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Lara CODECA
Born on 4 June 1986 in Riyadh, (Saudi Arabia)

DYNAMIC VEHICULAR ROUTING IN URBAN ENVIRONMENTS

Dissertation defence committee

Dr Thomas ENGEL, dissertation supervisor
Professor, Université du Luxembourg

Dr Francesco VITI, Chairman
A. Professor, Université du Luxembourg

Dr Mario GERLA, Vice Chairman
Professor, University of California, Los Angeles

Dr Jérôme HÄRRI
A. Professor, Eurecom, Sophia Antipolis, France

Dr-Ing Christoph SOMMER
A. Professor, Paderborn University, Germany

Dr Raphaël FRANK
Research scientist, Université du Luxembourg

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Abstract

Traffic congestion is a persistent issue that most of the people living in a city have to face every day. Traffic density is constantly increasing and, in many metropolitan areas, the road network has reached its limits and cannot easily be extended to meet the growing traffic demand. Intelligent Transportation System (ITS) is a world wide trend in traffic monitoring that uses technology and infrastructure improvements in advanced communication and sensors to tackle transportation issues such as mobility efficiency, safety, and traffic congestion. The purpose of ITS is to take advantage of all available technologies to improve every aspect of mobility and traffic. Our focus in this thesis is to use these advancements in technology and infrastructure to mitigate traffic congestion. We discuss the state of the art in traffic flow optimization methods, their limitations, and the benefits of a new point of view. The traffic monitoring mechanism that we propose uses vehicular telecommunication to gather the traffic information that is fundamental to the creation of a consistent overview of the traffic situation, to provision real-time information to drivers, and to optimizing their routes.

In order to study the impact of dynamic rerouting on the traffic congestion experienced in the urban environment, we need a reliable representation of the traffic situation. In this thesis, traffic flow theory, together with mobility models and propagation models, are the basis to providing a simulation environment capable of providing a realistic and interactive urban mobility, which is used to test and validate our solution for mitigating traffic congestion. The topology of the urban environment plays a fundamental role in traffic optimization, not only in terms of mobility patterns, but also in the connectivity and infrastructure available. Given the complexity of the problem, we start by defining the main parameters we want to optimize, and the user interaction required, in order to achieve the goal. We aim to optimize the travel time from origin to destination with a selfish approach, focusing on each driver. We then evaluated constraints and added values of the proposed optimization, providing a preliminary study on its impact on a simple scenario. Our evaluation is made in a best-case scenario using complete information, then in a more realistic scenario with partial information on the global traffic situation, where connectivity and coverage play a major role. The lack of a general-purpose, freely-available, realistic and dependable scenario for Vehicular Ad Hoc Networks (VANETs) creates many problems in the research community in providing and comparing realistic results. To address these issues, we implemented a synthetic traffic scenario, based on a real city, to evaluate dynamic routing in a realistic urban environment. The Luxembourg SUMO Traffic (LuST) Scenario is based on the mobility derived from the City of Luxembourg. The scenario is built for the Simulator of Urban MObiltiy (SUMO) and it is compatible with Vehicles in Network Simulation (VEINS) and Objective Modular Network Testbed in C++ (OMNet++), allowing it to be used in VANET simulations.

In this thesis we present a selfish traffic optimization approach based on dynamic rerouting, able to mitigate the impact of traffic congestion in urban environments on a global scale. The general-purpose traffic scenario built to validate our results is already being used by the research community, and is freely-available under the MIT licence, and is hosted on GitHub.

Contents

Acronyms

ACC Adaptive Cruise Control.

ADAS Advanced Driver-Assistance System.

ASOD All Sources Of Data.

ATIS Advanced Traveller Information System.

ATMS Advanced Traffic Management System.

AVL Automatic Vehicle Location.

CA Cellular Automaton.

CTM Cell-Transmission Model.

DSRC Dedicated Short Range Communication.

DUA Dynamic User Assignment.

DUA-T Dynamic User Assigned Traces.

DUE Dynamic User Equilibrium.

DUE-T Dynamic User Equilibrium Traces.

ETT Estimated Travel Time.

FCD Floating Car Data.

GIS Geographic Information System.

GPS Global Positioning System.

H2H Human to Human.

IDM Intelligent Driver Model.

ITS Intelligent Transportation System.

IVC Inter-Vehicle Communication.

LTE Long Term Evolution.

LuST Luxembourg SUMO Traffic.

LWR Lighthill-Whitham-Richards.

NSM Nagel-Schreckenberg Model.

O-D Origin-Destination.

O-FCD Only-FCD.

OBD On-Board Diagnostic.

OBU On-Board Unit.

OMNet++ Objective Modular Network Testbed in C++.

OSM OpenStreetMap.

RSU Road Side Unit.

RTTS Real-Time Traffic Situation.

SUMO Simulator of Urban MObiltiy.

TCP Traffic Coordination Point.

TIGER Topologically Integrated Geographic Encoding and Referencing.

TMC Traffic Message Channel.

TraCI Traffic Control Interface.

TVA Total Vehicles Arrived.

V2I Vehicle-to-Infrastructure.

V2V Vehicle-to-Vehicle.

VANET Vehicular Ad Hoc Network.

VEINS Vehicles in Network Simulation.

VPKI Vehicular Public-Key Infrastructure.

WAVE Wireless Access in Vehicular Environment.

WLAN Wireless Local Area Network.

xFCD extended Floating Car Data.

Chapter 1

Introduction

As people talk, text and browse,
telecommunication networks are capturing
urban flows in real time and crystallizing
them as Google's traffic congestion maps.

Carlo Ratti

Traffic congestion is a systemic issue that most of the people living in a city have to face every day. Traffic density is increasing continuously and, in many metropolitan areas, the road network has reached its limits and cannot easily be extended to meet the growing traffic demand. It is clear that public transport services will play a major role in enabling mobility of commuters and workers. However, with the continuous growth of economic and leisure activities, the demand for individual mobility will likewise increase, and must therefore be taken into consideration.

A congested traffic pattern is characterized by slower speeds, greater waiting times and stop-and-go behaviour. There are two main types of congested scenarios, one that results in temporary congestion, and the other that causes a chronic traffic jam [1]. Temporary traffic congestion is usually caused by local problems such as accidents, roadworks and construction sites, or events of various kinds that affect mobility. Another cause for temporary traffic congestion and perturbation in the traffic flow is related to human behaviour and reaction times, where sudden accelerations or decelerations, abrupt braking, and lane changes may create localized jams that, given their volatile causes, are called phantom jams. Chronic traffic congestion is of a completely different genre, and is systemic. It presents itself when the infrastructure is not able to deal with the traffic demand. Common examples are the traffic at rush hours, the presence of bottlenecks that cannot be avoided (e.g. geographical constraints such as bridges over valleys and rivers), and the traffic demand growth over time, which due to economic development cannot be avoided.

The problem of traffic congestion is studied in various research fields, spanning the range from traffic engineering and computer science, to sociology and human sciences. This wide spread interest results from traffic congestion being an ever-growing issue affecting the daily life of the vast majority of the population [2].

The Impact of Traffic Congestion Traffic congestion is a social issue that has repercussions on both economy and health. Many aspects that must be taken into consideration also have a direct impact on our personal and working life [3]. Delays and the time spent while stuck in traffic have an impact on stress and frustration, with direct health repercussions. Moreover, given that is not always feasible to plan ahead and take all the possible delays into account, being late has both social and work repercussions. Another issue related to the time wasted in traffic is the drop in productivity, once again, from both a personal and economic standpoint.

INRIX, in its annual mobility estimate of 2015 [4], reported 50 hours wasted in traffic for the average U.S. commuter. The top three U.S. cities are Los Angeles (CA), Washington (DC), and San Francisco (CA), with respectively 81, 75 and 74 hours wasted in traffic. In Europe, the most congested country is Belgium, with 44 hours wasted in traffic, followed by the Netherlands and Germany, with 39 and 38 hours respectively wasted per commuter a year. The most congested area in Europe is London Commute Zone (UK) with 101 hours spent in traffic a year, followed by Stuttgart (DE) and Antwerp (BE) with respectively 73 and 71 hours wasted per commuter. In the same report, INRIX presents a direct interaction between economic growth and traffic congestion, where the economic growth worsens traffic congestion, yet at the same time, congestion can threaten economic growth. In their conclusion, they present Intelligent Transportation Systems (ITSs) -based solutions as invaluable tools to break the growth-congestion cycle.

From an engineering perspective, reducing the waste of resources, such as time [5] and fuel [6], is fundamental in traffic optimization. Moreover, increasing congestion presents dangerous issues for emergency vehicles [7], which are delayed or stuck in traffic.

Possible Solutions to Traffic Congestion Over the years, with improvement in technology and infrastructure, various solutions have been proposed to mitigate traffic congestion [8]. One possible solution is the enhancement of road infrastructure through urban planning and redesign. This approach is very expensive and does not always reduce the problem. One of the reasons for this counterintuitive result is Braess' paradox [9]; it states that adding extra capacity to a congested network can, in some cases, reduce overall performance when the moving entities choose their routes selfishly. Another type of optimization may be achieved by artificially lowering the traffic demand, for example by changing opening and closing hours for services and businesses, in order to spread demand and decrease rush hours peaks. This option cannot be enforced, but many studies are trying to change driver behaviour to achieve the same result [10]. Road pricing and congestion tolls [11, 12] are implemented in various cities, where the price of the trip is increased in order to reduce the volume of travellers during congested hours. Congestion pricing encourages the traveller to avoid most expensive hours, or to chose alternative routes for trips.

ITSs use the technology and infrastructure improvements in advanced communication and sensors to tackle transportation issues, including mobility efficiency and traffic congestion. The approach that we are interested in studying is based on the mitigation of traffic congestion through vehicular traffic optimization and advances in technology and infrastructure. In this thesis we discuss the state of the art of traffic flow optimization methods, their limitations, and the benefits of a new point of view. One method for homogenizing traffic flow is to distributr the traffic demand more efficiently over the network, using dynamic routing and load balancing. Because this strategy can prevent traffic breakdowns by more efficient road usage, a detour may lead to a shorter travel time, even if it would take longer in normal situations. Our approach is based on vehicular telecommunications, which gather the traffic information that is fundamental to creating a consistent overview of the traffic situation, and providing real-time information for drivers, allowing them to optimize their route.

1.1 Research Question and Contributions

The research question that we address in this thesis is the following:

What is the impact of dynamic routing on traffic congestion in an urban environment?

In order to answer this question, we need a reliable representation of the traffic situation. In this thesis, traffic flow theory, mobility models, and propagation models are used to obtain a simulation environment capable of providing a realistic and interactive urban mobility. We then use this environment to test and validate our approach for mitigating traffic congestion. The topology of the urban environment plays a fundamental role in traffic optimization, not only in terms of mobility patterns, but also concerning the connectivity and infrastructure available.

We start by defining the type of optimization we want to achieve, with an evaluation of its constraints and added values. In the literature, there are two main views of traffic assignment and optimization: on one side, optimization is focused on each driver *selfishly* improving their traffic situation; while at the other end of the spectrum, we have a global optimization in which all drivers cooperate to achieve a system optimization. From a theoretical point of view, the global optimization is the best scenario that can be achieved. Unfortunately, the strict requirements in terms of information necessary for the optimization, and the lack of flexibility for the drivers, make the implementation and deployment of this kind of system nearly impossible in our cities. This solution would be feasible in a future with fully-automated vehicles, where driving is no longer a human activity. In this thesis we are interested in studying the *selfish* approach to traffic optimization, which is easier to implement and deploy because of its softer constraints. We study the trade-off between personalized routing and global traffic optimization, in order to find whether it is possible to approximate the global equilibrium using personalized routing, and under which circumstances.

The first contribution we present in this thesis is a traffic monitoring mechanism that is able to retrieve information from vehicles and provide optimized routes to each of them. We discuss an initial study on the impact of this optimization on a simple scenario, evaluating user participation rates, with both complete and partial information on the global traffic situation.

1.1.1 Impact of Dynamic Rerouting in Urban Settings

The idea of changing the route of selected vehicles in order to alleviate traffic congestion and to improve traffic flow is not new. Historically, traditional infrastructure-centred concepts are based on stationary detectors. The logic of such systems extracts traffic information from the detector data, estimates optimal routes for the main traffic flow directions, and transmits corresponding recommendations to drivers via variable message signs. Nowadays, the focus is on vehicle-based dynamic routing with traffic-dependent navigation alternatives. As explained in [1], these connected devices not only receive traffic information, but also send their positions in form of Floating Car Data (FCD) in an anonymized form to a traffic centre. There, the traffic state is continuously estimated and sent back to the devices for a recalculation of the fastest routes.

The optimisation of the available resources is based on the concept of dynamically modifying the routes of the vehicles to better distribute the traffic demand throughout the road network. To do this, the system continuously suggests to each vehicle the best route in terms of travel time to reach its destination, considering the actual traffic situation. This can be modelled as a flow optimisation problem [13–15]. In this thesis, we use a different approach to finding alternative routes for the vehicles based on the First Wardrop principle [16]. This principle is known as the user-optimal equilibrium and provides the best solution for each individual user.

We use a simple Manhattan grid topology to study the extent to which dynamic rerouting would help in alleviating traffic congestion in urban environment. We propose a traffic monitoring mechanism able to gather traffic data and redistribute optimized routes to the vehicles. We evaluate the user participation required to obtain some improvement in the traffic flow, and discuss the quality of the information collected to be used in the optimization, in order to have successful results. The results show that a selfish approach can improve the traffic situation even with a low user participation rate, but the geographical coverage of the information retrieved and used in the optimization is crucial, and cannot be dismissed or underestimated.

Publications This contribution is presented in Chapter 4, and has previously been published in two separate papers: *Improving traffic in urban environments applying the Wardrop equilibrium* [17] and *Traffic routing in urban environments: The impact of partial information* [18].

Once we know that user-oriented dynamic rerouting is able to alleviate traffic congestion in a simplified environment, it is necessary to evaluate it in a realistic scenario. Realistic small scale scenarios are commonly used by the Vehicular Ad Hoc Network (VANET) community to test communication protocol and applications. When it comes to traffic flow optimization, a small-scale scenario is not representative of the traffic pattern in a city, and usable large-scale scenarios are not available to the VANET research community. For this reason, the second contribution presented in this thesis is a synthetic traffic scenario based on a real city, which we implemented to evaluate dynamic routing in a realistic urban environment.

1.1.2 Testing Tools and the Luxembourg SUMO Traffic (LuST) Scenario

When working on problems related to vehicular traffic optimization and intelligent transportation systems, a vehicular traffic simulator with an appropriate scenario for the problem at hand is used to reproduce realistic mobility patterns. Many optimization studies are done on simplified scenarios, which are easy to manage, but lack realism. Many mobility simulators are available to the community and the choice is made based on the type of simulation required; however, a common problem is finding a realistic, properly-working, and freely-available scenario.

Due to the lack of usable scenarios, the usual approach is to build a simple scenario that fulfils the purpose of the application. This approach results in several problems that are well known to the VANET research community, the most prominent being the lack of repeatable experiments allowing the comparison of various solutions and approaches that solve the same problem. Another problem that may be encountered is the specificity of the scenario and the consequent lack of generality or realism.

In Chapter 5 we show the process used to build, evaluate and validate the Luxembourg SUMO Traffic (LuST) Scenario, a general-purpose, freely-available simulation scenario based on the City of Luxembourg. In the interest of building a realistic scenario, we used information from a real city with a typical topology common in mid-size European cities, and realistic traffic demand and mobility patterns. We present the process behind the topology generation in detail to meet all the simulation requirements, and the evaluation and generation of various mobility traces. The LuST Scenario is already being used by the vehicular research community, and plans for future improvement and additional features are mainly driven by the needs expressed by the community itself.

Using the LuST Scenario, we show that a selfish dynamic rerouting mechanism provides an interactive and reactive solution that behaves realistically and closely matches the precomputed globally optimized mobility, allowing us to evaluate the impact of dynamic routing on traffic congestion in an urban environment.

Publications The LuST Scenario is freely available to the whole community under an MIT license, and is hosted on GitHub (`https://github.com/lcodeca/LuSTScenario`). Description of generation and validation have been published in two papers: *LuST: a 24-hour Scenario of Luxembourg City for SUMO Traffic simulations* [19] and *Luxembourg SUMO Traffic (LuST) Scenario: 24 hours of mobility for vehicular networking research* [20], the latter receiving the Best Paper Award at Vehicular Networking Conference (VNC), 2015.

1.2 Structure of the Thesis

The rest of this thesis is organized as follows. In Chapter 2 we briefly present the main concepts of traffic flow theory, explaining the mobility models available to the community and providing an overview of the tools and framework that can be used to study mobility patterns, focusing on ITS. In Chapter 3 we provide an overview of the technology behind the navigation software and devices available on the market, and discuss the use of traffic information and the methodologies to collect them, then introduce traffic flow optimization theory. In Chapter 4 we present our study of traffic routing in the urban environments, explaining the methodology behind the traffic monitoring mechanisms and the vehicle routing, leading to its evaluation with complete and partial information. In Chapter 5 we present the LuST Scenario, a freely-available mobility scenario for the SUMO simulator, able to provide realistic mobility patterns in an urban setting; we explain in detail its generation, the evaluation process and provide some real use case scenarios gathered from the scientific community. We conclude our thesis in Chapter 6 and provide an overview of future work.

Chapter 2

Mobility Models and Simulation Tools

In the last century, the scientific community studied vehicular traffic and mobility patterns from many angles and using tools from different disciplines. Ever-growing urban telecommunication networks have made an increasing amount of traffic information available for collection in our cities. This facilitates research on transportation systems and mobility patterns, but also introduces new problems related to the communication required among all the interconnected devices used for gathering the traffic data. Many researchers from different communities are working on a variety of problems centred on the traffic information gathered and its use. These range from the collection of traffic information with a safe, secure and reliable methodology, to its storage and distribution. Other studies concern communication infrastructure, traffic signal control and coordination, mobility and multi-modal transportation, Vehicular Ad Hoc Network (VANET), and more generally Intelligent Transportation System (ITS) and how the traffic information can be used to improve the mobility in our cities.

The requirements and scalability of the simulation tools used differ, depending on the research problem being addressed. The transportation community is mainly focused on traffic optimization and urban planning, and is rarely interested in the behaviour of individual vehicles. These applications favour tools able to provide a reliable overview of the system. On the other hand, the networking community is concerned about the position and behaviour of each individual vehicle and how this impacts communications and related applications.

In order to study mobility patterns, traffic congestion or new communication protocols, the industrial and scientific communities need appropriate and realistic traffic models, as well as simulation tools. This Chapter presents an introduction to the theories, models, and tools required to understand and study the ITS issues that we want to discuss in this work. Section 2.1 provides a brief explanation of traffic flow dynamics. Section 2.2 presents the various mobility models used to study transportation issues. The two sections only provide an introduction of the models, giving just a couple of examples. Since the discussion of traffic flow dynamics is beyond the scope of this work, for more details we refer to M. Treiber and A. Kesting, Traffic Flow Dynamics [1]. Moving from traffic mobility to the surrounding environment, an analysis of network topologies with their common uses is provided in Section 2.3 and, finally, an overview of the simulation tools is presented in Section 2.4.

2.1 Traffic Flow Theory

Through the study and visualization of traffic flow data and their aggregation, it is possible to observe emerging patterns and draw conclusions. From the time series of aggregated quantities such as speed, flow, and density, we can observe the temporal developments. The speed-density and flow-density diagrams are used to make statements about the average driving behaviour on the observed road segment. When single-vehicle data is available, it is used to obtain distributions of microscopic values such as vehicle speeds and time gaps.

With the support of the large amount of traffic flow data currently available, many measurements have been used as the basis for building mathematical models. The information collected from the vehicles range from the acceleration characteristics of single drivers to the data obtained by stationary detectors. With the rapidly-growing amount of data obtained by Global Positioning System (GPS), Wireless Local Area Network (WLAN), and mobile phones, the precision of the measurements enables the comparison of a mathematical model's predictions with the data. To achieve realism, the model is calibrated by varying its applicable parameters, to obtain a optimum fit with the observations.

To understand the mobility models and the simulation tools that implement them, we need to give an overview of traffic flow theory, that is, the mathematical description of the dynamics of vehicular traffic. The theory describes the interaction between vehicles and the emerging behaviour that results shows collective effects that do not depend on the details of the individuals.

There are numerous applications for traffic flow dynamics and simulation, but we are most interested in those concerned with ITSs. For example, many navigation systems integrate the traffic flow data collected in real time from various sources with traffic flow theory to determine the optimal routes. Other applications are the evaluation of traffic-related effects of Advanced Driver-Assistance Systems (ADASs) on traffic congestion.

2.1.1 Fundamental Diagrams of Traffic Flow

Figure 2.1 presents the fundamental diagrams used to describe the relation between traffic flow, density, and speed. All three diagram types are equivalent by the hydrodynamic relation $Q = \rho V$, where Q is the flow, ρ is the density, and V is the speed. This figure is from M. Treiber and A. Kesting, Traffic Flow Dynamics (Figure 4.12, [1]). It plots all three fundamental diagrams from 1-minute data captured on the A5 Autobahn near Frankfurt, Germany, using harmonic mean speed (black dots). The lines (in green and red) show the fit of a traffic-stream model.

Speed-Density Diagram Plotting the aggregated vehicle speed over traffic density, we obtain a speed-density diagram (see Figure 2.1, bottom-left). This diagram reflects the average behaviour of a typical vehicle subject to different densities and external factors, such as speed limits or weather conditions.

In very low-density traffic (green line), drivers are usually not influenced by other vehicles and the average free speed is obtained. The average speed is lower in denser traffic (red line). The average free speed is defined as the minimum of three different speeds. The first is the the actual desired speed of the drivers, the second is the physically attainable speed, and is particularly relevant for specific settings (for example, heavy vehicle on a slope). The last is the speed limit on the road segment under observation, possibly taking into consideration drivers tendency to exceed the official limit.

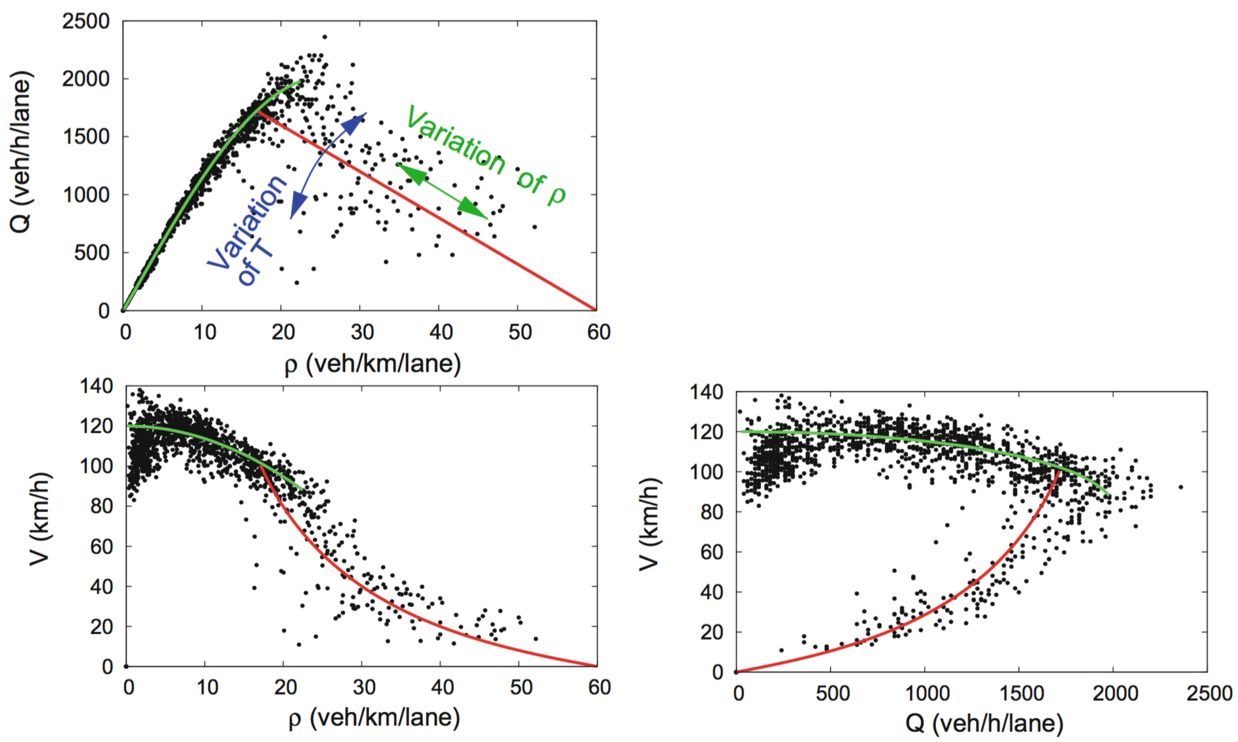


Figure 2.1: Fundamental diagrams of traffic flow. Flow-density, speed-density, and speed-flow diagrams of the 1-minute data captured on the A5 Autobahn near Frankfurt, Germany, using harmonic mean speed. This is Figure 4.12 in [1].

Speed-density diagrams are based on aggregated data, so they might conflate heterogeneous traffic and different external conditions. This has to be considered when interpreting them. For example, different weather conditions, a varying percentage of trucks over the day, a time-dependent speed limit, or the combination of many of these, can result in artefacts in the diagrams that are not representative of realistic behaviour. This also applies to the flow-density diagrams, as discussed shortly.

Flow-Density Diagram A flow-density diagram (see Figure 2.1, top-left) is obtained by plotting traffic flow against density; it allows study of the average behaviour of a vehicle. The fitting lines follow its idealized form, a triangle, where the data aggregation is performed with a steady-state equilibrium of identical vehicles. Free traffic flow (in green), or free flow for short, is usually observed when the vehicle density in traffic is sufficiently low. At low density, interactions between vehicles in free flow are negligible, therefore vehicles have an opportunity to move with their desired maximum speeds. A congested traffic pattern (in red) is a spatio-temporal traffic pattern within which there is congested traffic. The congested flow is separated from free flow by the downstream and upstream fronts. At the downstream front, vehicles accelerate from a lower to a higher speed in free flow downstream; at the upstream front, vehicles decelerate from a free-flow speed to a lower speed within the congested pattern. It has been observed that a sudden drop in the maximum possible traffic flow (capacity drop) occurs with a traffic breakdown[1] [21]. In this case the traffic shows hysteresis effects, because the dynamics depend not only on the traffic demand, but also on the history of the system. This implies that once a traffic jam has emerged, the traffic demand has to fall to a much lower value to dissolve the jam. An explanation for the strong scattering of the flow-density data in congested traffic is due to the variation of time gaps. These variations in the gaps are caused not only by heterogeneous traffic, but also by non-equilibrium traffic dynamics.

It is important to take into account that the fundamental diagram describes the theoretical relation between density and flow in stationary homogeneous traffic. This implies that when the flow-density diagram is used to represent aggregated empirical data, the results may differ completely, because the data generally comes from non-stationary heterogeneous traffic. The dataset from the book [1] is an example of this, where the cloud of points does not show a clear trend. Given the discrepancies, it is important to keep in mind the difference between measured flow-density data and the idealized form of the fundamental diagram when drawing conclusions from it.

Speed-Flow Diagram For completeness we show the speed-flow diagram (see Figure 2.1, bottom-right). However, unlike the flow-density diagram, this diagram is not usually used for modelling because, without knowing the density, it is not possible to distinguish between free and congested flow.

2.1.2 The Three-Phase Model

Boris Kerner developed an alternative theory of traffic flow that focuses mainly on the explanation of the behaviour in congested traffic on highways. His theory [22] describes three phases of traffic (instead of the classical two based on the fundamental diagram of traffic flow), taking free flow into account, but distinguishing between two distinct phases in congested traffic: synchronized flow, and wide moving jam.

A wide moving jam maintains the mean velocity of the downstream jam front, even while propagating through highway bottlenecks and the other different traffic states of free or synchronized flow. Vehicles accelerate at the downstream jam front, from low speed states inside the jam, to higher speeds downstream of the jam. This is a characteristic feature of the wide moving jam phase.

In the synchronized flow phase, in contrast to the wide moving jam traffic phase, the downstream front of the synchronized flow does not maintain the mean velocity of the downstream front. In particular, the downstream front of synchronized flow is often fixed at a bottleneck. In other words, the synchronized flow traffic does not show the wide moving jam characteristic.

A controversy in the area of traffic modelling arises from the different definitions of what constitutes a traffic phase and how well it is possible to detect and model the change of state from one phase to the other. In the context of three-phase traffic theory, the definition of a phase is focused on equilibrium physics and, in principle, it should be able to determine the phase on the basis of local criteria and measurements at a single detector. However, as explained in [23], this goal is not completely reached, because in order to distinguish between moving synchronized patterns and wide moving jams it is

[1]Traffic breakdown is the presence of congested traffic in an initial free traffic flow. Traffic breakdown occurs mostly at road bottlenecks like on and offramps, roadworks, reduction of road lanes, etc.

necessary to obtain additional external data, in order to know whether the congestion pattern is propagating through the next bottleneck area or not. Moreover, it has been shown [23] that three-phase traffic theory can be reproduced with simple two-phase models, if the parameters are suitably specified and they take into account characteristic such as the effects of measurement noise, vehicle heterogeneity, or the actual motorway design in real traffic flows.

Starting from the general concepts presented in traffic flow theory and using the fundamental diagrams discussed above, it is possible to build various traffic flows models capable of describing and simulating specific events and behaviours observed in actual traffic.

2.2 Mobility Models

To discuss the mathematics and simulation of traffic flow models, we provide an overview of the different classes and we discuss the main categories of macroscopic and microscopic models in detail. While microscopic models describe traffic flow from the point of view of individual drivers and vehicles, macroscopic models describe the collective state in terms of spatio-temporal trends for the local density, speed, and flow.

2.2.1 Macroscopic Models

In macroscopic models [24], traffic flow is described using the analogy with liquids or gases in motion. For this reason, they are sometimes called hydrodynamic models. Variables such as the traffic density, flow, and mean speed or its variance, are locally aggregated quantities that generally vary across space and time. They provide an overview of the system and they are able to describe collective phenomena such as the evolution of traffic congestion in the observed area.

Macroscopic models are very useful when input data requires fusion and aggregation, for example when it comes from heterogeneous sources, or there are inconsistencies. Another useful side effect of these models is that it is not necessary to consider effects that are difficult to describe macroscopically (e.g. lane changes, heterogeneous vehicle types and behaviour), in order to obtain useful results. They provide fast results even for complex systems, making them very useful when the computation time of the simulation is critical. These properties are particularly important for traffic state estimations and predictions, where the future traffic state is predicted over a time horizon and the predictions are updated over smaller time intervals. The traffic predictions can be used to alter the system itself, for example updating variable-message signs, or to change the behaviour of the vehicles by using the new data as input for connected navigation devices.

Lighthill-Whitham-Richards (LWR) First-Order Models The foundations of every macroscopic traffic model are the hydrodynamic relations, where *flow is equal to density x speed* and the continuity equation describing the temporal evolution of the density as a function of flow differences or gradients. The macroscopic vehicle speed is defined so as to satisfy the hydrodynamic relation and the continuity equation is directly derived from the conservation of vehicle flows. Thus, both equations are parameter-free and hold for arbitrary macroscopic models. Given the equation, a model is defined by specifying flow or local speed. There is a class of models based on a simpler approach in which the flow is given as a static function of the density. These models are called Lighthill-Whitham-Richards (LWR) models and they differ only in the functional form of the fundamental diagram and in their mathematical representation. All models in this class have only one dynamic equation: the continuity equation, consequently they are also referred to as first-order models [25].

Since the continuity equation is completely determined by the geometry of the road infrastructure, macroscopic models differ only in their modelling of speed or flow. Lighthill and Whitham, and independently also Richards, proposed a static relation to complement the continuity equation. This relation assumes that traffic flow or the speed is always in local equilibrium with respect to the actual density. This means that traffic flow and local speed instantaneously follow the density, not only for steady-state traffic but in all situations.

The simplest of the LWR models uses a triangular fundamental diagram like the one in Figure 2.1. Its continuous formulation is known as the section-based model and is the most efficient in simulations. Due to the specific properties of the triangular fundamental diagram (only two distinct propagation velocities of density variations; one for free traffic and one for congested traffic), it is possible to break down the road into sections in order to have a bottleneck at the downstream end. Then, instead of solving the model equation for all locations, it is sufficient to solve a single integral for the motion of the jam front. The discrete version is called the Cell-Transmission Model (CTM), and because of the special shape of the fundamental diagram, it is possible to formulate efficient numeric update rules for it as well. Moreover, it is straightforward to generalize the CTM from road segments to road networks. Furthermore, it is the only macroscopic model for pedestrians in common use. Another implication of the fixed propagation velocities is the absence of dispersion at the transitions from high to low density. Sometimes a weak dispersion is observed in reality; however, the absence of such dispersion is certainly more realistic than the very strong dispersion implicit in most of the other fundamental diagrams.

From a microscopic point of view, in the first-order models the instantaneous speed adaptations imply unbounded accelerations which, clearly, is unrealistic. Moreover, traffic flow instabilities such as traffic shock-waves[2] and capacity-drop phenomena are modelled through finite speed adaptation times and reaction times; consequently first-order models cannot describe these observations. To do this, second-order models are required.

Payne-Whitham Second-Order Models A simple representative of a local second-order macroscopic model is the Payne-Whitham model [26]. Payne's model is a special case of the general macroscopic acceleration equation for a constant speed relaxation time, zero diffusion, and a density dependent traffic pressure. As in the LWR models, a variety of equations for the steady-state speed-density relation characterize a whole class of Payne-Whitham models.

In the first-order models, the local speed and flow are statically coupled to the density by the fundamental relation. In the second-order models the local speed possesses its own dynamic acceleration equation, describing speed changes as a function of density, local speed, their rates of change, and possibly other exogenous factors. Second-order models are the best choice to macroscopically describe traffic-flow instabilities leading to traffic shock-waves, capacity drop phenomena, and scattered

[2]Traffic shock-waves or stop-and-go waves can be described as the local traffic perturbation that can be observed for example around a on-ramp on the motorway.

flow-density data. In order to model traffic-flow instabilities, the local speed is treated as a second independent field, governed by a second dynamic acceleration equation. Such an equation describes the local acceleration as a function of density, speed, their rates of change thereof, and possibly other exogenous factors. The different second-order models are distinguished solely by their acceleration function.

2.2.2 Microscopic Models

In microscopic models [27] the behaviour of every vehicle is described individually, taking into account the surroundings, collectively forming a traffic flow. Examples are car-following models and most cellular automata, where the reaction of every driver (accelerating, braking, lane-changing) depends on the surrounding traffic and is expressed with variables such as vehicle positions, speeds, and accelerations.

In contrast to macroscopic models, microscopic models allow the heterogeneity of traffic to be studied in detail. This allows the effects of any traffic control action on a specific vehicle or class of vehicles to be simulated, for example changing the navigation route or changing speed limits (or overtaking bans) for trucks. The level of detail allows the visualization of interactions between various traffic participants (cars, trucks, buses, cyclists, pedestrians, etc.) and the description of human driving behaviour including estimation errors, reaction times, inattentiveness, and anticipation. Among other things, microscopic models are used to assess how different driving styles affect traffic capacity and stability.

Nagel-Schreckenberg Model (NSM) A Cellular Automaton (CA) describes traffic dynamics in a completely discrete way. The space is divided into cells and the time into time-steps. Quantities such as speed or acceleration are integer multiples of the corresponding basic units. Cellular automata are easy and fast to simulate, but they reproduce real-life traffic only in a schematic way, due to their discrete and deterministic nature.

The Nagel-Schreckenberg Model (NSM) [28] is the simplest and most generic representation of a traffic-related CA and it has proved useful for traffic flow simulations. In its basic form, it describes single-lane traffic consisting of identical vehicles of effective length 7.5 m. Given that each vehicle occupies exactly one cell, this is also the cell length. The update time step is 1s, and it is performed by applying the following rules; for every vehicle:

- Acceleration: if the current speed is less than the maximum speed, it is incremented by one unit.
- Deceleration: if the distance (number of cells) to the vehicle in front is smaller than the current speed, the new speed is reduced to the number of empty cells in front of the car, in order to avoid a collision.
- Randomization: the reaction time of the driver is modelled by reducing the speed by one unit with a probability common to all the vehicles.

Finally, every vehicle is moved forward by the number of cells equal to the computed speed. Figure 2.2 shows the update rules applied to three vehicles over five seconds.

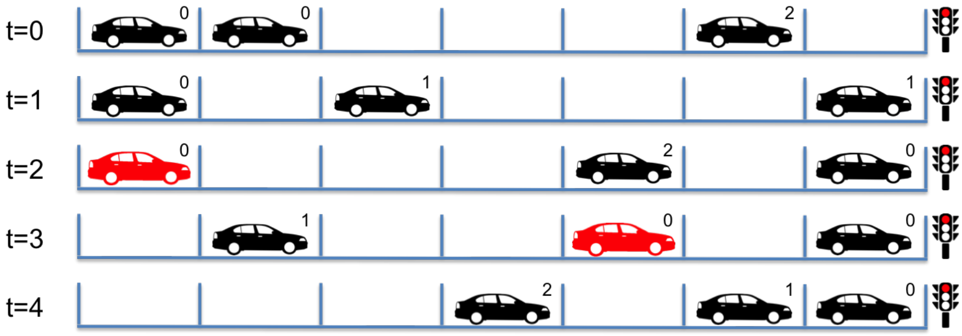


Figure 2.2: Visualization of the update rules of NSM with maximum speed of 2 cells/time-step. The number above the vehicle represents the speed in the previous time-step. A vehicle highlighted in red had slowed down in the time-step due to randomization.

While the coarse discretization does not allow for a realistic description of single-vehicle dynamics, nevertheless, on a macroscopic level, it shows some plausible results. For example, in the simulation of a highway scenario, the congestion created by the presence of on-ramps is modelled and the patterns inside the congested region move upstream with a realistic velocity. Because of the stochastic nature of the NSM and other cellular automata, no steady-state equilibrium exits and, consequently, there is no fundamental diagram in the strict sense. In spite of being a microscopic model, the NSM can only be used to describe the macroscopic dynamics.

Gipps' and Krauss' Car-Following Models All car-following models [1] are defined by ordinary differential equations, describing the complete dynamics of the vehicles' positions and velocities. The input variables for the vehicles are their own speed, the bumper-to-bumper distance to the leading vehicle, and the speed of the leading vehicle. The equation of motion of each vehicle is characterized by an acceleration function that depends on those inputs. In general, the driving behaviour of a single vehicle might depend not only on the immediate leader but on the vehicles ahead of that leader. A car-following model (or any other microscopic model) is complete if it is able to describe all situations including (1) acceleration and cruising in free traffic, (2) following other vehicles in stationary and non-stationary situations, (3) approaching slow or standing vehicles, and (4) red traffic lights.

Gipps' model [29] is one of the simplest complete and accident-free models that leads to accelerations within a realistic range. Accidents are prevented by introducing a safe speed, which depends on the speed of the leading vehicle and the distance to it. It is based on the assumptions that braking manoeuvres are always executed with constant deceleration and there is no distinction between comfortable and (physically possible) maximum deceleration. The reaction time is constant, and even if the leading vehicle suddenly stops (worst case scenario) the distance gap should not become smaller than a minimum gap. In this model the update time-step is equal to the reaction time. Gipps' model produces good and realistic results for both motorway scenarios and city traffic. The flow-density diagram for motorway traffic shows a strongly scattered cloud of data points in the region of congested traffic, with the wide scattering in agreement with empirical data.

Many modified versions of Gipps' model are used in simulation, among them there is Krauss' model [30], which is essentially a stochastic version of the Gipps model. In Krauss' model, a stochastic component is introduced in order to model reaction times and human behaviour. For each discrete time-step, the deterministic component of the speed is computed as the minimum of the maximum speed allowed for a vehicle and the safe speed, where the minimum is used to ensure collision avoidance. The probabilistic human inaccuracy is then applied to the deterministic speed. This randomization allows the modelling of phantom jams[3] and gives a more realistic representation of traffic. Lastly, the position update is computed from the two components of the speed using the previous position. This also model the lane-changing issues. Here, the lane change behaviour takes into account whether changes are safe and favourable, while introducing some randomness to the behaviour of the driver with a small probability for a lane change that is safe but not favourable.

Intelligent Driver Model (IDM) The time-continuous Intelligent Driver Model (IDM) [31] is a simple and complete accident-free model, able to produce realistic acceleration profiles and plausible behaviour in all single-lane traffic situations. The IDM is characterized by the acceleration equation that fulfils the general conditions for a complete model [1], the bumper-to-bumper spacing that preserves the safe distance (no collisions), and an intelligent and smooth braking strategy that exceeds the comfortable value only in a critical situation, with gradual transitions between different driving modes. These characteristics represent a series of parameters with an intuitive interpretation. Since the IDM has no explicit reaction time and its driving behaviour is given in term of a continuously differentiable acceleration function, the IDM more closely describes the characteristics of semi-automated driving by Adaptive Cruise Control (ACC) than that of a human driver. However, it can easily be extended to capture human aspects like estimation errors, reaction times, or looking several vehicles ahead. The IDM explicitly distinguishes between the safe time gap, the speed adaptation time, and the reaction time. This allows it not only to reflect the conceptual difference between ACCs and human drivers, but also to differentiate between various driving styles.

2.2.3 Mesoscopic Models

Mesoscopic models present an intermediate third possibility for modelling traffic flows. They combine microscopic and macroscopic approaches to a hybrid model, based on analysis of the statistical distribution of individual behaviour. In this models' definition, the parameters of a microscopic model may depend on macroscopic quantities such as traffic density or local speed and speed variance. Conversely, the dynamics of a macroscopic quantity (the number of vehicles in a traffic jam) is described in terms of microscopic stochastic rate equations for in- and out-flowing vehicles. Collisions are modelled using gas-kinetic traffic models, where an idealized phase-space density is computed using traffic density and the local probability distribution of vehicle speed. In these hybrid models, only the critical parts of the traffic network, such as intersections and traffic lights, are described microscopically; all the rest are macroscopic. Often this class of models is used when there is a requirement to be able to zoom in on the microscopic model to see the vehicle behaviour, but the overall system is so complex that it can only be simulated with a macroscopic model. A case-by-case analysis is required to ensure that the required details from the microscopic model are surfaced. This means that there is no generic

[3] A phantom jam is a small disturbances in the traffic flow, for example a sudden brake or a lane change, that in heavy traffic can become amplified into a full-blown, self-sustaining traffic jam.

model and they vary in definition and implementation [32–34].

Going back to the scope of this work, we are more interested in microscopic models. These are particularly suited to studying how single vehicles affect traffic, so they are fundamental in the study of advanced driver-assistance systems such as state of the art navigation systems, and other applications of ITS.

2.3 Network Topology

In order to study traffic optimization in connection with ITS, we need to have a reliable representation of the transportation infrastructure, as well as some means of taking into consideration the telecommunication aspects, needed to properly collect and share traffic information.

Once the behaviour of the vehicles and their interaction have been properly modelled, the next step focuses on the creation of a model for the environment and the network topology. The level of detail required to model the environment is very specific to the problem being studied. Aspects such as intersection geometry, road priority, or traffic light system coordination, requires the gathering of much information if it is to be modelled correctly. Variation such as the coordination in a green wave[4] [35], or the lane priority in an unsignalized intersection [36], would modify the resultant mobility patterns. Given the intrinsic complexity of modelling every aspect of a situation, there is no general-purpose solution. The model is usually built based on the problem to be solved, and the amount of information that is available.

The structure of an urban environment is defined by specific rules and parameters, and can be represented using concepts from various methodologies ranging from graph theory to social network structures. In this section, we study the most relevant ways of modelling such environments for our purposes. Moreover, given that mobility patterns and traffic models depend on the topology and its description, this section serves as a basis for the description of the tools and simulators discussed in Section 2.4.

Urban Environment In contrast to the surrounding areas, the urban environment is characterized by a dense human population, various buildings and several built features. The metropolitan area includes not only the urban zone, but also satellite cities and the surrounding countryside, which are socio-economically connected to the urban core.

Defining the shape and composition of the urban area is an important and complex issue. Many studies have been made in order to supply useful knowledge to urban planners and designers. Urban morphology is an area of urban studies that deals with the shape of cities. The rise of complex system science and its associated paradigms, coupled with the increasing availability of spatial and time geo-referenced data, has given a boost to these studies. In this area, the main subject of investigation is the composition of the city in terms of the neighbourhood, street, plot and building. The aim is to look for a small-world structure and a scale-free property for both street length and degree of

[4] A green wave occurs when a series of traffic lights are coordinated to allow continuous traffic flow over several intersections in one main direction.

connectivity, using various centrality indices as indicators of the importance of streets. However, an important open question in urban morphology has to do with the characterization of classes of cities based on their form [37].

With the aid of urban morphology and the use of Geographic Information System (GIS), it is possible to import real data from cities, then study and model them. Cities can have different levels of geographic constraint, from those traversed or limited by large natural water features to those built on uninterrupted plains. History plays an important role. The varying prominence of planning history, from cities that are self-organized or only fragmentarily planned, to those whose street layout has primarily been determined by a single planning vision.

A spatial analysis, where cities are represented as networks in geographical space, allows an extended visualization and characterization of the internal structure of a city. Planned and self-organized cities clearly belong to two different universality classes. In particular, self-organized cities exhibit scale-free properties similar to those found in the degree distributions of non-spatial networks [38].

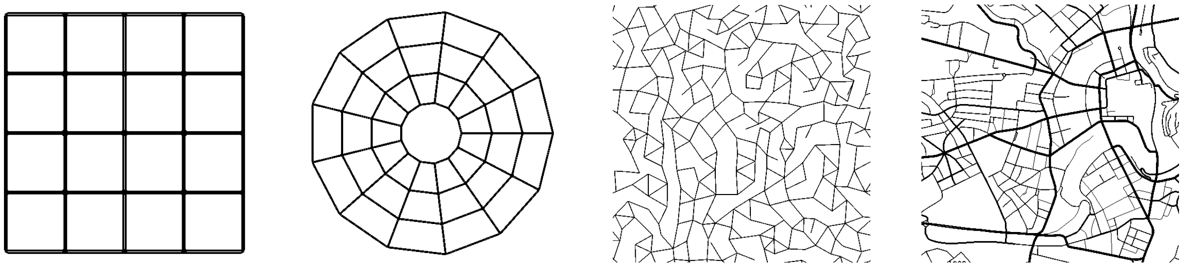
The lack of a general topology embodying all the properties of a real city, gives rise up the problem of having to choose a new scenario before any model can be run.

Road Network Representation Spatial networks are used to model a number of real phenomena; among these, they are well suited to describe the street pattern of cities. The use of a network approach to urban modelling poses several questions concerning distance metrics, the various usable graph representations, and relationship with the measures we want to investigate. One possible representation of street networks is based on a primal graph, where the intersections are turned into nodes and the streets into edges. Another representation possibility is a dual graph, where the streets are nodes and the intersections are edges. The dual graph allows the continuity of streets over a multitude of edges to be represented [39]. The networks are also weighted with various values or properties, expressing parameters such as type of street or intersection, number of lanes, traffic light coordination, maximum speed allowed, and so on. Networks of street patterns belong to a particular class of graphs known as planar graphs. Which have among their properties that links may cross only at nodes.

In transportation, land-use planning, and economic geography, the network representation is used to study metrics such as accessibility, integration, connectivity, and cost. All these metrics are based on the idea that some places (or streets) are more important than others because they are more central. This idea originated in structural sociology [40], well before its use in urban studies. There are studies on the structural properties of the primal graph representation as compared with the dual [41]. Using the primal approach is possible to capture the backbone of the urban structure that impacts spatial cognition[5] and collective behaviours. Moreover, the distributions of centrality in self-organized cities are different from those in planned cities.

The study of the geometric properties of the networks has generally focused on the distribution of various metrics, with the aim of finding common patterns: street length, angles formed between street intersections and the relation between dead-end link length and the area of the cycle they belong to [37]. As briefly discussed above, there is no emerging general topology, but some specific patterns have been identified.

[5]Spatial cognition is concerned with the organization and utilization of knowledge about environments. This knowledge base enable humans to manage basic and high-level cognitive tasks in everyday life.



(a) Manhattan grid. (b) Spider-web. (c) Random. (d) Real city.

Figure 2.3: Network Topologies.

Road and Telecommunication Networks The term network topology can refer both to the street topology and to the telecommunication links topology. Usually the context suggests the correct definition, but when it comes to VANETs, the context is not helpful because the two concepts are linked. A large volume of research into vehicular, ad hoc, and sensor networks has shown that the telecommunication network topology has a great impact on communications performance, and depending on the technology that is used, street topology is directly linked with the communication network in many cases.

An example of this correlation between telecommunication and street topology is provided in wireless sensor networks, which are used in smart cities to collect many types of environmental data. Recent studies have shown that the optimal positioning of such networks and the impact of the resulting topology on telecommunications is important when it comes to real world deployment [42,43]. Performance studies of node placement in sensor networks have shown that the location of the sensors has a strong impact on many aspects of performance, including fault tolerance [44], coverage and congestion mitigation [45], and data collection capabilities performances [46]. An investigation of the impact of the topology on a geographic routing scheme [47] showed that different topologies can lead to a difference of up to 25% in delivery ratio and average route length and more than 100% in overall cost of transmissions.

2.3.1 Topology Classification

We have classified topologies according to their level of complexity and realism. It is important to take into consideration that, depending on the problem we are studying, the use of a model representing a real city in all its complexity can be counter-productive at best, if not actually misleading. This is due to the properties and issues related to the evolution of complex systems [48]. Given a complex system with a defined set of variables, a small perturbation in the initial set of values may lead to a completely different outcome. This is why simplified topologies have been used for years, yielding results that are more than acceptable and realistic. Among the most-used simplifications of city models are the Manhattan grid, the spider-web, and the random topology. An example of each is shown in Figure 2.3.

Manhattan Grid The grid topology is a type of city plan in which streets run parallel and intersect at right angles to each other, forming a grid [49], as shown in Figure 2.3a. From an urban planning perspective, the inflexibility of the grid leads to the disregard of environmentally sensitive areas, such as small streams, creeks, or woodlands, in preference to the application of the immutable geometry. Its name, Manhattan grid topology, comes from the street topology of the well-known island that forms a part of the city of New York. Many times, we can find a grid topology framed and surrounded by discontinuous street patterns that follow the configuration of natural features, without disrupting them. Even for cities that present a more complex topology, when the internal structure of the blocks is ignored, the grid provides a rational and simplified representation of the main streets and transportation backbone. We can find different degrees of urban grids all over the world and, given their simplicity, they are used as a model to study many different problems.

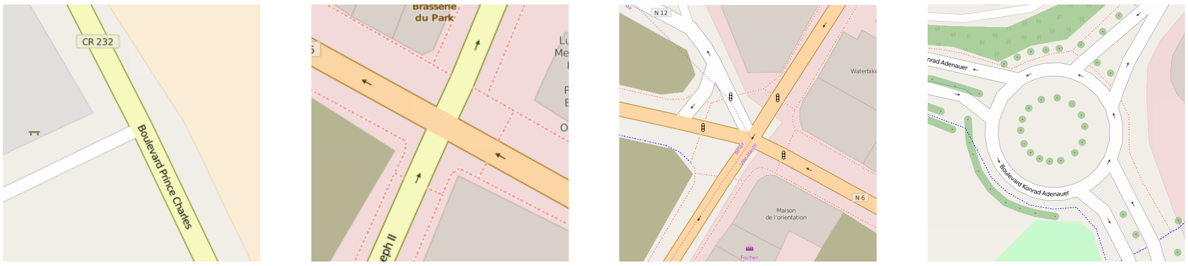
Spider-Web Topology Figure 2.3b shows a spider-web topology or radial network [49]. Many medieval European cities follow a radial pattern, with the old town (or the city centre) in the middle, surrounded by neighbourhoods that have grown over time. The discussion that applies to the grid, also applies to radial network. Even for cities that present a more complex topology, a radial topology provides a simplified representation of the main streets and transportation backbone, when the internal structure of the blocks is ignored. Once again, the symmetry and simplicity of this topology allows it to be used as a base model for the study of many problems.

Random Topology Staying with generic topologies, the next possibility, which allows a model to be more complex, but not completely corresponding to a specific city, is the random topology presented in Figure 2.3c. Such a topology is built using planar graphs [49]. Existing studies of urban morphology supply values that can be used to generate them, namely the average length of a street, and the average number of streets at an intersection (degree of a node). The model's lack of symmetry is very helpful in studying optimization problems, but its randomness may bring issues specific to the topology itself but never present in a real city.

Real City Figure 2.3d presents the city centre and several neighbourhoods of the City of Luxembourg. Using a real topology can be optimal when studying specific problems, but on the other hand, its complexity can be overwhelming for a model in terms of scalability. It is important to take into consideration that gathering all the information required to model a real city is a complicated task, that is not always achievable due to, for example, privacy issues or proprietary information. The use of partial information may cause bigger issues than using a simplified version of the city. In addition, the possibility of encountering issues and idiosyncrasies specific to the topology must be recognised when using a real city as a model.

Road Intersections The theory behind design and construction of road intersections has its roots in the past, but continues to innovate through the use of modern technology. Resources such as [50] and [51] provide a detailed study on traffic control systems and traffic signal timing respectively, providing explanations and suggesting directive on how to design and build intersections.

For the purpose of this thesis, we focus only on the basics and geometry of an intersection, which is the connection of two or more roads. The shape of an intersection usually depends on the number



(a) (b) (c) (d)

Figure 2.4: Sample of road intersections from OpenStreetMap [52].

of streets involved, their priority, and the geography of the terrain.

A sample of the various intersections available is shown in Figure 2.4. Figures 2.4a, 2.4b, and 2.4c represent the most common intersections between, respectively, three, four and five roads with various priority levels. Figure 2.4d shows a roundabout between three streets having the same level of priority.

The primary goal of the geometry of an intersection is to regulate its access and use, and to limit the conflicts among road users. Many intersections can be only priority based (e.g. right-before-left), but busy intersections are often controlled by traffic lights and/or a roundabout. Intersection channelization [53] is a design concept used to reduce conflicts in access to and use of intersections. It employs constructions such as raised medians and traffic islands to discourage wrong-way turns and other undesirable movements. The lines and markings used to delineate vehicle paths are also part of channelization techniques. The creation of turn lanes and the use of angles of incidence between streets as close to 90 degrees as possible are used as practical way to minimize potential conflicts among the road users.

It's important to realise that enhancing the detail of a topology representation, also increases the complexity of a mobility model that can use the additional information properly. A complex mobility model that takes into account all the environmental constraints provided by the topology is bound to have scalability issues, although these can usually be tackled in a straightforward manner. The greater the geographical area to be considered, the lower should be the complexity of the topology representation if modelling is to remain treatable. Moreover, the application plays a fundamental role. For example, using a model of an entire city with all the roads from motorways to bicycle paths, would be useless for studying the impact of changing the speed limit on the motorway. This example is extreme, but such decisions must be made regarding street geometry, intersection representation, the inclusion of building or not.

Once the mobility model is defined and the network topology is established, they have to be implemented in order to to be used in simulations.

2.4 Simulation Tools

When studying traffic optimization in the context of interconnected vehicles and ITSs, the aid of computer simulations is fundamental. In order to study VANETs, it is necessary to use a network communication model in addition to a mobility model.

One of the problems faced when studying VANETs is the need to dynamically modify vehicular mobility as a consequence of the communication protocols. Many models have been developed by the community in order to provide this interaction; these are mainly divided in two paradigms. One option is to implement both models in the same simulator or emulator; the other is to keep the models separated, but provide some means of connection in order to obtain the required interaction. However, given the large number of available models, and the different and not-always comparable features, the evaluation of their capabilities and their degree of realism is difficult. In the literature, surveys such as [54, 55] address exactly these problems.

In the following sections we present an overview of the tools and frameworks that are appropriate for studying VANETs and ITSs.

2.4.1 VANET simulators and emulators

As explained previously, it is possible to have both mobility and network models in the same implementation. In this case, the direct feedback-loop between mobility and connectivity is integrated by design. However, some combined simulators have limited or very specific features concerning mobility and communications.

VANET simulation and emulation is used to study the behaviour of interconnected vehicles by modelling the interaction between the different entities using mathematical formulas, or actually capturing and playing back observations from a real testbed. Various attributes of the environment can be altered in a controlled manner to assess how the interaction would behave under different conditions. Compared to the cost, time, and difficulties involved in setting up an entire testbed containing multiple components, VANET simulators and emulators are relatively fast and inexpensive. This is especially true where experimentation in the real world (public and/or crowded places) is constrained by regulations and laws.

Focus on the propagation model AutoMesh [56] includes a driving simulator module, a radio propagation module, and a network simulator module. The mobility model is very simplistic, but the radio propagation module is very detailed. It uses 3D maps and digital elevation models in order to obtain a realistic radio propagation model in urban areas.

Focus on scalability and distributed computing MoVes [57] is an embedded system that generates vehicular mobility traces and also contains a basic network simulator. The major asset of this project is its ability to partition the geographical area into clusters, distributing the processing of each task. It is based on Artis [58], which provides scalable and distributed simulation middleware. The main feature of this tool is its parallel computing ability. However, the mobility model is simple and it provides weak network simulation capabilities.

Emulation capabilities The National Chiao Tung University Network Simulaton (NCTUns) [59] is a high-fidelity and extensible network simulator and emulator capable of simulating various protocols used in both wired and wireless IP networks. Its novelty is the support of seamless integration of emulation and simulation. It can run any real-life UNIX application program on a simulated node without any modifications. It can run parallel simulations on multi-core machines. It requires the Fedora 12 Linux distribution to be installed, which poses a problem for the majority of VANET researchers, limiting its wide usage.

Another VANET emulator similar to NCTUns is the Mobile network Virtualized Testbed (MoViT) [60]. It provides a virtualized environment for developing and testing mobile applications and protocols for any hardware and software platform that can be virtualized. The infrastructure is UNIX-based and it requires a modified Linux kernel. For this reason and given the lack of active developers, the project has been discontinued.

Test-bed integration GrooveNet [61] is a hybrid simulator which enables communication between simulated vehicles and real vehicles. It provides multiple network interfaces, and allows GPS-triggered events. It supports three types of simulated nodes: (i) vehicles which are capable of multi-hopping data over one or more dedicated short-range communications channels, (ii) fixed infrastructure nodes, and (iii) mobile gateways capable of Vehicle-to-Vehicle (V2V) and glsV2I communication. GrooveNet generates street-level maps by importing TIGER[6] files.

Behavioural analysis MobiREAL [62] provides a framework for modelling and simulating realistic mobility fo humans and vehicles. It is often used in the cognitive modelling of human behaviour. The mobility aspects are supported by the Georgia Tech Network Simulator (GTNetS) [63]. MobiREAL Animator dynamically visualizes the simulation. Moreover, it is able to simulate collision avoidance among pedestrians.

2.4.2 Mobility simulators

Mobility models are used to obtain the movement of agents in terms of location, velocity and acceleration changes over time. There are different classes of mobile models [54]: *survey-based models* extract the mobility patterns from surveys; *trace-based models* use real mobility traces to generate mobility patterns; *synthetic models* are based on mathematical models; *traffic simulator-based models*, where vehicular mobility traces are extracted from a detailed traffic simulator that implements one of the models previously discussed.

Model-based mobility Developed for urban traffic engineering, simulators such as PARAMICS [64], CORSIM [65], VISSIM [66], and TRANSIMS [67], are able to model urban traffic, energy consumption, and even pollution or noise level at the microscopic level. However, these simulators cannot be used easily with network simulators, because no interfaces have yet been developed and the mobility traces are generally incompatible.

[6]Topologically Integrated Geographic Encoding and Referencing (TIGER) are spatial extracts from the Census Bureau's MAF/TIGER database, containing topographical features. See https://www.census.gov/geo/maps-data/data/tiger.html for details.

Another simulator developed by and for the traffic engineering community is Simulator of Urban MObiltiy (SUMO) [68], an open source, highly portable, microscopic road traffic simulation framework designed to handle large road networks. It can manage large environments, and it can import many network formats such as Visum [69], Vissim [66], and XML descriptions. For access and interaction with the running simulations, SUMO provides a socket-based connection, Traffic Control Interface (TraCI) [70]. TraCI provides a standard to couple the mobility data with any external simulator or script language. For example, SUMO can be compiled in order to be used directly through Python scripting.

Model-based mobility for VANETs Some mobility simulators have been developed in order to have interfaces with, and output standard formats used by, network simulators. For example, Vanet-MobiSim [71] is an extension of the CANU Mobility Simulation Environment (CanuMobiSim) [72] which focuses on vehicular mobility, and features realistic automotive motion models at both macroscopic and microscopic levels. It can generate movement traces in different formats, supporting different network simulators including ns-2 [73], GloMoSim [74], and QualNet [75]. Another simulator able to generate realistic mobility models for VANET simulations is MOVE (MObility model generator for VEhicular networks) [76]. Built on top of SUMO, its output is a mobility trace file that contains information on realistic vehicle movements, which can be immediately used by popular network simulation tools. In addition, MOVE provides a GUI that allows the user to quickly generate simple simulation scenarios without writing simulation scripts.

Trace-based mobility. A project worth mentioning is STRAW (STreet RAndom Waypoint) [77] because it simulates vehicular mobility using a model based on real vehicular traffic. STRAW is part of the C3 (Car-to-Car Cooperation) project [78]. Its current implementation is written for the JiST/SWANS [79] discrete-event simulator. Unfortunately, the mobility traces cannot be directly used by other network simulators, and its constraints on movement (mobility limited according to vehicular congestion and simplified traffic control mechanisms) lack realism in a general scenario. Another mobility generator based on user-generated traffic data (or converted from real-time information) is FreeSim [80], a fully-customizable macroscopic and microscopic free-flow traffic simulator specialized for motorway scenarios.

Agent-based mobility. Another well-known traffic simulator is MATSim [81]. It provides a modular framework able to implement large-scale, agent-based, transport simulations. Currently, it offers modules for demand modelling, route re-planning, agent-based mobility simulation (traffic flow simulation) and the possibility to work on optimizations through iteration, where the agents use the information provided by the previous run in order to make decisions.

2.4.3 Network simulators

Network simulation is used to study the behaviour of a network by modelling the interaction between the different entities using mathematical formulas. Various attributes of the environment can be altered in a controlled manner to assess how the network would behave under different conditions.

Compared to the cost, time, and difficulty involved in setting up an entire test-bed containing multiple components, network simulators are relatively fast and inexpensive.

Simulators such as ns-2 [73] and its refactoring (with improvements) ns-3 [82] are discrete event simulators able to model node mobility, together with radio network interfaces with a realistic physical layer and propagation model for which many wireless protocols are already implemented. ns-2 and ns-3 can be used with mobile traces provided by a mobility simulator.

The well-known and widely-used QualNet [75] simulator is a commercial version of GloMoSim [74]. These are scalable simulation environments for wireless and wired network. They have been built using a layered approach with standard APIs in order to integrate different models from different developers. GloMoSim was designed using the parallel discrete-event simulation capability provided by Parsec [83].

Among general purpose frameworks, we find JiST [79], a high-performance discrete event simulation engine that uses a standard Java virtual machine. It uses a general-purpose approach to building discrete event simulators. SWANS [84] is a scalable wireless network simulator built on top of the JiST platform. Its capabilities are similar to ns-2 and GloMoSim, but SWANS is able to simulate much larger networks.

Traditional wireless network simulators are limited in speed and scale because they perform many redundant computations. SNS [85] is a Staged Network Simulator implemented to eliminate redundant computations through function caching and reuse. It is a staged simulator based on ns-2, but it is not specifically designed to simulate VANET scenarios.

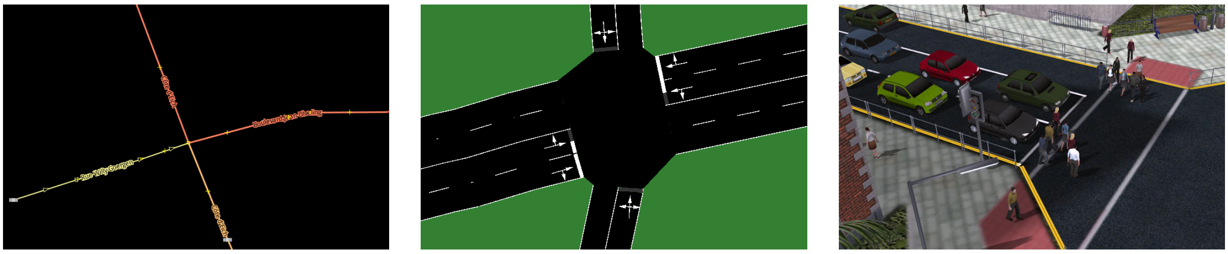
Another general-purpose framework for network simulation is Objective Modular Network Testbed in C++ (OMNet++) [86]. It provides a complete framework writing models, (graphically) assembling them and run the simulations. The software is open-source and has a free licence for academic use. There are many module libraries that can be used to extend the functionality easily. One of the most common libraries for OMNet++ is the INET Framework [87], which offers a wide range of functionality for IP-based networking. The possibilities for extension make OMNet++ a very popular network simulator in the research community.

2.4.4 VANET frameworks

VANET frameworks provide the missing link between mobility and network simulators. They implement the interface to interact with both, at the same time providing in some cases a direct feedback loop between mobility and connectivity.

Traffic and Network Simulation Environment (TraNS) [88] uses the SUMO traffic simulator and the ns-2 network simulator. It provides two ready-to-use VANET scenarios, a road danger warning for safety applications, and a dynamic reroute for traffic efficiency. Moreover, it allows Google Earth visualization, although for TIGER files only, unfortunately.

Vehicles in Network Simulation (VEINS) [89] is an open-source framework library for the OMNet++ network simulator specifically implemented for VANETs. It implements the TraCI interface to couple the connectivity simulation, performed by the OMNeT++ framework, with the vehicular mobility simulation provided by SUMO. The two are able to interact with each other, providing a feedback loop where the decisions made by the network simulator directly alter the mobility, and vice



(a) Point-wise intersection in JOSM [93].

(b) Multi-lane intersection in SUMO GUI [68].

(c) 3D Intersction in Paramics [64].

Figure 2.5: Road intersections representation.

versa. This interaction enables researchers to simulate and investigate the effects of telecommunications on traffic, in order to optimize traffic flows and test communication protocols.

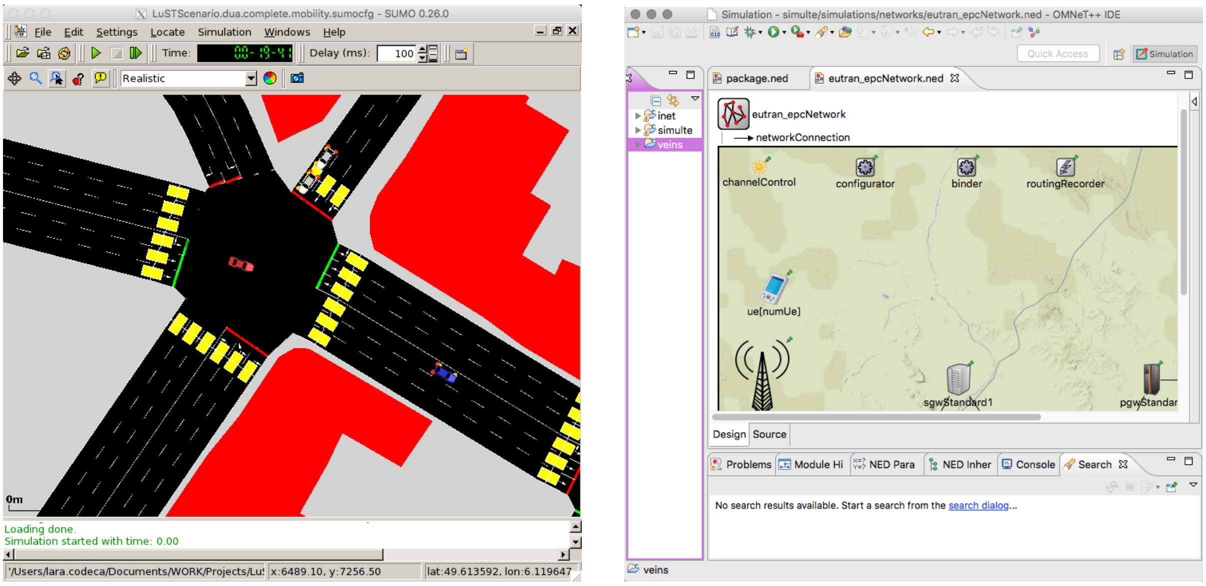
iTETRIS [90] is an open framework for ITS simulations that integrates and extends SUMO and ns-3. It enables large scale evaluation and it provides modules for the three main actors communicating in an ITS scenario: vehicles, roadside units, and central subsystems. Among major features implemented for the networking are (i) dynamic and adaptive communication technology and transmission mode selection; and (ii) IEEE 802.11p, WiMAX, and UMTS wireless communication support and channel modelling.

2.4.5 Road Intersections in Simulation

Road Intersections come many configurations and their definition significantly affects mobility and connectivity simulations. The representation and the interaction model for a roundabout [91] is very different from that for merging traffic on motorway [92]. The intersection between streets can be represented in many different ways depending on the issues to be studied and the models used.

Figure 2.5 provides an example of the different levels of detail that can be used in representing an intersection between two roads. The representation of an intersection is specific to the model used to represent the mobility and the simulator that will be used.

A simple representation of an intersection can be seen in Figure 2.5a, where the two streets (edges) intersect at one point (node). This representation is usually defined as point-wise intersection and is commonly used with macroscopic traffic flow models [94]. For example, [25] provides a rigorous methodology for FIFO intersection modelling within the LWR framework. A more complex representation of an intersection is shown in Figure 2.5b, where it is possible to see the different lanes and the directions (white arrows) that must be respected while approaching it. The complexity of a multi-lane intersection can involve traffic light signalling, internal links to cross the intersection, pedestrian crossings, and more. This level of detail is most frequently used with microscopic traffic flow models. For example, [36] studies the traffic flow at an unsignalized urban intersection, using an enhanced version of the cellular automation paradigm, where heterogeneity and inconsistency are simulated by incorporation of different categories of driver behaviour. An example of advanced 3D modelling of an intersection is shown in Figure 2.5c. 3D models have very specific uses in the design of the urban landscape [95,96] or, for example, to study visualization and propagation models for VANETs [97,98].



(a) SUMO GUI. (b) OMNet++ IDE with Veins.

Figure 2.6: SUMO GUI and OMNet++ IDE with VEINS.

2.4.6 Our Framework: SUMO, OMNet++ and VEINS

The number of different simulators available to the community is very large. We decided to use SUMO (see Figure 2.6a) for mobility generation and OMNet++ with VEINS (see Figure 2.6b) for network simulation, mainly for practical reasons.

OMNet++ is open source, modular, and general purpose allowing us to use all the modules already implemented, to modify them in case of need, or to implement new features from scratch.

SUMO is open source, highly portable, microscopic road traffic simulation framework designed to handle large road networks. It implements several mobility models, among them, the Krauss car-following model [30], the Kerner three-phase model [22], and the Intelligent Driver Model [31]. Its main features include collision-free vehicle movement, different vehicle types, single-vehicle routing, multi-lane streets with lane changing, junction-based right-of-way rules, a hierarchy of junction types, and dynamic routing, all presented through an OpenGL Graphical User Interface. SUMO can manage large environments, and can import many network formats, such as Visum [69], Vissim [66], and XML descriptions. It provides the possibility of creating synthetic road networks, in order to perform simulations on standard scenarios (e.g. grid, radial and random topology). There are also existing tools to import road networks from publicly-available map information systems such as OpenStreetMap (OSM) [52]. For access and interaction with the simulation at run-time, SUMO provides a socket-based connection named TraCI [70]. TraCI provides a standard to couple the mobility with any external software or script of sort. For example, SUMO can be compiled in order to be used directly through Python scripting. SUMO is supported by a large and heterogeneous community, and provides a high level of detail, many customization options, and dependable reliability.

VEINS extends SUMO and OMNeT++, offering a suite of models specifically implemented for

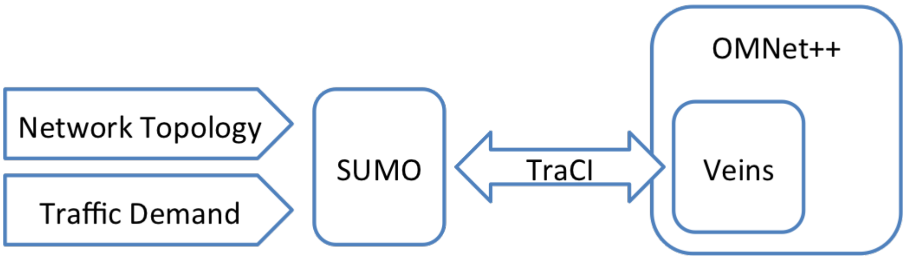


Figure 2.7: Overview of the interactions between SUMO, OMNet++ and VEINS.

interconnected vehicle simulation. As VEINS is open source, it can easily be extended to support new communication protocols or ITSs. It implements the TraCI protocol to interact with SUMO and provides the basic modules for vehicles and infrastructure needed to build complex simulations. Given that it uses the mobility simulation provided by SUMO, and because it has the support of large community and is reliable, VEINS is our preferred choice for simulating VANETs.

Figure 2.7 shows the interactions between the three components. SUMO requires the network topology and the traffic demand in order to simulate the mobility. Built in the OMNet++ framework and able to use other OMNet++ modules, VEINS uses the TraCI connection to interact at run-time with SUMO.

Last but not least, the communities using and implementing both OMNet++ and SUMO are large and active. This aids research by providing frequent updates and patches, with support in case of problems. Both packages are platform independent, working on Linux, Mac OS and Windows systems.

Remarks

In order to work with VANETs and ITSs we need to use a framework able to provide reliable traffic mobility and realistic connectivity patterns.

In this chapter we provided an overview of traffic flow theory and the three categories of mobility model available, macro- meso- and microscopic, presenting some examples. We have summarized the main network topologies available to model the urban environment and have discussed the relationship between network representation and complexity of the models involved. Lastly we have provided an overview on the tools available to the community, together with our reasoning about why we decided to use SUMO as the mobility simulator and OMNet++ with VEINS for the connectivity in order to study traffic flow optimization and vehicular re-routing. Additionally, in this work we will present a realistic traffic scenario for SUMO, usable with VEINS. We discuss its generation process and we validate the synthetic mobility using empirical data.

Chapter 3

Vehicular Traffic Optimization and Navigation

The methods used to collect traffic data evolved considerably in recent years, so access to real-time traffic information is becoming routine worldwide. This constant research and innovation is mostly technology driven. All the improvements that have enabled the collection of accurate traffic information, increasing processing power and better means of distribution, have made possible the achievement many objectives, ranging from location-based services to navigation systems and route optimization. This information is used in Advanced Traveller Information Systems (ATISs), Advanced Traffic Management Systems (ATMSs) and Intelligent Transportation Systems (ITSs). Among the challenges that must be faced, this Chapter discusses the evolution of navigation systems, the introduction of floating car data, and their impact on traffic flow analysis and optimization.

The basic idea behind a navigation system is to guide an entity that is moving from one place to another. The services that can be provided by a navigation system have changed over the time, due to improvements in communication and positioning technologies. Their evolution went from external navigation devices plugged into a vehicle, through embedded navigation systems, and recently, to navigation applications that can be provided by a smartphone. Many services are location-aware, and, more frequently, are updated in real-time.

Early systems monitored the traffic situation using a variety of on-road sensors (e.g. inductive loops and traffic cameras). These means of collecting traffic data are still necessary, but are not sufficient to provide an up-to-date traffic situation, because of their limited coverage and their high deployment and maintenance costs. Additionally the authorities retrieving the traffic data are not linked to each other, meaning that a global overview of the system is not available. Moreover, not all on-road sensors are designed to provide real-time data. Recently, because of the evolution of mobile devices (e.g. on-board computers and smartphones), we have seen the emergence of alternative data sources. For example, the use of data collected directly by the vehicles is a promising cost-effective solution, which can be integrate with the data collected from fixed detectors. Floating Car Data (FCD) refers to the data generated by one vehicle, usually composed of basic telemetry such as speed, direction and, most important, the position of the vehicle [99]. When the amount of information collected reaches a critical mass, FCD can be sampled to assess overall traffic conditions; it can also be used to track the device in question when collected over time.

The increase in location-based applications makes protecting personal location information a major challenge, raising many privacy and security issues. Many studies have been done on the integration of FCD into the architecture and applications of real-time traffic information systems [100–102]. This can be achieved using FCD collected from public transportation and private fleets such as taxi services or delivery companies. For example, using fleets leads to a nearly complete data coverage of all major roads, at almost no additional costs for the fleet owners, while reducing privacy-related issues.

All the traffic information collected can be used to perform traffic analysis and optimization. The engineering approach to the analysis of traffic flow problems and urban planning is primarily based on empirical evaluations. Considering the problem to be solved, one or more of the models presented in Chapter 2 can be used, depending on the macro-, micro-, and mesoscopic features required. Once we have a realistic traffic demand, the resultant traffic scenario can be used to understand the implications of various traffic optimizations and routing approaches,using different sources of traffic information.

This Chapter is organized as follows. In Section 3.1 we give an overview of the different navigation systems, the technology behind them, and their evolution. In Section 3.2 we present traffic information and floating car data, explaining what they are and their uses. The final Section, 3.3, is about traffic flow optimization, giving an overview of the underlying theory, with a focus on simulation-based optimization.

3.1 Navigation Systems

Navigation systems are used to guide an entity from source to destination using spatial information. They can be found in any transportation system, from naval to aerial. This Chapter focusses on road-based systems. While navigation is the process that guides movement, navigation systems comprises the hardware and software components that facilitate automated and intelligent navigation. They require spatial data storage, positioning, communication, and processing technologies in order to provide their services.

The deployment of the Global Positioning System (GPS) has drastically improved modern navigation. It uses a system of satellites that provide geo-spatial positioning with global coverage. Using a receiver, it is possible to determine location in terms of longitude, latitude, and elevation, with high precision. The location is usually computed by triangulation, and as the name implies, to obtain precise information, the location must be covered by at least three satellites. The signals also allow the computation of the current time with high precision, allowing time synchronisation [103].

The availability of GPS and other positioning technologies revolutionized all forms of navigation, bringing the ability to accurately determine the position of moving objects, and creating a new generation of services known as location-based services [104].

Modern navigation devices are an integrated hardware and software system that uses information, such as position and orientation, together with computing power and communication capabilities, to facilitate movement from one place to another. They can be used to determine position, course, and distance travelled [105].

3.1.1 Automotive Navigation Systems

Many modern vehicles are equipped with devices that are capable of determining the current position, which is dynamically displayed and updated on a digital road map. When directions to a specific destination are required, the route can be calculated and, when information about real-time traffic is available, possibly adjusted. Navigation devices come in many forms, such as embedded navigation systems, portable navigator devices, on-board computers, or smartphones, all with location-enabled capabilities. From our perspective, the differences between them are not relevant, unless explicitly specified, and from now on we refer to them as navigation systems, or On-Board Units (OBUs).

Many OBUs are equipped with additional sensors such as a gyrocompass or an accelerometer. The use of this additional information enables navigation via dead reckoning when a GPS signal is temporarily unavailable [106].

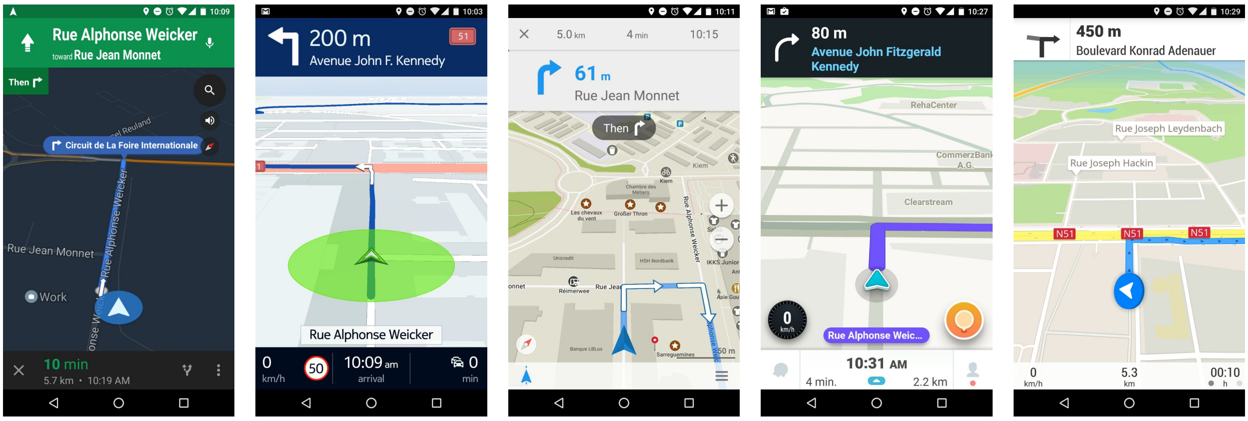
The software of navigation systems is based on a road database, usually defined as a vector map, where street names and house numbers are encoded as geographic coordinates that allow the user to find most desired destinations by street address. Following the same principle, points of interest such as restaurants, museums, or filling stations are stored with their geographic coordinates, as well. [107]

Some OBUs can receive and display real-time information on traffic congestion by using either Traffic Message Channel[1], or by GPRS/3G [105]. The integration of traffic data in navigation systems' software occurs in many different ways, none of which are explicitly explained by the manufacturer. Nevertheless, many research papers have proposed various sources for real-time data and integration techniques. For example, in [101] the overall architecture and the possible applications of a real-time traffic information system are explained. This system uses GPS-based information collected from taxi fleets. The taxis are already equipped with GPS-enabled devices for fleet-management purposes, and, in addition, provide real-time traffic information. The overall traffic situation can be redistributed back to the vehicles in order to provide a realistic travel time. Another example is found in [108], where the authors discuss traffic estimation and prediction based on real-time traffic information. They propose two algorithms based on artificial neural networks and pattern-matching to perform short-term predictions of link travel speeds in real time, and a system to deliver this information throughout the Italian motorway network.

Applications Usually, a navigation software is able to indicate the routes available, proposing alternatives based on real-time or historical data, and compute the best route between the two locations based on a selection of options, such as shortest or fastest path, and whether highways or back roads should be used. In many cases they show points of interest such as restaurants, banks, hotels, filling stations, airports and more.

One of the standard interaction patterns with the user is turn-by-turn navigation [109], where the directions for a selected route are continually presented in the form of spoken and visual instructions. The idea is to keep the user up to date about the best route to the destination, and also when it is updated according to factors such as unexpected changes in the current position, traffic, and road conditions.

[1]Traffic Message Channel (TMC) is a technology for delivering traffic and travel information to vehicles. It is digitally coded and carried via conventional FM radio broadcasts. It can also be transmitted on Digital Audio Broadcasting or satellite radio. TMC allows silent delivery of dynamic information without interrupting audio broadcast services.



(a) Google Maps (b) HERE Maps (c) MAPS.ME (d) Waze (e) Scout

Figure 3.1: Mobile mapping and navigation applications.

Navigation capabilities for mobile phones include both on-line and off-line applications. On-line applications require a constant connection to the Internet, while off-line implementations usually download the maps in advance and compute the route on the fly. Obviously, an application that is off-line cannot provide real-time traffic information. Because of applications such as Google Maps Navigation [110] and Apple Maps [111], which are included in the respective operative system by default, most smartphone users only need their phone in order to have a personal navigation assistant. There are many other applications designed for mapping and navigation purposes for all mobile operative systems; among them, the most used are Waze [112], HERE Maps [113], MapFactor [114], MapQuest [115], Sygic [116], Navigon [117], Scout [118], CoPilot [119], Garmin [120], MotionX GPS [121], and MAPS.ME [122]. In Figure 3.1 we see the navigation interfaces of some of these applications. All mapping and navigation applications provide roughly the same features, but they may vary in off-line capabilities, usability, and implementation details.

Automatic Vehicle Location The technology used in navigation systems enables Automatic Vehicle Location (AVL), where the geographical location of a vehicle is transmitted to a tracking system for monitoring or coordination purposes.

AVL systems are used to manage fleets and track mobile assets. For example, an ambulance fleet has the objective of arriving on location within a specific time-frame upon receiving a request. The use of an AVL system allows the evaluation of all available vehicles in order to select the one that is most likely to arrive at the destination soonest.

Some uses for AVL are:

- *Fleet management* [123, 124] and *asset tracking* [125, 126]: the use of the real-time location of all vehicles allows management to meet customer needs more efficiently, or simply to monitor movement and operating status.
- *Passenger Information* [127, 128]: in the case of public transport services, real-time passenger information such as expected arrival and departure times is based on AVL.

- *Emergency vehicles* [129, 130]: in the case of disasters and emergencies, the use of AVL systems enable coordination and optimization of the resources available, providing the best coverage of the affected area.

More importantly for our purposes, an OBU with AVL capabilities, would provide the optimal set-up for collecting traffic information and distributing optimized suggestions to their users.

3.1.2 Privacy and tracking issues

Due to the popularity of location-enabled devices and applications, privacy of the user is a "hot topic" and a subject of debate. Strict ethical and security measures are strongly recommended for services that employ positioning, but regulations lag far behind the capabilities of technologies easily available to end users. Geo-location data should be considered sensitive information, but regulators are still debating on the details of the laws involved. Furthermore, implementation and enforcement of the policies may vary depending on the country. Usually, location-sensitive data[2] should not be stored, since this amounts to a privacy violation. However, depending on details and formulation of the laws, in some countries private companies have permission to store location-sensitive data.

In case of traffic management systems and routing optimization targeted to the general user, the standard information required is composed of the desired destination and the current location. Additionally, the traffic information is stored to provide a real-time overview of the traffic situation. In this context, the issues concerning privacy and tracking cannot be ignored. The discussion about location privacy in pervasive computing presents a trade-off between the convenience of location-aware applications, able to track our movements in order to provide better services, and the protection of our privacy. Some possible solutions are based on anonymous communication techniques together with metrics for assessing user anonymity [131]. In order to protect personal location information, a mechanism that provides users with direct control over their location information must be in place. The mechanism should minimize the extent to which the system intrudes on their lives, but require awareness from the user's side [132]. Context-aware computing that involves tracking a user's locations is usually based upon two types of location-based services: (i) location-tracking services that use the services of other parties to track the user's location, and (ii) position-aware services that rely on the device's knowledge of its own location. In [133] the authors study people's concern for location privacy and compare it to the use of location-based services. They find that the perceived usefulness of the two different types of services is the same, but location-tracking services generate more concern over privacy than position-aware services.

There is no definitive solution concerning privacy issues. The levels of privacy and anonymity change depending on legislation and the specific applications or technologies in use. The trade-off between the quality of service provided and the level of privacy maintained cannot be avoided.

3.2 Historical and Real-Time Traffic Information

The use of traditional on-road sensors for collecting traffic data is a necessary part of a traffic monitoring infrastructure, but not sufficient, due to their limited coverage, and high costs for deployment and maintenance. In addition, many on-road sensors are not designed to provide real-time

[2] Precise geographical data that pinpoints over time the whereabouts and/or the surroundings.

information; and importantly, particular sensors may be deployed for various specific purposes by multiple authorities, making extremely difficult integrate their data in order to obtain a picture of the overall traffic situation. Recent years have seen the emergence of alternative sources as a result of the evolution of mobile devices (e.g. on-board computers and smartphones). For example, the use of traffic information collected directly by vehicles is a promising solution to improve and complement the data collected from fixed detectors.

FCD is the information generated by one vehicle, usually composed of basic telemetry information such as speed, direction, and position. The FCD generated by moving vehicles can be used for road safety applications, in-vehicle diagnostics, traffic monitoring and more. FCD allows overall traffic conditions to be assessed and may provide a tracking method for the device in question [99]. The positional data collected over time is referred to as vehicle tracking data. FCD can be obtained using any location-enabled device. The accuracy of the data gathered depends on the hardware (and software) used to collect it. Depending on the collection method and data accuracy, more or less sophisticated algorithms must be used to filter and aggregate FCD [102,134], to match tracking data to a road network, and to use it in various applications. The tracking data can be modelled as a trajectory through interpolation [135]. FCD is a powerful means to assessing traffic conditions in urban areas, and when data is collected from vehicle fleets such as taxis, public transport and utility vehicles, it is possible to avoid some of the privacy issues raised by collecting data from private vehicles. Given the current lack of dedicated equipment and mature vehicular communication technologies deployed for the general public, FCD can be gathered and distributed using available communication technologies, such as Wi-Fi and cellular. When FCD is gathered and distributed in real time, it can be used to gather accurate travel times and speeds in a road network to detect obstruction in the traffic flow, to improve short-term predictions of travel conditions, and to compute optimal routes for selected vehicles.

The ideal traffic monitoring system is based on historical data and real-time traffic information. Usually the historical information is gathered through on-road detectors, and the real-time traffic situation uses live sensors and FCD. Our aim is to build and use a dependable traffic overview to study the impact of dynamic routing on traffic congestion.

3.2.1 Traffic Information Detectors

Stationary data is captured on the road by static detectors. The collected information is provided either directly as single-vehicle data or aggregated into macroscopic information. Only traffic density can be measured with a single traffic detector; other quantities (e.g. speed, vehicle type) require multiple detectors, and several estimation methods are available. A single detector usually can directly provide only a snapshot of the situation of a given time. Most detectors aggregate the microscopic single-vehicle data by averaging over fixed time intervals, but macroscopic data (aggregated data) can also be computed by using multiple detectors. Among the quantities collected, traffic flow, occupancy, arithmetic mean speed, and speed variance are the most common [1]. All the data gathered by these sources can be used as historical traffic information.

In table 3.1 we provide a brief overview of conventional road detector types, and here we summarize the technology involved [136,137].

Table 3.1: Road detectors specifications.

Name	Measurements	Known Issues
Inductive loops	Count, speed*, classification†, occupancy, presence	Difficulty differentiating between closely spaced vehicles, easily damaged by heavy vehicles, implementation and maintenance costs can be expensive.
Magnetic	Count, speed*, classification†, occupancy, presence	Easily damaged by heavy vehicles, implementation and maintenance costs can be expensive.
Pneumatic road tubes	Count, speed, classification	Limited lane coverage, the efficiency is subject to weather, temperature and it is not efficient in measuring low speed flows.
Active infrared	Count, speed, classification	Limited lane coverage, the efficiency is subject to weather conditions.
Passive infrared	Count, speed*, classification, occupancy, presence	Limited lane coverage, the efficiency is subject to weather conditions.
Microwave radar	Count, speed, classification, occupancy, presence	
Ultrasonic	Count, presence	Limited lane coverage, the efficiency is subject to weather conditions.
Passive acoustic	Count, speed, classification, occupancy, presence	Limited lane coverage, the efficiency is subject to weather conditions.
Video image processing	Count, speed, classification, occupancy, presence	Efficiency is subject to weather conditions.
Note:	(*) Multiple detectors are required to measure the quantity. (†) Classification performed through vehicle signature.	

- Magnetic loops [138]: the most conventional technology used to collect traffic data. The loops are embedded in roadways in a square formation that generates a magnetic field. The information is then recorded by a counting device placed on the side of the road.

- Pneumatic road tubes [139]: plastic tubes are placed under the road. The detection is based on pressure changes that are produced when a vehicle tyre passes over the tube. The flow of air that is created is measured by a counter located on the side of the road.

- Piezoelectric sensors [140]: the sensors are placed along roadway surface. They convert mechanical energy into electrical. The mechanical deformation modifies the surface charge density of the material so that a potential difference appears between the electrodes. The amplitude and frequency of the signal are directly proportional to the degree of deformation.

- Microwave radar [141]: this technology can detect moving vehicles and speed using the Doppler effect.

- Ultrasonic and passive acoustic [137]: these devices emit sound waves to detect vehicles by measuring the time taken for the signal to return to the device. Ultrasonic sensors are placed over the lane and passive acoustic devices are installed along the road.
- Passive and active infrared [142]: infrared energy radiating from or reflected by the detection area is recorded and processed to obtain the measurements.
- Video image detection [143]: video cameras record and process images of a roadway to retrieve traffic-related measurements.

The improvement of traffic monitoring and management systems requires a vast amount of high-quality traffic information, possibly in real time. Given that the use of traditional on-road sensors is not sufficient because of their limited coverage and high costs, recent years have seen an exploration of alternative data sources. The idea of collecting data through smartphones and location-enabled devices is not new, but has only recently seen widespread a wide range of applications and benefits [136].

3.2.2 Floating Car Data

As previously mentioned, FCD are collected using probe vehicles moving in the traffic stream. The probe vehicles collect geo-referenced information over time, including location, speed and direction of travel. After being collected and processed (usually map-matched to a road and aggregated), useful information such as the status of traffic can be redistributed to the drivers on the road.

A problem that must be taken into account is that many equipped vehicles are part of a commercial fleet, which may not be representative of traffic as a whole, because of specific driving patterns, or due to the lower maximum speed allowed for trucks and so on. However, it has been proven that this issue is not relevant in congested situations, where free-flow speed differences do not matter [1].

When the probe vehicles retrieve additional data from On-Board Diagnostic (OBD) devices, the augmented information is also referred to as extended Floating Car Data (xFCD). The additional metrics can include the distance to the leading vehicle, position of the accelerator and brake pedals, activation of turning signals, and the rotation angle of the steering wheel. In principle, every quantity available via the vehicle's Controller Area Network bus (CAN-bus) can be recorded in the xFCD [144]. The main difference between FCD and xFCD is that FCD is mainly used to determine traffic conditions, providing a macroscopic view of the system; xFCD is used to collect individual vehicle data that provide a microscopic view of the environment that closely surround the vehicle itself. The information provided by standard FCD is sufficient for our traffic optimization purposes.

When compared with existing technologies, FCD is an alternative, or rather, a complementary source of high-quality data, able to help improve the safety, efficiency and reliability of the transportation system. The quality of the OBUs used to collect FCD may vary depending on the hardware and software available. One of the main components that we need to be highly accurate is the GPS.

In case of OBUs using external GPS devices, the precision of the location is relatively high, but so far only a limited number of vehicles are equipped with this system; typically these are part of a fleet management service. In the case of urban traffic, taxi fleets are particularly useful because their data is widely used as a source of real-time information by many service providers, but it suffers from

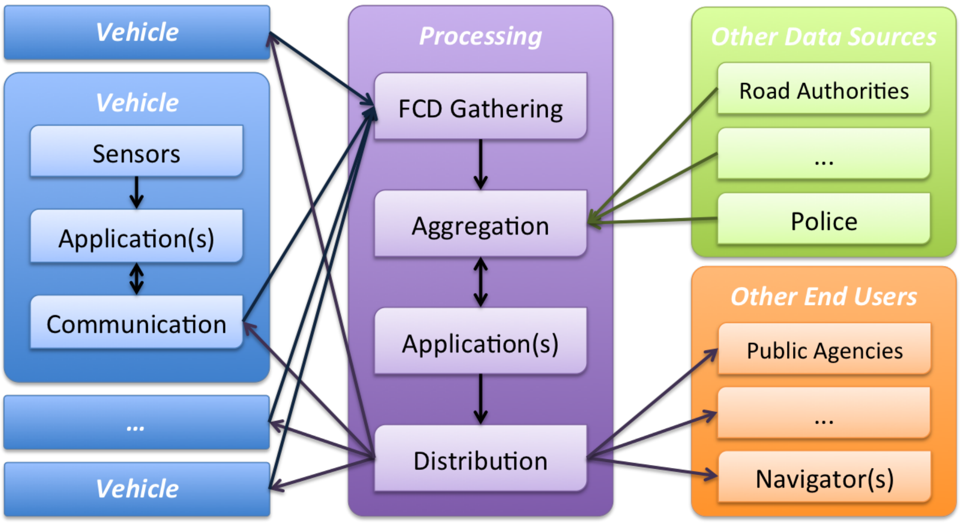


Figure 3.2: Example of traffic information processing flow.

a limited number of equipped vehicles and high equipment costs compared to FCD gathered from cellular data. Moreover, they usually do not provide accurate information on motorways and rural areas [101].

Taking into account the widespread use of smartphones nowadays, it may be worthwhile using them as anonymous traffic probes. Their position is usually computed by means of triangulation or by other techniques [145], and further data can be sampled or estimated using the sensors built into the devices. In order for this to be possible, smartphones need to be turned on, but not necessarily in use. This approach has proved to be well adapted to deliver relatively accurate information in urban areas due to the lower distance between antennas [146]. Given that no special hardware is necessary, the use of smartphones has proved to be less expensive than conventional detectors and offers greater coverage capabilities.

FCD can be gathered through crowd-sourcing [100, 147, 148]. In this way the effort of numerous volunteers and/or users is combined to achieve a cumulative result. Crowd-sourcing information usually lowers costs and provides flexibility and scalability, although the quality and diversity of the information must be addressed on a case-to-case basis. Even though the location precision is generally low, this weakness is partially compensated by the large number of devices, provided that sophisticated algorithms are used to extract and treat both low- and high-quality data before it is used [102, 134].

FCD processing flow In the best-case scenario, these improvements will affect all transportation actors, although to different degrees. Nevertheless, as illustrated in Figure 3.2, sampling, gathering, processing and distributing the information is complex, and should not be underestimated [102]. Communication should be bidirectional in order to collect data from the vehicles and to redistribute it once processed. Depending on the technology in use, some problems may be still open [149, 150]. Moreover, the methodologies used to extract and aggregate the information are far from being trivial. Accuracy plays a fundamental role when reconstructing trajectories and mapping the data to a road network [102, 134]. The aggregation of the FCD with other sources of traffic information can be even more problematic when standards and metrics are heterogeneous [134]. Reverse geo-coding is an expensive problem to solve, more so when taking into account the large volume of information that must be handled efficiently [151]. Lastly, it is possible that not all the journeys being undertaken are relevant to the issue at hand; in this case they must be filtered out. In many circumstances, to tackle privacy issues, transmission and processing costs at the origin, it would be preferable to transmit anonymized, filtered, aggregated, and compressed data, rather than individual values [152].

In the literature, there are many proposals for systems able to handle large-scale intelligent transportation systems based on FCD; here we present one of the most recent, SmartCar (SMARTphone-based floating CAR data collection) [153] as an example. The work presents a system able to support augmented FCD through smartphone-based crowd-sensing. The authors show that off-the-shelf consumer devices and standard networking technologies (such as Wi-Fi and cellular) can compensate for the current lack of dedicated equipment and mature vehicular communication technologies. The proposed platform contributes to the support of early ITS applications on a large scale through the use of smartphones to collect extended FCD from in-vehicle metrics and external sensors, together with an offloading strategy based on Wi-Fi hotspots to alleviate the load on the cellular network. A prototype was implemented and results from preliminary field trials were corroborated with a large-scale simulation exercise under realistic settings.

Accuracy and sampling issues The level of accuracy expected from FCD depends on many factors, such as the positioning errors, the precision of the sensors embedded in the smartphones, and the metrics collectable from the in-vehicle devices. The methods used to calculate the smartphone location vary considerably and the impact of weather conditions is non-negligible both in location and in communication issues. Obviously, any errors in the location or in additional information could significantly affect the estimates of traffic flows. Moreover, the problem of determining the minimum number of vehicles that should be tracked, as well as the proper time intervals, are critical factors that must be considered if a reliable overview of the traffic conditions is to be obtained [136].

Over the years, a wide number of studies [154–156] have addressed problems such as accuracy, sample size, and timing issues associated with FCD, by comparing different measurements methods with regard to sampling time optimization, speed and travel times estimates, and so on. However, the problems are not yet solved and further effort is still needed. Nevertheless, FCD can be stored and used to perform historical data analysis, where the lack of full coverage in real-time is not an issue.

Privacy concerns As discussed in Section 3.1.2 concerning location data, the use of FCD raises many concerns about privacy issues. The usual questions involve the type of data that is collected, who is collecting it, when it is collected, and how long the devices are monitored and the data is stored. These are fundamental issues for probe-vehicle systems, so several approaches have been implemented to make FCD systems anonymous [152, 157, 158]. Nevertheless, concern over the treatment of personal data from the user perspective has yet to be fully addressed. A solution must include clear policy messages to gain users' trust, and even respecting the laws, the phone operators are hesitant about exploiting their clients' data. The lack of standard procedures common to all service providers could be a source of public distrust of this technology. The ownership of the data is another issue that cannot be globally solved because it is closely linked to legislation, and, for a similar reason, the

Table 3.2: Wireless technologies for V2V and V2I communications.

	Wi-Fi	802.11p	LTE
Frequency	2.4 and 5.2 GHz	5.86 - 5.92 GHz	700 - 2690 MHz
Bit rate	6 - 54 Mb/s	3 - 27 Mb/s	Up to 300 Mb/s
Range	Up to 100 m	Up to 1 km	Up to 30 km
Coverage	Intermittent	Intermittent	Ubiquitous
Mobility	Low	Medium	High
V2I	Yes	Yes	Yes
V2V	Yes	Yes	No
Availability	High	Low	Medium

policies concerning sharing the information present critical issues that must be dealt with in a fast and effective way, given the rapid growth of the market.

Applications While keeping the limitations of FCD in mind, the use of accurate and relevant real-time traffic information leads to improvements in many areas [136]. For example, in urban planning FCD is used to improve Origin-Destination (O-D) matrices in commuter plans, to plan for future investments, to optimize existing infrastructure through better use of the available resources, and to open new perspectives in transport modelling through short-term predictions. Other examples in the traffic management sector include the reduction of chronic congestion, the detection of traffic queues, improved accident management, and the use of dynamic traffic control mechanisms. Improvement and optimizations can be made to information services such as traffic information, dynamic route guidance, or variable road message signs. In addition, through better information distribution, it is possible to diminish the travel costs by reducing driving times and fuel consumption, and to reduce pollution and emissions.

3.2.3 FCD Gathering and Distribution

FCD is usually collected by vehicles and uploaded to processing centres using Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) technologies. The main wireless technologies for on-the-road communications are summarized in Table 3.2.

Dedicated Short Range Communications and 802.11p Dedicated Short Range Communication (DSRC) are short-range to medium-range wireless communication channels specifically designed for automotive use. They are mainly used for vehicle safety applications (e.g. cooperative forward collision warning, and intersection collision avoidance), because both V2V and V2I communications need short time delays and secure, wireless interface dependability in extreme weather conditions. Among other uses for DSRC technology, we can find cooperative adaptive cruise control and platooning[3],

[3] Platoons decrease the distances between vehicles using electronic or mechanical coupling. Grouping vehicles into platoons can be used to increase the capacity of roads.

transit or emergency vehicle signal priority, electronic parking payments and electronic toll collection, and last, but not least for our purposes, for probe data collection [159, 160].

In Vehicular Ad Hoc Network (VANET) communications, the main protocol used is IEEE 802.11p, an approved amendment to the IEEE 802.11 standard adding capabilities suited to Wireless Access in Vehicular Environment (WAVE), for a vehicular communication system [161]. These include data exchange between high-speed vehicles (V2V) and between the vehicles and the roadside infrastructure (V2I) in the licensed ITS band. IEEE 1609 is a family of higher layer standards based on IEEE 802.11p being formulated by the 1609 Dedicated Short Range Communication Working Group [162].

LTE Although DSRC is considered the most appropriate standard for on-the-road communications, the VANET community has started to investigate the usability of Long Term Evolution (LTE) to support vehicular applications. There is an agreement in the community on taking advantage of the strengths of LTE (high capacity, wide coverage, high penetration) to counter the well-known drawbacks of 802.11p (low capacity, intermittent connectivity) [163]. During the initial deployment phase of vehicular networks, LTE will probably play a critical role in overcoming situations where no 802.11p-equipped vehicle is within transmission range. In addition, LTE can be helpful at intersections by enabling reliable cross-traffic assistance applications, when 802.11p communications suffer from non-line-of-sight conditions due to obstacles. The wide coverage of LTE can be beneficially exploited for the reliable gathering and dissemination of safety messages and traffic information over large areas. Nevertheless, the impact on the current LTE traffic of using LTE for vehicular communication has yet to be studied. A broader understanding of LTE performance and its practical capacity is still required. Moreover, architectural design, vehicular device deployment, and resource management would be completely different between LTE and DSRC, and more standardization would be required.

Meanwhile, projects such as LTE4V2X [164], LTE for a Centralized VANET Organization, and VEINS-LTE [165], a VANET-specific implementation based on SimuLTE [166], are frameworks that allow the study of a centralized vehicular network organization using LTE. LTE4V2X uses the NS-3 simulation environment and VEINS-LTE uses Objective Modular Network Testbed in C++ (OMNet++); both require a realistic urban mobility model in order to provide reliable data.

Mixed Traffic and Wi-Fi Offload As previously mentioned, in order to use LTE technology for VANET applications is necessary to analyse its impact on existing LTE communications. VANET communications are characterized by high frequency and small data size, which occupy network resources frequently and may have an impact on other LTE services, such as Human to Human (H2H) traffic, which is characterized by low frequency and large data size. In [167], the authors design a new FCD transmission scheme for LTE-VANET heterogeneous networks and evaluate its impact on H2H traffic. Their results show that compared to other schemes, they managed to lower the impact of LTE-VANET transmission on traditional H2H cellular traffic. However, this result is achieved by increasing the overhead on the VANET.

Wi-Fi offload is an alternative mechanism used to decrease the impact of LTE-VANET communications on H2H cellular traffic. In [168], the authors present an analytical framework for offloading cellular traffic using an outdoor Wi-Fi network in the vehicular environment. They consider a generic vehicular user with Poisson data service arrivals downloading/uploading data from/to the Internet using either the cost-effective Wi-Fi network or, should that not be available, the cellular network, which provides full service coverage. They validate the analytical framework through simulations based on VANETMobisim [71] and real-world map data sets. This framework can be used to provide guidelines to both vehicular users and network operators.

Assuming that we have a means for obtaining reliable traffic information, our focus moves to traffic flow optimization in order to provide a dynamic routing scheme able to alleviate traffic congestion. In the following Section we discuss the role of traffic optimization in the context of modelling realistic mobility patterns and obtaining dependable simulation scenarios.

3.3 Traffic Flow Optimization

In mathematics and computer science, an optimization problem presents the issue of finding the best solution among all feasible ones. In traffic flow optimization, usually we have to minimize or maximize a cost function, where the cost definition varies depending on the problem. Every optimization problem requires the collection of metrics necessary to quantify the impact of the different solutions.

Given that we are interested in minimizing traffic congestion in urban environments, metrics such as average speed, travel time, waiting time, and distance travelled are usually used, due to their direct impact on travellers, and because they are easily quantifiable. For example, there is a correlation between travel time and congestion, because in congested traffic speed is reduced and waiting times are higher; hence, travel time increases. A typical approach may use the data, previously obtained by simulations and/or observations, to minimize the travel time by changing parameters and vehicle behaviour. Depending on the aggregation level and the amount of detail available, there are several usable macroscopic and microscopic models.

The main methods used to optimize the traffic are *transportation planning* done ahead of time, *modification of infrastructure* done to alleviate structural issues, and *behavioural changes* that can be done on-demand and in real time in order to face a transient issue. Given that changes in one measure influences the others, all must be studied and used together.

Transportation planning measures and the modification of infrastructure are intended to provide static control of the spatial and temporal traffic demand [169]. They act mainly over long time-scales. Examples include constructing new roads, improving or removing existing roads, or implementing new traffic regulations. For static but temporary bottlenecks due to construction sites or similar occurrences and events, the problem can be alleviated by shifting the main activities to periods with low traffic volume. Behavioural changes may include vehicle tolls to enter the inner-city limits, car-pool lanes reserved for vehicles transporting two or more persons, or initiatives to shift the modal split away from vehicular traffic. For example, the presence of bicycle sharing services, and the construction of bicycle and pedestrian paths would improve short-range mobility; or in case of public transport, improvements such as the introduction of more buses, trams, or train lines, optimization of the frequency of service, building Park & Ride car parks, or prioritizing public transport at intersections, would greatly impact the mobility in the city.

In contrast to static changes, dynamic control measures depend on the traffic situation [170]. These include dynamic routing by road signs or mobile devices when the principal route is congested. For example, when the traffic flow on the main road is on the verge of breakdown, a control measure is ramp metering, where the incoming traffic is temporarily reduced (or blocked) to mitigate the congestion ahead. Some congested situations are due to local disturbances that may be caused by abrupt lane changes, braking manoeuvres, or other un-anticipated actions. In cities, many examples of such phenomena are observed in the proximity of temporary obstruction and pedestrian crossings [171]. The most widespread measures used to mitigate these local perturbations are speed limits, and overtaking bans applied in a selective manner (i.e. only if there is high traffic volume, or at specific hours).

Another approach to the evaluation of measures that can increase efficiency and stability of traffic flows is based on the main actors within the optimization of the existing road infrastructure. These can be divided into two main categories: road-based and vehicle-based optimizations.

Road-based measures are flow-based, and are intended to affect all the vehicles (or a specific subset of them) travelling in a distinct geographical location, possibly during limited hours. Some examples of road-based measures are variable message signs for traffic-adaptive speed limits, dynamic routing, ramp metering and others.

On the other hand, *vehicle-based measures* are specific to a user or a class of users. They have recently entered the market and are expected to have a significant market penetration (and influence) in the near future. Examples of vehicle-based measures are considerably more interesting than road-based from our point of view. They include automated driving, adaptive cruise control, individual traffic-adaptive navigation, traffic-light assistants, and other driver-assistance systems.

From the analysis of traffic flows, it is possible to conclude that most traffic breakdowns are caused by the action of one or all of the following factors [1]: (i) high traffic demand in relation to road capacity, (ii) local reduction of the road capacity (bottleneck), and (iii) local perturbations in the traffic flow itself (phantom jams). Consequently, traffic-flow optimization aims to remove or reduce at least one of these factors.

3.3.1 Traffic Assignment

With traffic assignment, we refer to the process of allocating a given set of trips to the specified transportation system. Its main aim is to reproduce the pattern of vehicular movements in the transportation system, matching those that would be observed when the travel demand is satisfied. Among the problems that traffic assignment procedures are intended to solve, we find the estimation of traffic volumes, the main routes used between Origin-Destination (O-D) pairs, and the collection of overall metrics from the model [172]. The estimation of traffic volume on links can be used to identify heavily congested links. The routes computed between O-D pairs are used to assess travel costs and, more generally, zone-to-zone costs. Once the model has been created, network metrics such as vehicular flows, distance covered by the vehicles, and system travel time can be obtained.

Wardrop Principles of Equilibrium In studies of traffic assignment in transportation networks that are subject to congestion, various network equilibrium models are commonly used for the prediction of traffic patterns. In 1952, John Glen Wardrop, an English mathematician and transport analyst, stated two principles that formalize the notion of equilibrium in case of vehicular mobility [16].

Wardrop's first principle states that the journey times in all routes actually used are equal and less than those that would be experienced by a single vehicle on any unused route. Each user non-

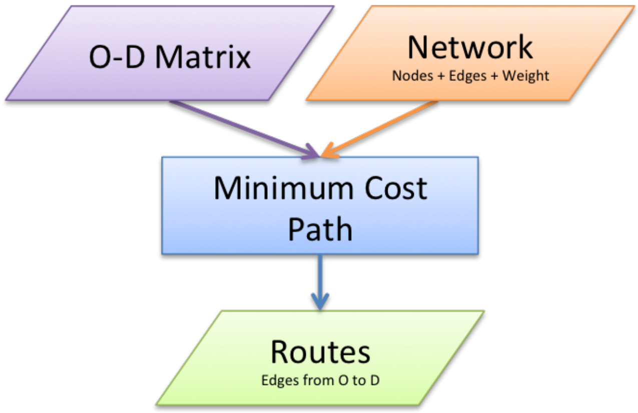


Figure 3.3: Minimum Cost Path Assignment diagram.

cooperatively seeks to minimize his cost of transportation. The traffic flows that satisfy this principle are usually referred to as *user equilibrium* flows, since each user chooses the route that is the best. Specifically, a user-optimized equilibrium is reached when no user may lower his transportation cost through unilateral action. Wardrop's first principle of route choice, which is identical to the notion postulated by Knight, became accepted as a sound and simple behavioural principle to describe the spreading of trips over alternate routes due to congested conditions [173].

Wardrop's second principle states that, at equilibrium, the average journey time is at its minimum. In congested networks, under equilibrium conditions, traffic arranges itself in such a way that no individual trip maker can reduce his path costs by switching routes. This implies that all users behave cooperatively in choosing their routes, to ensure the most efficient use of the whole system. Traffic flows satisfying Wardrop's second principle are generally deemed system-optimal. An example of this global coordination can be used to optimize a system in the case of fully-automated driving.

Various traffic assignment methods have been studied; we give an overview of them below. The concepts presented in this section provide the basis for simulation-based traffic assignment, the method chosen to tackle our traffic optimization problem.

Minimum Cost Path Assignment This method is among the least sophisticated, but its simplicity enables its most important practical application: it is a building block for other types of more complex assignment techniques. As suggested by its name, this assignment method computes the minimum cost path for each O-D pair [172]. On its own, this model is unrealistic because only one path between every O-D pair is used; if there is another path with the same or similar travel cost, it is discarded. The traffic on the links is assigned without any consideration of adequate capacity or heavy congestion; the departure time is a fixed input and does not vary with the congestion. Nevertheless, this method presents a reasonable approximation to normal human behaviour and is used to identify the route that the drivers would be most likely to use in the absence of congestion.

Figure 3.3 shows a graphical representation of the minimum cost path assignment method. Given that the status of the network is immutable, the departure time parameter is ignored.

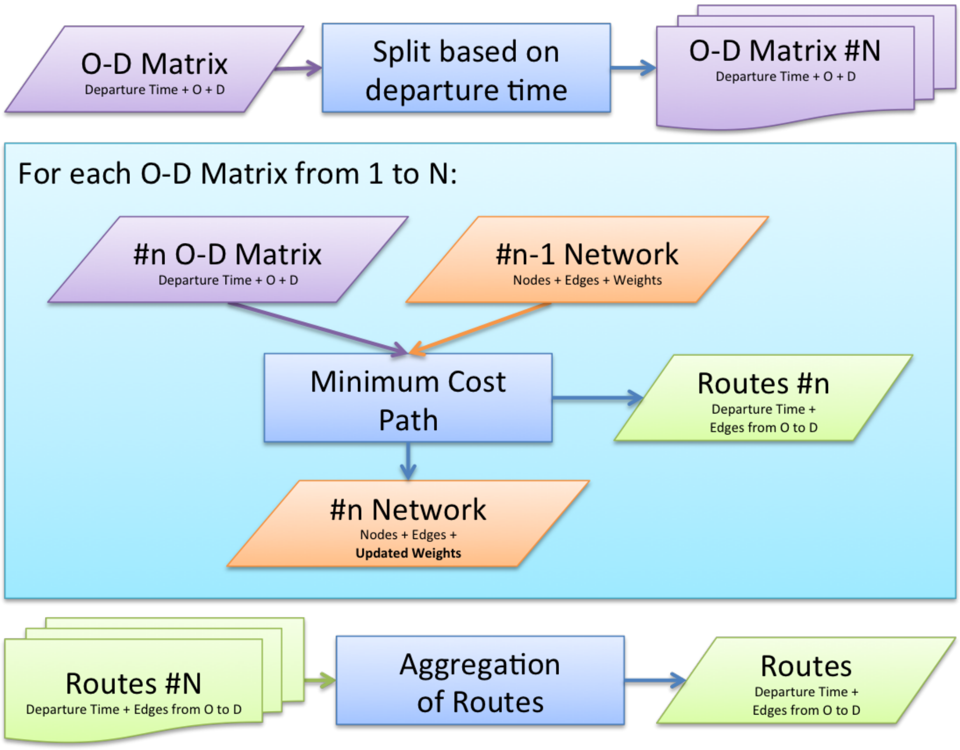
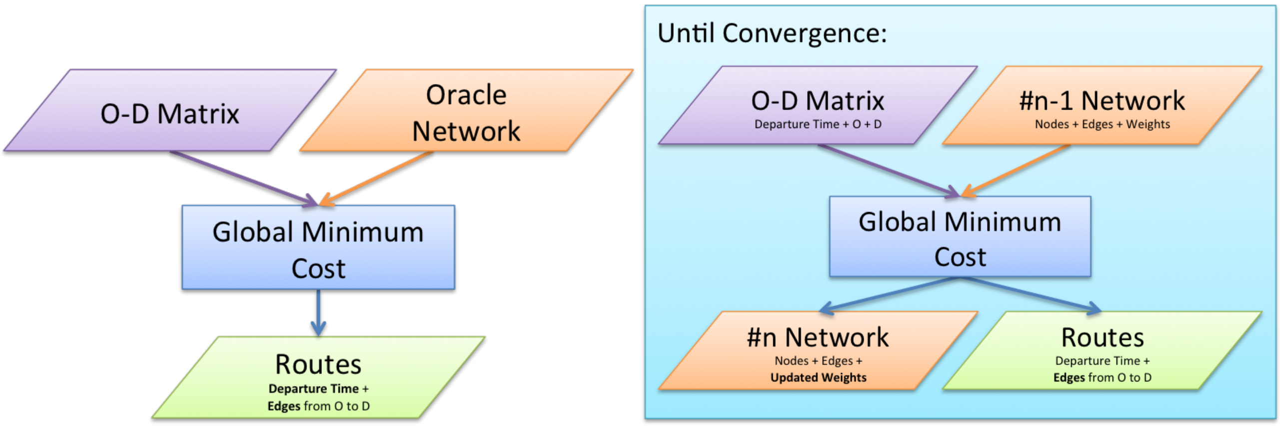


Figure 3.4: Incremental Assignment diagram.

Incremental Assignment The incremental assignment method divides the total traffic volume into fractions based on the departure time for each trip, and every fraction is assigned in steps. For each step, a fixed proportion of total demand is assigned using the minimum cost path assignment presented above [172]. After each step, the new cost assigned to the links (e.g. travel time, traffic volume, waiting time, average speed) is recalculated based on the assigned traffic. The process finishes when all the traffic demand has been assigned. Using an elevated number of increments, the resultant flows may resemble a traffic equilibrium; however, this method does not yield an equilibrium solution. The outcome of the incremental assignment is influenced by the order in which volumes for O-D pairs are assigned, creating the possibility of anomalies and bias in the results.

Figure 3.4 shows a graphical representation of the incremental assignment based on the minimum cost path assignment method. The basic assumption is that the weights in the initial network represent free-flow (or the empty network).

System Optimum Assignment The system optimum assignment is based on Wardrop's second principle [16], which states that drivers cooperate with one another in order to minimise total system travel time. This assignment can be thought of as a model in which congestion is minimised when drivers are told which routes to use. Obviously, this is not a behaviourally realistic model, but it can be useful to transport planners and engineers, who are trying to manage the traffic to minimise travel costs and therefore achieve an optimum social equilibrium. This represents the best possible scenario



(a) System Optimum Assignment. (b) Dynamic System Optimum Assignment.

Figure 3.5: System Optimum Assignment diagrams.

in which the infrastructure is used at its best and the users experience the least amount of congestion in their trips.

Dynamic System Optimum Assignment The dynamic version of system optimum assignment introduces constraints on the departure times of the vehicles. An example of system optimum assignment is presented in [174], where the authors attempt to obtain a solution for a centralized traffic management system in the case of congested traffic. They propose conceptual and mathematical formulations for various scenarios, based on the amount of information available to the traffic controller. They study the ideal case, where all the information is known; providing time-dependent origin-destination flows over the whole planning horizon. They propose extensions and variants of the basic formulation when the information available to the controller is incomplete.

Figures 3.5a and 3.5b show a graphical representation of both system optimum assignment methods. The basic assumption for the dynamic system optimum is that the weights in the initial network represent free-flow (or the empty network) and that the computation ends when the output routes converge. It is important to notice that, in the basic system optimum assignment, there are no constraints concerning departure time, and that the system has complete information on the status of the network at any time (Oracle Network). Here the resultant output represents the best possible usage of the infrastructure. For the dynamic version, the network used to compute each step is based on the previous iteration step, and the departure times are a constraints. These may be strictly defined or they may allow a time window, depending on the problem.

User Equilibrium Assignment The user equilibrium assignment is based on Wardrop's first principle [16], which states that no driver can unilaterally reduce the travel costs by changing the route. If it is assumed that drivers have perfect knowledge about travel costs on a network and choose the best route according to Wardrop's first principle; this behavioural assumption leads to deterministic user equilibrium.

Stochastic User Equilibrium Assignment In the user equilibrium assignment procedures based on Wardrop's principle is assumed that all drivers perceive costs in an identical manner. The stochastic assignment models explicitly allow non minimum-cost routes to be selected [175]. Virtually all such models assume that drivers' perception of costs on any given route are not identical and that the trips between each O-D pair are divided among the routes, with the cheapest route attracting most trips.

It has an important advantage over other models because it loads many routes between individual pairs of network nodes in a single pass through the tree building process. It results in assignments that are more stable and less sensitive to slight variations in network definitions or link costs. This assignment is most appropriate for use in uncongested traffic conditions such as in off-peak periods or lightly-trafficked rural areas.

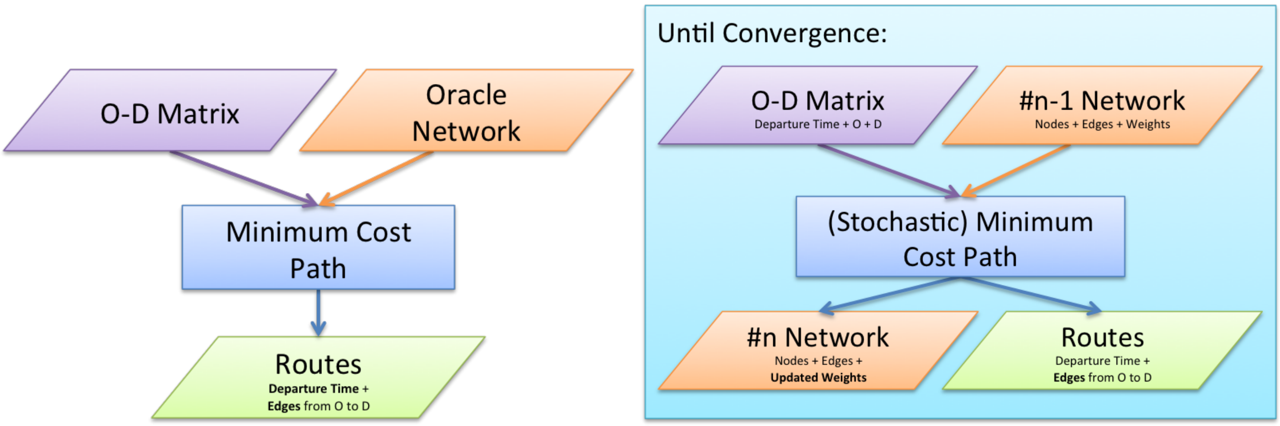
Dynamic User Equilibrium Assignment The Dynamic User Equilibrium (DUE) is formulated as the dynamic version of the Wardrop's user equilibrium: *If, for each O-D pair at each instant of time, the actual travel times experienced by travellers departing at the same time are equal and minimal, the dynamic traffic flow over the network is a time-based dynamic user equilibrium state.* The existence of such equilibria in complex networks has not been proven theoretically and, even if they do exist, the question of uniqueness remains open [176].

Nevertheless, various formulations and solutions for the DUE assignment problem have been studied, ranging from mathematical optimization, to optimal control, and simulation-based [177–179]. In [180] the authors present a dynamic traffic assignment heuristic that generates approximate solutions to DUE in an efficient manner for large networks. It is not a convergent solution algorithm for DUE, but has been designed to produce assignments that approximate the DUE optimality conditions.

Among the various solutions, Gawron's iterative algorithm [181] can be used to determine the DUE in a traffic simulation model. Each driver's route choice is modelled by a discrete probability distribution, which is used to select a route in the simulation. This method is widely-used because the algorithm does not depend on the simulation model.

Figures 3.6a and 3.6b show a graphical representation of the two user equilibrium assignment methods. The basic assumption for the dynamic user equilibrium is that the weights in the initial network represent free-flow (or the empty network) and that the computation ends when the output routes converges. It is important to notice that in the basic user equilibrium assignment there are no constraints concerning departure time and that the system has complete information on the status of the network at any time (Oracle Network). For the dynamic version, the network used to compute each step is based on the previous iteration step, and the departure times are a constraint. They may be strictly defined or may allow a time window, depending on the problem. To compute the dynamic user equilibrium, it is possible to use either minimum cost path assignment, or the stochastic version.

To achieve our goal, we need an efficient method to study traffic optimization in complex networks. For this reason, we decided to focus on simulation-based assignment and the impact of DUE.



(a) User Equilibrium Assignment. (b) Dynamic User Equilibrium Assignment.

Figure 3.6: User Equilibrium Assignment diagrams.

3.3.2 Simulation-based Dynamic User Equilibrium Assignment

When we want to solve a real-world problem concerning traffic optimization, we assume that the problem is highly disaggregated and the demand is given on a second-by-second basis. The network information may vary arbitrarily depending on the problem and available details.

For practical applications, the current analytical theory of simulation-based assignment requires improvement before it can address all practical cases. However, there is a recent consensus that such problems can be approached with detailed micro-simulations. Using micro-simulation, it is possible to study problems like uniqueness, variability, robustness, and the validation of various solutions [182].

The use of traffic simulation and a simulation-assignment methodology enables correct dynamic-flow modelling and practical evaluation of an otherwise intractable objective function, while accounting for issues related to time-dependent relationships [174].

Applications of Simulation-based Dynamic Traffic Assignment A milestone for simulation-based dynamic traffic assignment was attained by Mahut et al. in [183], where they present the method's calibration and application on a portion of the road network the city of Calgary in Alberta, Canada. Their model iteratively reassigns flow to paths by using the method of successive averages on the basis of travel times obtained with a traffic simulation model. They improved the original network extracted from a regional planning model by adding more zones and a more precise representation of arterial intersections, including traffic signal control plans. The detailed O-D matrix was estimated from an extensive database of turning movement counts via a trip generation/distribution model and a matrix adjustment algorithm.

Starting from Mahut approach, Florian et al. [184] evaluated on-line intelligent transportation system measures that depend on the use of faster-than-real-time traffic simulation models. They noticed that the testing of ITS strategies and planning studies is composed of repetitive and iterative operations, so they proposed a loading method for the time-dependent path flows that is able to provide reasonably accurate results with very little computational effort. They then applied the model to the

Stockholm road network, which consists of 2,100 links, 1,191 nodes, and 228 zones. Their results show that this model is applicable to medium-sized networks with a very reasonable computation time.

Remarks

Drivers are already using various navigation systems in their daily life to optimize their travel. In order to study and improve the traffic congestion in our cities, we need to build traffic monitoring and management systems capable of providing complete and reliable traffic information. On top of these, we can implement robust and efficient traffic optimization methods.

In this Chapter we have given an overview of the evolution of navigation systems over time and presented their requirements, limitations and their pervasive impact on the everyday life of drivers. We have summarized possible ways to collect traffic information and explained how the use of floating car data can be a powerful tool to build up-to-date traffic management systems. Lastly, we presented the theory behind traffic flow optimization and the importance of traffic assignment methods in the study of traffic management systems.

In the next Chapter we present a traffic optimization study on the feasibility and impact of dynamic vehicular rerouting on the overall traffic congestion detected in a system.

Chapter 4

Traffic Routing in Urban Environments

One of the most obvious methods for homogenizing traffic flow is to distribute the traffic demand more efficiently over the network using dynamic routing and load balancing. Because this strategy may prevent traffic breakdowns[1] through more efficient road usage, a detour may lead to a shorter travel time even if it would be longer in uncongested situations. In the literature, the meaning of dynamic routing varies depending on the context being discussing. One version of dynamic routing and optimization uses a fixed origin and destination for each trip, but allows the departure time to vary during the optimization [177, 185]. In our case, departure time, origin and destination of the trip are fixed, and our goal is to dynamically recompute a better route on the fly, using information about traffic congestion. Here we present a study of the impact of dynamic routing on traffic congestion in urban environments. This study has previously been published in two separate papers: *Improving traffic in urban environments applying the Wardrop equilibrium* [17] and *Traffic routing in urban environments: The impact of partial information* [18].

As presented at length in Chapter 2, the urban environment is characterised by short road segments and various types of intersections. Urban traffic comprises of different types of vehicles, pedestrians and unexpected obstacles. In recent decades, many models have been developed to describe and analyse complex vehicular mobility [186–189]. In order to match growing traffic demand, one possibility is to increase the capacity of the transportation network. This can be achieved by physically increasing the number of roads and their size; another option is to rearrange the topology of the network; or to optimize the usage of the resources already available. This last option can be achieved by collaborative traffic management systems that are able to orchestrate the routes of vehicles moving in metropolitan areas to reduce congestion.

We present a gathering protocol for the traffic information based on real-time Floating Car Data (FCD) and how to use it to dynamically change the routes of the vehicles involved. Several studies have recently proposed methods to efficiently sense traffic-relevant information [190–194]. The real-time FCD is aggregated to obtain an accurate and reliable overview of the traffic situation. Because the number of On-Board Unit (OBU), such as navigation systems and smart phones, has significantly increased over the years, this data can now be retrieved on a large scale, enabling the research community to explore other, more dynamic, approaches to improve traffic conditions. We then evaluate

[1] Traffic breakdown is the presence of congested traffic in an initial free traffic flow. Traffic breakdown occurs mostly at road bottlenecks like on and offramps, roadworks, reduction of road lanes, etc.

the protocol with different parameters and percentage of vehicles involved. Our final step is to evaluate the impact of the dynamic routing when the information collected is insufficient to provide a complete overview of the system.

In Section 4.1 of this Chapter we present a traffic management protocol used to gather traffic information and to enable efficient routing of the vehicles. Section 4.2 describes an extensive evaluation, and finally, in Section 4.3 we discuss and evaluate the impact of partial information on the presented routing mechanism. In Section 4.4 we discuss the contributions of this work to the scientific community.

4.1 Data Gathering and Routing Mechanism

The urban transportation infrastructure was designed decades ago to serve a defined amount of traffic. Nowadays, the number of vehicles has increased significantly and the road network frequently reaches its capacity limit during rush hours. The naïve solution to this problem consists in modifying and expanding the infrastructure to match the increasing demand. This solution is not always feasible due to lack of available space or limited resources. Moreover, the Braess paradox [195] states that increasing the overall capacity of a network when the traffic is not coordinated can reduce the overall system performance in some cases. The approach that we propose is to coordinate the traffic by modifying the routes of the vehicles in the city to efficiently exploit the transportation infrastructure to better serve the traffic demand. Our objective is to provide a traffic management protocol able to efficiently collect the FCD from the vehicles and provide the best route to the users. Much work has been done to define models, analyse traffic patterns and optimize traffic flows in metropolitan areas.

For example, NAVOPT [196] is a vehicular route optimiser that utilises traffic information gathered from vehicles to estimate travel times and to find optimal routes. It uses a Flow Deviation routing algorithm to compute optimal routes. NAVOPT improves average speed by about 25% compared to shortest-path routing and reduces total travel time by 40%. Transitr [197] is a system developed to reduce travel delays. The authors describe the development of a public transport trip planner for mobile devices and evaluate its performance. They predict the shortest paths between any two points in the transit network using real-time information provided by a third-party bus arrival prediction system. To assess the optimality and accuracy of the prediction they make an a posteriori comparison with a schedule-based transit trip planner and the GPS traces of the transit vehicles.

In [198], the authors describe a mathematical model used to show an adaptive control approach to relieve congestion and improve urban mobility. The basic idea consists in dividing the city into neighbourhoods of dimensions comparable to trip length and to shift the modelling emphasis from microscopic predictions to macroscopic monitoring and control. They propose this idea and also discuss the relation to reality and the need for validation of its assumptions. In [15], the authors model vehicular dynamics using cellular automata associated with a congestion-aware vehicle routing strategy similar to that used in the Internet. This model is based on agents able to communicate among themselves to build local knowledge. The congestion-aware strategy is based on the level of local knowledge of the agents and their decision to chose a less-congested route. In [14] the authors evaluate different stigmergy strategies[2] in relation to the traffic management. In their system vehicles share dynamic information and drivers can dynamically chose their route. They model the real-time

[2]Stigmergy is a mechanism of indirect coordination among agents based on the environment. In principle, a trace left in the environment enables actions by the same or a different agent.

information as a stigmergy. They propose anticipatory stigmergy for sharing information, which is validated by an allocation strategy that decides the assignment of drivers who can use the recommended route. The aim is to study the expiration time and the communication radius of the information shared among the agents' and so achieve better traffic management. An algorithmic solution to the Closed-loop Adaptive Shortest Path Routing Problem (CASPRP) is discussed in [13]. The authors solve this formulation of the problem using dynamic programming with an approximate probabilistic treatment for the labelling of the classic shortest path problem. This algorithm does not provide the full route to follow, but instead indicates the best next road segment. The authors assume complete global knowledge in terms of topology of the network and current estimates of travel times on individual link. The travel time is modelled as a random variable with its mean and standard deviation predicted on the basis of a priori historical travel time information. An evaluation of the differences between the proposed algorithm and other routing algorithms is presented.

Among the possible routing strategies, we chose to base ours on Wardrop's first principle of equilibrium. A theoretical mathematical model is presented in [199], where the aim is to find a Wardrop equilibrium in transport networks in the case of uncertain situations. The authors investigate user-optimized and system-optimised transportation networks. Using Dempster-Shafer theory to find the paths having minimal cost, they model a game to investigate cooperative or competitive user behaviours. This work is the analytical counterpart to the routing problem we tackle with our traffic management protocol. Our goal is to propose a deployable traffic management system based on the first Wardrop principle and evaluate it using a microscopic traffic simulator.

4.1.1 Wardrop Equilibrium

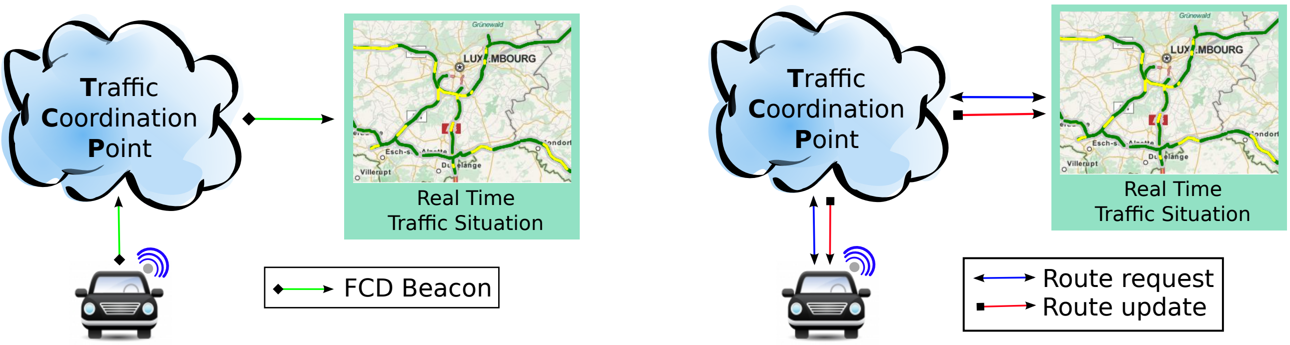
The traffic flow optimisation problem has been addressed with different methodologies and algorithms such as those presented in [13–15]. Our approach is based on the Wardrop equilibrium [16] to optimize the traffic flows, which provides an explanation accepted as common behaviour to describe how trips spread over different routes due to congested traffic conditions [173]. The routing mechanism implemented here is based on the selfish-user-centred policy defined by Wardrop's first principle of equilibrium. This principle states that every user (selfishly) selects a route that minimizes the travel cost between source and destination. Wardrop's second principle posits that users minimize the total travel time in the system. We call $R_{o,d}$ the set of all the possible routes from the origin o to the destination d, with $route^i$ the route chosen by the vehicle i:

$$route^i_{o,d} = \min(R_{o,d}).$$

To provide $route^i_{o,d}$, we need to define a traffic management protocol able to efficiently collect the FCD from the vehicles and provide the best route to each user.

4.1.2 Traffic Management Protocol

The architecture of the system is based on a Vehicle-to-Infrastructure (V2I) communication network in which the vehicles in the monitored area communicate with a local Traffic Coordination Point (TCP) using their OBU. The communication protocol is presented in Figure 4.1 and is divided in two parts: Information Beaconing and Route Management.



(a) Information Beaconing

(b) Route Management

Figure 4.1: Protocol Overview.

Information Beaconing The first part is Information Beaconing (Figure 4.1a). As the vehicles move through the road network, the OBU collects traffic metrics (location, direction and speed) into beacon messages and sends them to the local TCP via a mobile data network (e.g. 3G/4G). The size of each beacon is small enough not to place any specific requirements on the connection in terms of bandwidth. The TCP aggregates these metrics continuously to update the traffic situation in real time.

Route Management The second part is Route Management (Figure 4.1b). The OBU sends the current location and desired destination to the local TCP, which uses the real-time traffic data to compute the fastest route in terms of travel time. The optimal route is sent as a reply to the OBU. If the optimal route changes due to the traffic dynamics, the OBU receives a route update.

The minimum delay route is computed using Dijkstra's algorithm [200] with dynamic edge costs in which the weight is the Estimated Travel Time (ETT). The ETT_s for a road segment is computed using its length, l_s, divided by the average speed $\overline{v_s}$ of all vehicles currently travelling along that segment.

$$\overline{v_s} = \frac{1}{n_s}\sum_{i=1}^{n_s} v_i,$$

$$ETT_s = \frac{l_s}{\overline{v_s}}.$$

where n_s is the number of vehicles on the segment and v_i is the speed of the vehicle i. A route r is composed of multiple segments and its overall cost, ETT_r, is obtained as follows:

$$ETT_r = \sum_{i=1}^{m_r} ETT_{s_i}.$$

where m_r is the number of segments making up the route. The minimum delay route mdr between the origin o and the destination d is the one that minimises the ETT.

$$mdr^i_{o,d} = \min(ETT_{R_{o,d}}).$$

The $mdr^i_{o,d}$ is the route provided to the vehicle i from the system.

Having defined the traffic management protocol, we evaluated its efficacy by means of microscopic traffic simulation.

4.2 Evaluation of the Routing Mechanism

In order to study traffic congestion and traffic flow optimization, it is necessary to use a model able to describe traffic dynamics. In Chapter 2, we presented several of the macro- and microscopic traffic flow models that have been proposed over time, with their strength and weaknesses. For the evaluation our idea we chose a microscopic traffic simulator. The road topology for all the tested scenarios is a 10x10 Manhattan grid and the vehicles in the simulation are parametrized according to the Krauss car-following model. The experiments were structured to investigate the performance of the proposed system in respect to (i) the traffic density, (ii) the monitoring interval, and (iii) the participation rate of vehicles. Another aspect that we investigated is the comparative traffic distribution in coordinated[3] and uncoordinated traffic scenarios[4].

In Section 2.3 we provide general information on the Manhattan grid topology and we compare it with other topologies. We chose it for this evaluation because of its symmetry and simplicity allow better control on the environment, for a precise and reliable comparison between the coordinated and uncoordinated traffic scenarios. In addition, we want to provide results not biased by the specific topology of the territory.

In the following paragraph we evaluate and discuss in detail how, by applying Wardrop's first principle of equilibrium, we are able to substantially increase the volume of traffic served, improve overall traffic fluidity, and reduce the delays experienced by the vehicles.

4.2.1 Experimental Set-up

The experimental set-up is based on Simulator of Urban MObiltiy (SUMO) [201], a microscopic traffic simulator, with Traffic Control Interface (TraCI) [70] providing the interface to interact with the simulation at run time. The motivation behind this decision is discussed in Section 2.4.6.

As shown in Figure 4.2, the topology we used for all the scenarios is a 10x10 Manhattan grid with a segment length of 500m, in which every segment has the same priority. Every intersection follows the right-before-left priority rule and each road segment has one lane in each direction. For all our simulations we used the Krauss car-following model and the vehicles were parametrized as shown in table 4.1, where Sigma is the driver imperfection (defined between 0 and 1) [30]. Each trip has a source and destination chosen at random among all the edges in the Manhattan topology. The route for each trip is computed using `duarouter` [202], a tool provided by SUMO that uses Dijkstra's algorithm to compute the path having the minimum cost. Here the cost is determined by the length and priority of the segment.

[3]In a coordinated traffic scenario the vehicles follow the instructions provided by an authority.

[4]In a uncoordinated traffic scenario the vehicles behave as they seem fit, without external instructions.

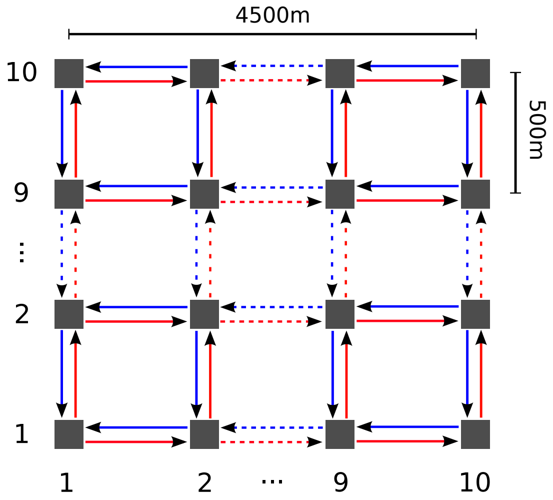


Figure 4.2: Topology of the Manhattan grid.

Acceleration $[m/s^2]$	0.8
Deceleration $[m/s^2]$	4.5
Sigma	0.5
Length $[m]$	5
Max Speed $[km/h]$	70

Table 4.1: Krauss model parameters.

Simulation set-ups We used two different simulation set-ups. The first has a fixed duration of one hour with a constant traffic density, so a new vehicle is added to the simulation each time another vehicle's journey ends. With this set-up the parameters explored are (i) the average density of vehicles in the whole scenario, (ii) the participation rate of vehicles in the experiment, and (iii) the monitoring interval. In the second set-up, the number of vehicles is fixed and the simulation stops when every vehicle has reached its destination. With this set-up we measured (i) the time necessary to serve the complete traffic demand, (ii) the average speed, (iii) the waiting time, and (iv) the traffic flow distribution.

In every experiment, the comparison was made between (i) the uncoordinated traffic scenario in which the vehicles follow the route initially provided (e.g., off-line navigation system) and (ii) the coordinated traffic scenario, in which a proportion of the vehicles is dynamically rerouted to follow the route that minimises the delay. In the first simulation set-up we used the number of vehicles that reached their destination after one hour of simulation to compare the coordinated and uncoordinated traffic scenarios.

Definitions We define as *Total Vehicles Arrived (TVA)*, the number of vehicles that have reached their destination at the end of the simulation. The *Shortest Route* is defined in terms of route length and the *Minimum Delay Route* in terms of travel delay. The *Monitoring Interval* is the amount of time between two computations of the minimum delay routes for the vehicles and the possible rerouteing of vehicles if needed. The *Participation Rate* is the percentage of vehicles that is taking active part in the experiment, or more precisely, the vehicles that are following the suggested route.

It is reasonable to assume that a vehicle that travels from one place to another will use the shortest route. In a sparse traffic situation, the shortest route and the minimum delay route will coincide. In the case of traffic congestion, the difference between the two routes is significant for the optimisation problem. Following this logic, when the congested traffic flows are distributed throughout the road

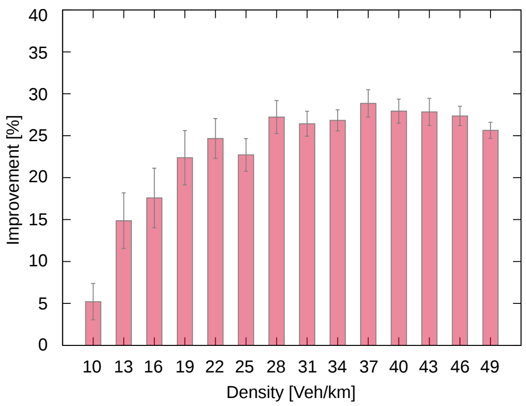


Figure 4.3: Improvement of TVA in the coordinated traffic scenario compared to the uncoordinated and corresponding standard deviation for the *average vehicular traffic density* with 100% user participation rate.

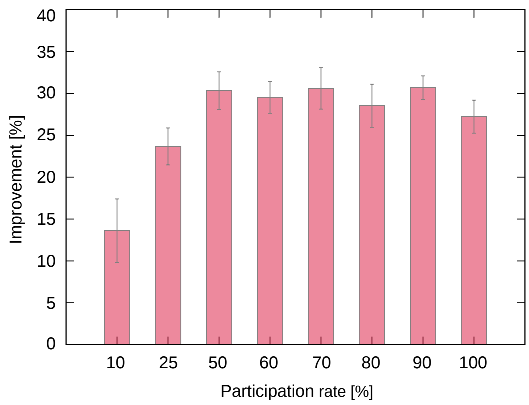


Figure 4.4: Improvement of TVA in the coordinated traffic scenario compared to the uncoordinated and corresponding standard deviation for the *participation rate* with traffic density of 28 veh/km.

network, the difference between the two routes again becomes less significant.

4.2.2 Traffic Density

The traffic conditions in a metropolitan area vary considerably over the day. We decided to investigate the impact of the different average densities of vehicles on the TVA for one hour of simulation. Choosing different densities allowed us to go from a sparse to a fully-congested traffic scenario. The system proposed in this thesis is designed to accommodate congested and heavily-congested traffic conditions. Given that determining the traffic situation in real-time is not an easy task [188, 189], the system must be effective in all traffic conditions in order to be deployable. In this experiment the monitoring interval was fixed at 60s (see Section 4.2.4 for further details), and the participation rate at 100% to study the upper-bound performance. The average densities taken into account ranged from 10 to 49 vehicles per km with an increment of three. Figure 4.3 shows the percentage improvement in TVA in the coordinated traffic scenario compared to uncoordinated one. The histogram shows that, even for a sparse traffic scenario (10 Veh/km), there is a TVA improvement around 5%. In our road topology, we estimated that the traffic becomes heavily congested around 30 vehicles per km; it can be seen that TVA keeps improving up to 28 vehicles per km and then, for very congested scenarios, the improvement varies between 24% and 29%. As previously discussed, in a sparse traffic situation or with mild traffic congestion the difference between the shortest route and the minimum delay route is minimal, so the improvement in TVA is low. On the other hand, when the system becomes heavily or fully congested, it is possible for gridlock [198] to occur or for the road network to reach its upper bound capacity.

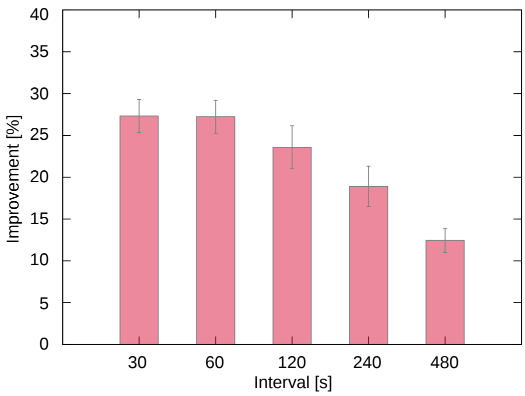


Figure 4.5: Improvement of TVA in the coordinated traffic scenario compared to the uncoordinated and corresponding standard deviation for the *monitoring interval*.

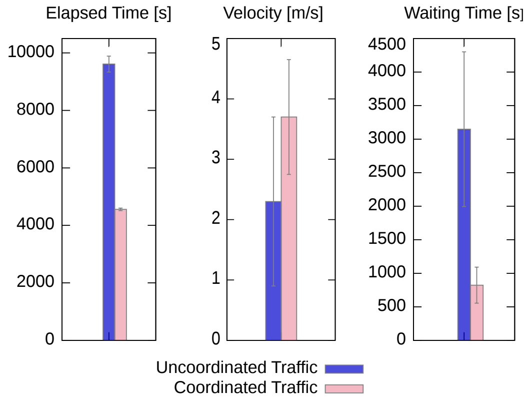


Figure 4.6: Comparison of the duration of the simulation, the average vehicle speed and the waiting time between the coordinated and uncoordinated traffic scenarios.

4.2.3 Participation Rate

The participation rate is a critical parameter for the actual success of a system. If the protocol requires too many users to work properly, it will be hardly feasible to deploy it in a city. For this reason, we studied the impact of different participation rates on the performance of the protocol. In this case the monitoring interval is fixed at 60s (see Section 4.2.4 for further details), and the average density of vehicles at 28 per km (as motivated in Section 4.2.2). Different participation rates ranging from 10% to 100% were tested. Figure 4.4 shows the percentage of improvement in TVA in the coordinated traffic scenario compared to the uncoordinated. With 10% of active vehicles, TVA is improved by 13.3%, implying that is possible to improve traffic fluidity even during the roll-out phase of the deployment (i.e. with only a few participants). By increasing the participation rate to 50%, the improvement in TVA reaches 30%, remaining stable between 27% and 30% until full participation is attained. The fluctuation in improvement with a participation rate higher than 50% is due to the randomization of the different trips for the vehicles. As previously mentioned, an average traffic density of 28 vehicles per km implies a heavily-congested scenario. This is the reason that the maximum TVA improvement is around 30%: the traffic congestion is distributed over the whole road infrastructure and the difference between the shortest path and the minimum delay path becomes less significant. The application of the first Wardrop principle to a congested traffic situation implies that active users always experience a personal improvement by using the protocol.

4.2.4 Monitoring Interval

Timing plays a crucial role when it comes to the real world implementation. Even in rush hours, the global traffic situation evolves slowly and with small monitoring intervals is not possible to observe significant changes. Another factor to take into account is the number of participating vehicles and the bandwidth consumption when the interval between one communication and the next is too short. With this experiment we wanted to investigate different monitoring intervals to find the best trade-off in terms of flow optimisation and number of transmissions. The different monitoring intervals that we used were 30, 60, 120, 240 and 480 seconds; for this scenario the participation rate of the vehicles is fixed at 100% to study the upper-bound performance, and the average density of vehicles to 28 per km (as motivated in Section 4.2.2). Figure 4.5 shows the percentage of improvement for the TVA in the coordinated traffic scenario compared to the uncoordinated. We can see that, with 30 and 60 second intervals, the improvement in TVA the same ($\sim$ 27%). This implies that is not necessary to investigate monitoring intervals shorter than 60 seconds when seeking to increase the performance of the system. With a monitoring interval of 120, the improvement in TVA is still above 20%, and increasing the monitoring interval by repeatedly doubling it up to 480 seconds, we can see a linear decrease in the TVA improvement. As our protocol does not impose strict time constraints, it will be possible to set various monitoring intervals to optimize different aspects of the system (e.g., battery consumption in the case of an application for smartphones).

4.2.5 Speed and Waiting Time

Given the selfish-user approach adopted in this optimization, we wanted to evaluate parameters such as average speed and waiting time, because they are directly experienced by the users. To do this, we performed an additional simulation study using the same topology as above, where we fixed the participation rate at 100% to study the upper-bound performance and the monitoring interval at 60s (as motivated in Section 4.2.4). The simulation started with 10,000 vehicles and the aim was to measure the time necessary for all of them to reach their destinations. For every vehicle, we measured the average speed and the waiting time, defined as the amount of time during which the vehicle is stopped (less than 0.1 m/s). Figure 4.6 presents the three results. For the coordinated traffic simulation, we can see that the duration is decreased by around 52% relative to the uncoordinated case, meaning that the same traffic demand can be served in half of the time. Regarding the average speed, in the coordinated traffic scenario the mean is 61% higher and the standard deviation is 58% lower compared to the uncoordinated case. With a decrease in standard deviation, we have less variation in the speed, meaning that the users would experience stop-and-go behaviour less often. The final histogram shows that the waiting time can be reduced by 74%, as compared to the uncoordinated environment. These last two results have a direct impact on the possible usage and adoption of this protocol: waiting time and speed are factors that drivers readily notice and with this system every vehicle would immediately experience improvements.

4.2.6 Traffic Distribution

In the case of flow optimization, traffic distribution plays a crucial role. Figure 4.7 compares four snapshots of the traffic density for every road segment at different simulation times, the intervals being based on the shortest simulation (the coordinated case). In the coordinated scenario, the traffic flows are distributed over the road topology by applying the first Wardrop equilibrium. We can see that, by coordinating the behaviour of the vehicles from the outset, it is possible to delay or even avoid gridlocks. This result is shown in the snapshot at simulation time 1,500 where the gridlock effect, indicated by circles with high density traffic, is present only in the uncoordinated traffic simulation.

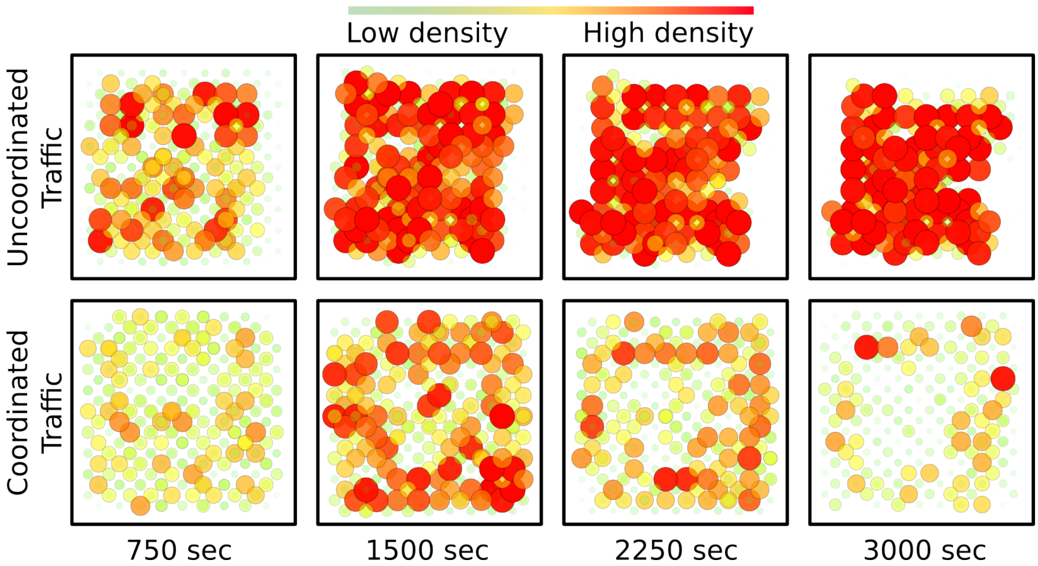


Figure 4.7: Vehicular traffic density.

4.2.7 Discussion

The traffic management system here evaluated enables the coordination of vehicular flows in urban environments. It is based on real-time traffic information gathered by an OBU and transmitted via a mobile network to a local TCP for aggregation. The routing algorithm is based on the first Wardrop principle and computes the minimum delay route using Dijkstra's algorithm with dynamic edge costs.

We support the use of a selfish, user-centred approach rather than a global one on many grounds. The main reason is related to the constraints imposed by the global approach. The optimum in terms of minimum overall delay can be achieved only with the global and fully coordinated approach, but this would imply that all the vehicles in the monitored area are part of the system and that they are 100% compliant with the instructions provided; these assumptions may be realistic in a fully-autonomous driving scenario, but they are unrealistic with human drivers. In addition, it would be necessary to have an oracle able to predict when and where all the vehicles would appear in the monitored area, as well as all the environmental variables such as pedestrians, bicycles, delivery trucks and so on. Last but not least, the computational cost of the solution is very high. It would be possible to explore various approximations for this solution, but we decided to directly try the least expensive approach in term of computation and the most flexible in terms of assumptions. A user-centred approach is more robust, easier to deploy in cities, and it would ensure the best result for the user (to achieve a global optimization with the minimum overall delay, some users might experience much larger delays).

The results show that our system is able to increase the capacity of the road network by better distributing of the traffic demand. Further, we show that the global travel time is reduced by 50%, the average speed is increased by 60% and the average waiting time is reduced by 70% compared to the uncoordinated traffic scenarios. Moreover this system reaches its full potential at participation rate of only 50%, allowing it to be deployed in cities with an immediate gain for early adopters. The main result in the evaluation of the traffic management protocol is the increased capacity of the system due to better usage of the road network. The two possible interpretations are that (i) the same amount of demand can be served in less time or (ii) that the system is able to serve an increased demand with the same level of congestion. To give an example backed by numbers, in the uncoordinated traffic scenario with a density of 28 vehicles/km/lane in one hour of simulation the TVA is around 9,800. In the coordinated traffic scenario with an interval of 60 seconds the corresponding TVA is around 12,300.

In this first evaluation we assumed complete information concerning traffic conditions. A simulator is able to provide perfect information on every vehicle, intersection, and road segment in the entire scenario at any given time. In the real world, even assuming no privacy issues, perfect information is hardly achievable due to uneven connectivity coverage of the territory and incomplete users participation rate. The straightforward extension of this traffic management protocol is the evaluation of its effectiveness in case of partial and incomplete information.

4.3 The Impact of Incomplete Information

Once the proposed traffic management protocol has been evaluated in the best-case scenario (where a complete and accurate overview of the system is constructed using the real-time FCD), we need to test the impact of partial and incomplete information. Several studies have proposed methods for sensing traffic-relevant information in the form of FCD, such as [203–206]. Once the FCD has been collected, it must be aggregated to provide a reliable overview of the traffic situation in the monitored area. In the literature, many algorithms have been proposed to solve this issue [207–209].

Problems such as FCD sampling and aggregation, Road Side Unit (RSU) coverage, and vehicular traffic optimization have been widely studied in recent decades. In [210], the authors present a framework enabling the use of big data analysis and cloud computing to process massive amounts of information in near real time. The only possible error taken into account is that related to the GPS position, while assuming complete information in terms of coverage of the territory. Another example of FCD aggregation is presented in [211]. Here the authors integrate information collected from a variety of sensors such as on-board camera, GPS, and the on-board diagnostics (OBD) unit. They take into consideration the errors resulting from the image processing (qualitative errors) but not the possibility of having uneven coverage of the monitored area (quantitative errors). SOTIS [212], based on Vehicle-to-Vehicle (V2V) communications, allows gathering, analysing and broadcasting traffic information without the use of a central entity. With a user participation rate of 2%, it manages to obtain roughly 30-minute-old information concerning the area within around a 50-km radius of the car. This kind of information is very useful in tracking major congestion in extra-urban environments, but cannot monitor the real-time traffic situation in urban areas. Here, the problem of sparse information is solved by keeping all data, regardless of its age.

In [213], the authors address the problem of RSU coverage and present a forwarding algorithm that relies only on local information. They use V2V communication with 802.11p connectivity. Their result explores RSU coverage extension and the improvement it brings in terms of data dissemination. However, they do not take into account the level of user participation, assuming that all the vehicles are equipped with an OBU. Another solution to the RSU coverage problem is proposed in [208]. The authors present a specific aggregation scheme in order to minimize the overall bandwidth necessary to transmit FCD. They assume a user participation rate of 5% and use a genetic algorithm to identify the best position for the deployment of RSUs that achieves a strategic coverage of the territory that maximizes the effectiveness of the information gathered.

In relation to the traffic optimization problem, [214] studies different kinds of vehicular route optimizations that utilize traffic information gathered from vehicles to estimate travel times and to find optimal routes. The authors study the difference between proactive and flow-based methods. They do not take the user participation rate into account and they assume that perfect information concerning the real-time traffic situation is available at decision time.

In all of the above-mentioned studies, there is an assumption that, once the FCD are gathered, it is possible to build a complete and reliable overview of the traffic situation. The goal of this study is to investigate the impact of only having partial information available in terms of user participation rate and RSU coverage to deal with the problems of route optimization and traffic congestion.

4.3.1 Infrastructure and Data Aggregation

In every optimization problem, the correctness and reliability of the information plays an important role. When the solution to the optimization problem must be provided at run-time, it is important to test the impact of partial information to discover boundaries and understand where particular behaviours originate. The reason we focused on this evaluation is to provide ground truth information for the deployment of a realistic traffic management system.

First and foremost, we decided to investigate how the connectivity affects the behaviour of the traffic monitoring system itself. We chose to use Wi-Fi because many cities have this type of network coverage provided in different ways [215, 216]. Moreover, cellular networks are increasingly overloaded with traffic due to the rapid growth of mobile broadband traffic. One of the solutions proposed for this problem is cellular traffic offloading through Wi-Fi networks [217, 218]. The completeness of the information is directly correlated with the level of user participation, the coverage in terms of infrastructure and connectivity in the monitored area, and the nature of the environment involved.

In this study we thoroughly evaluate, by means of simulation, how these parameters affect routing mechanisms and traffic congestion in metropolitan environments. The complexity of both the topology and the mobility models has an impact on the various aggregation methods and the level of detail and correctness of the represented traffic situation. To describe this complex environment many models have been developed in different fields of science [187, 219, 220].

Traffic Information Infrastructure We take into consideration different types of information concerning traffic demand and the speed of specific vehicles. Figure 4.8 shows an example of these different sources of information. FCD is collected through the OBUs in the vehicles and gathered by the RSUs. In addition, the traffic demand and the global overview of the system are obtained through sources such as traffic cameras, inductive loop detectors, and historical information. The full traffic situation is easily obtained in simulation because the simulator itself provides complete information.

By OBU we mean any device (e.g. smartphone, single-board computer, embedded system, etc.) deployed in a vehicle, able to collect traffic data, and having connectivity capabilities. The FCD sampled by the OBU consist of GPS position, speed and direction. In our topology, this data is

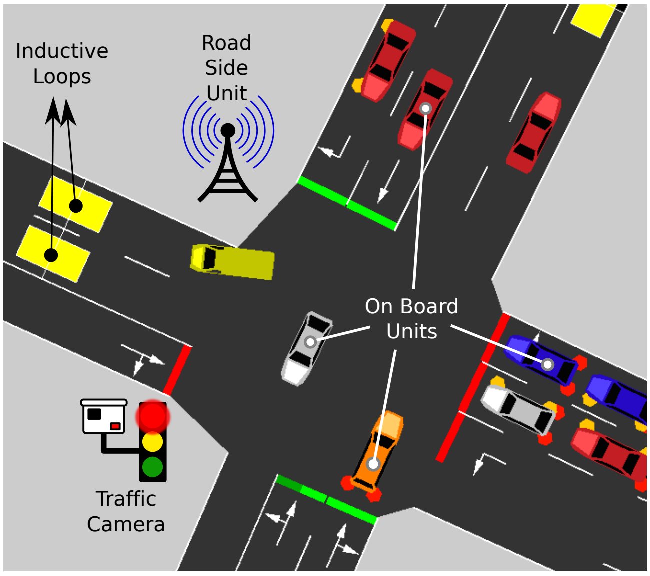
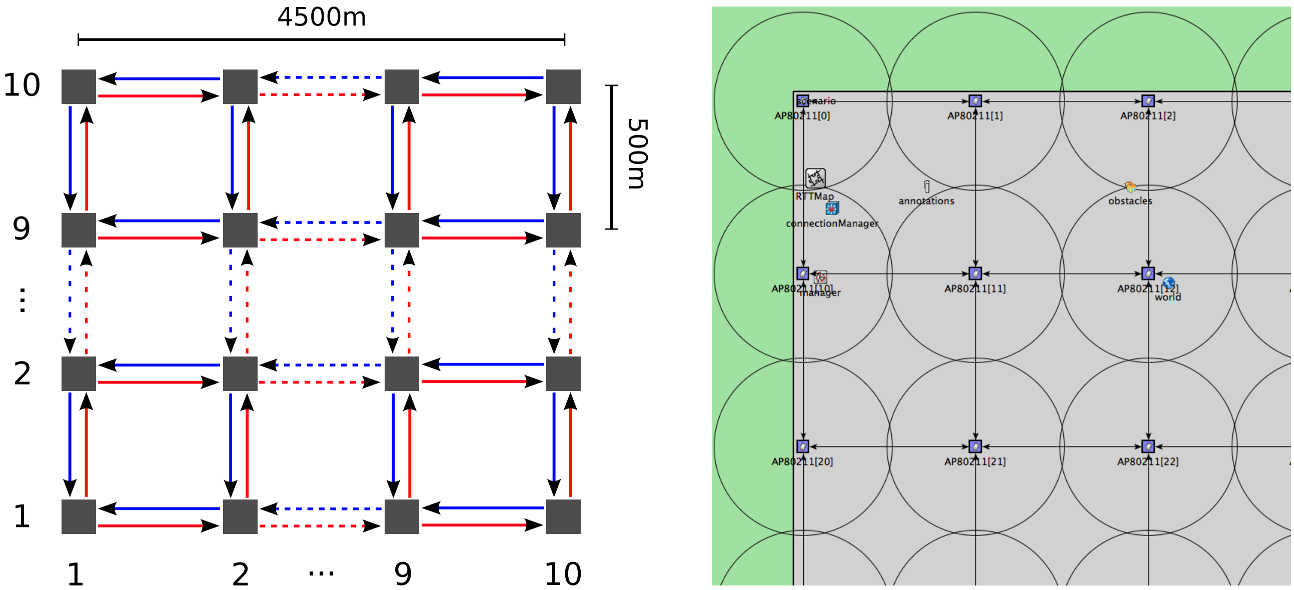


Figure 4.8: Infrastructure example: Vehicles (with and without OBU), RSUs, Inductive Loops and Traffic Cameras.

gathered by RSUs located at intersections. Even assuming that all FCD is reliable and correct, the consistency of the overall traffic view (computed from the FCD) with the real traffic situation depends on the numbers of active vehicles that are cooperating with the traffic monitoring system, and on the proportion of intersections covered by the RSUs.

In the literature there are many aggregation algorithms that allow different sources of traffic information to be used to obtain a global picture of the situation [207–209]. Nevertheless, even if the infrastructure is already deployed, legal issues and other constraints make the information provided by inductive loops and traffic cameras hard to obtain, rarely real time, and not always available. We decided to compare the behaviour of the traffic monitoring system in two different settings. The first considers only FCD, while the second considers the overview computed from all the aggregated sources, FCD included.

To study the impact of the RSUs' coverage on the real-time traffic overview, we use the same 10x10 Manhattan grid topology presented and discussed in Section 4.2.1. Figure 4.9a shows the Manhattan grid and Figure 4.9b shows the coverage provided by the RSUs as using the visualization provided by Objective Modular Network Testbed in C++ (OMNet++). All streets are bidirectional with a speed limit of 50km/h, and have the same priority. Each intersection follows the right-before-left priority rule, and, is equipped with a Wi-Fi access point acting as an RSU. The street segments are 500m long and the RSU radius is 250m. Our aim is to provide a ground study with general results in order to quantify the impact of incomplete information in a simple setting. By using a regular topology, we are able to minimize the impact of RSU coverage patterns, which can vary depending on intersection location. All communications are based on a V2I paradigm in which the vehicles in the monitored area are able to communicate with a local RSU using their OBU. The traffic management protocol is as already presented in Section 4.1 and is divided into two parts: Information Beaconing, and Route



(a) Topology of the Manhattan grid.

(b) RSU coverage in OMNet++

Figure 4.9: Experimental Set-up.

Management. Both of these parts require a reliable representation of the traffic situation.

Real-Time Data Aggregation By Real-Time Traffic Situation (RTTS) we mean the overview of the system provided through the aggregation of all the different data pertaining to vehicular traffic. We use this information to compute the optimum user equilibrium and decide the best route for each vehicle. The two scenarios that we explore in this paper are differentiated by the kinds of information used to build the RTTS, as shown in Figure 4.10. More precisely, we define: *Only-FCD (O-FCD)* (green arrow labelled 1), the dataset composed of information collected in real time through the OBUs of the vehicles; *All Sources Of Data (ASOD)* (red arrow labelled 2), the dataset composed of all the aggregated information gathered from RSUs, inductive loops, traffic cameras, and both stationary (infrastructure) and FCD data.

In this implementation, where the RTTS is computed with the O-FCD dataset, the aggregation consists of the average of the samples specific to a segment. Every segment has a predefined limited-time buffer of 10 minutes and all samples prior to that time window are discarded.

In the event of a lack of information, we use a static value for the speed, half of the maximum speed allowed on the segment, 6.8 m/s. The decision was made after comparing the behaviour of this solution with the one using free-flow and congested average speeds. Both free-flow and congested traffic are the extreme of the spectrum of possibilities, and they don't represent the average situation.

Concerning the scenario with the RTTS built from the ASOD dataset, we do not need to implement any specific aggregation method since the mobility simulator has exact knowledge of the number of vehicles in every segment and their velocities. The RTTS computed with O-FCD with less than 100% user participation rate and 100% infrastructure coverage will have partial information. In contrast,

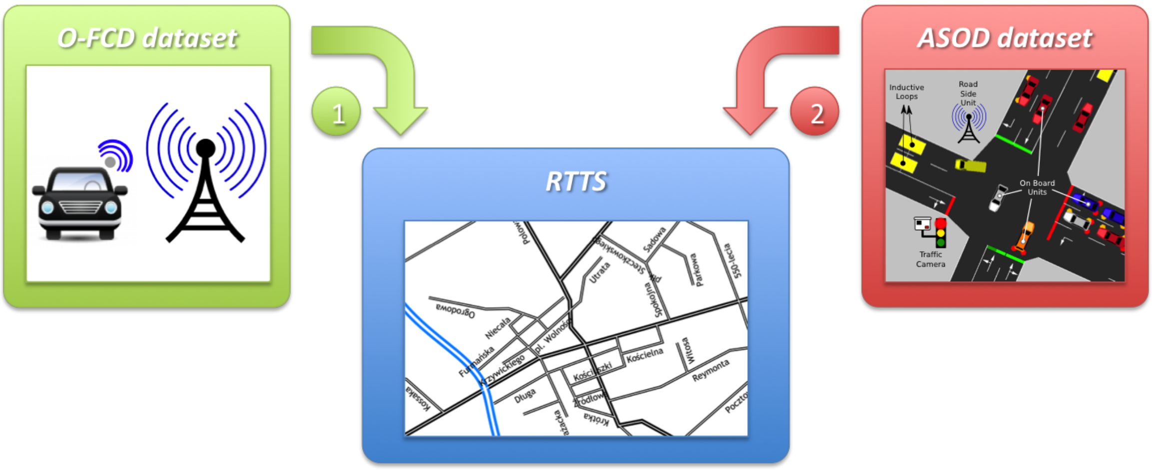


Figure 4.10: RTTS information sources. The two possible datasets are composed of O-FCD and ASOD, FCD included.

the RTTS computed with ASOD will act as an oracle, knowing information from every vehicle in every segment. The RTTS is used to provide the minimum cost route to the vehicles that request the service through the traffic management protocol.

We explained in Section 4.2 the reasons we support the use of a selfish, user-centred approach rather than a global. The main reasons are related to the the constraints imposed by the global compared to the user-centred approach, which is more robust, easier to deploy in cities, and reasonable from a user perspective.

4.3.2 Simulation Environment

We built the topology described in the previous Section in a simulated environment using OMNet++ [221] for the wireless network and SUMO [68] for the vehicular mobility model. The bidirectional coupling mechanism between the network and mobility model is provided by Vehicles in Network Simulation (VEINS) [222]. Each intersection is equipped with a Wi-Fi access point acting as a RSU. Once again we chose the Krauss car-following model to simulate an urban traffic flow; the parameters we use for the vehicles are those given in the original document [30]. Each vehicle has a source and a destination randomly chosen among all the edges of the Manhattan topology. To compute the route from source to destination, we use `duarouter` [223], a tool provided by SUMO that uses Dijkstra's algorithm to identify the path having minimal cost. In this case, cost is determined using the length, maximum speed, and priority of the segment.

Evaluation parameters The aim of this evaluation is to quantify the impact of partial information on the solution proposed by the routing protocol. We ran a scenario with 10,000 vehicles, all starting their trip at the beginning of the simulation. The aim is to measure the time necessary for all of them to reach their destinations. We collected statistics on vehicular mobility (e.g. average speed, waiting

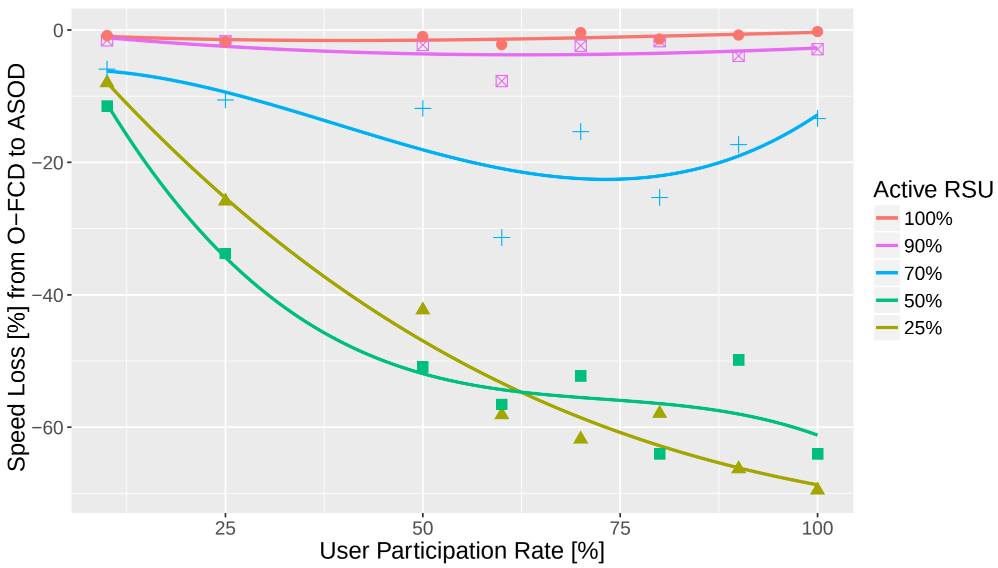


Figure 4.11: Average speed comparison between O-FCD and ASOD scenarios varying user participation rate and RSUs coverage.

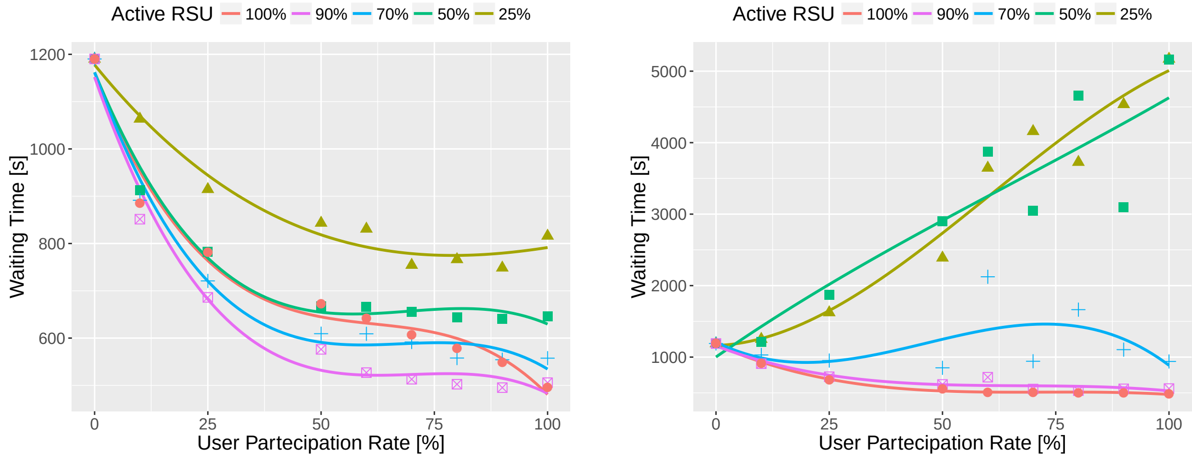
time of each vehicle, and density) and RSU coverage. The completeness of the overview given by the information depends on the different participation rates of the vehicles and RSU coverage at the intersections. These are very important parameters to consider when it comes to the deployment of the system. For our evaluation we used: 10%, 25%, 50%, 60%, 70%, 80%, 90%, and 100% rates both for RSU coverage and user participation. The intersections covered by the RSUs and the vehicles equipped with the OBUs were randomly selected.

To show how the use of partial information influences the routing mechanism, we compared the behaviour of the protocol with the two different sets of information collected and aggregated into the RTTS. In one scenario the RTTS is computed using the O-FCD dataset and in the other, the ASOD dataset.

The interval between two routing requests (and consequently both beaconing interval and route update) sent from a given vehicle was fixed at 60 seconds. Section 4.2.4 shows that using a smaller time interval does not significantly alter the performance of the routing mechanism because both vehicular mobility and overall traffic conditions change relatively slowly.

4.3.3 Speed

Figure 4.11 gives a quantitative comparison between the average speed of all the vehicles in the two different scenarios. The data points are fitted with a second degree polynomial function. In the first, the RTTS is computed using the ASOD dataset and the measured average speed is used as a basis for the comparison. This represents the ideal situation in which we have a global overview of the system even without full cooperation from the users (i.e. the traffic information is complete and reliable even without active vehicles, due to traffic cameras, etc.). In the second scenario, the RTTS is computed using O-FCD collected from the active RSUs. The value represented in the graph is the delta (as a



(a) Average waiting time, ASOD dataset

(b) Average waiting time, O-FCD dataset

Figure 4.12: Average waiting time.

percentage) between the average speed measured in the second scenario compared with the first. We chose to plot the more representative percentages from all the experiments. We hypothesized that a routing system that takes decisions based on a dataset with partial information will behave differently based on the completeness of the dataset itself.

We investigated the boundary between the normal behaviour expected from the routing mechanism and compromised behaviour caused by the use of partial information. We found the threshold to occur when around 70% of intersections are covered by RSUs. It can be seen that, without ASOD information, coverage plays an important role. With 80% or more coverage, the performance of the routing mechanism is consistent in both scenarios, even with low user participation. When the coverage is 70% or less, the information collected by the RSUs can be misleading, and the protocol fails to relieve congestion. This behaviour is due to the fact that when the ratio of intersections covered by the RSUs is insufficient, the overview of the situation is incomplete and the user equilibrium is computed with misleading information. In this graph it is easy to see that the user participation rate has a minor impact on the behaviour of the routing mechanism relative to the percentage of intersections with active RSUs, ant it became critical only when the un-even coverage provided by the active/inactive RSUs ration is not sufficient to provide a complete traffic overview. If the impact of the user participation would have been higher, even with lack of coverage, we would have seen an improvement in 25% and 50% coverage with 50% and higher user participation rate, as is visible with 70% active RSUs.

4.3.4 Waiting Time

Another aspect that we analysed is the impact of partial information on the average waiting time encountered by the vehicles. The background truth scenario used for the comparison is the one without a traffic monitoring infrastructure in place. We obtain it by running a simulation in which the vehicles

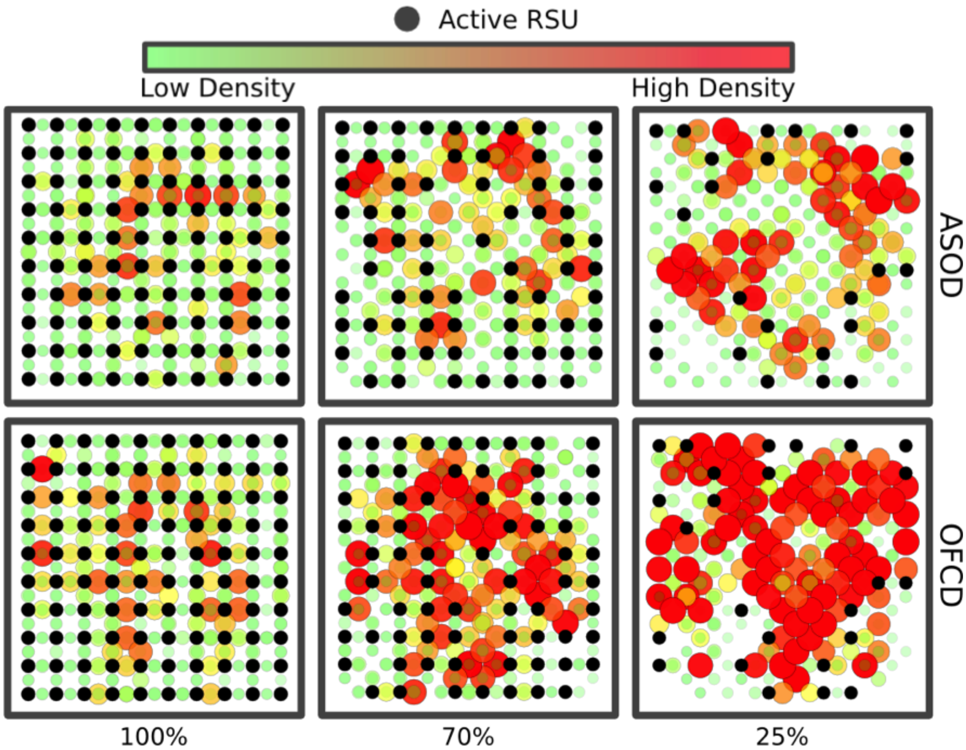


Figure 4.13: Vehicular Density and RSU Coverage in different scenario at the same simulation time.

provide no information and the routing mechanism is not in place. We define waiting time as the amount of time during which the vehicle is moving slower than 0.1 m/s.

More precisely, Figure 4.12a shows the average waiting time encountered by each vehicle in the scenario with complete information. It can be seen that, independent of the coverage, even with 25% participation, there is an improvement due to the use of complete information. On the other hand, two different behaviours are visible in Figure 4.12b. With coverage of 70% or less, the trends again show erratic behaviour among the vehicles. In both figures the data points are fitted with a second degree polynomial function.

4.3.5 Traffic Distribution

In Figure 4.13 we show the vehicular distribution on the grid, comparing the same routing mechanism applied to two different RTTSs, one computed with ASOD, the other with O-FCD. The black dots represent the active RSUs. On the grid, the size and colour of the dots represents the occupancy of a specific segment. All these snapshots of the traffic situation are taken at the same simulation time and all the scenario are based on the same user participation rate (100%).

With 100% RSU coverage, vehicle density levels are comparable in both scenarios. The threshold of 70% discovered previously reveals a visible difference between ASOD and O-FCD in vehicular distribution. The segments leading to intersections not covered by an active RSU, in case of O-FCD, are more congested than the others. This behaviour is similar but less apparent with ASOD. This is the case because the lack of coverage at an intersection not only decreases the amount of FCD, but also prevents route updates from reaching interested vehicles. This behaviour becomes more accentuated when only 25% of intersections are covered by active RSUs. While with ASOD, the situation is still acceptable, for O-FCD, the traffic congestion is worsened by the fact that the few route updates that are received may be sub-optimal due to the use of partial information.

4.3.6 Discussion

With the evaluation of the impact of incomplete information on the behaviour of the traffic monitoring system, we found an interesting threshold: with less than 70% coverage, the routing mechanism fails, increasing congestion instead of mitigating it. Without proper coverage, the overview of the traffic situation is incomplete and the user equilibrium is computed with misleading information. We also show that the ratio between active and inactive RSUs (i.e. the connectivity coverage of the intersections) has a greater impact on the behaviour than the actual user participation rate.

The problems highlighted by the use of partial information can be further investigated in a number of ways. Firstly, employing heuristics to compute the RTTS is a promising approach to avoiding errors when dealing with incomplete information. Secondly, it could be fruitful to investigate the use of probabilistic algorithms to compute user equilibrium and route updates. Nevertheless, our work indicates that, with a deterministic aggregation that assumes an average traffic flow situation (not free-flow nor congested) in case of missing information and a deterministic routing mechanism, the completeness of the information plays a major role and must be taken into account during the deployment of such a system.

4.4 Contribution and Final Remarks

In this Chapter we have presented a traffic management system able to coordinate vehicular flows in urban environments, and have evaluated it in the cases of both perfect and incomplete information.

The traffic management protocol is based on real-time traffic information gathered by an On-Board Units (OBU) and transmitted to the local Traffic Coordination Point (TCP) for aggregation. The routing algorithm is based on the first Wardrop principle and computes the minimum delay route using Dijkstra's algorithm with dynamic edge costs.

With complete information, we evaluated the system using SUMO as a microscopic traffic simulator on a 10x10 Manhattan grid topology. The results show that our system is able to increase the capacity of the road network due to a better distribution of the traffic demand. Further, we show that the global travel time is reduced by 50%, the average speed is increased by 60% and the average waiting time is reduced by 70% compared to the uncoordinated traffic scenarios, and that this system reaches its full potential at participation rate of only 50%, allowing it to be deployed in cities with an immediate gain for early adopters.

In case of partial information, the mechanism is still able to update the route of the vehicles, and so relieve traffic congestion, but requires a reliable real-time traffic overview of the system to take decisions. The correctness of this overview depends on various parameters such as the user participation rate and the percentage of intersections covered by RSUs. Our results show that with less than 70% of RSU coverage, the traffic overview does not coherently represent the real traffic situation and it can present security issues. This behaviour does not vary significantly with the user participation rate. This result indicates that the percentage of intersections covered by RSUs plays a major role in information-gathering and route updates. With insufficient coverage, the routing mechanism fails to relieve congestion and, due to misleading information, may worsen it.

In this work we used a Manhattan topology to better control the environment and allow a precise and reliable comparison between the coordinated and uncoordinated traffic scenarios, and to provide a result not biased by a specific topology. A reasonable extension of this work would be based on the use of more complex road topologies with different types of intersections, a greater number of lanes and different priority rules. Further investigation will bring the Dynamic User Equilibrium (DUE) into play, and given that the appropriate infrastructure coverage presents one of the main problem when dealing with partial information, a more complex and realistic simulation scenario is required.

In the next Chapter, we present the Luxembourg SUMO Traffic (LuST) Scenario, a general-purpose, freely-available simulation scenario able to meet all the basic requirements in terms of size and realism, in order to have a common basis for evaluations. We used information from a real city with a typical topology common in mid-size European cities, and realistic traffic demand and mobility patterns. We show the process used to build the LuST Scenario, both the topology and the mobility traces, and present a summary of its characteristics, together with our evaluation and validation of the traffic demand and mobility patterns.

Chapter 5

Luxembourg SUMO Traffic Scenario

When working on problems related to vehicular traffic optimization and intelligent transportation systems, a vehicular traffic simulator with an appropriate scenario for the problem at hand is used to reproduce realistic mobility patterns. As we discussed in Chapter 2, many mobility simulators are available to the Vehicular Ad Hoc Network (VANET) community and, while a choice can be made based on the type of simulation required, a common problem is finding a realistic, properly-working, and freely-available scenario.

As we saw in the previous Chapter, due to the lack of usable scenarios, the usual approach is to build a simple scenario that fulfils the purpose of the application. This approach results in several problems that are well known to the VANET community, the most prominent being the lack of repeatable experiments allowing the comparison of different solutions or approaches that address the same problem. Another difficulty that may be encountered is the specificity of the scenario and the consequent lack of generalization or realism.

In order to focus on Vehicle-to-X problems and solutions, the VANET community needs a scenario that fulfils the following requirements:

- It must be able to support different kinds of traffic demand, such as congested or free-flow patterns.
- It must include various road categories (e.g. residential, arterial and highway).
- It should support a range of scenario dimensions (from a small neighbourhood to complete city).
- It should allow multi-modal traffic evaluations (e.g. vehicles, public transport and pedestrian).
- It should describe a realistic traffic scenario (i.e. avoid gridlocks and unrealistic mobility patterns) over one day in order to include traffic mobility during rush hours (high density), during the rest of day (moderate density) and during the night (low density).

In this Chapter we explain in detail the steps required to build and evaluate a scenario able to meet all these requirements, in order to have a common basis for evaluations. We decided to use the road network of a real city as the basis for our scenario in order to reproduce real traffic demand and mobility patterns. We chose the City of Luxembourg because its topology is comparable to that of many of European cities and because its traffic statistics are available, and can be used to calibrate traffic demand. Another advantage is that its size is reasonable in terms of complexity for a microscopic simulator. These simulations are generally preferred by the vehicular networking community [55]. In Section 5.1 we present an overview of other mobility scenarios. We then discuss the generation of the traffic scenario in detail, focusing on network topology in Section 5.2 and on traffic demand in Section 5.3. The evaluation of the mobility model is presented in Section 5.4, and in Section 5.5 we validate mobility using empirical data. Finally, in Section 5.6, we present an overview of a number of projects elsewhere in the vehicular traffic research community that have already produced results using the Luxembourg SUMO Traffic (LuST) Scenario. We conclude the Chapter with Section 5.7, which gives final remarks on the scenario and the future of the project.

5.1 Traffic Scenarios

When it comes to traffic simulations, a recurrent problem is that there are very few properly-working and freely-available scenarios for the VANET community.

A scenario available for MATSim [81] is the Sioux Falls test scenario [224]. It is a small-scale, multi-modal mobility scenario with realistic traffic demand, based on Sioux Falls city (Figure 5.1a), which utilizes all the major features of MATSim, but covers only the city's main streets. Another issue is that MATSim is difficult to couple with external scripts and simulators (e.g. network simulators).

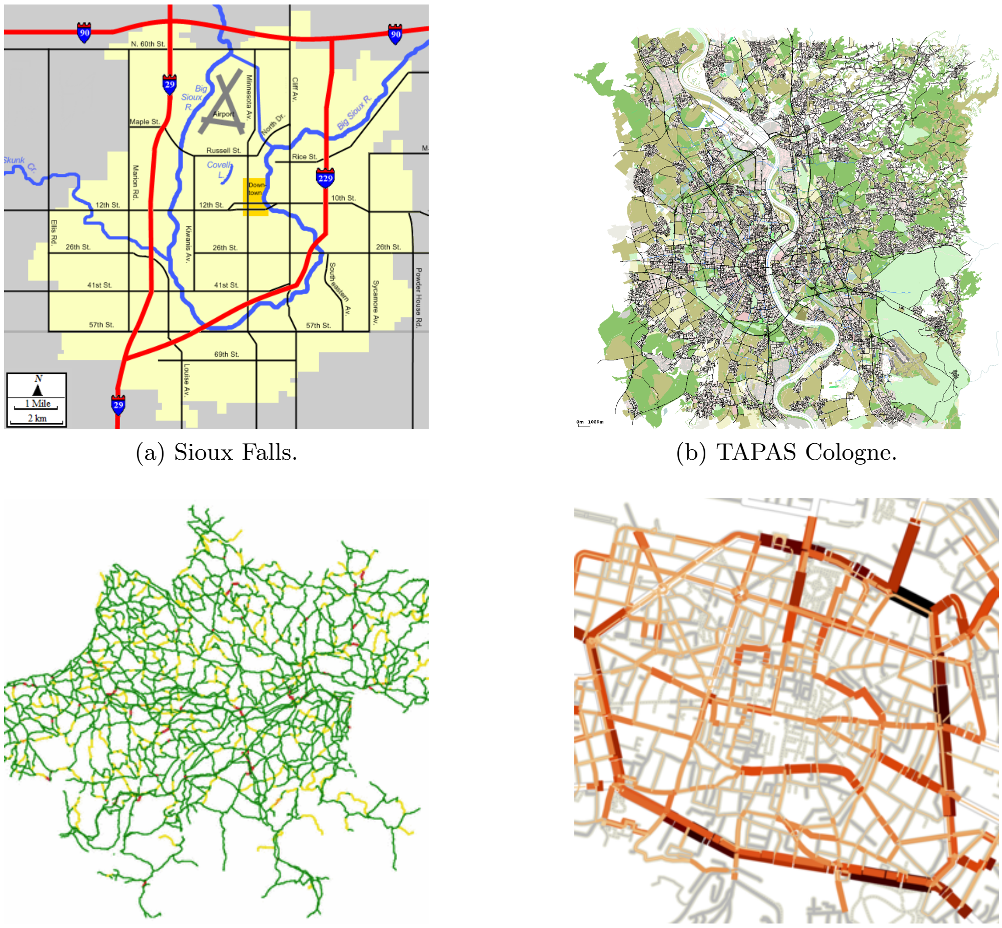
Simulator of Urban MObiltiy (SUMO) [201] provides the TAPASCologne [225] scenario package (Figure 5.1b), which includes road networks imported from OpenStreetMap (OSM) [52] and the traffic demand for the period between 6:00 and 8:00 in the morning. Unfortunately, this scenario is cumbersome and requires additional work to improve the quality of its network, and to verify how routes are mapped onto both the network and the traffic demand.

An example of a very small-scale scenario with a high level of detail is the Europarc roundabout, Creteil, France [226]. This synthetic dataset focuses on a roundabout with six entrances/exits, multiple car lanes, a bus lane, and 15 traffic signals. The SUMO mobility traces are two rush-hour periods of two hours each.

On a completely different scale, the ITS Austria West scenario [227] (Figure 5.1c) presents a real-life traffic monitoring system that uses a mesoscopic version of SUMO, MESO [228]. This scenario is a good example of the effort required to build and maintain a traffic scenario. The project monitors an infrastructure with ∼245,000 nodes and ∼320,000 edges with a total length of ∼27,000 km. It uses five different traffic information sources providing floating car data and a traffic demand model for the simulation of 1.2 million routes and 1.6 million vehicles. Unfortunately, it relies on proprietary information and is not freely available to the research community.

A realistic traffic scenario from the city of Bologna [229] (Figure 5.1d), built in the iTETRIS [230] framework, provides a good introductory model for the research community, but has some limitations. The traffic demand is only defined over one hour, and the scope of the scenario, which is relatively small, covers only one neighbourhood, and so is lacking in generality.

The final general-purpose scenario created for SUMO considered here is VehiLux [231]. This scenario presents the same issues as the TAPASCologne scenario. Without fine tuning, the scenario cannot be used to provide reliable data. The first version of LuST Scenario [20] is based on the same tools and sources of information as VehLux, but has been fine-tuned and hand-checked in order to be



(a) Sioux Falls. (b) TAPAS Cologne.

(c) ITS Austria West. (d) Bologna City Centre.

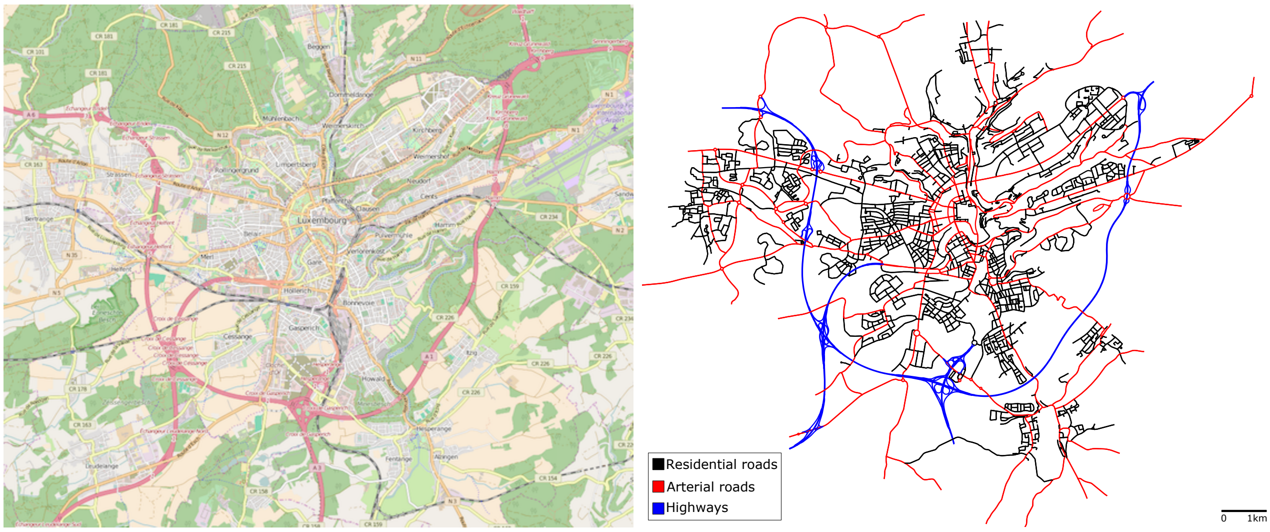
Figure 5.1: Some examples of traffic scenarios.

realistic and provide reliable data. In the more recent version of the LuST Scenario, we enhanced the mobility traces and validated the scenario with real traffic data.

Our purpose is to provide a realistic mobility scenario generic enough to be easily used and adapted by the research community in order to use it as a common ground for research purposes and for comparing solutions.

5.2 Network Generation

The choice of the mobility simulator depends on the nature of the studies to be made. The original motivation behind the creation of the LuST scenario was its use for VANET simulations [232]. For this purpose, the vehicular mobility must be coupled with a network simulator, so consequently, a micromobilty simulator such as SUMO is appropriate for our needs. Next we evaluate the requirements



(a) Luxembourg City from OpenStreetMap. (b) LuST Scenario for SUMO.

Figure 5.2: Topology of Luxembourg City.

and decide which city it is possible to model within the simulator while presenting all the characteristics that we expect from the scenario.

5.2.1 The City

In Chapter 2 we discussed the topology of modern cities and its impact on mobility. There are characteristic patterns in many European cities, which usually consist of a central downtown area, surrounded by different neighbourhoods, linked by arterial roads [233]. Another important detail is the presence of a highway on the outskirts that surrounds the city. The size of the metropolitan area is important both in terms of geographical area and traffic demand. In order to have a realistic but usable scenario, the area should be large enough to show the standard congestion patterns visible in contemporary cities, but it must also be small enough to permit simulations to run in a reasonable amount of time. The City of Luxembourg (Figure 5.2a) fits the description, with a population of 110,000 inhabitants in 2014, and almost 1,400 kilometers of roads in its metropolitan area. One peculiarity of the city is that, during a normal working day, its population triples [234, 235].

We gathered the necessary information concerning the city's topology from OSM [52], a project that relies on an active community of mappers who contribute and maintain data about roads, trails, points of interest, and more, all around the globe. The accuracy of the information provided by OSM is characterized in [236]. In order to work on the data provided by OSM, we used JOSM [93] to manually select and change points of interest and road segments. In this phase, we retrieved information about roads of all kinds (but removing those which are bus-only, bike-only and pedestrian), traffic signals, locations and names of bus stops; we also saved additional information about schools, workplaces and residential areas to be used in the activity generation process. At the same time we saved the geometry and the locations of car parks and buildings.

The LuST Scenario is built with tools such as JOSM and `netconvert` [237] using an iterative process to adapt the road topology to the needs of the simulator. Over recent years, the SUMO community has released a new editor, `netedit` [238]; this has been very helpful in speeding up the iteration process, which adds precision and details for new versions of the scenario. Figure 5.2b shows the final topology of the LuST Scenario, with streets coloured by class. Highways are shown in blue, main arterial roads in red and residential roads in black.

In the following sections we discuss the process behind the generation of LuST Scenario.

5.2.2 Topology Generation

Although SUMO is able to simulate a scenario with a high level of detail (from the type of vehicles allowed in a street to the location of the pedestrian crossings), to have a properly-functioning city, many simplifications are required. To allow the scenario to be easily and predictably modified, the roads have been categorized into different classes and speed limits have been fixed based on the road type.

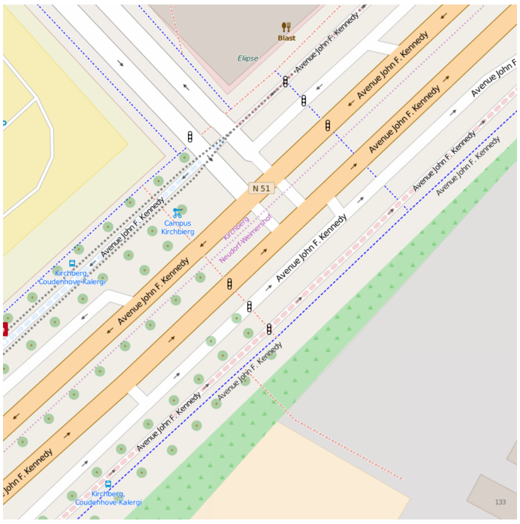
In addition, SUMO has requirements concerning the geometry and shape of intersections and road segments to provide a realistic mobility simulation, and those requirements must be met by adjusting the geometry of intersections and roads. These changes, even if kept to a minimum, have affected the final topology and they need to be taken into consideration while specifying bus routes and stops, as well as the locations of buildings.

Figure 5.3 shows an example of an intersection that is part of the scenario. Figure 5.3a shows the intersection as represented by Google Earth. In this intersection we have a junction where a secondary road meets a primary road. For the primary road, there are three separated roadways in each direction. The main roadway has three lanes and is usable by all type of vehicle. The second is a road with car parking spaces on one side, and the third is the bus lane. In addition there are pedestrian walks and bicycle paths on both sides. The secondary road has only two lanes in each direction and the bicycle/pedestrian path. This intersection is regulated by a traffic light system. Figure 5.3b shows how the intersection is represented in OSM, where all of these components except the number of lanes[1] are easily identifiable.

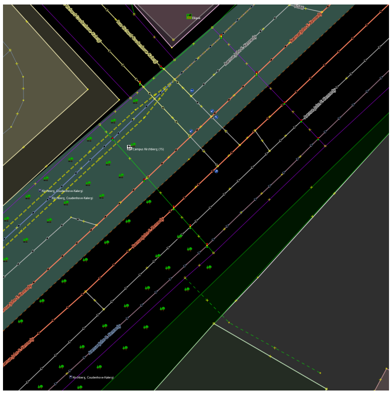
In order to build this intersection for SUMO, we extracted it from OSM and imported it into JOSM. All the details available in JOSM are shown in Figure 5.3c. From this point it is possible to directly convert it with `netconvert`, and the result is shown in Figure 5.3d. It can easily be seen that the automated conversion is not precise enough to obtain a functional intersection. Even if the number of lanes is similar, the geometry does not provide a realistic representation of the intersection. To obtain a usable intersection is necessary to use JOSM to simplify the network and recompute the intersection with `netconvert`. Figure 5.3e is the final result after the iteration through hand-validation and conversions. A change that has been made is the removal of the restriction imposed on some roads concerning the types of vehicles allowed to use them. The number of lanes and geometry of the intersections involved have been modified accordingly, in order to obtain realistic traffic patterns. We have presented a single example here, but the vast majority of intersections had to be corrected and hand-validated. Furthermore, all the changes had to be consistent throughout the network.

[1] In OSM format, miscellaneous information is stored as parameters in the XML file, and is not directly identifiable in the graphical representation provided online.

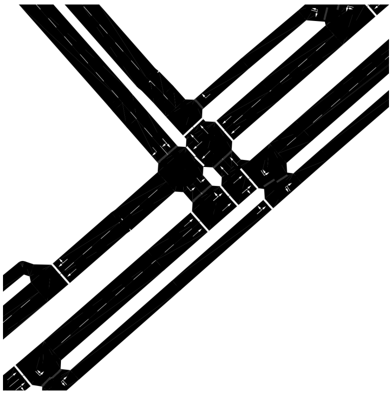
(a) In Google Earth.



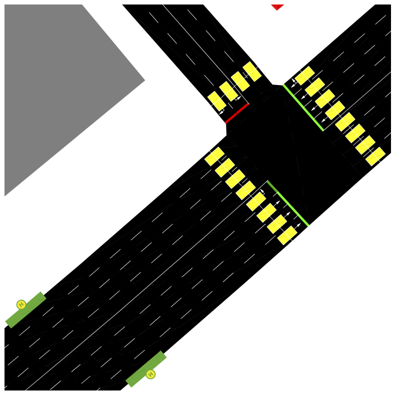
(b) In OpenStreetMap.



(c) Imported in JOSM.



(d) Automatically converted.



(e) Manually corrected.

Figure 5.3: Conversion of an intersection from OpenStreetMap to a usable net format for SUMO.

Traffic light systems play an important role in vehicular mobility. Our main objective is to configure each intersection using a simple but efficient method. SUMO provides various traffic light logics, of which the *actuated* option is the best for our scenario. Deploying only actuated traffic light intersections, all using the the same program, provides an efficient, realistic, and easy-to-use scenario. The parameters for the generic program are based on the *Traffic signal timing manual* [51]. In addition, we provide the configuration for static traffic lights. This configuration is useful when the dynamic behaviour of actuated traffic lights would introduce too much variability in the simulation while testing specific parameters. For example, when studying various algorithms for dynamic route optimization, the use of static traffic lights would make it easier to test the proposed solution for undesirable behaviour.

The static information concerning the network topology is summarised in Table 5.1. The LuST

Table 5.1: Topology information.

Area	155.95 km^2	Intersections	4,473
Total roads	930.11 km	Traffic lights	203
Highways only	88.79 km	Inductive loops	3,157
Bus stops	561	Car Parks	175
Bus lines	38	Buildings	13,553

Scenario covers an area of almost 156 km^2 with a total of 930 km of roads of different classes. There are more than 4,000 intersections, with 200 of them regulated by the traffic signal system.

By adding further configuration files, we defined the locations and sampling behaviour of the simulated inductive loops. In the scenario we positioned them five meters [51] from each intersection with a traffic signal system, in both directions. Keeping in mind that we were building a general-purpose scenario, we fixed the location of each inductive loop close to the intersection to enable the monitoring of obstructions and occupancy of the junction itself. Additional inductive loops are on the highways, and on their ramps, in order to easily monitor traffic flows on the peripheral roads.

5.2.3 Buildings and car parks

As mentioned previously, this scenario can be used with a network simulator such as NS3 [239] or OMNet++ [86] in order to simulate vehicular communications. For this purpose, the wireless propagation models require information on the shapes and positions of the buildings. This information is extracted from OSM and refined with JOSM to match the modified network topology. The transformation from the OSM format to the SUMO network is not completely straightforward. In OSM, the streets are defined as dots (intersections) and segments (roads) having length and shape, but without the lane size. Once the street is converted for SUMO, the actual dimensions of the lanes play a crucial role in avoiding having buildings in the middle of roads. Importing the geometry of the buildings directly from OSM may create an overlap between the lanes and the edges of the polygons.

Although OSM provides a great deal of information concerning the points of interest on a map, the miscellaneous information is not always consistent due to different sources, cooperative contributions, and versioning. For this reason we decided to import only the shape of the points of interest and to focus on two types of polygon. Firstly, car parks are important for studies concerning mobility, for example to evaluate multi-modal strategies. The second type of polygon represents all buildings (including apartments, houses and construction sites), which are of importance if realistic results are to be obtained when evaluating communication protocols. Without the position and shape of the buildings, it is not possible to simulate the wireless propagation model correctly, resulting in unrealistic behaviour of the communication channel.

Figure 5.4 shows the location of the buildings (in red) and the car parks (in grey) in a business district of the LuST Scenario.

Once the topology of the network has been defined, we are able to move our focus to the traffic demand for the scenario.

Figure 5.4: An example of the building (in red) and car park (in grey) information in the LuST Scenario.

5.3 Traffic Demand Generation

The best way to achieve realistic traffic patterns is using real demographic data, published by the public agencies, to generate the activity demand for the `activitygen` [240] tool. For Luxembourg City, demographic data such as population and age distribution, is available on the Internet site of the Luxembourg National Institute of Statistics and Economic studies (STATEC) [234].

The `activitygen` tool utilises the definition of a road network and the description of the population to generate a traffic demand for a scenario. It uses an activity-based traffic model that relies on a multi-modal trip planner including buses, cars, bicycles and pedestrians to derive daily activities such as work, school, and leisure.

The city's public transport database was used to extract information about bus routes [241]. A total of 561 bus stops were introduced in the scenario, with 38 bus routes inside the city for a total of 2,240 buses over the 24 hour period. The locations of the bus stops in the LuST Scenario are not the same as those in the OSM file (as mentioned earlier); however we tried to keep them as close as possible. For this reason, we had to rebuild the bus routes to match the new bus stop locations.

`activitygen` provides an initial mobility estimate but requires more work and fine tuning in order to be realistic. We used the traffic data presented in a mobility study that describes traffic characteristics over recent years in Luxembourg [242] to improve it. The complete traffic demand is composed of buses, local and transit mobility. We define as *local* a vehicle that has either an origin, a destination, or both inside the city. We define as *transit* a vehicle that has both origin and destination outside the boundaries of the scenario and which is routed through the peripheral highway surrounding the city. Instead of the bus routes provided by the tool, we used a scheme manually generated from the actual information and then optimised for the scenario. Given that the `activitygen` traces were localized in the inner city and that transit mobility was not properly taken into consideration, we tuned the available routes in order to get closer to the model and also added transit mobility.

Buses and transit mobility follow a fixed route, but the local mobility must be generated and optimized in order to achieve realistic traces.

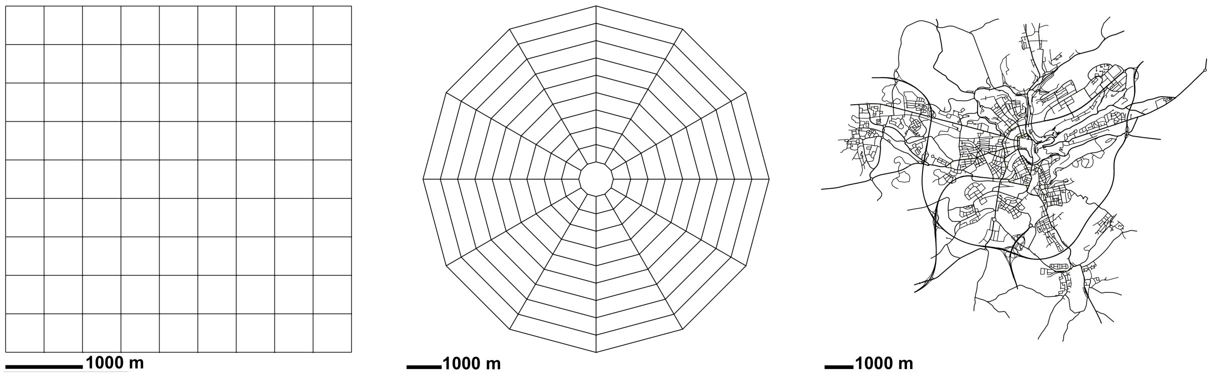
5.3.1 Traffic Flows Optimization in SUMO

In traffic simulation, the Dynamic User Equilibrium (DUE) is formulated as the dynamic version of the Wardrop's user equilibrium [16]: *"If, for each Origin-Destination pair at each instant of time, the actual travel times experienced by travellers departing at the same time are equal and minimal, the dynamic traffic flow over the network is a time-based dynamic user equilibrium state."* [176]. It is important to take into consideration that in this definition, the term *dynamic* refers to the time-based definition of the equilibrium, and the actual path taken to obtain the equilibrium is fixed. In a discrete simulation environment, this equilibrium can be obtained through an iterative optimization process. A single step of the iteration is performed with Dynamic User Assignment (DUA) and is comparable with incremental assignment, in which the minimum-cost path is recomputed each time, re-evaluating the cost on each link depending on the traffic volume.

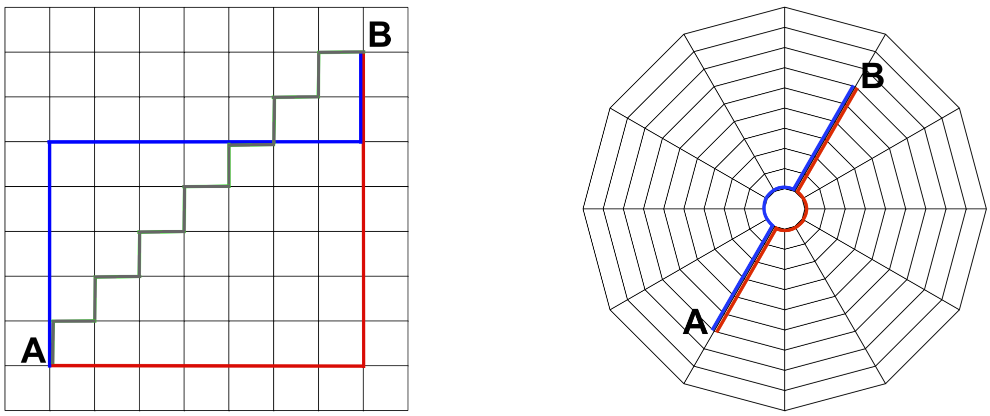
A widely-used iterative optimization is the Gawron [181] method, which computes the stochastic user equilibrium for each vehicle and iteratively optimizes each route, running many simulations and recomputing the DUA over a network with different costs for the roads. The number of iterations required varies depending on the topology. After each iteration, new routes are added to the set of those available for a vehicle, and a new simulation is performed.

Among the tools provided by SUMO, we find `duarouter` [202], which is used to compute the user-optimal path routing for the vehicles based on DUA, and `duaIterate` [243], which iterates `duarouter` in order to compute the approximate DUE. As suggested by its name, the `duaIterate` tool iteratively optimizes each route without changing the departure time, running many simulations to save the status of the network over time, and recomputing the DUA using the network with different costs for the roads, provided by the previous simulation. The first iteration uses `duaroute` over the empty network. The number of iterations required varies depending on the topology. In order to converge, the route is selected by choosing randomly among the best routes, rather then selecting the cheapest one. SUMO provides the option of using two different sets of routes; the first and mandatory set of routes requires one route defined for each vehicle. The second set of routes is optional and allows the definition of alternatives for each vehicle. After each iteration, new routes are added to the set of alternative routes available for a vehicle, and a new simulation is performed.

In addition, SUMO implements run-time routing capabilities [244]. In the simulation, each vehicle can be equipped with different types of devices [245] in order to interact with the environment, collect data (e.g. battery level for electric vehicles and carbon emissions for conventional) and to simulate a behaviour (e.g. routing device or a custom device). The routing device provided by SUMO allows the equipped vehicle to change the route to its destination at run time. The change can happen at regular intervals, globally defined for all the routing devices. The routing mechanism can be



(a) Manhattan grid. (b) Radial network. (c) LuST Scenario.



(d) Shortest Paths from A to B. (e) Shortest Paths from A to B.

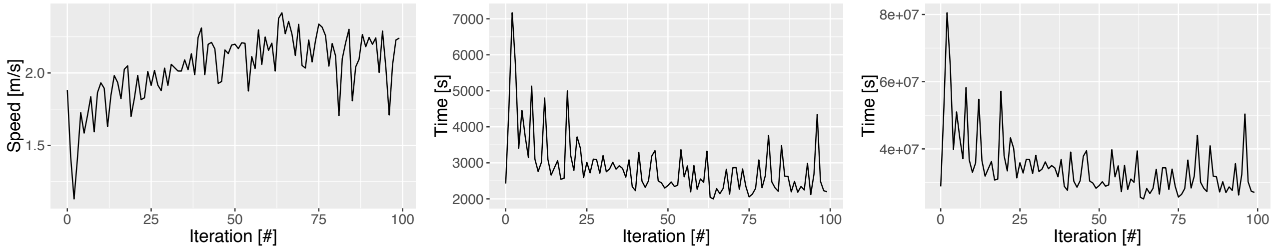
Figure 5.5: Network Topologies.

explained as follows: if a vehicle is equipped with a routing device, an optimal-route check is issued to the simulator following a fixed time interval. SUMO uses the current position of the vehicle, its destination and the current status of the network to compute the optimal path with `duarouter`. If and only if the new path is faster than the current one, the vehicle will change route. The resulting behaviour is that being allowed to change route does not imply a change of path at every time interval.

5.3.2 Impact of Traffic Optimization in Different Topologies

The first step in understanding the implications of using `duarouter` and `duaIterate` to generate the mobility for LuST Scenario is to use them to generate the mobility on simpler networks.

Figure 5.5 shows the three topologies that we examined: a Manhattan grid in Figure 5.5a, a radial network in Figure 5.5b, and, finally, the LuST Scenario in Figure 5.5c. This allows us evaluate the tools and the optimization with increasing level of complexity. In addition, Figures 5.5d and 5.5e show the shortest path between intersections A and B in a Manhattan grid and a radial network. The



(a) Speed. (b) Time lost. (c) Total travel time.

Figure 5.6: Iterations: Manhattan grid.

important thing to note is that, in a radial network, you have a very limited number of shortest paths (maximum two in our topology), but in a grid, in order to know how many shortest paths you have from A to B, we must solve a combinatorial problem; one way to do this is by using lattice paths [246]. Assuming that the origin has coordinates $(0, 0)$, and the destination has (x, y) where both $0 \leq x$ and $0 \leq y$, the only allowed movements are north and east. We can compute the lattice paths as follows:

$$\binom{x+y}{x} = \binom{x+y}{y} = \frac{(x+y)!}{x!y!}.$$

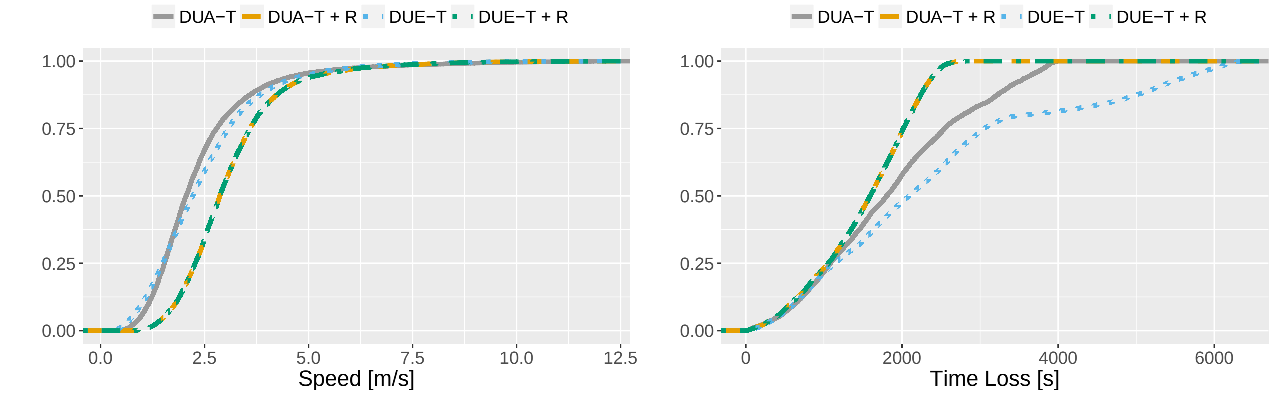
In our example, $A(1, 1)$ and $B(8, 8)$ we have 3,432 lattice paths.

For the Manhattan grid and the radial topology, the initial traffic demand is generated using random sources and destinations, and the number of vehicles is tuned to achieve elevated congestion levels. In the case of the LuST Scenario, we use the local mobility generated by the `activitygen` and enhanced with the data provided by the sources previously mentioned [234, 235, 242].

We compare four different simulations based on two sets of traces. The first set of traces, Dynamic User Assigned Traces (DUA-T), provides the fastest path from origin to destination without taking traffic congestion into account, and is the output generated by `duarouter` on the empty network. The second set of traces, Dynamic User Equilibrium Traces (DUE-T) represents the approximated equilibrium for the traffic demand of the scenario. In order to obtain this equilibrium, we use `duaIterate` with a fixed iteration count. We apply the device routing mechanism provided by SUMO on top of the DUA-T and DUE-T. All the vehicles in the simulation are equipped with the device, with a route check done every 300 seconds. The idea behind these simulations is to check whether DUA-T with routing is better than DUA-T, and that DUE-T with routing is worse than DUE-T. If DUE-T with routing were better, that would mean that DUE-T is not the best-case scenario, and `duaIterate` is not able to provide the approximate equilibrium that we are looking for.

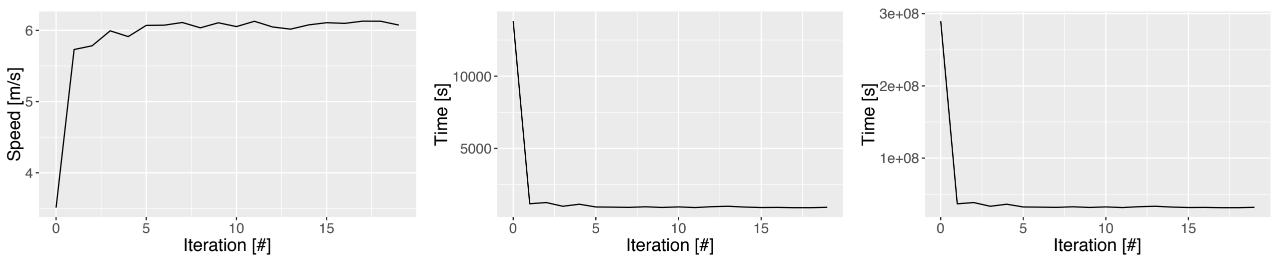
Traffic Optimization on the Manhattan Grid Figure 5.6 shows the results obtained from 100 iteration of `duaIterate` in terms of average speed, time lost, and total travel time[2]. Apart from the initial improvement visible in the first ten iterations, the tool is unable to converge to an equilibrium. The reason is quite simple, and is related to the symmetry of the grid. A shown in Figure 5.5d, all

[2]The total travel time is the cumulative sum of all the travel times of each vehicle in the simulation.



(a) CDF Speed. (b) CDF Time Lost.

Figure 5.7: Evaluation: Manhattan grid.



(a) Speed. (b) Time lost. (c) Total travel time.

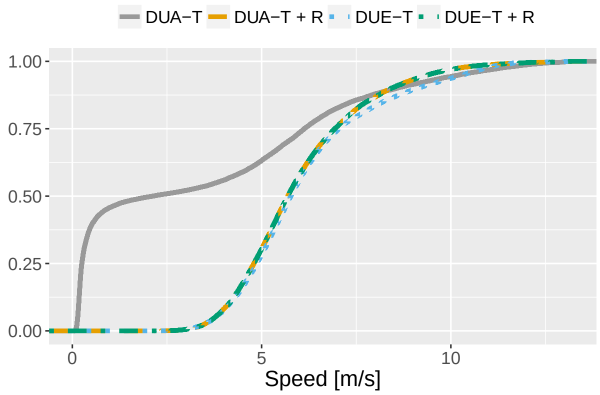
Figure 5.8: Iterations: Radial topology.

paths from intersection A that always move in the direction of intersection B have all the same length, implying that the only variable is the congestion in the network. After each iteration, `duarouter` provides a new set of routes that simply move the congestion from one location to another.

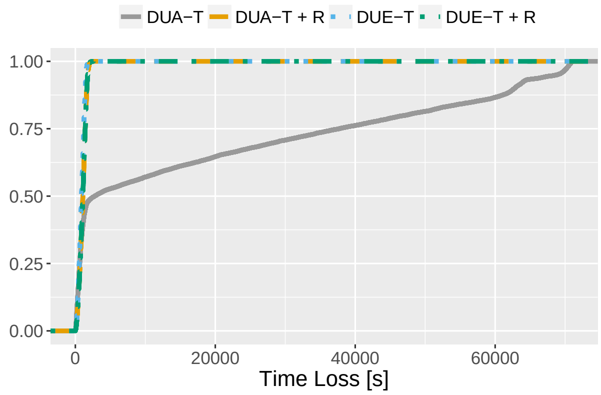
Nevertheless, in Figure 5.7 we see that some improvement is possible: compared with DUA-T, the mean speed in DUE-T is increased and the mean time lost is decreased. On the other hand, the fact that `duaIterate` was not able to converge is shown by the improvement provided by both DUA-T with routing and DUE-T with routing.

Traffic Optimization on the Radial Topology Figure 5.8 shows the results obtained from 20 iterations of `duaIterate` in terms of average speed, time lost, and total travel time. In this case `duaIterate` converges fast and approximate equilibrium is achieved in a couple of iterations.

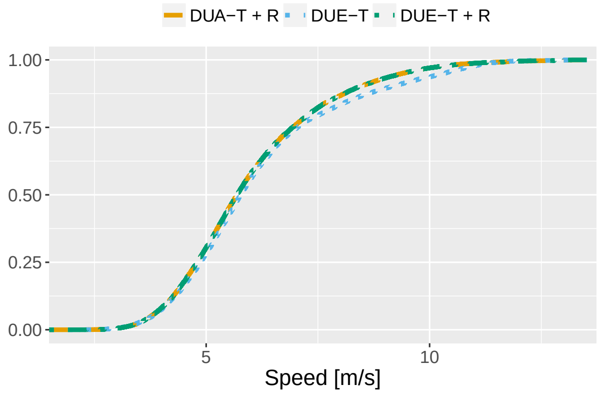
Figure 5.9 shows cumulative distribution functions for speed and time lost in a radial topology. Comparing DUA-T with DUE-T, the mean speed is almost doubled (from 3.485 to 6.193 m/s) and the mean time lost is decreased by an order of magnitude (from 19,360 to 878 seconds). With the radial topology, the fact that `duaIterate` was able to converge is shown by DUA-T with routing having an



(a) CDF Speed.



(b) CDF Time Lost.



(c) CDF Speed without DUA-T.

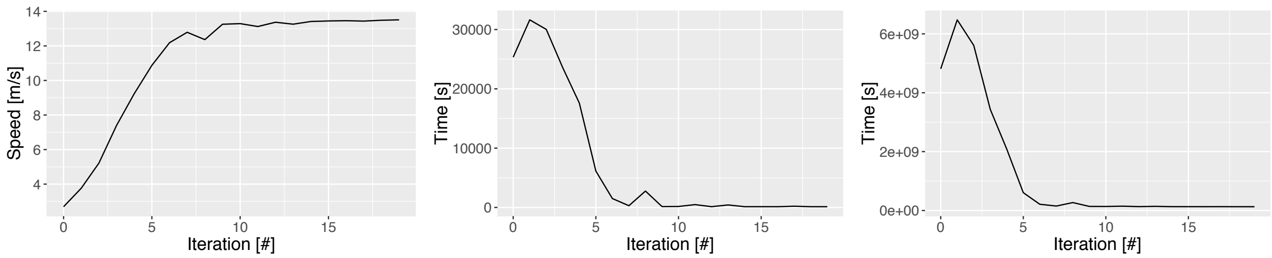
(d) Time Lost without DUA-T.

Figure 5.9: Evaluation: Radial topology.

improvement compared with DUA-T; in the case of DUE-T with routing, there is a small decrease in performance compared with DUE-T.

Traffic Optimization on the LuST Scenario Figure 5.10 shows the results obtained from 20 iterations of `duaIterate` in terms of average speed, time lost, and total travel time. In this case `duaIterate` converges, and an approximate equilibrium is achieved with ten iterations.

Figure 5.11 shows cumulative distribution function for speed and time lost in the LuST Scenario. The speed distribution of DUA-T compared with with DUE-T is remarkably different. The mean speed increases from 2.8 m/s in DUA-T to 13.8 m/s in DUE-T. Concerning the mean time lost, this is decreased by almost two orders of magnitude, from 18,830s in DUA-T to 188s in DUE-T. As in the radial topology results, the fact that `duaIterate` was able to converge is shown by the routing providing an improvement only for DUA-T. The complete evaluation and validation of the mobility provided by the LuST Scenario is presented in Sections 5.4 and 5.5 below.



(a) Speed. (b) Time lost. (c) Total travel time.

Figure 5.10: Iterations: LuST Scenario.

Table 5.2: Number of vehicles over 24 hours.

Buses	2,240
Local mobility	215,526
Transit mobility	70,484

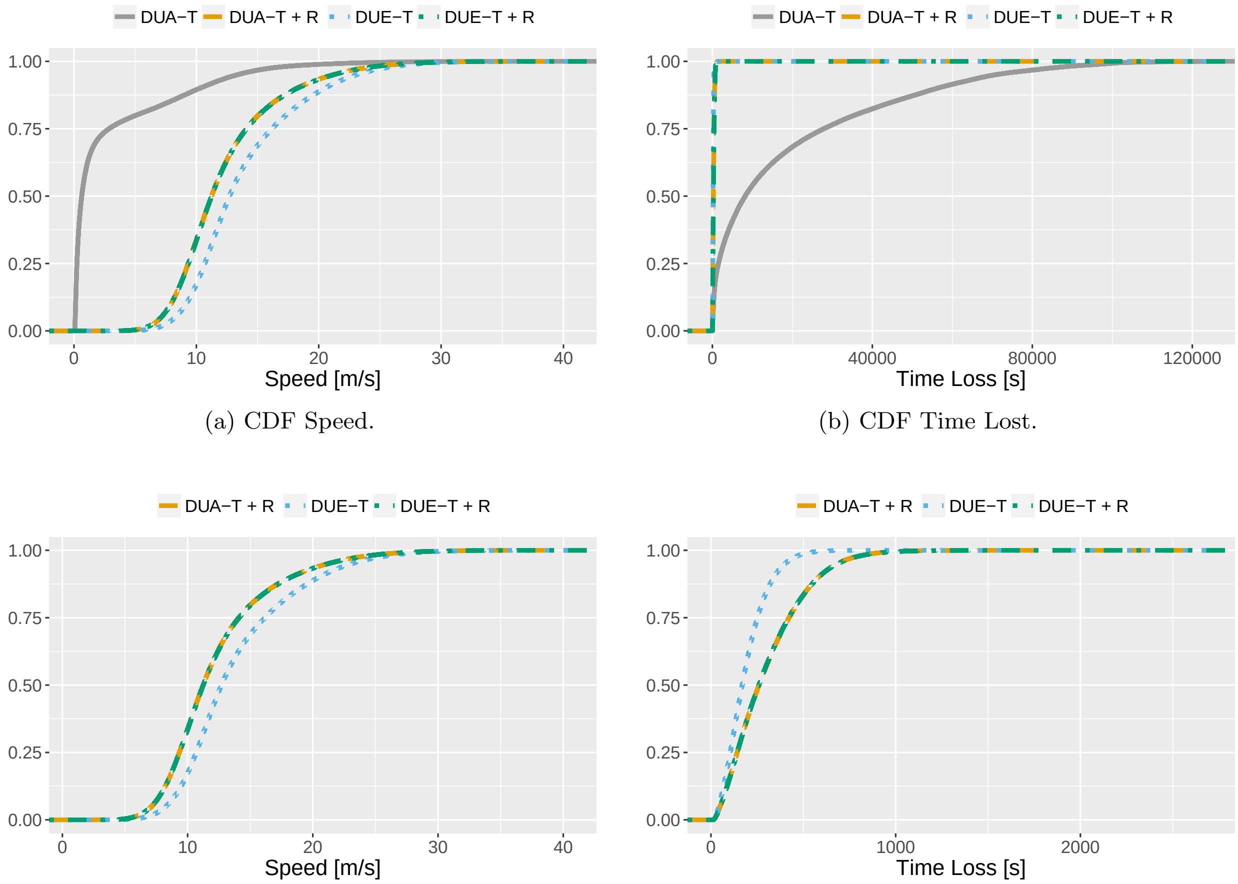
5.3.3 LuST Scenario Mobility

The traffic demand obtained from DUE-T over the entire day is depicted in Figure 5.12a. We can clearly see the morning and evening rush hour peaks around 08:15 and 18:30 respectively, and a lower peak period around lunchtime. Figure 5.12b highlights the bus coverage in red. The numbers of vehicles over the 24 hours of mobility are summarized in Table 5.2.

5.4 LuST Mobility Evaluation

As explained in Section 5.3, in a SUMO simulation, each vehicle can be equipped with different types of devices in order to interact with the environment. Among these, we are interested in using the routing device to enable the equipped vehicle to change the route to its destination at run-time. Given that the change can happen at regular intervals, globally defined for all the routing devices, it is necessary to study the impact of this time interval on routing optimization. We also need to evaluate how the percentage of vehicles equipped with the routing device impacts the final mobility.

Two different mobility traces are provided with the scenario. DUA-T mobility provides the fastest path from origin to destination on an empty network. DUE-T mobility provides the approximate equilibrium for the traffic demand of the scenario. In order to obtain this equilibrium, we used `duaIterate` with a fixed iteration count of 50. After the first ten iterations, the results were stable, and from these, we selected the mobility traces that minimized the total travel time in the simulation. DUA-T and DUE-T traces represent the upper and the lower bounds of mobility optimization. We studied the impact of the routing device on mobility by changing the number of vehicles equipped with the device (user participation rate) and the interval used to check whether a change of route is required. Taking the initial mobility from DUA-T, we varied the parameters associated with the



(a) CDF Speed.

(b) CDF Time Lost.

(c) CDF Speed without DUA-T.

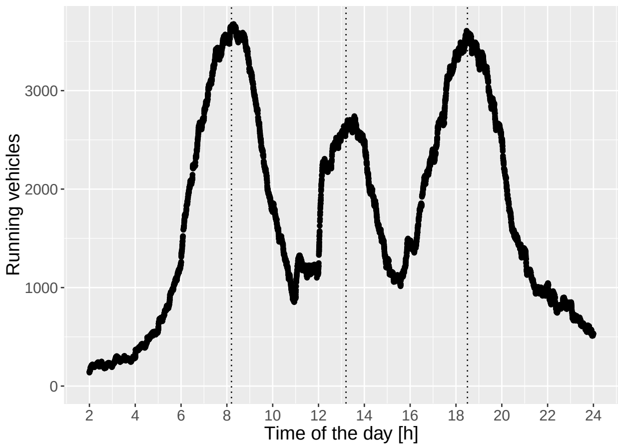
(d) Time Lost without DUA-T.

Figure 5.11: Evaluation: LuST Scenario.

routing device. The user participation rate varied from 10% to 100%, and we evaluated intervals from 30s to 900s. In the following discussion, we call the experiment by the name of the mobility trace used (i.e. DUA-T and DUE-T) and we add a suffix R, followed by the number of seconds, for the interval in case of Rerouting (e.g. R300 or R60).

Time Loss The parameter that we evaluated is the time loss, which is provided by SUMO, and is computed for each vehicle in the simulation as actual trip duration minus theoretical trip duration. The theoretical trip duration is the minimum time required for the vehicle to drive from origin to destination on an empty road network.

Figure 5.13 shows the improvement in time loss, while varying user participation rate, for the experiments DUA-T R600, DUA-T R300 and DUA-T R60. We used DUA-T, in red, as the upper bound (or worst-case scenario), and DUE-T, in green, as the lower bound (or best-case scenario), both without routing devices allowed. In Figure 5.13a, in order to isolate the behaviour of the routing



(a) Traffic demand.

(b) Bus coverage.

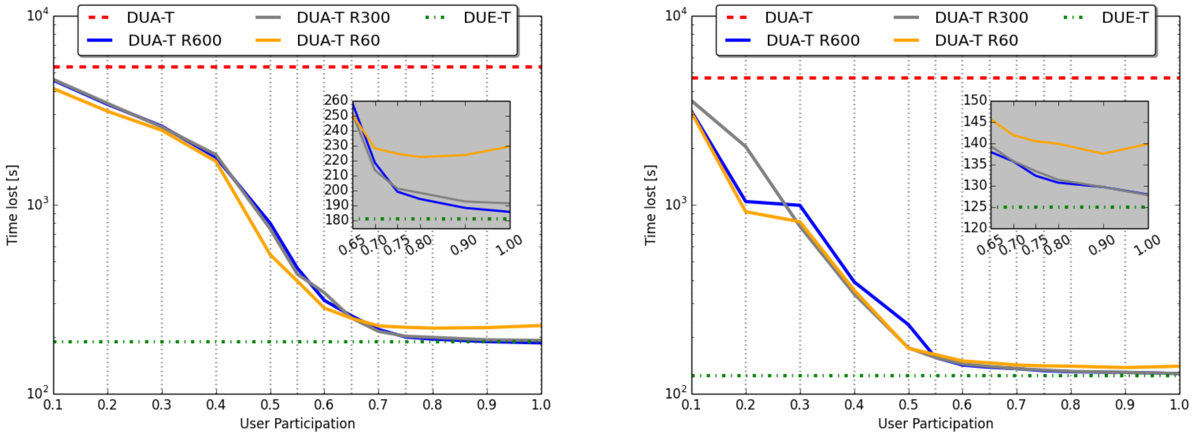
Figure 5.12: LuST Scenario mobility traces.

mechanism, we used static traffic lights instead of actuated. Using actuated traffic lights would have raised the issue of having two independent optimizations (traffic light timing and vehicular routing) acting at the same time. Additionally, we decided to examine the interaction between the two independent optimizations: actuated traffic lights and dynamic rerouting. The results are shown in Figure 5.13b.

In Figure 5.13a we can see that, as we increase the percentage of users allowed to reroute, time loss (and hence the level of congestion) decreases. In all the experiments, the greatest improvement can be observed between 50% and 75% of user participation. With 50% of users or more, the probability of having a car in a congested situation that is allowed to reroute is high enough to trigger a significant change in global congestion levels. Additionally, because the vehicles that are part of the congestion and allowed to change route, congestion decreases for the remaining vehicles. We can find the same behaviour in Figure 5.13b, noting that, with the actuated traffic lights, the order of magnitude changes, and the traffic is already better optimized. In both cases, above 75% user participation, the decrease in the time loss is less significant and we reach a limit that cannot be improved by rerouting.

For the sake of completeness, we reran all the experiments with the rerouting applied to DUE-T. In this case we have two possible outcomes: the rerouting may or may not improve the DUE-T mobility. If the use of rerouting improves the mobility, DUE-T was not the best-case scenario in the first place. In these experiments, as in Section 5.3.2, time loss increases independently of user participation rate or rerouting interval, and the lowest value measured is the same as for DUA-T.

We selected the more significant rerouting intervals to discuss the interaction between how often a vehicle is allowed to change its route and the congestion in the network. As explained above, because we apply the routing on top of DUA-T, the level of congestion and of user participation are directly linked. In this case, we can see that the two set-ups show different behaviours. As shown in Figure 5.13a with DUA-T R60, at higher levels of congestion, being allowed to reroute frequently will allow



(a) With static traffic lights.

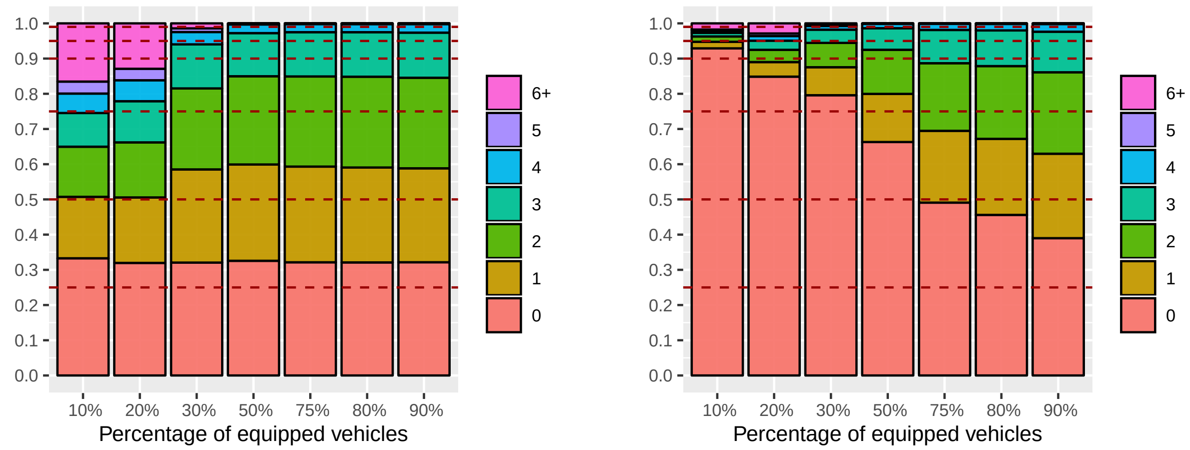
(b) With actuated traffic lights.

Figure 5.13: Comparison of the time lost for different mobility traces: DUA-T, DUA-T R600, DUA-T R300, DUA-T R60 and DUE-T. The time loss is on a logarithmic scale in the external graph and linear in the internal one.

the user to save some time on the road and improve the driving experience. But with lower congestion levels, being allowed to change the route too often becomes counterproductive. The reason for this behaviour is that the traffic changes slowly and the lack of a forecast would create less than optimal routing choices. On the other hand, with DUA-T R600, we see improvement when a high level of congestion is present, and at low levels of congestion we reach the best optimization we can achieve without traffic forecasting. On the other hand, in Figure 5.13b we can see that DUA-T R600 improves faster than DUA-T R60. We assume that this behaviour is due to the fact that the actuated traffic light system presents a better optimization compared to the rerouting mechanism. This is easily explained, since the traffic light optimization covers 100% of the traffic lights and they are distributed all over the city, but the percentage of vehicles allowed to change route varies. With vehicles allowed to improve their route less frequently, the actuated traffic light system is able to produce better results. Once again, with more than 75% user participation, the behaviour in the two scenarios is indistinguishable.

It is important to note that the routing interval has an impact on the performance of the simulation; for this reason we suggest using a 75% user participation with an interval of 300s in in both scenarios, in order to produce conditions as close as possible to equilibrium behaviour while being able to react reasonably fast to the changes introduced in the simulation. Nevertheless, it is important to evaluate whether the behaviour provided by the routing device is realistic.

Realistic Route Changing Behaviour The behaviour created by the routing devices in the simulation can be explained by the fact that, in the real world, most local commuters are familiar with the road network and know at least one alternative path. Further, more and more cars are equipped with real-time navigation services, allowing a better usage of the available road capacity. Allowing



(a) Number of route changes only for the vehicles equipped with the routing device.

(b) Number of route changes computed over the whole traffic demand.

Figure 5.14: Scenario DUA-T R300 with actuated traffic lights.

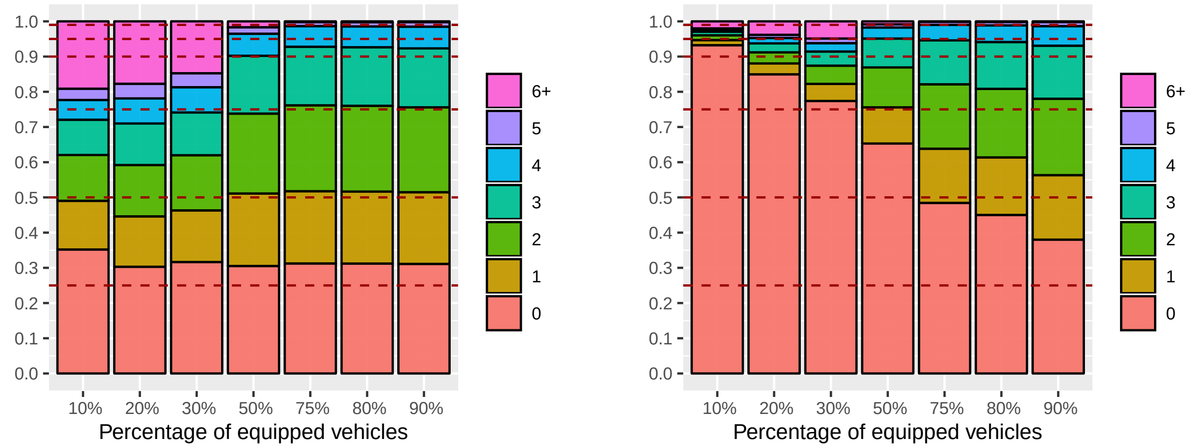
vehicles to change route if needed may introduce unrealistic patterns and behaviours that need to be verified. Being allowed to change the route, does not imply that the route will actually change at every check. This behaviour can be seen in Figures 5.14 and 5.15. Defining what is an acceptable number of changes in a single trip is complex, due to the lack of data and statistics on the subject. We decided to consider any vehicle that changes route more than six times as an anomaly.

Figure 5.14a shows the ratio of route changes for each participation rate computed among only the vehicles equipped with the device. At the bottom, in red, we have the vehicles that, even if allowed to change, have never changed their route. At the top, in purple, we have the vehicles that changed route more than six times. Varying the percentage of vehicles equipped, we see how the percentage of anomalies changes. With few vehicles allowed to react to the traffic situation and elevated levels of congestion, the median number of route changes is high. Increasing the percentage of vehicles equipped, we reduce the number of anomalies rapidly, until, at 75% participation, congestion is lower and anomalies are contained. From 75% on, the behaviour is almost unchanged, and this result is corroborated by Figure 5.13b.

Figure 5.14b shows the overall trend for the whole traffic demand, representing the behaviour of all the vehicles in the simulation. The number of anomalies is contained with more than 50% of equipped vehicles, and with 75% (and above) we have a median of one route change.

If we examine only the suggested scenario (DUA-T R300 with 75% of equipped vehicles with actuated traffic lights), 49% of vehicles never change route, 69.5% change at most once, 88.7% at most twice. Fewer than 0.1% of the vehicles make an anomalously large number of route changes.

For completeness, Figure 5.15 shows the rerouting behaviour with static traffic lights. A significant change can be found only in Figure 5.15a for 10% and 20% of equipped vehicles. In this case, the traffic congestion is so severe that we reach around 20% of anomalies with 10% and 20% of user participation. Nevertheless, Figure 5.15b shows the overall trend for the whole traffic demand, representing the behaviour of all the vehicles in the simulation. The number of anomalies is contained with more than



(a) Number of route changes only for the vehicles equipped with the routing device.

(b) Number of route changes computed over the whole traffic demand.

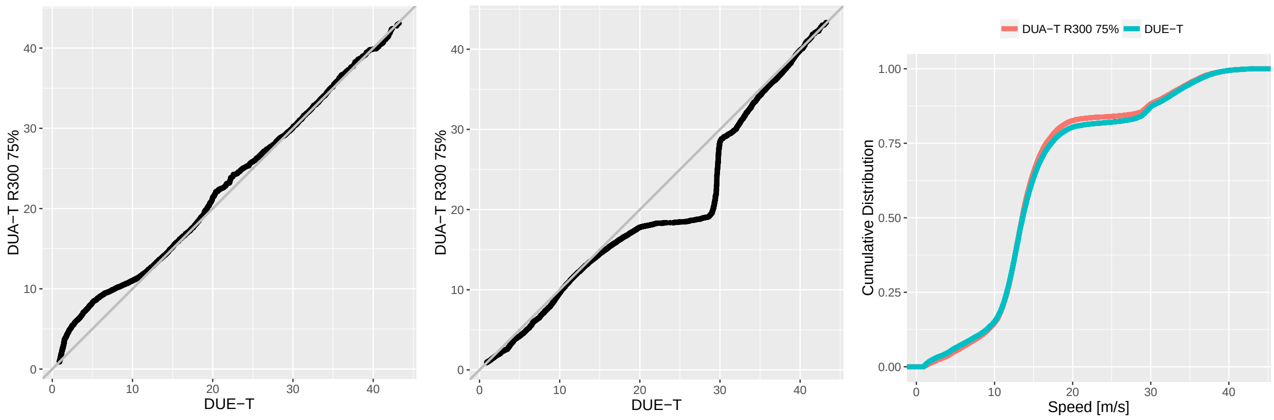
Figure 5.15: Scenario DUA-T R300 with static traffic lights.

50% of equipped vehicles, and with 75% (and above) we have a median of only one route change.

Pre-computed and run-time mobility optimization Considering that DUE-T is obtained with successive iterations of the simulation to obtain the best-case scenario, it is unlikely that the mobility in a real city could have this level of optimization. What is more, the equilibrium is completely limited to the predefined number of vehicles, with their origin, destination and precise departure time. Nevertheless the presence of this scenario is important for comparing different rerouting mechanisms with the best-case scenario. In order to obtain a realistic mobility, we showed that DUA-T R300 with 75% of equipped vehicles behaves similarly to DUE-T, and that it is able to adapt to run-time changes in the simulations.

Figures 5.16b and 5.16a show the quantile-to-quantile comparison of the speed distribution computed from traffic data extracted from DUE-T and DUA-T R300 75% mobility traces, during the morning peak and the afternoon off-peak respectively. Performing a two-sample Kolmogorov-Smirnov test [247] with the complete datasets (over the whole day) we can confirm that the two distributions are similar with distance D of 0.0263, and a p-value that is less than 0.05. The similarity is corroborated by Figure 5.16c, which shows the cumulative distribution of the speed over the entire day.

The routing device provided by SUMO implements the First Wardrop Principle of equilibrium [16], the "selfish user" approach. In this case, the vehicles have complete information concerning the overall traffic situation in order to take the best decision. A more detailed study concerning the impact of this behaviour with partial knowledge of the traffic situation can be found in [17] and [18], and is explored in Chapter 4.



(a) QQ comparison of the morning peak.

(b) QQ comparison of the afternoon off-peak.

(c) CDF over the day.

Figure 5.16: Quantile-to-quantile comparison and cumulative distribution of the speed computed from the DUE-T and DUA-T R300 75% mobility traces.

5.5 LuST Mobility Validation

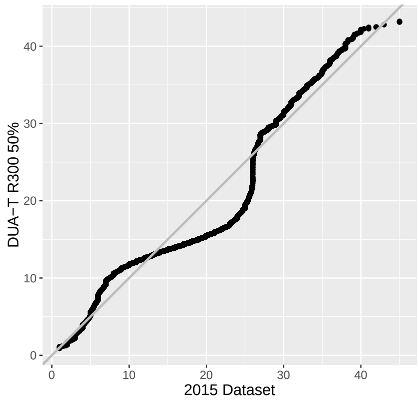
The reason we built the LuST Scenario is to have a common, usable, and realistic traffic scenario for VANET simulations. The aim of the validation presented here is to show that, with the LuST Scenario, it is possible to obtain macroscopic trends that match the empirical data collected in the city. Nonetheless, there are some differences between the scenario and reality that we characterise and explain in the following sections.

In order to measure the realism of the traffic demand offered by the LuST Scenario, we used a dataset collected between March and April 2015 in the City of Luxembourg. The dataset contains more than six million Floating Car Data (FCD) samples collected between 06:00 and 22:00 from more than ∼14,000 trips.

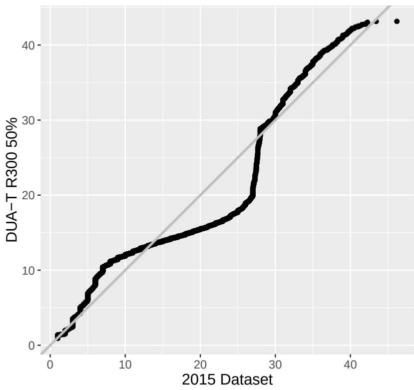
The validation of the traffic demand was performed by gathering FCD from the mobility traces provided in the scenario, DUA-T R300 with 50% of equipped vehicles, which closely matches both the empirical traces and optimized DUE-T. The information collected for each FCD is latitude, longitude and speed. All the speeds used in the following figures and explanations are from FCD, and are not trip-based. In the following sections, the morning peak is between 07:30 and 08:30, and the afternoon off-peak is between 15:30 and 16:30.

Comparison between 2015 Dataset, DUA-T 50% R300 and DUE-T mobility The number of vehicles allowed to change route when there is traffic congestion plays a crucial role in providing a mobility pattern that closely matches the empirical mobility recorded in the city. Varying the time interval and the percentage of vehicles allowed to reroute, we found that DUA-T R300 with 50% of equipped vehicles presents the closest behaviour to the empirical dataset.

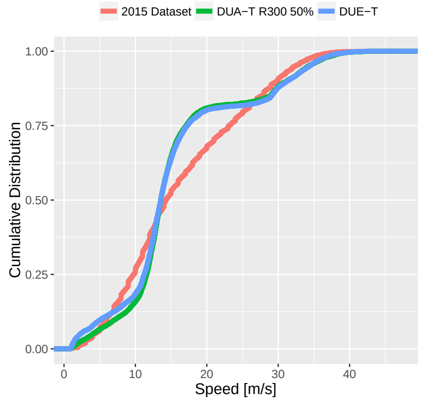
Figure 5.17a and 5.17b present the quantile-to-quantile comparison between DUA-T R300 50% and 2015 Dataset for the morning peak and for the off-peak hours in the afternoon. Performing the



(a) QQ comparison at morning peak.



(b) QQ comparison at afternoon off-peak.



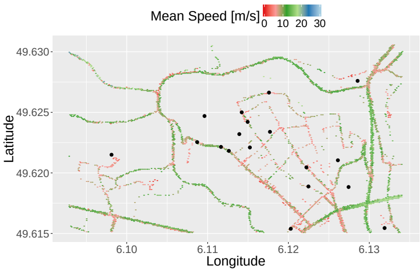
(c) CDF over the day.

Figure 5.17: Quantile-to-quantile comparison and cumulative distribution of the speed computed from the 2015 Dataset, DUE-T and DUA-T R300 50% traces.

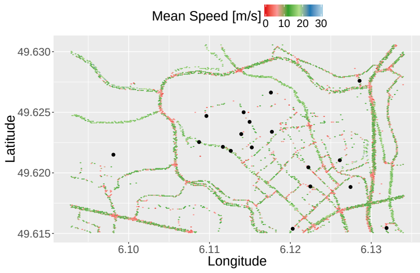
two-sample Kolmogorov-Smirnov test, we get a distance D of 0.1569 with p-value less than 0.05 during peak hours, and a distance D of 0.1582 with p-value less than 0.05 during off-peak hours. In both cases, we can see that the distributions are similar, which means that the LuST Scenario is capable of providing a realistic traffic demand and mobility traces.

Figure 5.17c compares the cumulative distribution functions of the speed collected from the FCD from DUE-T, DUA-T R300 50%, and 2015 Dataset traces. The average speed and standard deviation in the three datasets is comparable. The optimized DUE-T mobility has a mean speed of 16.1 m/s with a standard deviation of 8.7 m/s. DUA-T R300 50% has a mean speed of 15.8 m/s with a standard deviation of 8.4 m/s. Finally, the 2015 Dataset has a mean speed of 16.4 m/s with a standard deviation of 8.8 m/s. The speed distribution in the empirical dataset is smoother than in the simulations. Real drivers do not always respect speed regulations, are prone to distractions and are allowed to drive slower than the speed limit. In addition, the drivers interact with everything that is part of the environment, not just only the surrounding vehicles. These factors are only partially modelled in a vehicular simulator, where the changes in the speed distribution are only due to traffic congestion. For example, in the simulation, speeds between 20 and 30 m/s are possible only on a congested highway, but not inside the city. In reality, drivers can violate the speed limit on main roads inside the city while not congested, effectively changing the speed distribution in a way that cannot be simulated without a better behavioural model for the divers.

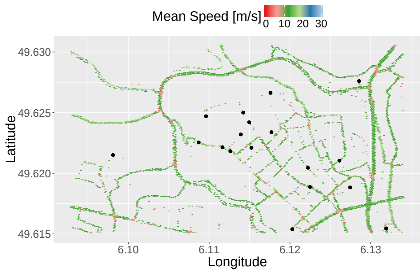
Aggregated Speed by Location Cities are complex systems where the overall traffic mobility is shaped by road topology, the locations and number of Points Of Interest (POIs), and interactions between pedestrians, bicycles, vehicles of various types, and public and private means of transportation. The LuST Scenario takes into account a limited number of POIs, and only public buses and a limited range of vehicle types. This implies that, where the traffic congestion is caused by pedestrian and bicycles, the mobility in the scenario is different from real life. In addition, the timing of the traffic



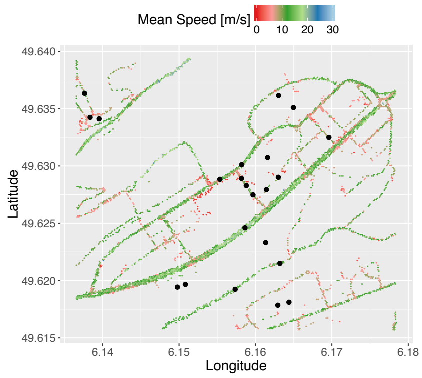
(a) 2015 Dataset Zone 1.



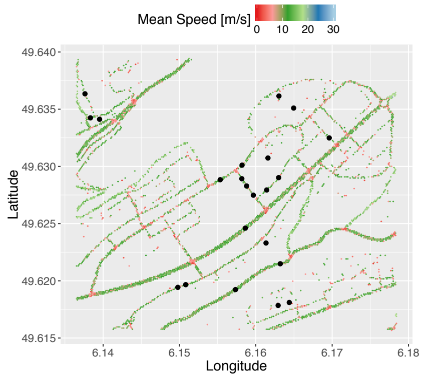
(b) DUA-T R300 50% Mobility Zone 1.



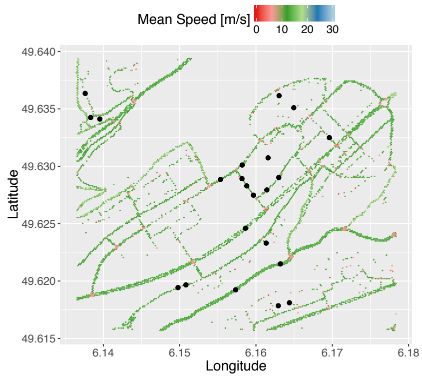
(c) DUE-T Mobility Zone 1.



(d) 2015 Dataset Zone 2.



(e) DUA-T R300 50% Mobility Zone 2.



(f) DUE-T Mobility Zone 2.

Figure 5.18: Aggregated speed computed in the morning peak hour using the FCD from the real dataset and the simulation. The black dots represent the location of the POIs.

light system in the scenario and in the actual city is not the same. Information about traffic light timing - which changes dynamically over time - was not available to us when we built the scenario.

To evaluate the differences between reality and simulation, and to show that the scenario is reliable despite these differences, we selected two neighbourhoods that present particular characteristics: different levels of interaction between pedestrians and vehicles, and different levels of simplification between reality and scenario. Zone 1 is mainly residential with only small businesses, and is home to many schools, from primary to high school, as well as a university campus. Zone 2 is mainly businesses and offices, with one of the biggest malls in the city, one hospital, another university campus and some schools. The main roads that connect the highway to the city centre are primary roads with separated paths for buses, vehicles, bicycles and pedestrians.

It is reasonable to say that primary roads have on average more complex intersections, and thus present more changes in the scenario relative to reality. In Zone 1, the difference between reality and scenario is negligible, because it is composed mainly of residential roads. In Zone 2, the topology in the scenario is simplified compared to the real city. Many primary roads are unified, the number of lanes is increased and the restrictions on the lanes are removed.

Figures 5.18a, 5.18b, and 5.18c show the aggregated speed in Zone 1 computed during the morning peak using the FCD from the 2015 Dataset, DUA-T R300 50% traces and DUE-T optimized mobility.

In this zone, the topology in the scenario closely matches reality. In Figure 5.18a, the data from the empirical dataset shows that the main congested areas (in red) are those around the POIs, where the vehicular traffic is not the only reason for traffic congestion. Pedestrians are able to cross the small roads without trouble, and, given that the morning peak coincides with the opening hours of the POIs, the amount of pedestrian traffic is elevated. In Figure 5.18b, the DUA-T R300 50% traces are able to replicate the traffic on the peripheral streets and the waiting time in the intersections, but fail to represent the stop and go behaviour due to the interactions between pedestrian and vehicular traffic, when they have to coexist in a small space.

Figures 5.18d, 5.18e, and 5.18f show the aggregated speed in Zone 2 computed during the morning peak using the FCD from the 2015 Dataset, DUA-T R300 50%, and DUE-T traces. The topology of the main roads in the scenario is heavily modified due to the change and removal of pedestrian and bicycle paths, bus lanes and car parks along the roads; the smaller roads and the residential areas closely match reality. Once again, the 2015 Dataset mobility presented in Figure 5.18d shows lower velocities where pedestrian mobility has a major impact on the vehicular traffic. In Figure 5.18e, DUA-T R300 50% traces fails to represent the congestion created by pedestrians and bicycles in the residential areas and around the POIs, but closely matches the patterns on the main roads, even though the topology of the scenario is considerably simplified.

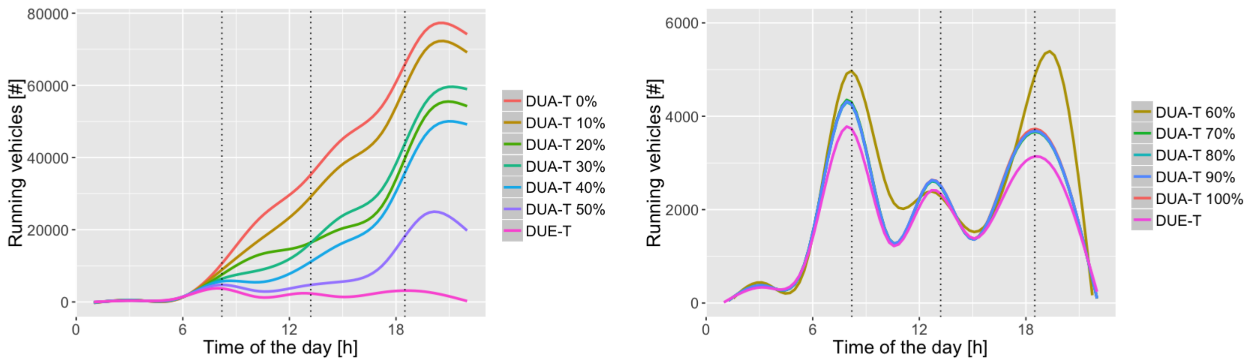
Figures 5.18c and 5.18f show that the approximated DUE virtually alleviates all the traffic problems, and can be used as a best-case scenario for comparison of various optimization problems.

In this validation we have showed that is possible to obtain macroscopic trends that closely match the empirical data collected in the city, even where pedestrians have an impact on mobility patterns. The main differences can be found in the residential and small business areas, where the location of the POIs plays a significant role not only on the number of vehicles in transit, but their behaviour due to their interaction with the surrounding environment, including pedestrians.

5.6 Use Cases

The LuST Scenario provides realistic mobility patterns for a mid-size city. The mobility traces provided can be used as an input for other types of simulators such as NS3 or OMNet++ in order to evaluate network protocols. Using the scenario in combination with these tools allows the study of both the performance of Vehicle-to-X protocols, and the related applications. Further, the scenario allows the evaluation of different multi-modal strategies. Using Vehicles in Network Simulation (VEINS) [89], it is possible to confine the computation of the connectivity network to a restricted area, enabling the simulation of a smaller traffic scenario that only uses a subset of the available road network, allowing testing of protocols and applications on different scales without changing the mobility patterns. In our urban area there are 203 intersections managed by a traffic light system. These intersections can be used to test different optimization strategies (e.g. green waves) or emergency protocols to allow fire-fighters, ambulances or the police to be prioritized.

Traffic Density and Routing For the default scenario, 70% of the vehicles are equipped with a routing device, allowing them to change route if congestion is encountered. We justify this parameter by assuming that most of the local commuters are familiar with the road network and know at least one alternative path. The study of the impact of dynamic routing on a real topology (and the lack



(a) With low user participation rate.

(b) With high user participation rate.

Figure 5.19: DUA-T R300: Running vehicles with different participation rates in routing and actuated traffic lights.

of any previous one) was the main reason behind the creation of LuST Scenario. For this reason we wish to show how the shape of the traffic demand varies depending on the routing, and how adjusting the percentage of vehicles allowed to change route can tune the level of congestion in the scenario, enabling its use for other purposes and research questions.

It is important to consider that the shape of the traffic demand will change as the percentage of rerouted vehicles is varied. The three-bell shaped traffic demand that represents the three rush hours (morning, noon and evening) is not visible in Figure 5.19a, where 50% or more of the vehicles are not allowed to change route: traffic congestion increases significantly and the mobility scenario becomes unrealistic. In Figure 5.19b, with 60% or more vehicles allowed to change route, traffic congestion is reduced significantly and the mobility scenario is more realistic. Even so, the use of a highly congested scenario with gridlocks in critical areas can be used, for example, to study crisis response times or similar problems.

Performance of Eco-Routing Methods Eco-routing is a vehicle navigation method that aims to minimize fuel or energy consumption for a given trip. It is based on the hypothesis that is possible to trade extra travel time for lower consumption. While the hypothesis has been experimentally verified, the design of a method that can fully exploit its potential proves challenging. Current solutions hinge on the assumption that energy spent on any given road does not change in time. In [248, 249], the authors challenge the validity of this assumption by studying the performance of such methods using, among other tools, the LuST Scenario. This has enabled them to quantify the real savings attainable with current eco-routing.

User Privacy and Anonymity in Vehicular Communication Systems In [250] the authors evaluate on-demand pseudonym acquisition policies in vehicular communication systems. The paper crafts three generally-applicable policies for Vehicular Public-Key Infrastructure (VPKI) and makes a systematic effort to experimentally evaluate system performance, using two large-scale mobility datasets, TAPAS Cologne and the LuST Scenario. The polices are evaluated in terms of efficiency, finding the most promising in terms of privacy protection can be supported with moderate overhead. In all cases, the work provides a tangible evidence that state-of-the-art VPKI can serve sizeable areas or domains with modest computing resources.

In [251], the authors use mobility data from the LuST Scenario in a study of the decentralized enforcement of k-anonymity for location privacy using secret sharing. To protect location privacy, a well-known concept that is typically implemented using a privacy proxy is reducing the accuracy of location data, until a desired level of privacy is reached. To eliminate the risks associated with a central, trusted party, the authors suggest a generic method to enforce k-anonymity of location data in a decentralized manner, using a distributed secret-sharing algorithm and the concept of location- and time-specific keys. They describe the method in the context of a system for privacy-friendly traffic-flow analysis, in which participants report origin, destination, and the start and end time of their trips.

Geo-Spatial Resource Allocation In [252], the authors present preliminary results on geo-spatial resource allocation for heterogeneous vehicular communications. Vehicular networks need to make optimal use of their limited radio resources to achieve acceptable performance and reliability. However, the scale and dynamicity make it very challenging to optimize this use while meeting strict technical and legal requirements. The work proposes a centralized scheme able to improve overall network performance by using wide-scale information instead of the restricted local views used in distributed approaches. They evaluate their scheme using the LuST Scenario.

Automated Scenario Generation Realistic map data is the basis for meaningful simulation studies of Inter-Vehicle Communication (IVC) applications and protocols. Synthetic scenarios such as isolated intersections or a perfectly laid-out grid do not feature a typical mix of low and high traffic density roads and consequently cannot be used as a representative scenario for urban traffic. With cOSMetic [253], the authors' goal is to provide an algorithm to obtain reliable OSM to SUMO network conversion. While this project is only in its initial stages, it is using the LuST Scenario as ground truth to evaluate the conversion.

5.7 Contributions and Final Remarks

When working on problems related to vehicular traffic optimization and intelligent transportation systems, a vehicular traffic simulator, with an appropriate scenario for the problem at hand, is used to reproduce realistic mobility patterns. As we discussed in Chapter 2, many mobility simulators are available to the research community and the choice is made based on the type of simulation required; however a common problem is finding a suitable mobility scenario.

In this Chapter we have presented and evaluated the Luxembourg SUMO Traffic (LuST) Scenario, a realistic, properly-functioning, and freely-available mobility scenario. The scenario is built with information from a real mid-size city, with a typical European road topology and mobility patterns. The traffic demand is based on real information provided by a variety of data sources. Various mobility traces have been created in order to provide both the statically-optimized mobility with the best-case scenario, and a next-best option based on dynamic rerouting. The realism provided by this general-purpose traffic scenario has been evaluated and validated using real FCD collected in 2015. We have shown that the speed distributions from the mobility traces in the simulations are very similar to the real dataset. In addition, the results show that the use of dynamic rerouting provides an interactive scenario that behaves realistically and closely matches the precomputed optimized mobility.

The LuST Scenario is already being used by the vehicular research community and plans for future work are driven mainly by the needs expressed by the community itself. The LuST Scenario is freely available under an MIT licence to the whole community, and is hosted on GitHub (`https://github.com/lcodeca/LuSTScenario`).

Chapter 6

Conclusions

In this work we have studied the impact of dynamic rerouting on traffic congestion in urban environments. In Chapter 2 we presented traffic flow theory concepts and the mobility models required to study traffic patterns. We also provided an overview of the tools and frameworks that can be used to study traffic congestion, focusing on Intelligent Transportation System (ITS). In Chapter 3 we introduced traffic flow optimization theory, starting from the evolution and technology behind the navigation systems available on the market, then moving the focus to the importance of traffic information and its uses. We then presented our contributions on the subject of dynamic routing in urban environments. In Chapter 4 we presented our study of dynamic traffic rerouting, explaining the methodology behind the traffic monitoring mechanisms and the vehicle routing, finally evaluating it with both complete and partial information. We started from a simple topology in order to evaluate the proposed traffic management system, then we built Luxembourg SUMO Traffic (LuST) Scenario, a realistic, general-purpose, freely-available mobility scenario that enabled us to study how dynamic rerouting impacts the overall traffic congestion in a city. We discussed LuST Scenario in Chapter 5, explaining in detail its generation, the evaluation process and we provide some real use case scenario gathered from the scientific community.

6.1 Summary of Contributions

The research question posed at the beginning of this thesis was:

What is the impact of dynamic routing on traffic congestion in an urban environment?

6.1.1 Dynamic Routing using Wardrop's First Principle of Equilibrium

Our initial study of dynamic rerouting was based on a Manhattan grid topology, studying the various parameters required by the proposed traffic management system to alleviate traffic congestion in a simple scenario.

Our traffic management system gathers data and coordinates vehicular flows in urban environments. It is based on real-time traffic information gathered by On-Board Units (OBUs) and transmitted via a mobile network to the local Traffic Coordination Point (TCP) for aggregation. The routing algorithm is based on Wardrop's first principle and computes the minimum-delay route using Dijkstra's algorithm with dynamic edge costs.

We evaluated the system using Simulator of Urban MObiltiy (SUMO) as a microscopic traffic simulator on a 10x10 Manhattan grid topology. The results show that our system is able to increase the capacity of the road network by better distributing traffic demand. Further, we show that the global travel time is reduced by 50%, the average speed is increased by 60% and the average waiting time is reduced by 70% compared to the uncoordinated traffic scenarios. Theoretically, this system reaches its full potential when only 50% of vehicles are equipped with OBUs, allowing it to be deployed in cities with an immediate gain for early adopters.

In addition, we evaluated the behaviour of the traffic monitoring system in a more realistic situation, where information is partial due to uneven communication coverage and less than complete user participation. The mechanism is able to update the routes of the vehicles to relieve traffic congestion, but requires a reliable real-time traffic overview of the system to take decisions. The correctness of this overview depends on various parameters, such as the number of vehicles equipped with OBUs and the percentage of intersections covered by Road Side Units (RSUs).

Our results show that, with less than 70% RSU coverage, the traffic overview does not provides a coherent representation of the real traffic situation. The major role in information-gathering and route updates is taken by the percentage of intersections covered by RSUs. The user participation rate does not vary the behaviour of the traffic monitoring system significantly compared to the connectivity coverage, as proven by the lack of improvement in the traffic situation with full user participation but less than 70% RSU coverage. As we discussed in the introduction of Section 4.3, many other solutions proposed fail to address such problem, or postpone the evaluation of their impact. Our study showed that, with insufficient coverage, the routing mechanism fails to relieve congestion and, due to misleading information, may worsen it.

This study has been published in two separate papers: *Improving traffic in urban environments applying the Wardrop equilibrium* [17] and *Traffic routing in urban environments: The impact of partial information* [18].

In this initial work, we used a Manhattan topology to better control the environment and allow a precise and reliable comparison between the coordinated and uncoordinated traffic scenarios. Nevertheless, the use of a simplified scenario would not ensure similar results in a realistic road topology. The straightforward extension of this study is to use a more complex and realistic topology based on a real city, with different types of intersections, a greater number of lanes and a variety of priority rules. In Vehicular Ad Hoc Network (VANET) research, the usual approach is to build a small-scale realistic scenario based on a neighbourhood, or an even smaller section of a real city. In case of traffic optimization, it is not possible to use a small-scale scenario, but since large-scale, realistic mobility scenarios are not available, we created an innovative city-scale scenario to aid our research and that of the VANET community at large.

6.1.2 Luxembourg SUMO Traffic (LuST) Scenario

Due to the lack of realistic, properly-working, and freely-available scenarios, we built the LuST Scenario, a mobility scenario built for the vehicular networking research community. The scenario is based on information from a real mid-size city, with a typical European road topology and mobility patterns. The traffic demand is based on real information provided by various data sources.

The LuST scenario covers an area of 156 km^2 and 932 km of roads. There are almost 40 different bus routes with more than 550 bus stops throughout the city. All intersections with traffic lights and all highway ramps are equipped with inductive loops. Two different mobility traces and two traffic light configurations are shared, to provide both the static optimized mobility with the best-case scenario, and a next-best option based on dynamic rerouting. The level of realism provided by this general-purpose traffic scenario has been evaluated and validated using empirical Floating Car Data (FCD). Using this dataset, we have shown that the speed distributions from the mobility traces in the simulations reflect a realistic behaviour.

Finally, we used the LuST Scenario to show that the use of selfish dynamic rerouting provides an interactive scenario that behaves realistically and closely matches the precomputed optimized mobility.

The LuST Scenario is already being used by the research community and plans for future improvement and additional features are primarily driven by the needs expressed by the VANET community itself; it is freely available to the whole research community under an MIT license, and is hosted on GitHub (`https://github.com/lcodeca/LuSTScenario`).

The LuST Scenario has been published in two papers: *LuST: a 24-hour Scenario of Luxembourg City for SUMO Traffic simulations* [19] and *Luxembourg SUMO Traffic (LuST) Scenario: 24 hours of mobility for vehicular networking research* [20], the latter receiving the Best Paper Award at Vehicular Networking Conference (VNC), 2015.

6.2 Final Conclusions

The human factor is a very important component in traffic congestion. While much work has been done on how mitigate the issues of congestion, we believe that every solution that is implemented needs to take human behaviour into consideration. For this reason, a selfish approach to vehicular rerouting is likely to be easier to deploy in our city than a global optimization. The selfish approach provides direct feedback to the user, and is more flexible, without the need for full compliance (which is probably only achievable with fully-autonomous vehicles).

In addition, we saw that a simplified scenario may not provide realistic results in respect of optimizations, so the research community, with the availability of a realistic scenario such as LuST, can further investigate the issues and propose more alternatives. It must also be taken into account that the future will see connected vehicles, with the result that the amount of information collectable in real time will increase in quantity and precision, opening even more possibilities for the research community to find new ways to improve everyday life in our cities. Last but not least, the LuST Scenario can be incorporated in the SUMO framework, and with a growing user-base, and the implementation of additional features, the scenario can keep up with the needs of the VANET community, providing a common and shared base for work on our theories and to test our solutions, both for traffic congestion and in other fields.

6.3 Future Work

Tools should evolve over time, following the needs expressed by their users. For this reason, the list of improvements that can be made to the LuST Scenario is already long, and will grow longer. Our main concern is to increase the level of detail provided by the scenario. Currently, all the traffic lights in the scenario are actuated by only one program, and the only alternative provided being a static version. The traffic light system should be improved by differentiating both types and programs for specific intersections. At the moment, car parks are simply modelled as shapes and buildings; an interesting improvement would be to implement the internal structure of car parks and to add more parking spots along the road, as is the case in reality. More tools should be implemented to increase the usability of the scenario. For example, at the moment the Origin-Destination (O-D) matrix for the mobility is based on the specific road segment. Changing it from segments to zones (a set of segments, already implemented in the SUMO simulator) would reduce the complexity of generating and validating a new mobility after core modifications to the network.

The work presented in this thesis can be used as the basis for further studies on modelling and mobility optimization. The problem can be studied from different perspectives, from improving the mobility by introducing various means of transportation, to studying the issue of connectivity and distributed systems. Another possibility includes human behaviour, not only to propose optimization strategies that take it into account, but also to deploy new systems and improve the world in which we live; or its counterpart, the exploration of self-driving fully-automated vehicles and the use of global traffic flow optimization.

Multi-modality in the LuST Scenario The SUMO simulator enables the study of various means of transportation. A direct improvement can be made by introducing the railway infrastructure, together with its schedule. In addition, the SUMO simulator provides a pedestrian model, but its use is not straightforward. The introduction of pedestrians would alter the topology of the scenario and would require a complete reassessment of the mobility provided. These changes are fundamental if multi-modal mobility in a city is to be studied.

Network Infrastructure Without further modification, the scenario presented in this thesis can be used to study how interconnected vehicles can affect mobility. Using Vehicles in Network Simulation (VEINS), for example, it is possible to work on various mechanisms to collect traffic information and study how they may be used to improve traffic flows. Various approaches can be studied, from a centralized system based on LTE and mobile phones, to a completely distributed system based on VANET, and all the hybrid systems in between.

Behavioural Analysis and Automated Driving Last but not least, the users and their behaviours are central to the study needed to deploy a global traffic monitoring system. This suggests an interdisciplinary research area where social sciences work together with traffic and network engineers. In this thesis we have shown that user-centred traffic flow optimization can improve the system, without the need for a global solution requiring enforcements. The enforcing mechanism can be completely removed from the picture in case of self-driving fully-automated vehicles. In this case, people may use the time spent travelling in a useful and constructive way, reducing the impact of environmental conditions on their life.

List of Tables

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Acronyms

ACC	Adaptive Cruise Control.
ADAS	Advanced Driver-Assistance System.
ASOD	All Sources Of Data.
ATIS	Advanced Traveller Information System.
ATMS	Advanced Traffic Management System.
AVL	Automatic Vehicle Location.
CA	Cellular Automaton.
CTM	Cell-Transmission Model.
DSRC	Dedicated Short Range Communication.
DUA	Dynamic User Assignment.
DUA-T	Dynamic User Assigned Traces.
DUE	Dynamic User Equilibrium.
DUE-T	Dynamic User Equilibrium Traces.
ETT	Estimated Travel Time.
FCD	Floating Car Data.
GIS	Geographic Information System.
GPS	Global Positioning System.
H2H	Human to Human.
IDM	Intelligent Driver Model.
ITS	Intelligent Transportation System.
IVC	Inter-Vehicle Communication.
LTE	Long Term Evolution.
LuST	Luxembourg SUMO Traffic.
LWR	Lighthill-Whitham-Richards.

NSM	Nagel-Schreckenberg Model.
O-D	Origin-Destination.
O-FCD	Only-FCD.
OBD	On-Board Diagnostic.
OBU	On-Board Unit.
OMNet++	Objective Modular Network Testbed in C++.
OSM	OpenStreetMap.
RSU	Road Side Unit.
RTTS	Real-Time Traffic Situation.
SUMO	Simulator of Urban MObiltiy.
TCP	Traffic Coordination Point.
TIGER	Topologically Integrated Geographic Encoding and Referencing.
TMC	Traffic Message Channel.
TraCI	Traffic Control Interface.
TVA	Total Vehicles Arrived.
V2I	Vehicle-to-Infrastructure.
V2V	Vehicle-to-Vehicle.
VANET	Vehicular Ad Hoc Network.
VEINS	Vehicles in Network Simulation.
VPKI	Vehicular Public-Key Infrastructure.
WAVE	Wireless Access in Vehicular Environment.
WLAN	Wireless Local Area Network.
xFCD	extended Floating Car Data.

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