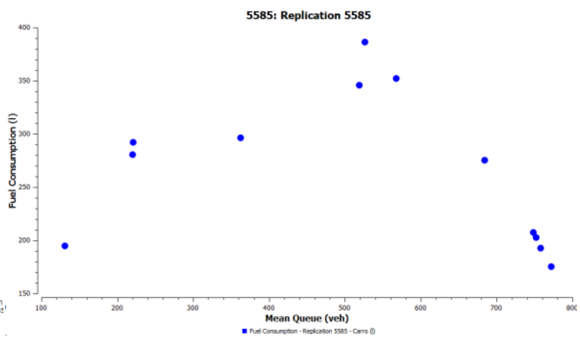
5.2.4.2.1 Statistical outputs

Table 14: Statistical Outputs for Alternate solution model during evening peak.

Time Series	Value	Standard Deviation	Units
Fuel Consumption - Carro	3201,5	N/A	l
IEM Emission - CO2 - Carro	6722846,17	N/A	g
IEM Emission - NOx - Carro	11339,06	N/A	g
IEM Emission - PM - Carro	1383,12	N/A	g
IEM Emission - VOC - Carro	61031,8	N/A	g
Mean Queue - Carro	521,88	N/A	veh
Number of Stops - Carro	0,13	N/A	#/veh/km
Speed - Carro	29,56	19,82	km/h
Stop Time - Carro	170,14	287,23	sec/km
Travel Time - Carro	253,77	290,1	sec/km

5.2.4.2.2 Graphical analyses





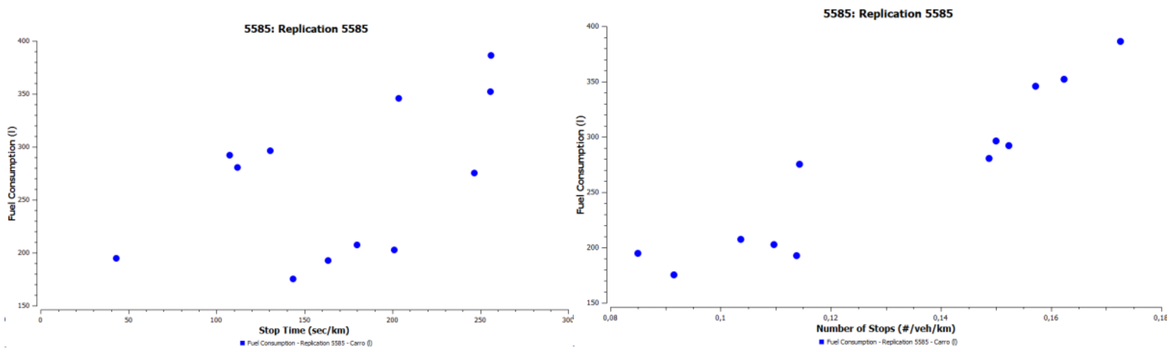


Figure 44: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

5.2.4.2.3 Map based outputs

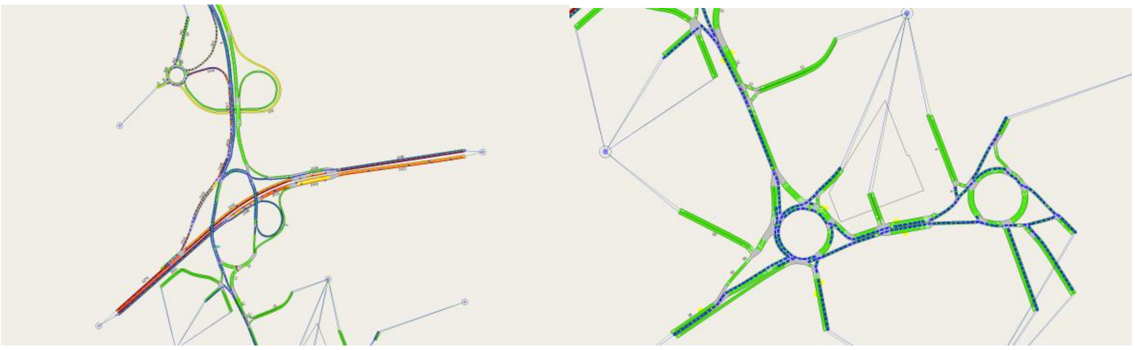


Figure 45: Map based outputs showing flow density in different sections with color coding

Here again the sections are all green around the Infias region because of minimal flow at the control plan based signal.

5.2.4.3 Observations during simulation

While the signals promise a controlled flow, the signal at the multi-junction led to queues that in turn effected the vehicles at the multi-junction. In case of heavy flow from the Infias roundabout direction, the signal rendered helpless in controlling the flow leading to heavy congestion in the Infias region.

5.2.5 Traffic signal at Infias roundabout

The traffic signal at the roundabout is designed for a cycle of 240 seconds with different green durations for every exit. The maximum duration is allotted to the exit from the section in front of Dom Diogo da Sousa school (60 seconds). Others are allotted 40 seconds each with 5 seconds of yellow time.

Figure 46: Traffic lights at Infias roundabout

5.2.5.1 Morning peak

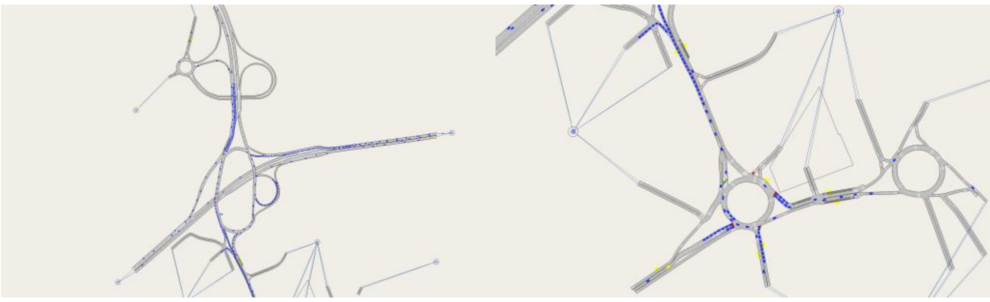


Figure 47: Simulation snapshot at the multi-junction and the Infias roundabout area

During the early periods of morning hours the signal proves to be controlling the traffic well but as the flow increases, the vehicles get jammed up due to less green time.

5.2.5.1.1 Statistical outputs

Table 15: Statistical Outputs for Alternate solution model during morning peak.

Time Series	Value	Standard Deviation	Units
Fuel Consumption - Carro	3142,6	N/A	l
IEM Emission - CO2 - Carro	5360422,2	N/A	g
IEM Emission - NOx - Carro	9225,69	N/A	g
IEM Emission - PM - Carro	1237,32	N/A	g
IEM Emission - VOC - Carro	39769,55	N/A	g
Mean Queue - Carro	309,39	N/A	veh
Number of Stops - Carro	0,12	N/A	#/veh/km
Speed - Carro	34,62	25,71	km/h
Stop Time - Carro	168,26	320,45	sec/km
Travel Time - Carro	250,36	326,92	sec/km

5.2.5.1.2 Graphical Analyses

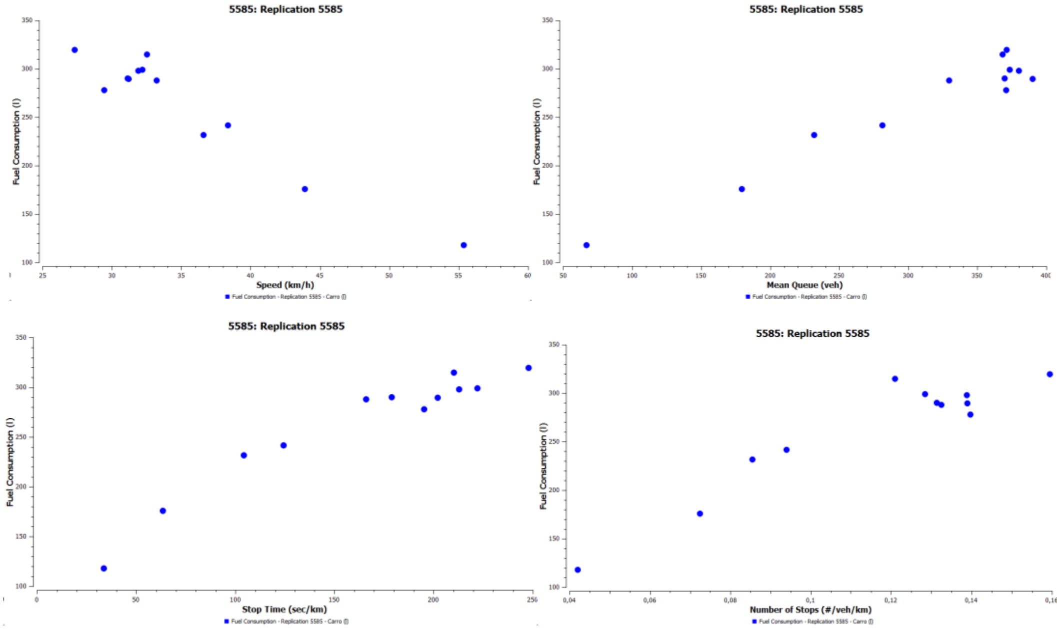


Figure 48: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

The KPIs correlate very well.

5.2.5.1.3 Map based outputs

Figure 49: Map based outputs showing flow density in different sections with color coding

We can see that because of the flow during early morning periods, the sections are yellow instead of green. The flow along N101 is normal.

5.2.5.2 Evening peak

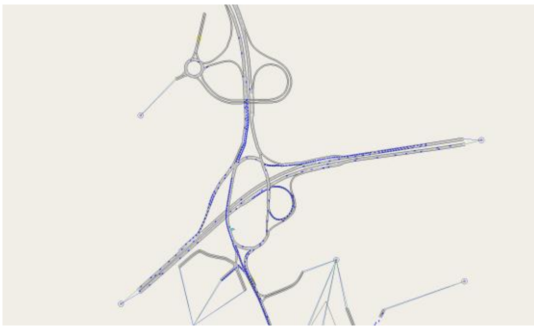


Figure 50: Simulation snapshot at the multi-junction and the Infias roundabout area

During the evening peak, roundabout traffic signal is not very effective because of the heavy traffic flow from all directions that want to go towards the multi-junction. And at the multi-junction, the flow from the north have the priority which leads to a huge amount of queuing up at every node near Infias and at the entrance to the multi-junction as well.

5.2.5.2.1 Statistical outputs

Table 16: Statistical Outputs for Alternate solution model during evening peak.

Time Series	Value	Standard Deviation	Units
Fuel Consumption - Carro	2591,12	N/A	l
IEM Emission - CO2 - Carro	6571729,09	N/A	g
IEM Emission - NOx - Carro	11927	N/A	g
IEM Emission - PM - Carro	1147,87	N/A	g
IEM Emission - VOC - Carro	70955,57	N/A	g
Mean Queue - Carro	642,16	N/A	veh
Number of Stops - Carro	0,11	N/A	#/veh/km
Speed - Carro	30,78	19,85	km/h
Stop Time - Carro	156,98	263,82	sec/km
Travel Time - Carro	243,82	271,65	sec/km

5.2.5.2.2 Graphical analyses

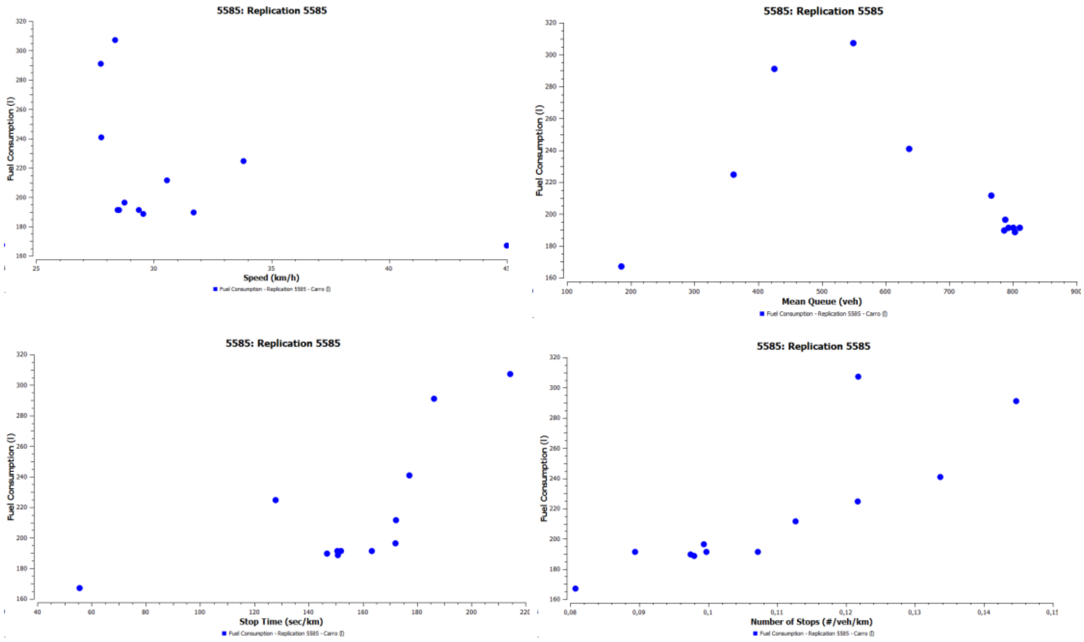


Figure 51: Graphical outputs showing the relation between fuel consumption and speed, queue length, stop time and number of stops respectively

5.2.5.2.3 Map based outputs

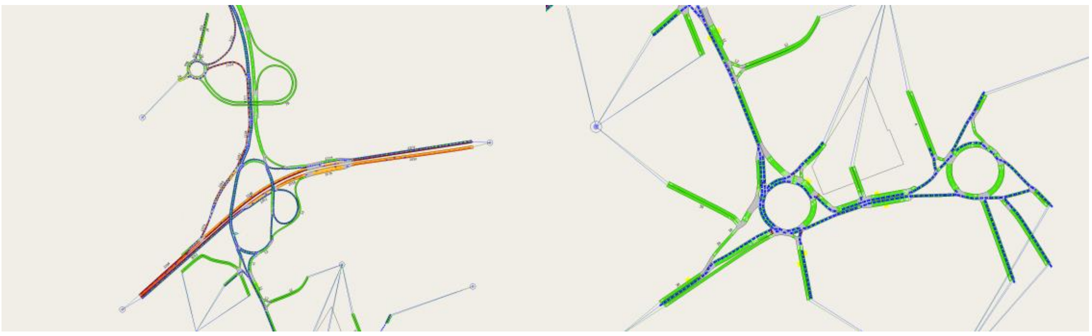


Figure 52: Map based outputs showing flow density in different sections with color coding

5.2.5.3 Observations during simulation

The signal at the Infias roundabout is simulated by allotting more duration for the exit flow from the direction of the school Dom Diogo da Sousa. However, due to the heavy input flow from the south, the signal is not effective and leads to more congestion in the area. The time allotted to each exit is proportional to the input flow.

5.2.6 Bus priority options

Here we will take a look at the travel times of the bus number 9 of TUB in 2 scenarios: heavy congestions with normal model and one with priority when the bus is detected. It is a simple visualization of the concept that can be used in series with multiple detectors depending on the extent of congestion.

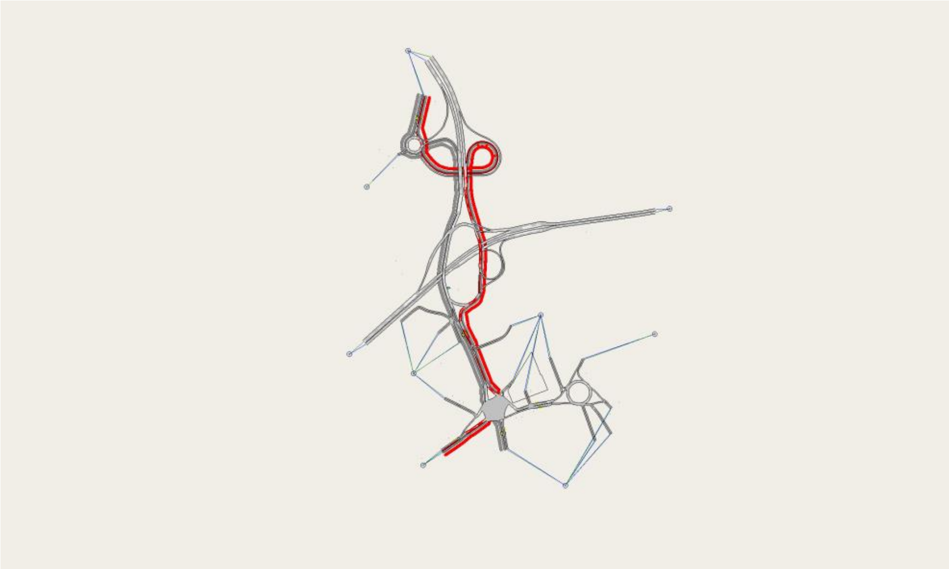


Figure 53: The route for TUB bus number 9

For the purposes of simulating the bus priority measures, we formed a single node at the Infias junction because the control plan definitions for multiple nodes were not working in sync when defined in Aimsun. So to facilitate the working of this node, we combined all the turns in one node.

Figure 54: Figure depicting a single node at Infias roundabout

In the figure above we can see that the roundabout is replaced by a single node. It is done because in Aimsun the control plan linking the individual plans for each of the input nodes were working with expected co-ordination. So, to make the simulation possible (for the purpose of illustration), we decided to form a single bigger node.

5.2.6.1 *Output without bus priority measures*

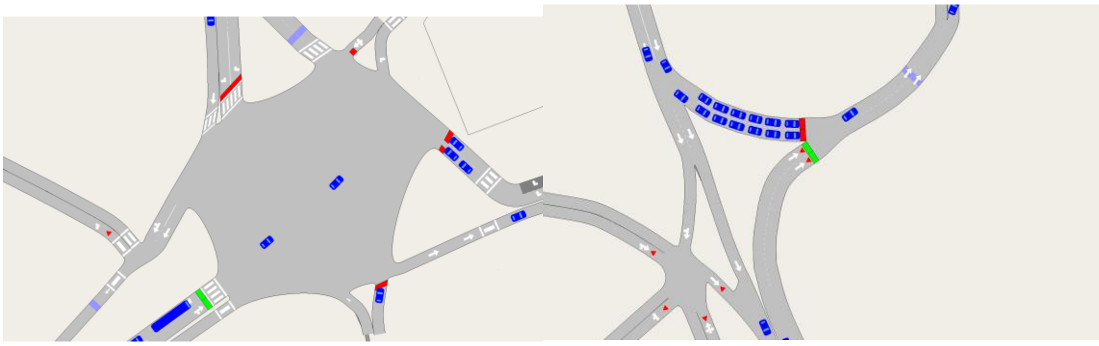


Figure 55: Traffic lights at the roundabout and the multi-junction

Without bus priority measures the buses from the center must wait for their turn at the roundabout. We compare the travel time of the TUB buses that go from origin SW3 to destination N.

Table 17: Comparison of bus travel time with and without control plans

Traffic condition	Without control plan	With control plan
Smooth flow	130 s	120 s
Congested	5-6 mins	2-3 mins

5.3 Data comparison

We compare the data in two parts: Infrastructural additions and traffic signal additions. For bus priority options we will compare the travel times for a bus route in different traffic conditions with and without the implementation of control plans.

5.3.1 Infrastructure additions

The outputs in the previous sections are compared below in MS Excel with color-coding to distinguish and compare the values better. The light-yellow color depicts the minimum values and as it gets darker it depicts higher values.

Table 18: Comparison of data from outputs in previous sections (infrastructural additions)

	Alt Sol 3		Alt Sol 2		Alt Sol 1		Real World		Units
Parameter	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**	
Fuel Consumption - Carro	3846,84	2059,67	3724,88	2099,58	4125,05	2191,76	3219,59	2909,04	l
IEM Emission -	6729672,72	3631905	6458851	3521261	6999657	3657346	6679742	4892732	g

CO2 - Carro									
IEM Emission - NOx - Carro	11113,79	6471,94	10410,05	6370,18	10768,91	6539,54	11353,77	8042,4	**g**
IEM Emission - PM - Carro	1583,38	842,01	1597,68	899,43	1884,38	943,37	1414,49	1279,94	**g**
IEM Emission - VOC - Carro	43313,94	17925,22	37332,06	12231,37	36524,38	13554,15	59298,92	25369,06	**g**
Mean Queue - Carro	302,69	89,74	243,29	32,32	235,84	51,18	525,59	159,35	**veh**
Number of Stops - Carro	0,1	0,07	0,1	0,04	0,13	0,06	0,14	0,11	**#/veh/km**
Speed - Carro	42,51	55,8	40,35	59,32	37,48	57,19	29,12	39,51	**km/h**
Stop Time - Carro	131,53	51,79	95,53	20,14	97,75	28,36	182,46	82,05	**sec/km**
Travel Time - Carro	205,42	113,21	183,75	81,22	185,88	90,57	266,13	154,18	**sec/km**

In every simulation, we found the values of KPIs such as fuel consumption, emissions etc are varying. This might be due to the different behavior of the model in each case. In some cases, the sections were saturated and further flow of vehicles was not possible.

Looking at the three solution models, we can make out how the KPIs will behave even before simulating them. For example, in model 1 the two bridges connecting the North and the Infias region will help traffic move faster for these directions. But this will mean there will be more input flow at the Infias roundabout which could lead to congestion. In model 2 we can see that there are more infrastructural additions that help the flow out of the Infias region. This resulted in better KPIs as these additions improved the overall model because the multi-junction functionality improved. In solution model 3 there are new additions but at the entrance to the multi-junction there are not additions. Thus the main problem (priority) is not overcome.

Comparing the three models and the real-world model, model 2 was expected to produce better results and it did.

5.3.2 Signal additions

Table 19: Comparison of data from outputs in previous sections (traffic signal additions)

	Real World		Infias Signal		Multi junction Signal		Units
Parameters	**AM**	**PM**	**AM**	**PM**	**AM**	**PM**	
Fuel Consumption - Carro	2909,04	3219,59	3142,6	2591,12	2875,36	3201,5	**l**
IEM Emission - CO2 - Carro	4892732	6679742	5360422,2	6571729,09	4817760,63	6722846,17	**g**
IEM Emission - NOx - Carro	8042,4	11353,77	9225,69	11927	8139,25	11339,06	**g**
IEM Emission - PM - Carro	1279,94	1414,49	1237,32	1147,87	1250,45	1383,12	**g**
IEM Emission - VOC - Carro	25369,06	59298,92	39769,55	70955,57	26003,16	61031,8	**g**
Mean Queue - Carro	159,35	525,59	309,39	642,16	165,27	521,88	**veh**
Number of Stops - Carro	0,110	0,140	0,120	0,110	0,100	0,130	**#/veh/km**
Speed - Carro	39,51	29,12	34,62	30,78	38,97	29,56	**km/h**
Stop Time - Carro	82,05	182,46	168,26	156,98	90,12	170,14	**sec/km**
Travel Time - Carro	154,18	266,13	250,36	243,82	161,82	253,77	**sec/km**

Signal additions did not produce the results that we expected. Even though the values might seem lower than some of the solution models, it is because in some instances the input flow was not possible due to saturation of the respective section. That means in some cases more vehicles couldn't enter the system.

In these two scenarios, the time allotted to each green signal was not enough in the case of heavy flow at the Infias roundabout. And in the case of the signal at the multi-junction, during heavy flow the priorities at the other parts of the multi-junction make it difficult for the insufficient green time signals from operating efficiently. It makes matters worse at other inputs of the multi-junction. So, we can say that the real-world model behaves better as compared to the two scenarios.

5.4 Data observations

In this section we compare and summarize the results from the simulations.

5.4.1 Infrastructural additions

5.4.1.1 Morning peak

Table 20: Summary of data for morning peak (minimum and maximum values)

Parameter	Minimum	Model	Maximum	Model
Fuel Consumption - Carro	3219,6	Real World	4125,1	Alt Sol 1
IEM Emission - CO2 - Carro	6458851,1	Alt Sol 3	6999656,6	Alt Sol 1

IEM Emission - NOx - Carro	10410,1	Alt Sol 2	11353,8	Real World
IEM Emission - PM - Carro	1414,5	Real World	1884,4	Alt Sol 1
IEM Emission - VOC - Carro	36524,4	Alt Sol 2	59298,9	Real World
Mean Queue - Carro	235,8	Alt Sol 2	525,6	Real World
Number of Stops - Carro	0,100	Alt Sol 3 and Alt Sol 2	0,140	Real World
Speed - Carro	29,1	Real World	42,5	Alt Sol 3
Stop Time - Carro	95,5	Alt Sol 2	182,5	Real World
Travel Time - Carro	183,8	Alt Sol 2	266,1	Real World

5.4.1.2 Evening peak

Table 21: Summary of data for evening peak (minimum and maximum values)

Parameter	Minimum	Model	Maximum	Model
Fuel Consumption - Carro	2059,7	Alt 3	2909,0	Real World
IEM Emission - CO2 - Carro	3521261,1	Alt Sol 2	4892732,0	Real World
IEM Emission - NOx - Carro	6370,2	Alt Sol 2	8042,4	Real World
IEM Emission – PM – Carro	842,0	Alt 3	1279,9	Real World
IEM Emission - VOC - Carro	12231,4	Alt Sol 2	25369,1	Real World
Mean Queue - Carro	32,3	Alt Sol 2	159,4	Real World
Number of Stops - Carro	0,040	Alt Sol 2	0,110	Real World
Speed - Carro	39,5	Real World	59,3	Alt Sol 1
Stop Time - Carro	20,1	Alt Sol 2	82,1	Real World
Travel Time - Carro	81,2	Alt Sol 2	154,2	Real World

From the comparisons above, we see that most of the KPIs have better values in solution model 2. And it is justified because the traffic flows are uninterrupted in most cases.

5.4.2 Traffic signal additions

5.4.2.1 Morning peak

Table 22: Summary of data for traffic signals during morning peak (minimum and maximum values)

Parameters	Minimum	Model	Maximum	Model
Fuel Consumption - Carro	2875,36	Multi Junction Signal	3142,6	Infias Signal
IEM Emission - CO2 - Carro	4817760,63	Multi Junction Signal	5360422,2	Infias Signal
IEM Emission - NOx - Carro	8042,4	Real World	9225,69	Infias Signal
IEM Emission - PM - Carro	1237,32	Infias Signal	1279,94	Real World
IEM Emission - VOC - Carro	25369,06	Real World	39769,55	Infias Signal
Mean Queue - Carro	159,35	Real World	309,39	Infias Signal
Number of Stops - Carro	0,1	Infias Signal	0,12	Infias Signal
Speed - Carro	34,62	Infias Signal	39,51	Real World
Stop Time - Carro	82,05	Real World	168,26	Infias Signal
Travel Time - Carro	154,18	Real World	250,36	Infias Signal

5.4.2.2 Evening peak

Table 23: Summary of data for traffic signals during evening peak (minimum and maximum values)

Parameters	Minimum	Model	Maximum	Model
Fuel Consumption - Carro	2591,12	Infias Signal	3219,59	Real World
IEM Emission - CO2 - Carro	6571729,09	Infias Signal	6722846,17	Multi Junction Signal
IEM Emission - NOx - Carro	11339,06	Multi Junction Signal	11927	Infias Signal
IEM Emission - PM - Carro	1147,87	Infias Signal	1414,49	Real World
IEM Emission - VOC - Carro	59298,92	Real World	70955,57	Infias Signal
Mean Queue - Carro	521,88	Multi Junction Signal	642,16	Infias Signal
Number of Stops - Carro	0,11	Infias Signal	0,14	Real World
Speed - Carro	29,12	Real World	30,78	Infias Signal
Stop Time - Carro	156,98	Infias Signal	182,46	Real World
Travel Time - Carro	243,82	Infias Signal	266,13	Real World

The decisions regarding re-design and/or traffic management measures need a lot more considerations than the scope of this project. Based on the results obtained from the simulations, we can draw some conclusions and understand their effects in terms of traffic congestion and pollutant emissions.

- With the exhaustion of fossil fuels right upon us, the need to minimize their usage is important. Not to forget usage reduction will lead to lesser pollutant emissions. It is worth noting the fact that more and more hybrid and electric vehicles are hitting the roads nowadays, which is a positive sign and in further studies the weights assigned to fuel consumption and emissions will drop drastically.
- Traffic emissions affect the health of all living beings and over time, with constant exposure to the smallest of amounts could lead to life-threatening illnesses. Therefore, it is also a factor that must be given higher weightage while considering re-design options.
- Another point worth discussing here is the duration of construction of the three models and the problems that could be faced during the construction phase. All three models involve construction along the highway so it is possible that it will in turn effect the traffic in the Infias region.
- Factors such as travel time, queue lengths, vehicle speed, stop time and number of stops are all directly proportional to fuel consumption and emissions. Therefore, they must be kept at the minimum except for the vehicle speed that must be maintained in the optimum efficiency zone (50-60 kmph).
- Public transport priority measures prove very helpful in substantially decreasing the travel times of the buses during heavily congested traffic conditions. With a series of detectors and traffic signals operating in synchronization, this could prove to be a major factor in efficient operation of PT and solving traffic congestion and moreover motivating more people to use PT.

5.5 Concluding remarks

After observing the different outputs from all simulations, we can say that each of them have their own drawbacks and advantages. Some involve construction on a large scale and produce some good outputs whereas others consist of lesser additions and not much improvements in terms of statistical outputs. There is a trade-off to be made between the construction and KPI improvement.

6 Chapter 6: Conclusions and suggestions for further work

The motivation for this study was to decrease the impact of vehicle pollutants by solving the traffic congestion issues. They might lead to life-threatening illnesses in living beings, if not taken care of. Traffic congestions cause several difficulties for commuters as well as city planners due to the rise in KPIs. This study contributes to the solution faced by the municipality of Braga in tackling the congestion issues in the narrow streets of Infias region and the adjacent multi-junction that connects the heaviest traffic flows across Braga.

The conditions at the Infias roundabout and the multi-junction are the same every morning and evening during peak hours. During morning peak hours, the opening time of the two schools in the area leads to a surge in incoming traffic at the Infias roundabout and causes congestion. But traffic simulated models help us understand these issues and tackle them with strategic management and/or infrastructure construction. The key objective of this study is to maintain the levels of KPIs and improve the functionality of the multi-junction.

This study required understanding the key concepts involved in traffic simulation, driver behavior, OD matrix estimation methods to name some. It was the part of the literature review chapter of this study. Other important subjects such as the ill-effects of vehicle emissions on humans and vehicle speed vs fuel efficiency are necessary to understand how decongestion can help decrease pollutants in the atmosphere and lower fuel consumption.

Model development in Aimsun required understanding the functioning of the software. This study required the use of microsimulation because of the small size of the study area and the need for simulation of different scenarios that adapted their functioning dynamically during the simulation. The real-world model reflects the actual landscape of the study area with accuracy. Aspects such as elevation, slope, road lane width, traffic signs such as give way, etc. and most importantly the traffic demand data are verified before running the simulation. Subsequently, alternative solution models suggested by the Municipality of Braga are modelled. These models have been approved by the municipality civil engineers in terms of construction execution.

The results are varying and there is no constant outcome while tracking the minimum values for fuel consumption, emissions etc. There are other factors such as cost of construction of infrastructure (duration of construction and its environmental effects), maintenance costs, congestions during construction etc. Therefore, the overall cost analysis is very complicated as we do not have enough information to decide the weights for each of the factors contributing to the scenarios. Even though the results might be classified as good or bad, we must keep in mind that this is a microsimulation study and we do not have any information about how the infrastructure additions or traffic signal installations will or will not affect traffic conditions in adjoining other parts of the city. For such purposes, a larger study considering whole of Braga must be conducted.

To strictly follow the above criterion, we will have a model that is a combination of all three models and the real-world model too. During the morning peak, we did not record observations consistent with a particular model. The results show all 4 models optimum in one or the other aspect. Alternate solution 2 has minimum values for stop time, NO_x emissions, number of stops and travel time. The model recorded second best results for the remaining parameters: vehicle speed, fuel consumption, CO_2 / VOC / PM emissions.

On the other hand, during the evening peak alternate solution model 2 produced the best results with minimum values for all parameters except for fuel consumption (second lowest with only 40 liters more). Moreover, the average vehicle speed is right in the optimum range at 59.9 kmph. Therefore, for the evening traffic demand between 17h30 and 19h30, alternate model 2 is ideal.

Traffic signal additions at the Infias and multi-junction have not produced desired results. Even though the statistical outputs seem low, observations during the simulation were not satisfactory in both cases.

The bus priority measures help reduce the bus travel time. Buses (TUB number 9 in our illustration) that took over 7 minutes to commute over a route, had their travel time reduced to around 2 minutes.

Based on the observations above, we can conclude (with limitations) that alternate solution 2 model is ideal for the re-design predictions based on the present traffic demand. It involves the construction of infrastructure, but all those additions are justified and serve their purpose with positive results in the simulation.

6.1 Future scope of the study

This study evaluated the re-design options for the Infias and multi-junction regions and the alternative model 2 recorded the best results. Following are a few pointers for future researchers to keep in mind:

- The data collection in our project was done individually by site visits and manual counting (15-min intervals) of vehicles. Smart technologies such as Intelligent Transport Systems (ITS) are available now and must be used for more accurate counts. Technologies such as Pneumatic road tubes, video feeds, piezoelectric sensors, inductive loops etc. must be used to make the model's OD matrix estimation highly accurate. These are costly methods but will lead to better model (and their analysis) and save a huge amount of time.
- There were three alternate solutions suggested by the municipality. But in a traffic simulator we have the freedom of creating models that might or might not be possible to execute in

terms of construction. So, constant consultation with civil engineers must be done to validate the models that show promising simulation results.

- In such study areas, the implementation of bus priority measures, cycling lanes and other such environment friendly measures is difficult to implement with such heavy traffic flow during peak hours. Studies to evaluate strategic implementation of these measures will help significantly in reducing congestion and pollutants as well.
- This study is done for a small region of Braga. But it is advisable to extend this study keeping in mind the traffic flow conditions of the whole city of Braga. Mesoscopic simulation studies are recommended for such large areas because we must define the model parameters on the lowest of levels. This way the results obtained will be thorough and valid for the entire city.
- Traffic management approaches such as the one illustrated in the form of PT bus priority need more work. Co-ordinated traffic signals operated by actuated detectors strategically placed across the study area could help the PT networks as well as traffic congestion conditions.

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Appendix I: About Braga

Braga is a city and a municipality in the northwestern Portuguese district of Braga, in the historical and cultural Minho Province. The city has a resident population of 173,946 inhabitants as of 2018, representing the seventh largest municipality in Portugal (by population). Its area is 183.40 square kilometers. Its agglomerated urban area extends from the Cávado River until the Este River. It is the third largest urban center in Portugal, after Lisbon and Porto.

Figure 56: Map of Portugal showing location of Braga; Source: Wikipedia

Figure 57: Detailed map of Braga; Source: Wikipedia

The Portuguese Road System

The highways of Braga were constructed in 1999. Three major highways pass through Braga namely N101, N103 and A11. The roads in Portugal are defined by the Plano Rodoviário Nacional (PRN), which describes the existing and planned network of Portuguese roads. The present plan in force is the PRN 2000, approved in 1998. It replaced PRN 1985, which itself had replaced PRN 1945.

In 1998, PRN 2000 was approved and published by law No. 222/98 of 17 July 1998. This was potentially an optimization of the previous PRN 1985 with the addition of about 1,500 kms of roads into the National Network, and the creation of the Rede Regional (Regional Network) of about 5000 kms of roads, as well as the identification of a Rede Nacional de Autoestradas (National Motorway Network), which includes 16,500 kms of roads. The road network is classified as following:

i) Fundamental Network: Itinerários Principais: 2,600 kms
ii) Complementary Network: Itenerarios Complementares: 3,016 kms and Estradas Nacionais: 5,513 kms
iii) Regional Network: Estradas Regionais: 5,000 kms
iv) Rede Nacional de Autoestradas: Autoestradas: 16,500 kms

Present Statistics

With urbanization, overall demand in a city is bound to increase. Cities at the threshold of industrialization trigger the demand for all the sectors known to mankind: IT, healthcare, manufacturing, construction and so on.

A road network of over 14,000 kilometers through the mountainous terrains connects Portugal to its extremities.

The number of motorized vehicles per 1000 habitants residing in Portugal has risen from 584.7 in 2010 up to 626.5 in 2017. In Braga, it being the third largest urban center in Portugal, the increase in number of vehicles has been substantial (PORDATA - Base de Dados Portugal Contemporaneo, 2017).

Table 24: Table showing the number of vehicles per 1000 habitants in Portugal; Source: Pordata

Year	Motorized Vehicles per 1000 habitants
2010	584.7
2011	586.3
2012	529.8
2013	538.5
2014	587.5
2015	588.3
2016	602.2
2017	626.5

The type of fuel that vehicles use is another factor that determines the environmental effects of the use of vehicles. Petrol and diesel driven vehicles produce more pollutants as compared to LPG and CNG driven vehicles (PORDATA - Base de Dados Portugal Contemporaneo, 2017). While the world continues to find solutions to reduce emissions, the demand for vehicles is ever increasing which in turn leads to increase in fuel demand.

Table 25: Table showing the distribution of vehicles based on the type of fuel used; Source: Pordata

Year	Type of Fuel				
	Total	Diesel	Petrol	LPG	Others
2010	6,182,051	3,546,659	2,587,487	38,982	8,923
2011	6,181,188	3,619,670	2,513,202	38,210	10,106
2012	5,556,041	3,334,430	2,172,762	37,899	10,950
2013	5,615,079	3,393,572	2,168,388	41,136	11,983
2014	6,095,506	3,746,210	2,286,681	47,775	14,840
2015	6,083,694	3,818,327	2,197,118	48,821	19,428
2016	6,208,350	3,964,235	2,168,246	50,016	25,853
2017	6,447,241	4,173,980	2,181,672	53,026	38,563

At the current fuel consumption rate around the world, only 50-60 years of oil and gas stock remain, and the use of petrol and diesel vehicles will lead to their exhaustion. A good road network, with continuous flow of traffic, helps in improving the performance of vehicles (in terms of mileage) and thus minimizing the consumption of fuel.

APPENDIX II: DATA

The OD matrices formed by the calculations in chapter 4 are listed here for both morning and evening peak hours that we have used for the simulations. Following is an image that can be referred to understand the location of the O/Ds.

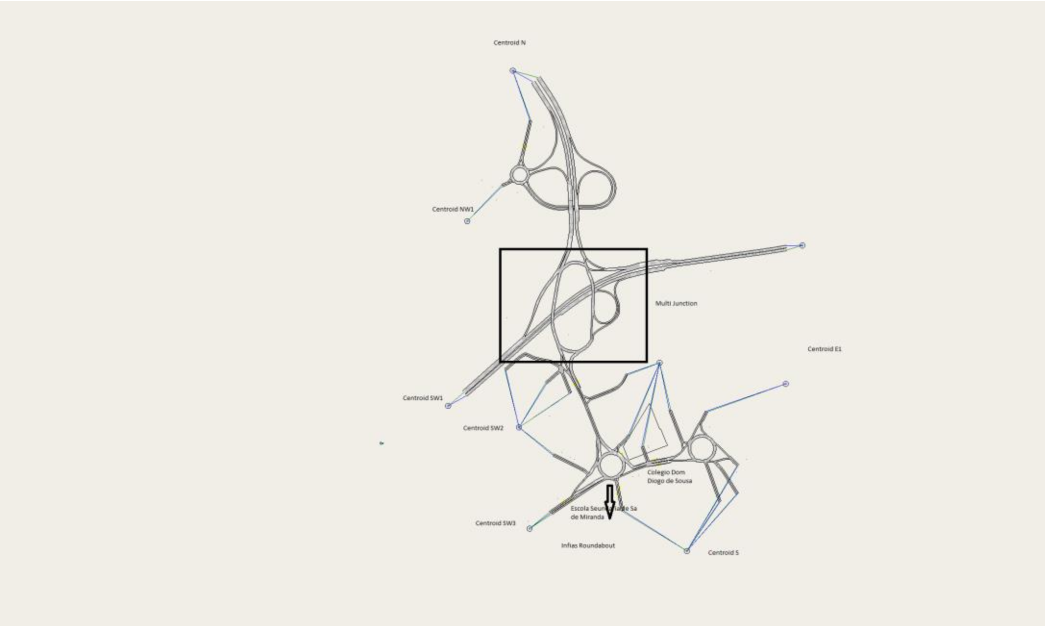


Figure 58: Indication of centroids, multi-junction and the Infias roundabout in the system model.

Following are the names of the ODs.

N: The northernmost OD pair.
NW: To the left of N, a bit towards the west (North-West). It has 2 input and output flow sections.
SW1, SW2 and SW3: Are the three OD pairs in the South-West.
S: Southernmost OD pair with 4 input and output flow sections.
C: Center of the network and has 4 input and output flow sections.
SE1: In the South and towards the East.
E: The Easternmost OD pair.

Morning ODMs

Table 26: ODM for 07:30 to 07:45

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	95,8029	108,577	8,04745	20,1825	3,19343	47,9015	9,19708	1,91606	294,818
E1	117,46	0	231,113	17,1296	42,9599	6,79745	101,962	19,5766	4,07847	541,077
N	100	200	0	20	40	10	100	20	10	500
NW1	7,09489	12,3175	13,9599	0	2,59489	0,410584	6,15876	1,18248	0,24635	43,9654
SW3	11,8248	20,5292	23,2664	1,72445	0	0,684307	10,2646	1,9708	0,410584	70,6751
SW2	3,46861	6,0219	6,82482	0,505839	1,26861	0	3,01095	0,578102	0,120438	21,7993
S	23,965	41,6058	47,1533	3,49489	8,76496	1,38686	0	3,99416	0,832117	131,197
SE1	1,57664	2,73723	3,10219	0,229927	0,576642	0,091241	1,36861	0	0,054745	9,73722
C	2	3	3	0	2	0	2	0	0	12
Total	267,39	382,015	436,997	51,1322	118,348	22,5639	272,666	56,4992	17,6588	1625,27

Table 27: ODM for 07:45 to 08:00

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	128,274	130,208	12,2024	26,6369	3,72024	57,4405	10,119	3,42262	372,024
E1	147,288	0	245,949	23,0489	50,3142	7,02712	108,499	19,1138	6,46495	607,705
N	100	200	0	20	40	10	100	20	10	500
NW1	9,53042	15,6779	15,9144	0	3,25562	0,454696	7,0205	1,23677	0,41832	53,5086
SW3	17,328	28,5053	28,9352	2,71164	0	0,82672	12,7646	2,24868	0,760582	94,0807
SW2	3,81217	6,27116	6,36574	0,596561	1,30225	0	2,8082	0,494709	0,167328	21,8181
S	34,6561	57,0106	57,8704	5,42328	11,8386	1,65344	0	4,49735	1,52116	174,471
SE1	4,33201	7,12632	7,2338	0,67791	1,47983	0,20668	3,19114	0	0,190146	24,4378
C	2	3	3	0	2	0	2	0	0	12
Total	318,947	445,865	495,477	64,6607	136,827	23,8889	293,724	57,7103	22,9451	1860,04

Table 28: ODM for 08:00 to 08:15

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	152,736	174,254	12,0383	27,5376	5,26676	64,104	12,4897	4,51436	452,941
E1	160,588	0	288,312	19,9179	45,5622	8,71409	106,063	20,6648	7,46922	657,291
N	100	200	0	20	40	10	100	20	10	500
NW1	17,1176	26,9371	30,7321	0	4,85663	0,928865	11,3056	2,20274	0,79617	94,8769
SW3	27,3529	43,0438	49,1081	3,39261	0	1,48427	18,0657	3,51984	1,27223	147,239
SW2	3,88235	6,10944	6,97018	0,481532	1,1015	0	2,56416	0,49959	0,180575	21,7893
S	61,7647	97,1956	110,889	7,66074	17,5239	3,35157	0	7,94802	2,87278	309,207
SE1	5,29412	8,33105	9,50479	0,656635	1,50205	0,287278	3,49658	0	0,246238	29,3187
C	2	3	3	0	2	0	2	0	0	12
Total	378	537,353	672,771	64,1477	140,084	30,0328	307,599	67,3248	27,3516	2224,66

Table 29: ODM for 08:15 to 08:30

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	172,359	153,092	9,70826	26,1376	5,22753	62,4316	8,81212	4,18202	441,95
E1	169,577	0	278,999	17,6926	47,634	9,5268	113,777	16,0595	7,62144	660,888
N	100	200	0	20	40	10	100	20	10	500
NW1	18,2621	33,8275	30,0461	0	5,12982	1,02596	12,2529	1,72948	0,820771	103,095
SW3	30,4369	56,3791	50,0768	3,1756	0	1,70994	20,4216	2,88247	1,36795	166,45
SW2	3,82635	7,08766	6,29537	0,399218	1,07482	0	2,56728	0,362367	0,171971	21,785
S	75,6575	140,142	124,477	7,89363	21,2521	4,25042	0	7,16499	3,40034	384,238
SE1	6,08738	11,2758	10,0154	0,63512	1,70994	0,341988	4,08431	0	0,27359	34,4235
C	2	3	3	0	2	0	2	0	0	12
Total	405,847	624,071	656,001	59,5045	144,938	32,0826	317,535	57,0109	27,8381	2324,83

Table 30: ODM for 08:30 to 08:45

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	167,968	164,306	12,1523	29,9646	5,82646	71,4157	13,4841	5,32705	470,445
E1	149,782	0	260,273	19,2501	47,4661	9,22952	113,128	21,3598	8,43842	628,926
N	100	200	0	20	40	10	100	20	10	500
NW1	16,4007	29,1344	28,4991	0	5,19741	1,01061	12,3872	2,33883	0,923983	95,8922
SW3	25,9399	46,0798	45,0751	3,33382	0	1,59841	19,5919	3,69918	1,4614	146,78
SW2	3,68179	6,54037	6,39776	0,473188	1,16676	0	2,78079	0,525044	0,207425	21,7731
S	77,1503	137,05	134,062	9,91544	24,449	4,75398	0	11,0021	4,34649	402,73
SE1	5,02062	8,91868	8,72422	0,645256	1,59104	0,309369	3,79199	0	0,282852	29,284
C	2	3	3	0	2	0	2	0	0	12
Total	379,975	598,692	650,337	65,7702	151,835	32,7283	325,095	72,409	30,9876	2307,83

Table 31: ODM for 08:45 to 09:00

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	148,358	194,941	26,9044	26,9044	5,38087	61,0345	10,9155	3,07478	477,514
E1	153,781	0	326,077	45,0028	45,0028	9,00056	102,092	18,2583	5,14317	704,358
N	100	200	0	20	40	10	100	20	10	500
NW1	14,1312	22,8037	29,9639	0	4,13539	0,827078	9,38143	1,67779	0,472616	83,3931
SW3	29,9249	48,2902	63,4529	8,7573	0	1,75146	19,8666	3,55296	1,00083	176,597
SW2	3,65749	5,90214	7,75535	1,07034	1,07034	0	2,42813	0,434251	0,122324	22,4404
S	68,1624	109,994	144,532	19,9472	19,9472	3,98944	0	8,09286	2,27968	376,945
SE1	6,64999	10,7312	14,1006	1,94607	1,94607	0,389213	4,41479	0	0,222408	40,4003
C	2	3	3	0	2	0	2	0	0	12
Total	378,307	549,08	783,823	123,628	141,006	31,3386	301,217	62,9316	22,3158	2393,65

Table 32: ODM for 09:00 to 09:15

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	133,24	155,991	7,28654	24,2389	3,71762	53,0876	10,1119	3,71762	391,391
E1	134,87	0	285,816	13,3508	44,4119	6,81164	97,2702	18,5277	6,81164	607,871
N	100	200	0	20	40	10	100	20	10	500
NW1	11,8724	21,4902	25,1599	0	3,9095	0,599616	8,56252	1,63096	0,599616	73,8248
SW3	22,1618	40,1151	46,9651	2,1938	0	1,11928	15,9834	3,04445	1,11928	132,702
SW2	3,48257	6,30381	7,38024	0,344739	1,14679	0	2,51167	0,478414	0,175887	21,8241
S	53,8216	97,4224	114,058	5,32779	17,7231	2,71826	0	7,39367	2,71826	301,183
SE1	5,54045	10,0288	11,7413	0,548449	1,82443	0,279821	3,99584	0	0,279821	34,2389
C	2	3	3	0	2	0	2	0	0	12
Total	333,749	511,6	650,113	49,0521	135,255	25,2462	283,411	61,1871	25,4221	2075,04

Table 33: ODM for 09:15 to 09:30

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	144,38	142,729	9,7353	26,2358	4,12513	61,2169	8,58027	4,62014	401,623
E1	126,384	0	230,151	15,6982	42,3053	6,65177	98,7123	13,8357	7,44998	541,188
N	100	200	0	20	40	10	100	20	10	500
NW1	10,6136	19,5514	19,3279	0	3,55277	0,558611	8,28979	1,16191	0,625645	63,6817
SW3	14,6958	27,0712	26,7618	1,82537	0	0,773462	11,4782	1,6088	0,866277	85,0808
SW2	3,5923	6,61739	6,54177	0,446201	1,20248	0	2,80578	0,393262	0,211757	21,8109
S	45,5569	83,9206	82,9615	5,65865	15,2496	2,39773	0	4,98728	2,68546	243,418
SE1	4,08216	7,51977	7,43383	0,507047	1,36645	0,21485	3,18838	0	0,240633	24,5531
C	2	3	3	0	2	0	2	0	0	12
Total	306,924	492,06	518,908	53,8707	131,912	24,7216	287,691	50,5672	26,6999	1893,35

Evening ODMs

Table 34: ODM for 17:30 to 17:45

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	127,173	233,689	9,68326	88,7632	31,3092	112,003	67,1373	9,68326	679,442
E1	113,357	0	208,3	8,63122	79,1195	27,9076	99,8345	59,8431	8,63122	605,624
N	96,4201	96,4201	0	7,34163	67,2983	23,7379	84,9182	50,902	7,34163	434,38
NW1	9,65686	9,65686	17,7451	0	6,7402	2,37745	8,5049	5,09804	0,735294	60,5147
SW3	39,816	39,816	73,1644	3,03167	0	9,80241	35,0664	21,0196	3,03167	224,748
SW2	7,42836	7,42836	13,6501	0,565611	5,18477	0	6,54223	3,92157	0,565611	45,2866
S	63,5867	63,5867	116,845	4,84163	44,3816	15,6546	0	33,5686	4,84163	347,306
SE1	9,35973	9,35973	17,1991	0,71267	6,53281	2,3043	8,24321	0	0,71267	54,4242
C	3	2	3	2	0	2	0	2	0	14
Total	342,624	355,441	683,593	36,8077	298,02	115,094	355,112	243,49	35,543	2465,73

Table 35: ODM for 17:45 to 18:00

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	99,6546	152,964	10,0855	73,7204	25,9342	92,9309	47,3059	11,2862	513,882
E1	149	0	159,25	10,5	76,75	27	96,75	49,25	11,75	580,25
N	93,2339	64,9196	0	6,57018	48,0249	16,8947	60,5395	30,8173	7,35234	328,352
NW1	14,595	10,1626	15,599	0	7,51791	2,64474	9,47697	4,8242	1,15095	65,9715
SW3	68,4006	47,6279	73,106	4,82018	0	12,3947	44,4145	22,6089	5,39401	278,767
SW2	14,595	10,1626	15,599	1,02851	7,51791	0	9,47697	4,8242	1,15095	64,3553
S	58,3801	40,6506	62,3962	4,11404	30,0716	10,5789	0	19,2968	4,6038	230,092
SE1	16,3377	11,3761	17,4616	1,15132	8,41557	2,96053	10,6086	0	1,28838	69,5998
C	3	2	3	2	0	2	0	2	0	14
Total	417,542	286,554	499,376	40,2697	252,018	100,408	324,197	180,927	43,9766	2145,27

Table 36: ODM for 18:00 to 18:15

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	181,91	202,625	7,48531	102,531	41,2562	108,798	67,7159	9,92238	722,245
E1	237,346	0	238,37	8,80576	120,619	48,5341	127,991	79,6615	11,6728	872,999
N	230,577	207,898	0	8,55463	117,179	47,15	124,341	77,3896	11,3399	824,428
NW1	11,1358	10,0405	11,1839	0	5,65919	2,27713	6,00509	3,73757	0,547664	50,5869
SW3	82,5362	74,4179	82,8922	3,06217	0	16,8775	44,5083	27,702	4,05916	336,055
SW2	18,7781	16,931	18,8591	0,696684	9,54295	0	10,1262	6,30256	0,923512	82,1601
S	95,6372	86,2302	96,0497	3,54823	48,6025	19,5565	0	32,0991	4,70347	386,427
SE1	9,82573	8,85927	9,86812	0,364544	4,99341	2,00923	5,29861	0	0,483233	41,7021
C	3	2	3	2	0	2	0	2	0	14
Total	688,836	588,287	662,849	34,5173	409,126	179,661	427,068	296,608	43,652	3330,6

Table 37: ODM for 18:15 to 18:30

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	277,689	337,251	16,1478	151,683	48,9728	177,626	17,2067	6,08851	1032,66
E1	269,095	0	358,231	17,1523	161,119	52,0193	188,676	18,2771	6,46727	1071,04
N	227,135	248,97	0	14,4778	135,996	43,908	159,255	15,4271	5,45883	850,628
NW1	24,4273	26,7756	32,5187	0	14,6258	4,72211	17,1272	1,65912	0,587073	122,443
SW3	116,03	127,184	154,464	7,39584	0	22,43	81,3543	7,88082	2,7886	519,528
SW2	25,2153	27,6394	33,5677	1,60725	15,0976	0	17,6797	1,71264	0,606011	123,126
S	136,714	149,857	182	8,71429	81,8571	26,4286	0	9,28571	3,28571	598,143
SE1	11,6227	12,74	15,4726	0,74084	6,95904	2,24681	8,14924	0	0,279333	58,2106
C	3	2	3	2	0	2	0	2	0	14
Total	813,239	872,856	1116,5	68,2361	567,338	202,728	649,867	73,4492	25,5613	4389,78

Table 38: ODM for 18:30 to 18:45

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	221,911	338,784	18,7391	122,544	49,3135	158,789	86,2986	12,3284	1008,71
E1	253,553	0	322,575	17,8426	116,681	46,9542	151,192	82,1698	11,7385	1002,71
N	216,167	180,139	0	15,2118	99,4769	40,0309	128,9	70,0541	10,0077	759,987
NW1	41,7714	34,8095	53,1425	0	19,2226	7,73545	24,9081	13,537	1,93386	197,061
SW3	120,093	100,077	152,785	8,45098	0	22,2394	71,6109	38,919	5,55985	519,735
SW2	31,3286	26,1071	39,8569	2,2046	14,4169	0	18,6811	10,1528	1,4504	144,198
S	155,807	129,839	198,222	10,9642	71,7003	28,8532	0	50,4931	7,2133	653,093
SE1	31,3286	26,1071	39,8569	2,2046	14,4169	5,80159	18,6811	0	1,4504	139,847
C	3	2	3	2	0	2	0	2	0	14
Total	853,048	720,991	1148,22	77,6179	458,459	202,928	572,763	353,624	51,6825	4439,33

Table 39: ODM for 18:45 to 19:00

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	263,5	208,75	32	94,75	23	145,25	17	10,5	794,75
E1	295,508	0	255,699	39,1969	116,06	28,1728	177,917	20,8234	12,8615	946,238
N	223,086	243,661	0	29,5907	87,6163	21,2683	134,314	15,7201	9,70946	764,967
NW1	33,9986	37,1342	29,4184	0	13,3528	3,24131	20,4696	2,39575	1,47973	141,49
SW3	113,406	123,865	98,1286	15,0425	0	10,8118	68,2787	7,99131	4,93581	442,46
SW2	25,1496	27,4691	21,7616	3,33591	9,87741	0	15,1419	1,7722	1,09459	105,602
S	144,61	157,947	125,129	19,1815	56,7951	13,7867	0	10,1902	6,29392	533,934
SE1	26,3139	28,7408	22,7691	3,49035	10,3347	2,50869	15,8429	0	1,14527	111,146
C	3	2	3	2	0	2	0	2	0	14
Total	865,073	884,318	764,655	143,838	388,786	104,79	577,215	77,8929	48,0203	3854,59

Table 40: ODM for 19:00 to 19:15

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	99,6546	152,964	10,0855	73,7204	25,9342	92,9309	47,3059	11,2862	513,882
E1	149	0	159,25	10,5	76,75	27	96,75	49,25	11,75	580,25
N	93,2339	64,9196	0	6,57018	48,0249	16,8947	60,5395	30,8173	7,35234	328,352
NW1	14,595	10,1626	15,599	0	7,51791	2,64474	9,47697	4,8242	1,15095	65,9715
SW3	68,4006	47,6279	73,106	4,82018	0	12,3947	44,4145	22,6089	5,39401	278,767
SW2	14,595	10,1626	15,599	1,02851	7,51791	0	9,47697	4,8242	1,15095	64,3553
S	58,3801	40,6506	62,3962	4,11404	30,0716	10,5789	0	19,2968	4,6038	230,092
SE1	16,3377	11,3761	17,4616	1,15132	8,41557	2,96053	10,6086	0	1,28838	69,5998
C	3	2	3	2	0	2	0	2	0	14
Total	417,542	286,554	499,376	40,2697	252,018	100,408	324,197	180,927	43,9766	2145,27

Table 41: ODM for 19:15 to 19:30

	SW1	E1	N	NW1	SW3	SW2	S	SE1	C	Total
SW1	0	127,173	233,689	9,68326	88,7632	31,3092	112,003	67,1373	9,68326	679,442
E1	157,376	0	208,3	8,63122	79,1195	27,9076	99,8345	59,8431	8,63122	649,643
N	133,862	96,4201	0	7,34163	67,2983	23,7379	84,9182	50,902	7,34163	471,822
NW1	13,4069	9,65686	17,7451	0	6,7402	2,37745	8,5049	5,09804	0,735294	64,2647
SW3	55,2775	39,816	73,1644	3,03167	0	9,80241	35,0664	21,0196	3,03167	240,21
SW2	10,313	7,42836	13,6501	0,565611	5,18477	0	6,54223	3,92157	0,565611	48,1712
S	88,279	63,5867	116,845	4,84163	44,3816	15,6546	0	33,5686	4,84163	371,998
SE1	12,9943	9,35973	17,1991	0,71267	6,53281	2,3043	8,24321	0	0,71267	58,0588
C	3	2	3	2	0	2	0	2	0	14
Total	474,509	355,441	683,593	36,8077	298,02	115,094	355,112	243,49	35,543	2597,61

APPENDIX III: AIMSUN MANUAL

Aimsun is an extensible environment that offers, in a single application, all necessary tools that a transportation professional would need.

Aimsun has three components that allow vehicle-based simulations: the Microscopic Simulator, the Mesoscopic Simulator and the Hybrid Simulator. They can deal with different traffic networks: urban networks, freeways, highways, ring roads, arterials and any combination thereof. The vehicle-based simulators have been designed and implemented as a tool for traffic analysis to help traffic engineers in the design and assessment of traffic systems. They have proven to be very useful for testing new traffic control systems and management policies, based either on traditional technologies or as implementation of Intelligent Transportation Systems (ITS).

The Microsimulator follows a microsimulation approach. This means that the behavior of each vehicle in the network is continuously modelled throughout the simulation time period while it travels through the traffic network, according to several vehicle-behavior models (e.g. car following, lane changing). The Microscopic simulator in Aimsun is a combined discrete/continuous simulator. This means that there are some elements of the system (vehicles, detectors) whose state changes continuously over simulated time, which is split into short fixed time intervals simulation cycles or steps. There are other elements (traffic signals, entrance points) whose state change discretely at specific points in simulation time. The system provides highly detailed modeling of the traffic network, it distinguishes between different types of vehicles and drivers, it enables a wide range of network geometrics to be dealt with, and it can also model incidents, conflicting manoeuvers, etc. Most traffic equipment present in a real traffic network is also modelled in the Microsimulator: traffic lights, traffic detectors, Variable Message Signs, ramp metering devices, etc.

The output provided by Aimsun Vehicle-based simulators are a continuous animated graphical representation of the traffic network performance., both in 2D and 3D, statistical output data (flow, speed, journey times, delays, stops), and data gathered by the simulated detectors (counts, occupancy, speed). Furthermore, a continuous animation of the simulation vehicles is also produced.

Aimsun is being used all over the world to solve complex traffic related problems. Some of the Aimsun case studies are mentioned below:

- Sheffield: City Center Mode
  Project Managers: Arup for Sheffield City Center Council

Brief: Build a large model incorporating route choice to model public transport priority proposals and help develop new transport models.

- Hong Kong: Vehicle and pedestrian integration in the Admiralty model
  In preparation for major new infrastructure developments in Hong Kong's CBD, the Transport Department of the Government of the Hong Kong Special Administrative Region commissioned Arup to conduct a large-scale assessment of the impact of the revamp on the local traffic.

- New York: Manhattan Traffic Model
  The Manhattan Traffic Model (MTM) is one of the most complex large-scale simulation models currently in existence. The MTM will permit the consistent assessment of the

network wide cumulative impact of current and future traffic management projects and provide a platform for future analyses and expansion to other boroughs and, where possible, the region.

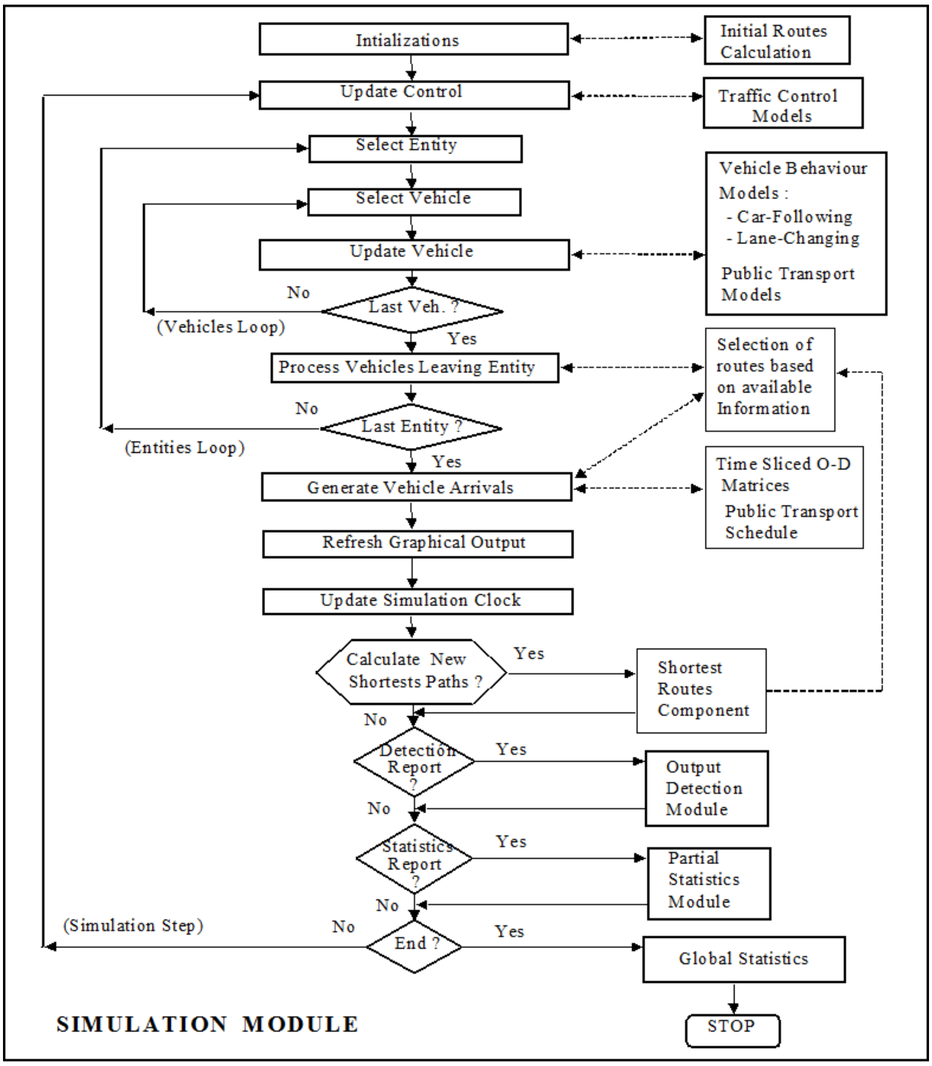
Now we look at the characteristics of the Aimsun Simulator that are specific and relevant to our project.

The Microsimulation Process

The logic of the simulation process in Aimsun is illustrated in the figure below for OD Matrices Demand). At each time interval (simulation step), the simulation cycle updates the unconditional events scheduling list (i.e. events such as traffic lights changes which do not depend on the termination of other activities). The “Update Control” box in the flow chart represents this step. After this updating process, a set of rested loops starts to loop over the entities (road sections and junctions at a lane level) and update each vehicle in the model. Once the last entity has been updated, the simulator performs the remaining operations such as inputting new vehicles, collecting new data, etc.

New vehicles are input into the network according to flow generation procedures (headway distribution for example) using one of these two options: with input sections and turn percentages (traffic states) or using sliced OD matrices and route selection.

In the OD Matrices demand, route based case, the simulation process includes an initial computation of routes going from every section to every destination according to link cost criteria specified by the user. A shortest route component periodically calculates the new shortest routes according to current time interval travel times provided by the simulator, and a route selection model assigns the new or re-routed vehicles to these. Vehicles keep their assigned route from origin to destination unless they have been identified as "Enroute" at generation time or at some point have become "Lost".



Model Management

One of the more time-consuming tasks in transport modelling is managing the variants of the traffic network. Different options for road network infrastructure, and the traffic control systems are tested in conjunction with different demand options such as land use, and public transport routes, and schedules. There is a combinational explosion in the number of variants of the transport model and consequently, a management problem in maintaining consistency across them.

The management problem is compounded when the modelling task focusses on a sub area of a wider transport model and a cordoned area is to be studied. Returning the changes made in the sub area as a result of that modelling exercise to the wide area model, and all the variants of that wide area model is a time consuming and potentially error prone task.

In Aimsun, the ability to create scenarios and experiments with different options of network topology, transport demand, simulation method, and sets of calibration variables provide an efficient method of generating the multiple model variants of a single traffic network and supporting the model management task.

Aimsun holds all options in one document and only brings them together as model for each of the variants modelled by an experiment within a scenario. Multiple scenarios may be created in one Aimsun document and as there is only one copy of each model component rather than multiple copies spread around multiple different models, the task of ensuring all modelled components are considered is greatly reduced. Furthermore, the method of simulation, (micro, meso, or hybrid), or whether it is to be a macro assignment is determined by the scenario and the model generated from the same data in the Aimsun document.

Well planned use of scenarios and experiments in Aimsun has the ability to save time in the transport modelling process and reduce the amount of error prone data transfers between modelling systems.

Scenarios and Experiments

A scenario is based in the method of running the model. Once the method of running the model is selected, the base network and demand conFiguretion is described for the scenario and different experiments are created which contain the options to be tested.

Assignment: A scenario is created with an assignment method for the experiments within it. The options are:

Dynamic Scenario: Experiments are run using micro, meso or hybrid vehicle-based simulation, and with a Stochastic Route Choice or Dynamic User Equilibrium (DUE) assignment.

Stochastic Route Choice: For Dynamic Traffic Assignment (DTA), the traffic demand is defined in terms of OD matrices, each one giving the number of trips from every origin centroid to every destination centroid, for a time slice and for a vehicle type. When a vehicle is generated at an origin, it is assigned to one of the available paths. Connecting the origin to the destination. The vehicle will travel along this path until it reaches its destination unless it is allowed to dynamically change its route en-route (i.e. it is a guided vehicle) when a better route exists from its current position on the assigned path to its destination. The simulation process based on time-dependent paths, consists of the following steps:

- Step 0: Calculate initial shortest path(s) for each OD pair using the defined initial costs.
- Step 1: Simulate for a predefined time interval (e.g. 5 minutes) known as the Route Choice Cycle, assigning to the available path fraction of the trips between each OD pair for that time interval according to the selected route choice model and obtain new average link travel times as a result of the simulation.

- Step 2: Recalculate shortest path, taking into account the experimented average link travel times.
- Step 3: If there are guided vehicles, or variable message signs suggesting rerouting, provide the information provided in Step 2 to the drivers that are dynamically allowed to reroute on trip.
- Step 4: Go to Step 1.

Dynamic User Equilibrium: For a DTA to become DUE, the behavioral assumption on how travelers choose the routes must be consistent with the DUE principle. Ran and Boyce 1996, formulate the dynamic version of Wardop's user equilibrium in the following terms: *If , for each OD pair at each instant of time, the actual travel times experienced by travelers departing at the same time are equal and minimal, the dynamic traffic flow over the network is in a travel-time-based DUE state.*

Static Assignment Scenario: In a Stochastic Assignment Scenario, trips are assigned to the network using a choice of deterministic algorithms or a stochastic method.

Four-Step Model Scenario: It links trip generation with travel mode choice and assignment to the transport network. This can include Generation/Attraction experiments, Distribution experiments, and Public Transport Assignment experiments. As with the static and dynamic assignment scenarios, different Four-Stage scenarios with different land use patterns and traveler response assumptions can be run using from a single Aimsun document incorporating different road networks changes as required.

Generation/Attraction Scenario: It takes socioeconomic data and the G/A factors corresponding to the G/A rates of each one of the socioeconomic values for each time period and trip purpose. Its output is a set of G/A vectors which go into a Four-Step scenario.

Distribution Scenario: The Distribution + Modal Split process transforms the G/A vectors into OD matrices for each user class.

Public Transport Assignment Scenario: The Public Transport OD Assignment scenario assigns passengers to the Public Transport Lines. The output is the loading on the Public Transport lines.

Network: There are two mandatory components of a traffic network:

The base network: This is the traffic network; the core of the Aimsun project. It holds the sections and nodes of the base road network and the fundamental objects such as Vehicle Types, Trip Purposes and User Class that describe the vehicles of the network.

A traffic demand object to describe the trips made by the vehicles travelling in the traffic network. This is either a set of Traffic States which move vehicles in the network to match observed flows or OD Matrices which provide the number of trips between centroids broken down by time of day, and User Class. A Centroid ConFiguretion is required for OD matrix demand and an Aimsun document may contain multiple centroid conFiguretions to manage different OD demands.

Traffic Demand

The traffic demand in a network is the number of vehicles travelling along each of the road sections and making turns at the road junctions. Aimsun offers two principle means of describing this traffic demand in the network; the first, a Traffic State Model, is based on directly modelling the observed flows on the road, the second, is based on Origin Destination (OD) matrices which models the trips made by travelers and includes first, their choice of routes, then as the scope of the transport model is extended their choice of transport mode, their reaction to advice from Intelligent Transportation System (ITS) and their decision to travel.

Traffic Demand Objects

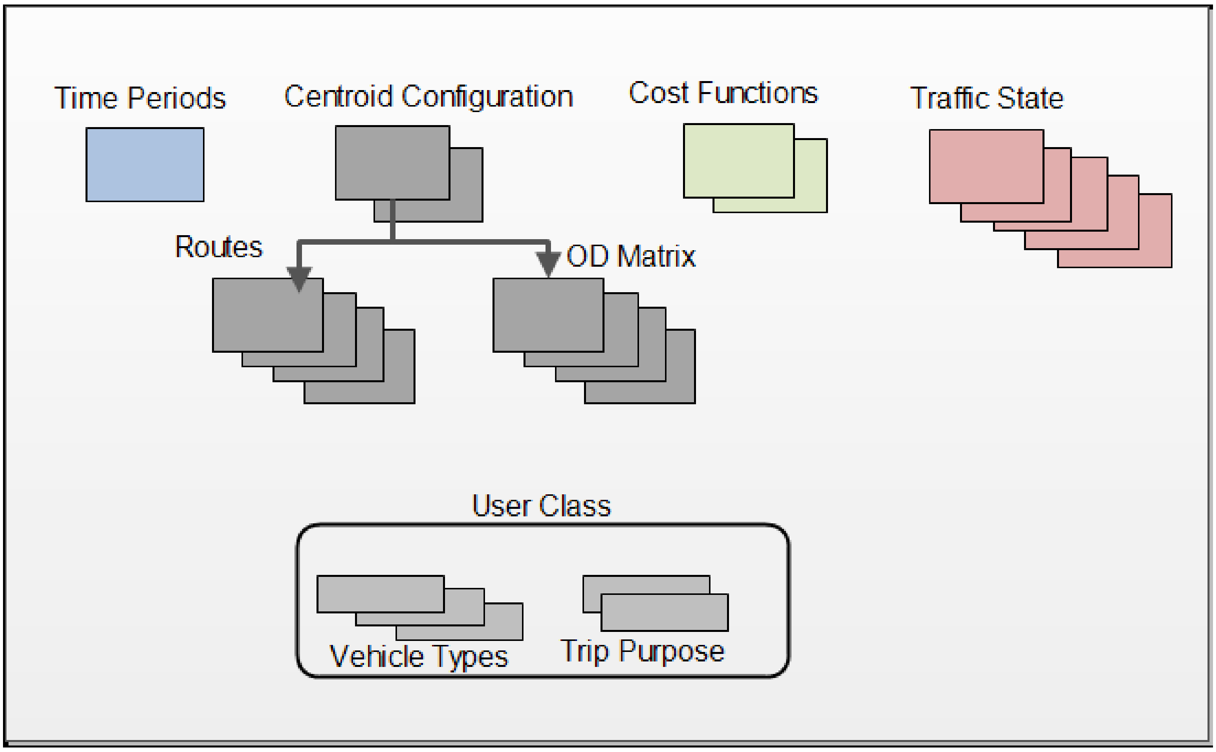
Every scenario in an Aimsun project or every experiment in a scenario has a Traffic Demand object associated with it. The traffic levels in a demand object are specified by a set of Traffic States or OD Matrices – but not a mixture of both. The Traffic Demand object enables traffic demands to be associated with a set of scenarios or a set of experiments within a scenario by providing a single demand object as opposed to editing the demand separately in every individual experiment.

There are two basic objects which describe the vehicles in the network:

Vehicle Type

Trip Purpose

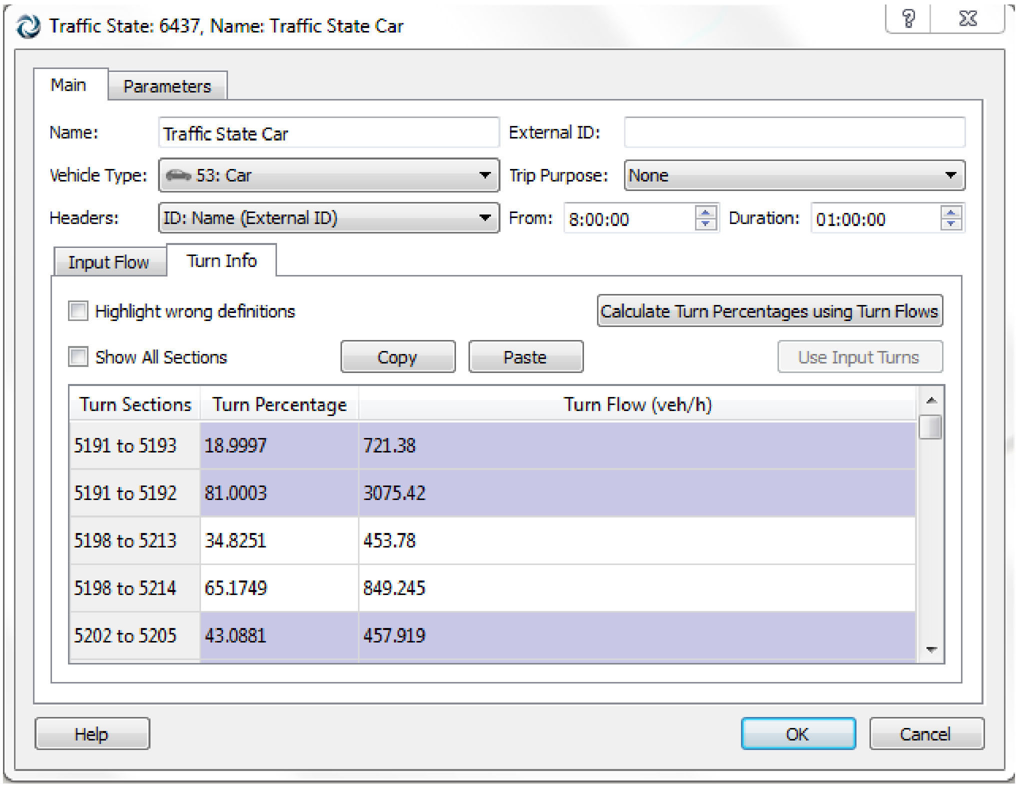
The Vehicle Type defines the physical behavior and appearance of the vehicle (i.e. car, bus, van etc.). The Trip Purpose defines the traveler's reason for the trip (i.e. business, leisure, commute etc.). Together the Vehicle Type and Trip Purpose form a User Class which can be further used in modelling trip and mode choice.



Traffic State vs OD Matrix

Traffic States

A Traffic State is composed of a set of flows at every input section in the network and a set of turn proportions at every junction for each Vehicle Type and Trip Purpose pair. The data requirement for a model using Traffic States are most often used for small area junction design or corridor improvement models where there is comprehensive observed data coverage and the emphasis in the model is on management, optimization, and detailed road design, with no traveler reaction to the traffic conditions other than normal or car following behavior. Traffic State demand cannot model network changes which may cause travelers to change travelers to change their route in reaction to congestion. Traffic States may vary across time intervals to model the changing patterns of flow during the day. One state may control a background level of traffic and place a constant flow of cars on the network while another may run in parallel and place a peak flow of cars on the same network to simulate a “school run” for example.

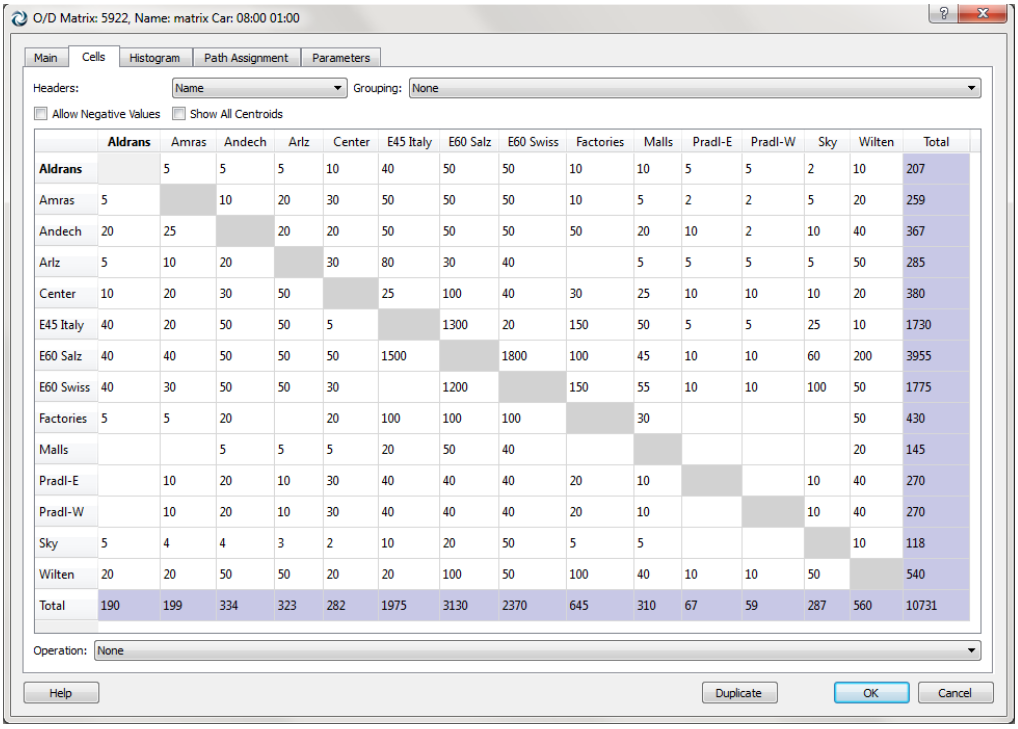


While models base on Traffic State demand may be simple to create, as their input is so closely taken from the observed data, they do have some disadvantages in that individual vehicles do not have a destination, they merely choose each turn based on the turning proportions at the next junction and traverse the network until they find an exit section. Using a model based on Traffic States to investigate the effect of adding a demand for a specific target to study the effect of route choice or to model a network with sparse observed data would not be possible.

OD Matrices

An OD Matrix based Traffic Demand is composed of a set of matrices each describing the number of trips between centroids for each Vehicle Type and Trip Purpose pair in a Time Period. The data requirement for a model using OD matrices is first an estimate of the number of trips between centroids, usually derived from land use and demographics. This estimate may be refined using observed flow and turn count data and here, unlike in Traffic State mode, the data may be sparse and not available for all turns and sections. OD Matrix based models require an extra stage in generating the model before it can be run; generating the OD matrices.

While models based on OD matrices may require more steps to create as their input has to be derived from the observed data often using quite sophisticated processes, they are capable of much more investigation into traveler activity than models based on Traffic States. Each vehicle has an origin and a destination and hence a route choice to make which can be varied depending on the congestion in traffic network. In generating the OD matrices, changes in land use and demographics, trip purposes, trip cost, and trip mode choice may be modelled and more investigation into the effect on the traffic network of changes in demand as well as changes in the network itself may be undertaken.



	Aldrans	Amras	Andech	Arlz	Center	E45 Italy	E60 Salz	E60 Swiss	Factories	Malls	Pradl-E	Pradl-W	Sky	Wilten	Total
Aldrans		5	5	5	10	40	50	50	10	10	5	5	2	10	207
Amras	5		10	20	30	50	50	50	10	5	2	2	5	20	259
Andech	20	25		20	20	50	50	50	50	20	10	2	10	40	367
Arlz	5	10	20		30	80	30	40		5	5	5	5	50	285
Center	10	20	30	50		25	100	40	30	25	10	10	10	20	380
E45 Italy	40	20	50	50	5		1300	20	150	50	5	5	25	10	1730
E60 Salz	40	40	50	50	50	1500		1800	100	45	10	10	60	200	3955
E60 Swiss	40	30	50	50	30		1200		150	55	10	10	100	50	1775
Factories	5	5	20		20	100	100	100		30				50	430
Malls			5	5	5	20	50	40						20	145
Pradl-E		10	20	10	30	40	40	40	20	10			10	40	270
Pradl-W		10	20	10	30	40	40	40	20	10			10	40	270
Sky	5	4	4	3	2	10	20	50	5	5				10	118
Wilten	20	20	50	50	20	20	100	50	100	40	10	10	50		540
Total	190	199	334	323	282	1975	3130	2370	645	310	67	59	287	560	10731

An OD Demand based model requires as a minimum the following objects:

A Centroid ConFiguretion which consists of a set of centroids. Each centroid represents a source or a sink of vehicles, either a land use zone or an edge of a network connection.

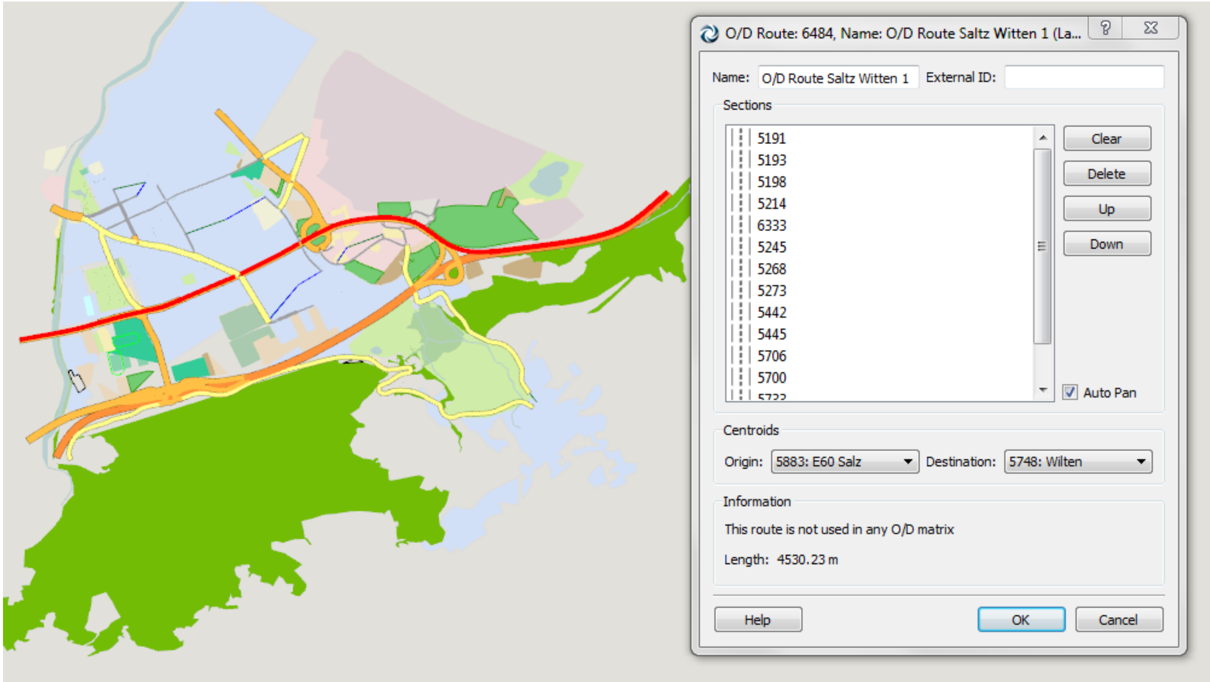
An OD Matrix corresponding to the Centroid ConFiguretion and containing the number of trips made by a Vehicle Type or a User Class in a Time Period.

A Vehicle Type and optionally a Trip Purpose where these together form a User Class.

A set of routes between centroids.

The route choice may be:

- The Initial Calculated Shortest Path (ICSP). This is the best route for the vehicle types in this OD matrix based on the uncongested speed in the road network.
- An OD route, a route edited by the user and allocated to a specific trip in an OD Matrix.



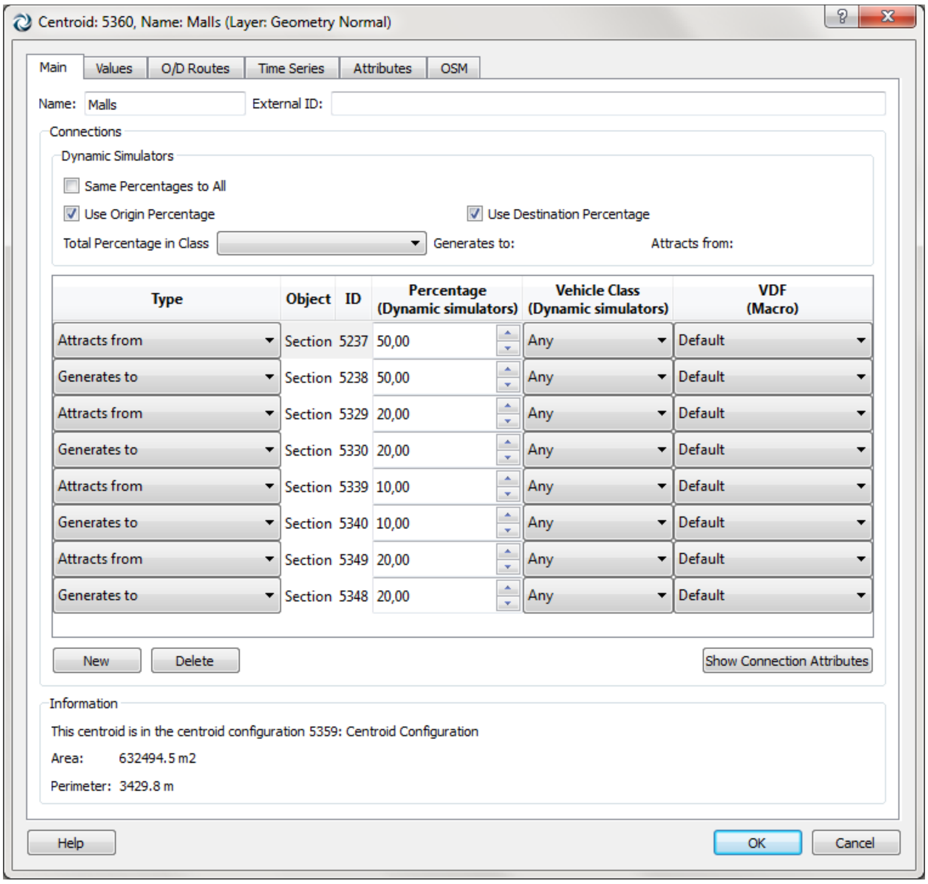
In the simplest OD matrix models, these two choice options will suffice. In more complex models, more sophisticated routing may be used:

Results from Path Assignment. A Path Assignment is the result of a previous dynamic simulation or a static assignment and contains one or more paths for each trip in an OD matrix.

A Dynamic Route Choice Model where a vehicle may change its route depending on congestion or on information received from ITS devices.

These route choice calculations may be extended by the choice of Cost Function used to estimate the perceived cost of traversing a link and hence the cost of the route. Cost functions take into account the travel time for a link, volume of traffic on it and delays at junctions as well as arbitrarily assigned user costs and weights on time, distance and toll.

Centroid ConFiguretion: A centroid conFiguretion holds a set of centroids and the OD matrices and the OD routes related to those centroids. A network may have multiple centroid conFiguretions; these are used to hold OD matrices for the whole network and OD matrices for sub areas of the wider network. Centroid conFiguretions can also be used to hold variations of demand due to future infrastructures, (for example a new road or a new park and ride area). A centroid can be in one conFiguretion only but centroids will be duplicated (and subsequently edited independently) when centroid conFiguretions are duplicated.



Data Analysis and Presentation

The primary purpose of a transport model is to demonstrate what will happen is a transport model when changes are made to the structure of the network, the control of the network or the demand placed on the network. The primary purpose of the data analysis and presentation functions in Aimsun is to convey the results of the model with clarity so that they may be readily understood and interpreted by transport decision makers.

Static assignment models use aggregated trips assigned to paths in the transport network to model the speed and flow of traffic. Their outputs are given in terms of these measurements, the speed and flow, the travel time between origin and destination and in terms of network wide accumulated values and average values.

Microsimulation models are capable of producing much more detailed data on the behavior of individual vehicles, on the actions of dynamic control systems and on the interactions between vehicles. Microsimulation models may also have their outputs aggregated so they can produce similar outputs to static assignments.

Presentation of results may be based on their distribution by location, i.e. to see where congestion is occurring or on their distribution by time, i.e. to see when congestion is occurring. Presentation may show a summary of the results on a map, in graphs, or – for microsimulation models – as a moving image of the vehicles in the network in 2D or 3D display with as high quality levels of video production applied if required.

This section on Data Analysis and Presentation is structured as follows:

Map Based Outputs

Vehicle Based Outputs

Traffic Controls

Map View Preferences

Vehicle View Preferences

Printing

Data Analysis Tools

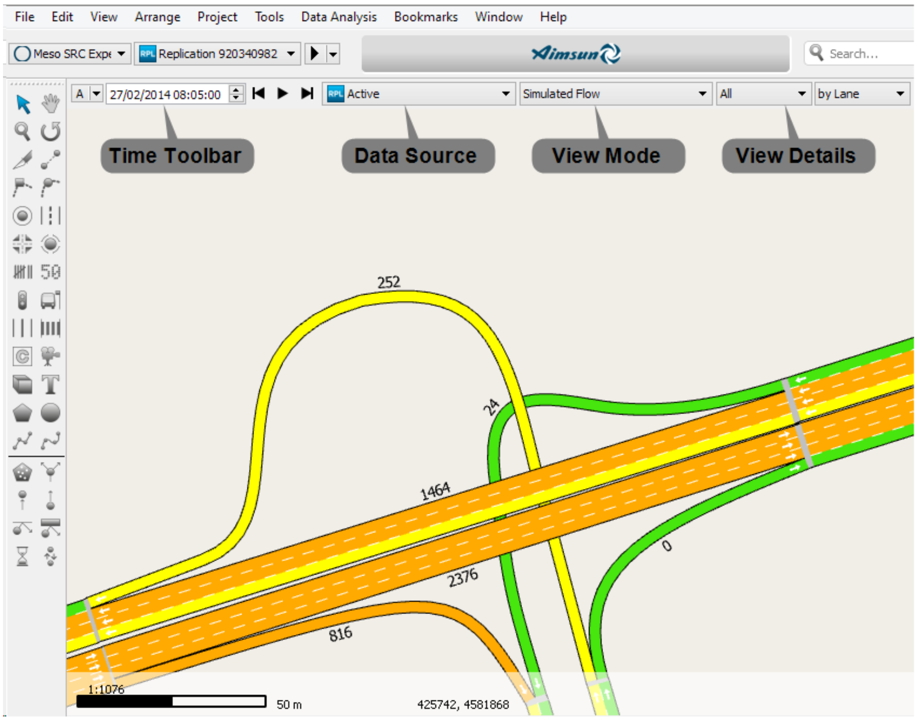
Data Outputs

Data Importers and Exporters

Map Based Outputs

Map based outputs are shown in the View Window and may display map based data from the road sections, junctions or centroids or they may display animated data in 2D or 3D showing the movement of vehicles in the simulation.

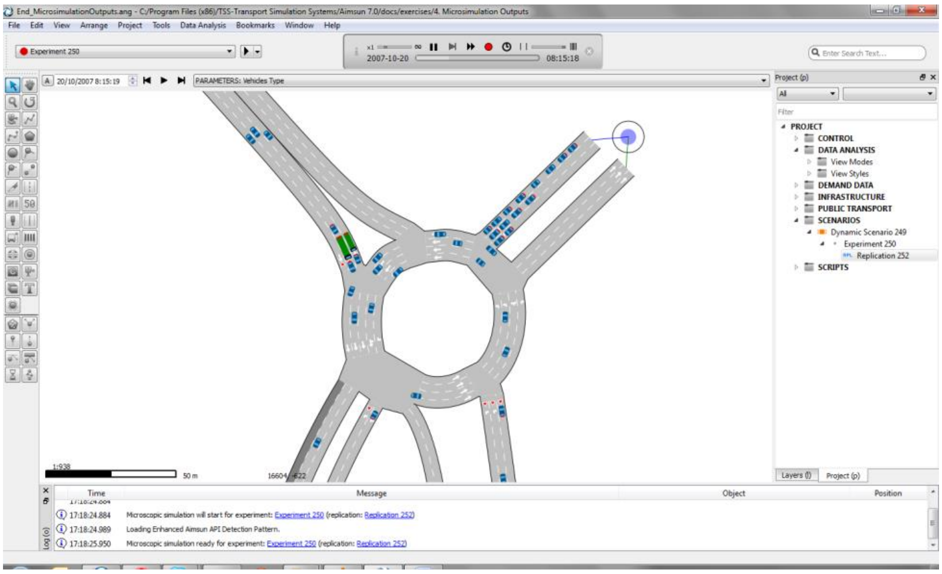
Information shown in the map view is not necessarily limited to simulation outputs, static information may also be displayed and used to debug networks, and identify coding anomalies.



The Legend Window is used to display information about objects shown in a view mode. Styles which are selected for display in the Legend Window have their range information reproduced in the window to aid interpretation of the display.

Aimsun provides a graphical animation of the microscopic simulation in 2D and 3D when an Interactive Simulation has been chosen.

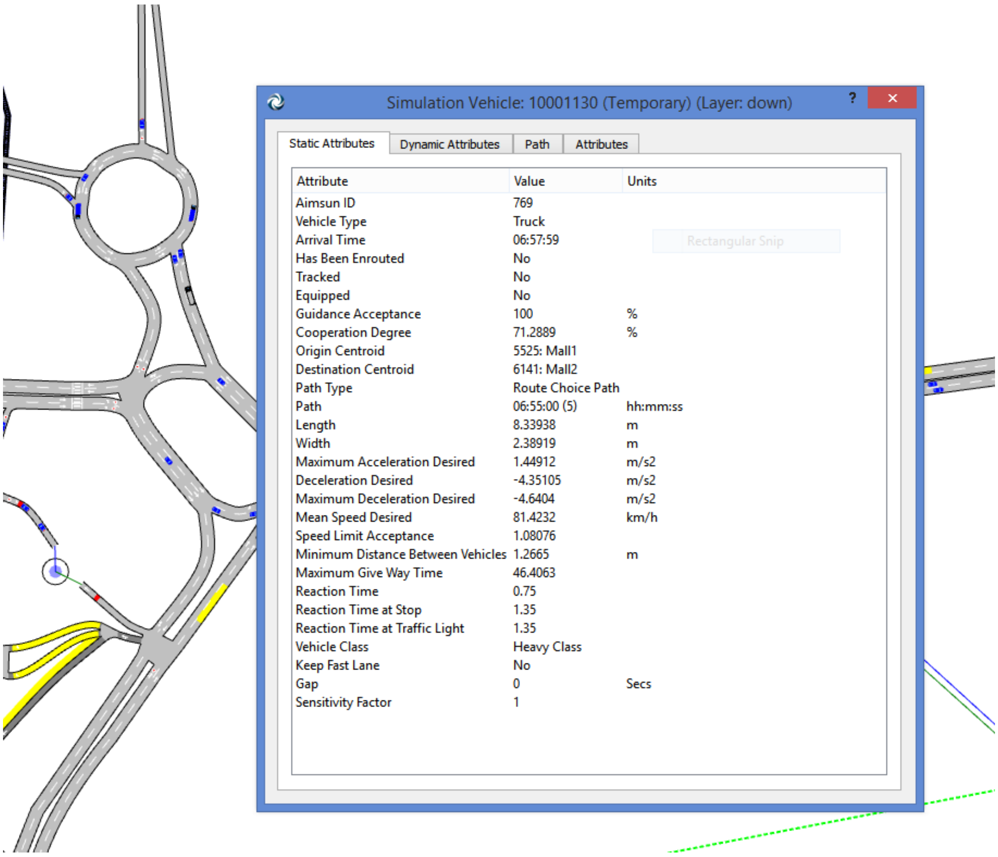
2D Views: The view may be recorded as a movie file. We can control the appearance of vehicles in the2D map such as shape of the vehicle (car, bus, truck, etc.), articulated parts of the vehicle, if any. It also includes display indicators when vehicles decide to turn or change lane, and brake lights that are illuminated when the vehicle brakes.



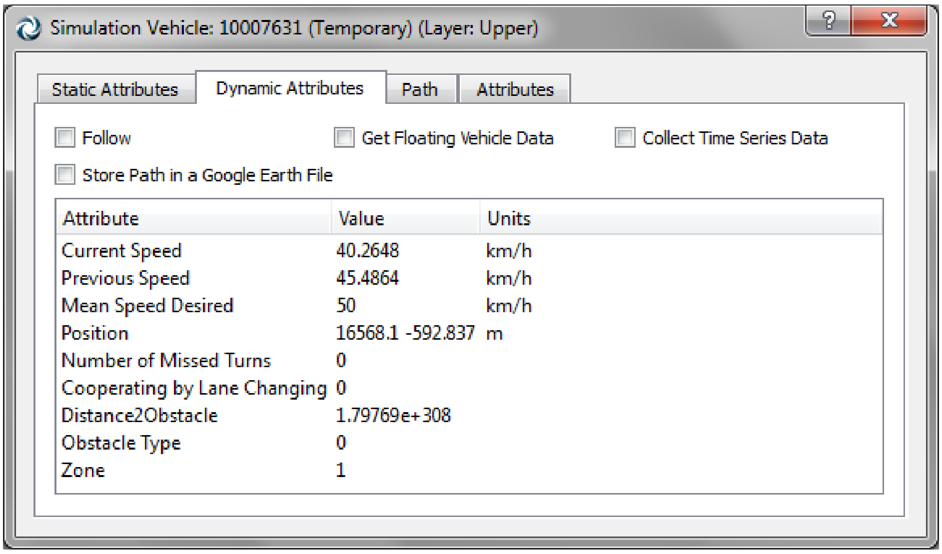
Displaying Vehicle Attributes: If the simulation is halted, detailed information on a particular vehicle is available by double clicking on it. The vehicle dialog window will then appear and the vehicle will be highlighted in a different color. When the model is restarted, the dynamic information contained in this dialog is then continuously updated until the vehicle exits the network or the window is closed. Multiple vehicle dialogs may be opened simultaneously.

The Vehicle dialog window provides two types of information from the Vehicle: Static Attributes and Dynamic Attributes.

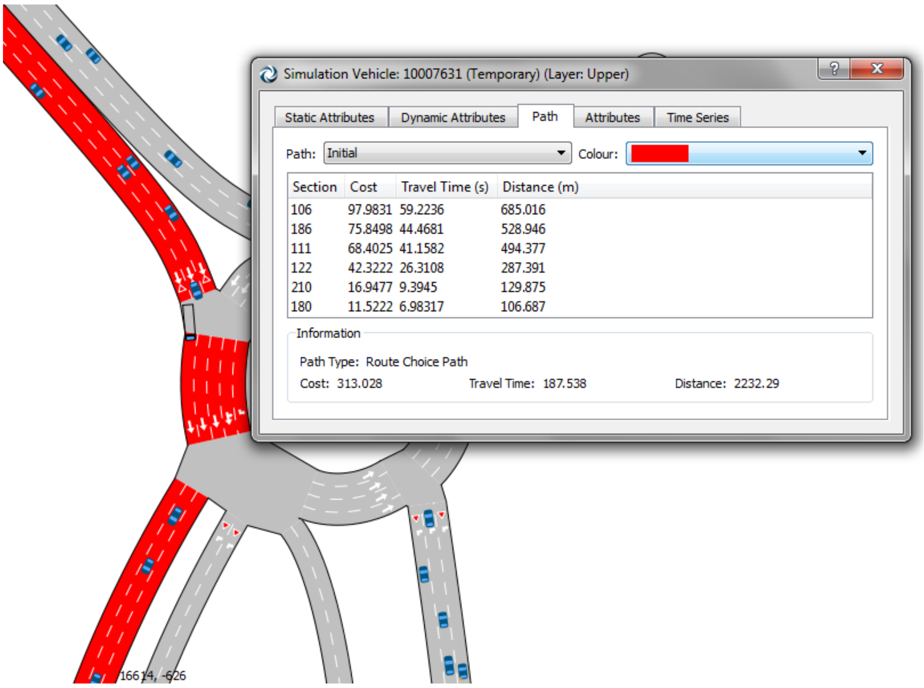
The Static Attributes tab show the vehicle identifier, vehicle type and vehicle class, as well as whether the vehicle is guided or not, tracked or not, equipped or not and the guidance acceptance level. The origin and destination centroids, destination section and path tree being used are given when running in the Route-based mode. Other vehicle static data provided are length, acceleration and deceleration rates, vehicle desired speed, speed acceptance, minimum distance to keep from previous vehicle and maximum give away time, reaction time and reaction time at stop.



As Dynamic Attributes tab shows the current and previous speed, desired speed and position are shown. Floating Car Data can also be obtained from this tab by clicking the "Get floating car data" toggle button. The distance traveled, the time being followed, the mean speed, the number of stops and the total stop time of the floating car are displayed in the dialog and continuously updated while the simulation runs until the vehicle exits the network or the window is closed.



When simulating using OD Matrices a Path tab is also available. In this tab, the sections composing the path are listed while the Cost, Travel Time and Distance for each section, as well as the complete path are provided.



3D Views: The 3D view adds to the 2D view by using different cameras to provide 3D views into the simulation. Vehicles are rendered using 3D shapes.

Simulation Outputs

After an experiment or a simulation has run, the properties dialog of the experiment or replication is expanded with a set of Output tabs. These contain a summary of the results from that assignment or simulation.

Data Outputs (Statistics)

Network Statistics

- Delay Time: Average delay per vehicle per kilometer. This is the difference between the expected travel time (the time it would take to traverse the system under ideal conditions) and the travel time. It is calculated as the average of all vehicles and then converted into time per kilometer.
- Density: Average number of vehicles per kilometer for the whole network.
- Flow: Average number of vehicles per hour that have passed through the network during simulation period. The vehicles are counted when leaving the network via an exit section.
- Harmonic Speed: Harmonic speed mean for all the vehicles that have left the system.
- Input Count: Number of vehicles that have entered the network during the simulation period. The vehicles are counted when entering the network via an entrance section.
- Input Flow: Number of vehicles per hour that have entered the network during the simulation period. The vehicles are counted when entering the network via an entrance section.
- Max Virtual Queue: Maximum virtual queue in the network during the simulation period. It is measured in number of vehicles.
- Mean Queue: Average queue in the network during the simulation period. It is measured in number of vehicles.
- Mean Virtual Queue: Average virtual queue in the network during the simulation period. It is measured in number of vehicles blocked from entering the network.
- Missed Turns: Total number of missed turns.
- Number of Lane Changes: Total number of lane changes per network kilometer.
- Number of Stops: Average number of stops per vehicle per kilometer.
- Speed: Average speed for all vehicles that have left the system. This is calculated using mean journey speed for each vehicle.
- Travel Time: Average time a vehicle needs to travel one kilometer inside the network. This is the mean of all the single travel times (exit time – entrance time) for every vehicle that has crossed the network, converted into time per kilometer.
- Stop Time: Average time at standstill per vehicle per kilometer.
- Total Number of Stops: Total number of stops in the network during the simulation period.
- Total Travel Time: Total travel time experienced by all the vehicles that have crossed the network.
- Total Travelled Distance: Total number of kilometers traveled by all the vehicles that have crossed the network.
- Vehicles Inside: Number of vehicles inside the network when the simulation finishes.
- Vehicles Lost Inside: If the route-based mode is being used, the number of lost vehicles that are currently in the network, that means a vehicle that has lost at least one of its pre-

assigned turns and is in a location from where its original destination can no longer be reached.

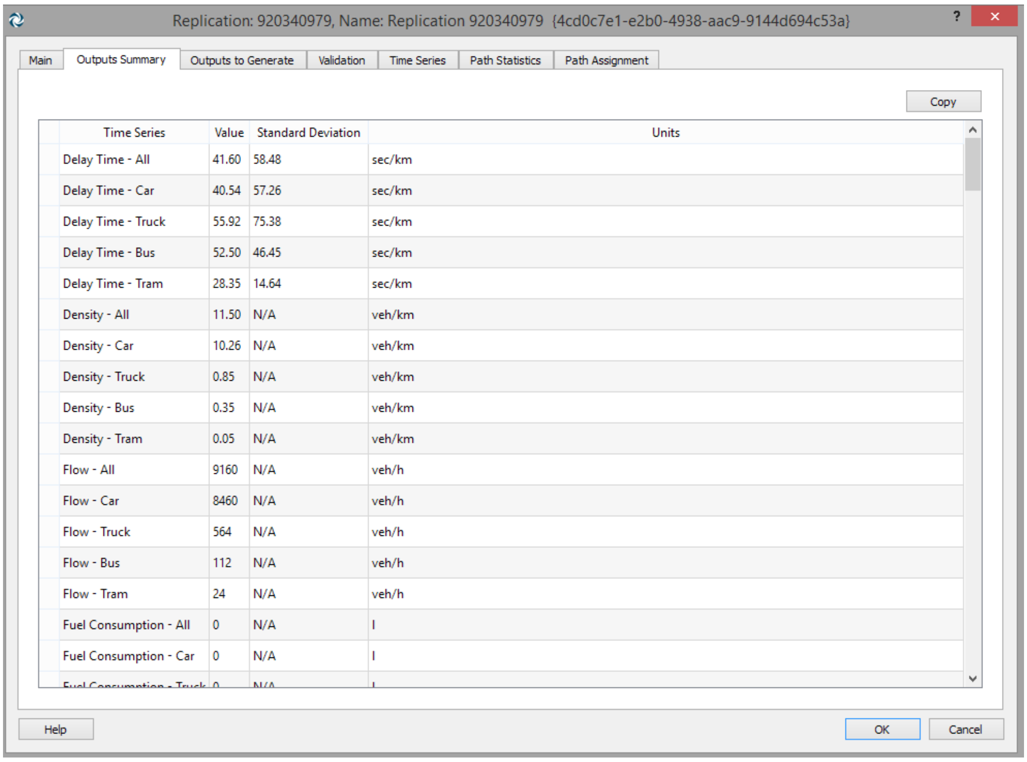
- Vehicles Lost Outside: If the route-based mode is being used, the number of lost vehicles that have left the network during the simulation period.
- Vehicles Outside: Number of vehicles that have left the network during the simulation.
- Vehicles Waiting to Enter: Number of vehicles that are waiting to enter the network.
- Waiting Time Virtual Queue: Average time in seconds that vehicles remain in the virtual queue.

Environmental Model Network Statistics

- Fuel Consumption: Total liters of fuel consumed by all vehicles that have crossed the network. This is only provided when the Fuel Consumption model is enabled.
- IEM Emission: For each pollutant, the total grams of pollution emission emitted by all the vehicles that have exited the network. It is only provided when the "Pollutant Emission (Panis et al, 2006)" model is enabled.
- Pollutant Emission: For each pollutant, total kilograms of pollution emitted by all the vehicles that have crossed the network. It is only provided when the "Pollutant Emission (QUARTET, 1992)" model is enabled.

Dynamic Experiment Outputs

The properties editor of a dynamic experiment Replication or Average will be extended after the experiment has run with an Outputs Summary tab, a Time Series tab, a Validation tab and, if OD matrices were used in the simulation, a Path Statistics tab, and a Path Assignment tab.



Time Series	Value	Standard Deviation	Units
Delay Time - All	41.60	58.48	sec/km
Delay Time - Car	40.54	57.26	sec/km
Delay Time - Truck	55.92	75.38	sec/km
Delay Time - Bus	52.50	46.45	sec/km
Delay Time - Tram	28.35	14.64	sec/km
Density - All	11.50	N/A	veh/km
Density - Car	10.26	N/A	veh/km
Density - Truck	0.85	N/A	veh/km
Density - Bus	0.35	N/A	veh/km
Density - Tram	0.05	N/A	veh/km
Flow - All	9160	N/A	veh/h
Flow - Car	8460	N/A	veh/h
Flow - Truck	564	N/A	veh/h
Flow - Bus	112	N/A	veh/h
Flow - Tram	24	N/A	veh/h
Fuel Consumption - All	0	N/A	l
Fuel Consumption - Car	0	N/A	l
Fuel Consumption - Truck	0	N/A	l

Outputs Summary Tab: The Outputs Summary Tab lists the global value of all simulation outputs with the value, standard deviation and the units.

Time Series Tab: The Time Series Tab uses the Time Series Viewer to show how a number of variables vary as the simulation runs and if multiple variables are selected, how they are correlated during the simulation. The variables listed in the Time Series are the global simulation measures.

Traffic Management

Aimsun vehicle-based simulators include support for traffic management operations to modify the traffic network conditions, to effect driver behavior or to simulate events on the traffic network.

A traffic management strategy consists of several policies which are applied to a traffic network to solve a problem or achieve a goal, i.e. reduce congestion at peak hour or to manage traffic around roadworks. Each policy has an action or may have a number of complimentary actions, i.e. a lane closure may be matched with a corresponding permission for private vehicles to use a public transport line or an incident resulting in a lane closure modelled on one side of a dual carriageway may be matched with a speed reduction on the other side to simulate the “rubber necking” behavior of curious drivers.

Strategies are intended to solve *Problems* where the *Problems* are owned by one or more Transport *Authorities*. In Aimsun, a strategy may contain multiple *Policies* where each policy may be owned by a different Authority, the simulation is therefore providing tools to include the administration of traffic management strategies in the model as well as the implementation of these strategies.

Authorities and Problems

Authorities: An *Authority* is the body responsible for approving a policy. A strategy may have several policies, with each policy the responsibility of a different authority. In order to apply a complete strategy, all the authorities must agree. This is typically true on large scale networks, for instance, networks which span administration or geographic boundaries.

The simulator slows experimentation with variations on this agreement. A strategy is activated at the scenario level, but the policies contained in that strategy are activated at experiment level. Therefore, it is possible to set up an experiment to test what happens if all the authorities agree or if only some of them give permission. Aimsun therefore applies Authorities in two ways:

Owner authority: The one that manages (that wants to apply) the strategy. This type is used in the strategy editor.

Operating authority: The one that must authorize the changes to be applied on the network. This is used in the Policy editor.

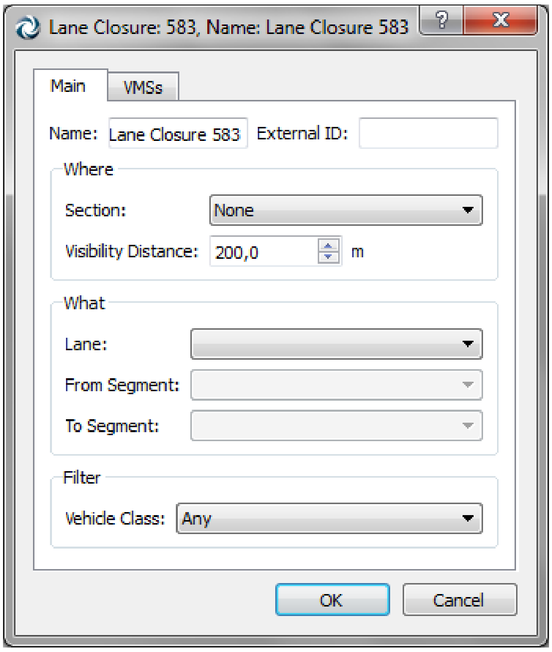
Authorities fulfil an informative function only, although Scripts may be used to automate which policies are implemented if only some, but not all, of the Authorities can act as the strategy is applied.

Problems: Problems identify the owner and contain a description of a traffic management issue for which strategies to solve it will be tested in the traffic model. Problems just supply information about a strategy and do not contribute to the simulation.

Strategies, Policies, Traffic Conditions and Actions

Strategies: A *Strategy* is a holder for a collection of policies which will be applied in whole or in part to the solution of the *Problem.*

- *Policy:* A *Policy* is a component of a Strategy and there may be several coordinated policies to implement a single strategy. Policies contain actions – changes to traffic network or to the management of the network – Policies may be implemented through multiple complementary actions, i.e. coordinated lane use change and speed restrictions.
- Traffic Conditions: A *Traffic Condition* is like a policy in that it is a collection of actions that are applied based on a set of triggers. The difference between a traffic condition and a strategy with policies is that traffic conditions are used to represent current changes on the network that are not part of any traffic management action. There is no management choice if they are applied or not, since they represent events that occur in a network. Traffic conditions simulate unplanned events on the network.
- For example, a speed reduction can be used by an operator to increase the capacity of a highway during peak hours. This change will be modelled using a policy. However a speed reduction may also be due to accidents or roadworks. Here the limitation is present in the network and cannot be "turned off". In this case, a traffic condition will be used. Traffic conditions also add a new type of action appropriate to a temporary unplanned event: this action closes a small length of lanes within a section.
- Actions: A policy contains one or several actions to apply to solve the problem such as: Lane Closure, Turn Closure, Speed Change, Forced Turn etc.

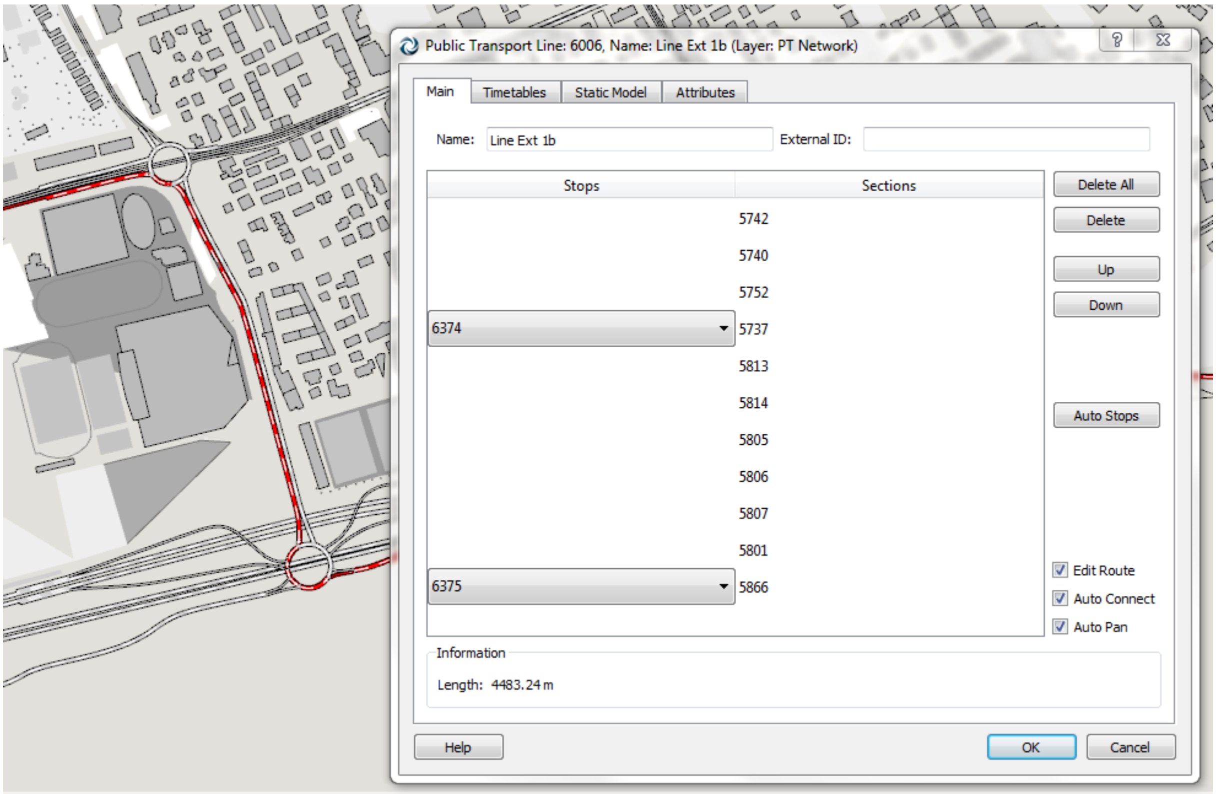


Public Transport (PT)

Public Transport vehicles are modelled in Aimsun by including vehicles in the simulation which follow fixed routes, run to a timetable, use lanes reserved for PT stops. Aimsun also includes Public Transport in Travel Demand Modelling using Static Public Transport Assignments and Adjustments to model the demand placed on Public Transport in traffic network.

A PT has a route and a set of timetables. Multiple timetables may be attached to a line each with multiple time slices. Time slices control the variation in the departure frequency by time of day, multiple timetables allow different options to be tested different scenarios or the service on different types of day to be programmed (i.e. workday, weekend etc.).

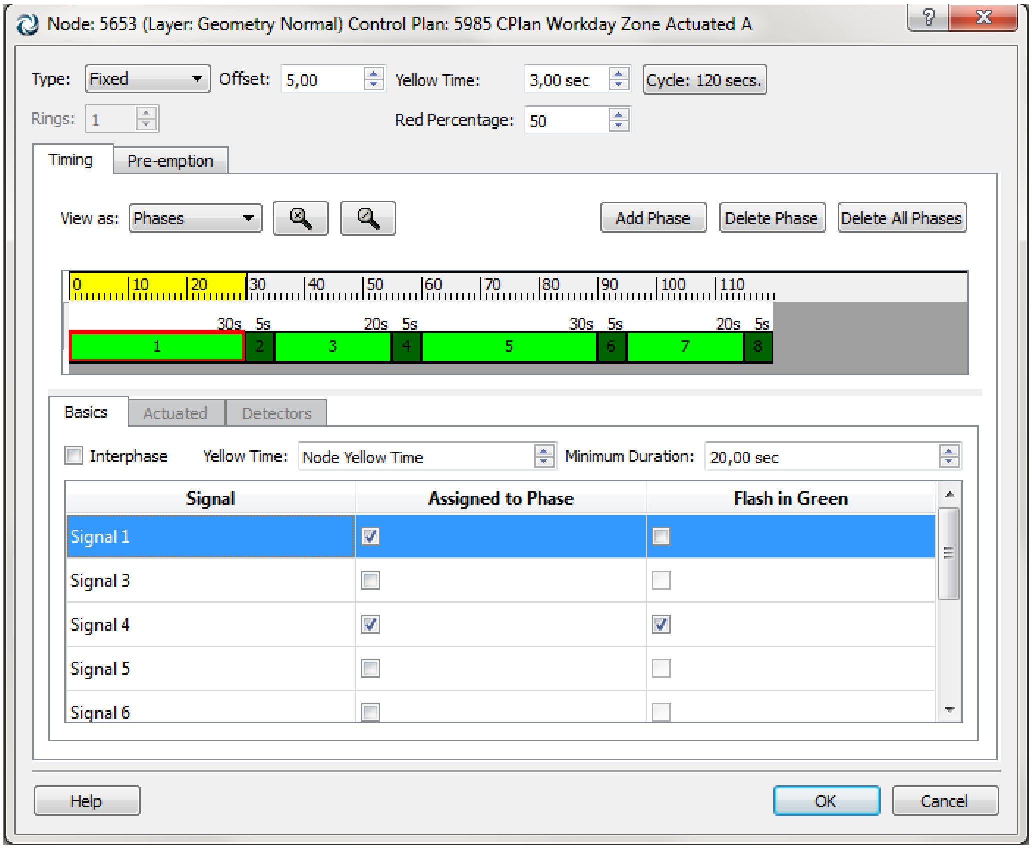
PT routes and timetables are assembled into a Public Transport Plan which is then linked to a scenario in the project. Different PT with different selection of routes and timetables are in effect the PT options that can be applied to the transport scenarios being tested in the project.

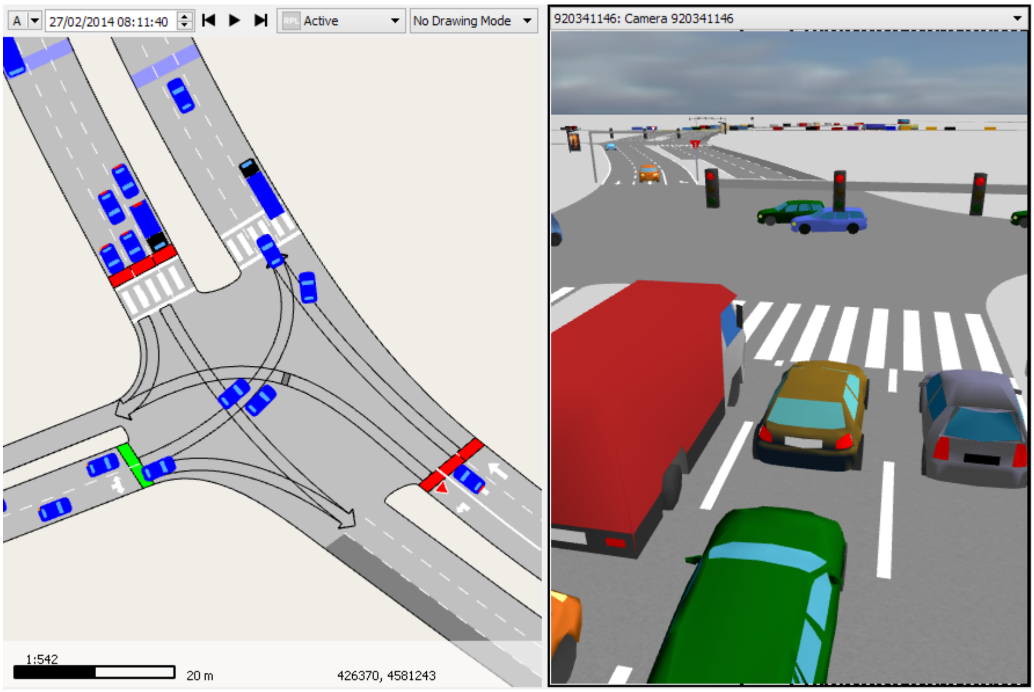


Public Transport Stop: Public Stops (for example, bus stops) are the locations along the PT Route at which public transport vehicles may stop in order to pick up or drop off passenger. Each PT stop belongs to one section, though a section may have several PT stops. However, for a particular PT Line, no more than one PT stop can be used in the same section. Different public transport lines can use the same PT stop.

4.7 Control Plans

A Control Plan specifies the control parameters applied to a set of junctions in a network, starting at a specified time. Each junction may have its own set of actions with phases, timings, offset and cycle time specific to that junction. A collection of signal control parameters for a number of junctions form a Control Plan. The main parameters for a junction are:





Control type: Unspecified, uncontrolled, fixed, external or actuated.

Offset: Used to set the beginning of the sequence of phases regarding to the control plan's initial time, and therefore synchronize adjacent junctions within the same control plan.

Phases: Determine the different time periods of green signal activation.