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Analysis of model-based decision support systems for traffic management

Master thesis

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CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF TRANSPORTATION SCIENCE

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Analýza modelově založených systémů podpory rozhodování pro řízení dopravy

Master’s thesis

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Norrköping, 2022

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During the elaboration of the master's thesis follow the outline below:

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- RQ2: What main modules in a decision support system are needed for traffic management?
- RQ3: What decision support system functionality does Dynameq software provide for analysis of traffic management scenarios?
- RQ4: How suitable is the Dynameq model for traffic planning usable for traffic management in Stockholm?

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TREIBER Martin, KESTING Arne. Traffic flow dynamics. en. 2013th ed. Berlin, Germany: Springer, Oct. 2012.8

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I confirm assumption of master's thesis assignment.

Richard Rek
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Abstract

For real-time traffic management it is essential to base all decisions of the traffic operator on all possible information from measured data and general traffic knowledge, which, through traffic management and control of traffic flows, will ensure an efficient and stable performance of the transport system and thus help to increase road safety or lower the effect on the living environment. Especially important are correct and quick decisions that happen in real-time in non-reoccurring congestion, which are crucial to detect right from the beginning to avoid greater consequences. These information-based decisions for the transport system are then supported by a system called Decision Support System (DSS), which, using traffic simulation, can provide traffic operators with important information and thus select the best possible strategy to apply.

This thesis presents an overview of the DSS and describes the main components of the system. These components are introduced from the perspective of the system architecture and are characterized. Individual methods and approaches to traffic flow management are also presented for the DSS in the context of a traffic management centre. The aim is to provide an analysis of model-based tools for which a search of available traffic simulators has been performed. The focus is then on the Dynameq software, which is used as a potential tool for DSS in Stockholm. A simulation of use cases was performed to obtain the necessary outputs to determine whether Dynameq software can be used as a tool to provide real-time decision-making support. Although Dynameq software is not entirely suitable as a stand-alone DSS for active traffic management purposes, it provides the necessary functionality that, when combined with other key functionality from other available tools, can generate the necessary outputs for real-time active traffic management.

Keywords: Decision Support System, Traffic management, Dynameq, simulation

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1 Introduction

Urban transport challenges lead to traffic states that create congestion, create a greater likelihood of a traffic accident, and have a negative effect on the environment. Congestion occurs when demand exceeds supply which is lately a problem given the fact that the car industry is increasingly growing. Travel demand is the number of trips people make under different conditions like demographics, network connectivity, pricing, etc. Traffic congestion is the delay that occurs when the road reaches its capacity. Congestion results in longer travel times, direct and indirect traffic costs, accidents, and environmental problems. It could be linked to the fact that more and more cars are appearing on the road which has an effect on congestion increase. Just for the year from 2020 to 2021 in Sweden, car ownership had grown by more than 41,000 despite the fact that the growth had been made during the pandemic [1]. In addition, most of the traffic is carried by cars, which are usually driven by one driver who is commuting daily. So-called ”stop and go” waves, repeating deceleration and acceleration, mostly observed in congestion result in kinetic energy losses and thus lead to higher fuel consumption and higher pollution. Another important element of congestion is time spend in them since that has an impact on the overall economy represented in congestion cost. In Europe, the inefficiency of the transport network of any mode, with a focus on road congestion, represents 1-1.5% of the EU's GDP [2]. Lastly, the accidents caused by not correctly managed traffic is reaching approximately 1.3 million people each year which results in direct and indirect costs regarding the cost of accidents being around 3% of GDP [3]. Likewise, the ever-growing hours spent commuting daily has grown where in 2019 the average commuting time was estimated at 25 minutes due to queues and other traffic problems [4]. This fact is of course connected with the growing number of people living in the vicinity of the capital cities and therefore the necessary commuting to the capital city for work. This can be represented by the so-called O-D matrix (Origin-Destination matrix) which represents from where drivers travel to where. Significant delays are also achieved during works on the infrastructure. Usually, roadworks are connected with capacity reduction resulting in congestion.

The usage of Intelligent Transport Systems (ITS) has become a standard in most cities as their goal is to create an environment that is less congested, more efficient, and safe by creating an information superstructure over the current traffic system with existing available infrastructure. The need to manage traffic has become more essential since more people are moving into cities which creates more traffic, given the fact that individual transport is gradually increasing. This creates traffic problems in cities like denser traffic resulting in congestion, followed by more dangerous situations and environmental problems. So-called telematics systems are used, i.e. systems or principles that represent the integration of several scientific fields together with the traffic engineering field. Thanks to the EU ITS architecture concept, telematic systems are subject to a framework for design, application, and use in individual EU countries so that they can adapt them to their own needs within the framework of the principles, which help to ensure clear organization of traffic management and provision of traffic information.

Recently, the urge for detailed real-time traffic management has become more relevant for big complex networks like those found in larger cities. The desire to mitigate the negative effects of traffic is the main idea of traffic management. The concept of traffic management could be seen as an extension of classical traffic management with simultaneous control of space and time, which ultimately leads to a real-time change of demand to match the available capacity [5]. The main importance of traffic management is in a dynamic overview of a traffic situation in real time because more informed and relative actions can then be taken. This has a big impact on traffic in the longer term when the right approach to traffic management can change driver behaviour as a result. Traffic information such as travel times flows, or speeds could then be used for planning purposes enabling to plan traffic in a more manageable way.

Processing large amounts of traffic data gathered from various sources on the infrastructure is a key element for traffic management. By collecting and processing the traffic data, with a combination of traffic models, traffic monitoring, management and organization can be used to control, navigate and plan traffic [6]. A related aspect of traffic management is how the data are acquired, which further affects the estimation and prediction results, in other words, the data collection method is important to take into consideration. When dividing different types of data collection methods, we can talk about data obtained from fixed points (Eulerian measurements), and data measured along a trajectory or on a given section (Lagrangian measurements). Depending on the devices used to collect data, their representation can also then differ. However, having data is not enough for making management decisions, and for that, measured data are often necessary to combine with traffic models [7]. Fundamental real-time traffic data such as speed, density, and volume are measured (in the case of density, occupancy can be measured instead) which enables recreatability of the real-time scenarios, with their application to a city model. By combining Eulerian and Lagrangian measurements, it is then possible to get an overall picture of dynamic traffic behaviour, to understand mobility patterns to a larger extent, and an even deeper understanding of the traffic processes [7]. Once the traffic data has been measured, an important element is to process it so that it can be used effectively in traffic management, for which statistical techniques and other various filtering concepts are primarily used.

The traffic management concept could then be envisioned as a data hub collecting live and continuous mobility data. In order to obtain a constant overview of the situation in the whole network and to manage and control traffic flow, it is necessary to work with a city or network model to which measured data are applied in combination with a traffic model capturing traffic behaviour. A model-based approach could be seen as a digital twin for a city with a lower level of detail of a network, and processes, respectively. The digital twin is a virtual model providing the opportunity to understand the interactions between entities inside of a model, or those affecting the model from external sources [8]. When the model-based approach is applied with a combination of available real-time data, a digital replica of a current traffic situation can be modelled and traffic can be monitored and controlled with high predictability.

The determination of traffic state estimation and prediction is important for traffic management and traffic information. Primarily prediction is convoluted because of predicting the unknown future. Typically, non-parametric models show a good ability to work on predicting reoccurring traffic states based on the principle of historical data, where future states are determined on the basis of several historic measurements. If the current state of traffic is similar to one of the historically measured states, it is assumed that the current state will evolve similarly [7]. In a non-parametric model, model shape and model parameters are established from historical data [9]. Parametric models for traffic prediction give better results during unpredictable situations, such as incidents or events. Traffic state prediction can be derived based on parametric models approaches as they work with predefined parametric structure [9]. The parametric model always describes only those states in traffic that have a determinable relationship between the parameters, with regard to the boundary conditions (usually in a form of demand as input) [9].

A key element of the traffic management framework is traffic models that allow estimating and predicting future states or correcting these states based on the application of collected data [7]. Static models are useful in traffic planning processes, but for real-time traffic management, the use of dynamic traffic models is necessary. While the use of traffic models is necessary to predict future traffic states, the use of different management strategies is further necessary to control those states to some extent [7]. Depending on the control strategy, there are then two types of area control strategies - centralized and decentralized, where the main difference is the area of operations on traffic control and in the way of collecting and working with the measured traffic data [10]. Dynamic traffic models are based on dynamic traffic assignment approaches, which are further divided into two main components, namely the problem of route choice and network loading.

Predicting future states is particularly important in discovering future states that may lead to a non-optimal state of operation of the traffic system, which in turn may ultimately lead to reduced performance (capacity) of the traffic system. Therefore, **simulation-based approaches** can be used to discover these future states, which, when applied to all the dynamic components of the transport system, and when all the simulation parameters are properly used and set, can provide insights into the future state, which can be acted upon by applying a given strategy to prevent that state in advance [10]. Simulation in **model-based approaches** is needed for traffic management since a more proactive approach can be applied [8]. It is especially needed when an unplanned event (like an accident) happens, providing the decision makers greater opportunity to act correctly by simulating the aftermath of the incident and the effect of a measure applied to mitigate it. Among other benefits, such as analysis of collected data, road-side system monitoring, or finding new opportunities to control traffic, simulation is also highly useful for future planning [11]. Often, the simulation is combined with artificial intelligence allowing automatic detection of any anomalies in the network. This leads subsequently to a self-adjustable system that acts accordingly on a measured input and optimizes its output simultaneously with every short step.

Due to the great interest, many tools have been developed to provide these simulations in a virtual environment. Traffic simulation software makes use of all available knowledge about the traffic flow and traffic as such, which is implemented in the simulation environment. These simulation tools can be used in conjunction with traffic knowledge to plan traffic infrastructure, to simulate and visualize traffic flows and their subsequent analysis, or, for example, to simulate the future state of traffic. For traffic management, this is one of the main components since it can represent decision support for traffic operators and can offer more informed decisions. Examples of such software include SUMO, Aimsun, PTV Vissim, and others.

Traffic models are used in simulation tools (Traffic Simulation Systems - TSS). The goal of traffic simulation is to reproduce real traffic situations and scenarios of drivers. Therefore, calibration of those simulated systems is crucial when it comes to the reliability and plausibility of the model. There are different types of traffic flow models - macroscopic, mesoscopic, microscopic.

State-of-the-art traffic management systems work more on a decision-support system (DSS) basis. Implementation of a decision support system for real-time traffic management is tightly connected with traffic simulation software as one of its components. A decision support system provides support to traffic personnel to make an informed decision over the network. Applying correct strategies is a key aspect in the traffic management concept since proposing and applying a management strategy without previous knowledge could be risky and potentially lead to system unbalance [5]. The base for a decision support system is data, an estimation of the current traffic giving an overview of the entire network, and traffic prediction functionality forecasting future states of traffic [12]. Utilization of all those parts (data, a model, a visualization model, etc.), authorities can get insight into the potentially applied strategy to do the decision better. Predictions are made using the traffic model with different inputs simulating what would happen if different measures would have been applied. Every possible scenario (decision possibly taken) can be simulated if defined beforehand, and comparison results among other strategies are generated making it easier to make more informed decisions.

DSS could be seen as an ultimate super-system covering all traffic management features and providing output in a form of the best possible actions to apply on the network. Therefore, the DSS should be able to handle:

- all data sources including their filtering and processing,
- the option to select an area for analysis (for example an incident area),
- estimation and adjustment of O-D matrix for the selected area,
- generation of traffic simulation model of the selected area,
- traffic network [5].

When the traffic situation requires action, traffic management operators can address that information and provide awareness. In general, those information are dispatched both to the end users (drivers, passengers) and to operators and other authorities interested in regulation, incident control, and monitoring traffic situations in the network. Traffic information message dispatching for road users (drivers) is managed through various methods currently in use, such as variable message signs, traffic lights, or radio. Traffic control can be understood as monitoring and controlling the actuators available in the network. In other words, anything that can be connected and administrated via traffic management centers, and which can implement the decisions being taken [13].

1.1 Aim

This thesis aims to provide an analysis of different traffic models that can be used in a traffic management decision tool and determine their characteristics and differences. Furthermore, the potential of using Dynameq as a decision support system in Stockholm will be analysed.

1.2 Research Questions

RQ1 and RQ2 are aimed at getting the answer about the main requirements for traffic simulation tools for making decision support systems usable in traffic management centers. In addition, this includes questions about traffic models and their usage in those tools. RQ3 aims at the description of Dynameq software and what functions can be provided or are missing to provide traffic management. Those functions are the ones found in the first and second RQ. RQ4 deals with the question of the potential usage of Dynameq software in the city of Stockholm for traffic management purposes by a use case simulation of an incident. The questions are as follows:

RQ1 What are the characteristics of different traffic simulation software for traffic management?

RQ2 What main modules in a decision support system are needed for traffic management?

RQ3 What decision support system functionality does Dynameq software provide for analysis of traffic management scenarios?

RQ4 How suitable is the Dynameq model for traffic planning usable for traffic management in Stockholm?

1.3 Methodology

The Methodology part includes approaches that need to be followed to fulfil the aim and answer the research questions presented above. The approach taken is divided into two main subsets:

1. Literature overview -> RQ1 & RQ2 & RQ3
2. Use case simulation -> RQ4

For studying the main characteristics of traffic software, the main approach taken is a literature overview. Many different articles and papers are examined and the main conclusions are drawn based on those research papers. The articles are selected from databases available online. The main databases used for searching are Google Scholar and Scopus, from which articles are downloaded. Other databases are also used if they are found to be credible enough and accessible for free. A closer selection of articles is then made by filtering them according to specific keywords and other attributes of the articles. Keyword relevance is taken into account so that only keywords related to the work are used, e.g., traffic management, traffic control, decision support system, incident detection, etc. Among them, the articles are then sorted according to the relevance of the year of publication and also according to the number of citations. The same approach is taken for answering RQ2 where deeper dive into the most important modules and their information are provided. All literature found is limited to English, Czech, and Swedish language.

For answering RQ3, in addition to articles, the official documentation for Dynameq software is studied to get more verified information from the developers. Besides Dynameq, other traffic simulation software is described which helps to define some of the other features currently available for traffic management. Previous findings from RQ1 and RQ2 are also used.

RQ4 is related to the case study and to the Dynameq tool where the simulation approach is applied and use case experiments are performed to get the answer to what can be done with the Dynameq tool. A Stockholm model is applied to the selected incident use cases and analysed are responses of the model to the given incidents. For the selected incident, quantitative evaluation criteria are applied meaning data from the simulation are measured and collected and conclusions are drawn comparing what can be done and what could be implemented to the software to provide traffic management functions. For the simulation, Dynameq traffic management software v.4.4.0 is used.

In order to have a good sample of representative results, scenario-based analysis in form of use cases is chosen to correspond to the most common incident types, and are a combination of:

- multiple types - standing vehicle, traffic light malfunction, road closure, etc.,
- different duration of incidents,
- different places/areas, different types of roads, respectively.

Real traffic data used for the investigation of the simulation results were measured on Stockholm's network with traffic detectors and probe data. The data are of the nature of traffic flow variables, but also data about incidents like type, their duration, length of forming queues, etc. Linköping university have provided access to their database with traffic data for the Stockholm area (LiU database). The origin of traffic data and traffic incident data is from INRIX database and by the traffic management center in Stockholm. All used data are processed using PgAdmin tool and SQL language is used.

First, quantitative methods are applied to real incident traffic data to investigate the incident and the effect on the network - its duration, spill-back effect, queue lengths, etc. Traffic estimation of road parameters such as road capacity, number of lanes, road design, etc., are based on map data available in the database and also in the Dynameq model. Traffic state estimation of an incident is based on fixed historical data from the database. Incident simulation is based on provided information by the data and their provided description like incident duration or delays, location, number of closed lanes, etc.

The performance of the Dynameq software as a decision support system (RQ4) is evaluated by comparing results from incident data analysis that are of probe and static detector data type, and data obtained from simulation measurements for defined use cases. Results are generated, evaluated, and presented from the Dynameq traffic planning model for Stockholm provided by the Swedish Transport Administration (Trafikverket).

1.4 Delimitations

The focus of the thesis is to compare different software that is currently available and used in control centers. The use case is limited to the Dynameq traffic model of Stockholm. Moreover, no control measures (or modelling of such) are investigated, only responses to incident use cases of the Dynameq software are analysed. The calibration of the provided model from Trafikverket is not assumed to be done within this work but the current version of the model is used and tested instead.

1.5 Outline

The structure of the document is as follows. First, the concept of traffic management and control is introduced and the transport centres are described, including some of the selected traffic management strategies in Chapter 2. Traffic modelling approaches are also presented and discussed and a short introduction to the DSS tool is presented. A deeper analysis of DSS is presented in Chapter 3 and DSS architecture is introduced with a description of every component. A comparison of different traffic simulation tools and some of their use cases, together with Dynameq software description is located in Chapter 4. The simulation case study is conducted in Chapter 5 together with results and their analysis. Finally, in Chapter 6, an evaluation of the work is proposed, followed by Chapter 7 with answers to all research questions, and suggestions for further research.

2 Traffic Management

Overload problems can be characterized as recurring and non-recurring. The difference between these two terms has a different character, in both cases, however, there is a reduction in capacity and the creation of queues.

- **Recurring congestion.** This is usually formed by the regularly recurring occurrence of a bottleneck with the same demand exceeding supply. The reoccurring factor may be caused by the specific time of the day (morning and afternoon peaks) or by in advance known capacity drops, but the reason is always the same - network overload by the current demand. Causes can include:
  - On- and off-ramps;
  - Merging of lanes;
  - Long-term road works, etc.
- **Non-recurring congestion.** Involves incidents with little predictability. They are associated with the fact that there is a significant decrease in available capacity during the incident period at the incident location. Reasons can involve:
  - Accidents;
  - Short-term road works;
  - Stand-still vehicles;
  - Weather;
  - Object on the road, etc.

The fight against congestion has been approached in different ways in recent years, ranging from increasing the supply by road constructions to the use of modern technologies or applying city policies. When it comes to increasing supply with the help of increased road construction in the long run, it has been shown that this results in an increment of demand and hence solves nothing ([14], [15]). Therefore, it has been necessary to come up with more intelligent transportation ways of managing traffic.

In this chapter, an overview of traffic management centres is described, and different levels of traffic management are presented. Different types of strategies and traffic management approaches are presented. Control theory is shown with an aim at traffic management and some examples of control strategies are shown. Next, various classifications of traffic models are discussed with their deeper definitions. Last, the decision support system is explained and the main principle is introduced.

2.1 Traffic Management Approach

The term ”Traffic management” can be included in most of the traffic processes that lead to mitigating traffic congestion, smoother and more controlled traffic with high efficiency, increased safety, and reduction of environmental impacts as its main goal. The goals can be ultimately identified as managing transportation processes at low cost and low time [16] for both stationary and moving traffic, which may include also pedestrians or cyclists. Since traffic is a complex system experiencing traffic problems, it has been noticed in past years the necessity of managing traffic processes and more centralized traffic operations needed to achieve a better environment. Traffic management uses existing infrastructure to which it applies control of a traffic flow and monitors events happening on roads by using smart city solutions. These actions are defined upon a transportation network and transport means, drivers, respectively, using that network. These elements are key subjects for traffic management and are often subject to change since they represent supply and demand (in traffic).

The study of transport management, and more specifically of traffic flow, began as early as the 1930s when the first study of traffic capacity was conducted by B.D. Greenshield took place in June 1934 in Ohio, USA [17] and describes the fundamental diagram. For example, in [18] a study of the traffic flow behaviour of stopping and accelerating vehicles is presented and explored are also various following mechanisms, or [19] where were examined and proposed several car-following models. Traffic dynamics were also studied for example in [20] introducing formulation of new traffic models for traffic flow with mediocre and concentrated traffic. Followed by numerous research in other fields like queuing theory ([21], [22], [23]), and modelling model like the one presented in [24] that introduced cell transmission model for dynamic visualization of traffic flow and compared it to the hydrodynamic theory, or the one presented in [25] that showcase a simulation model in urban networks by moving bit variables through a network that represented real network topology. The cell transmission model was also studied in [26], where three-legged junctions are modelled and time-varying origin-destination for numerical procedures aimed at disaster evacuation plans aiming at a more realistic representation of traffic streams.

Looking at the history of traffic management systems, the paper [27] describes a general approach to real-time traffic management using knowledge-based models. As claimed by the paper, this approach provides advantages in the modelling methods using rules and frames and is easier to apply because understanding the knowledge of the management content of the application is easy and in the simple understanding of a given output provided by the knowledge system. Since the first traffic control was applied on the road in a form of a traffic light in 1868 in London [28], the technology has evolved into more sophisticated forms. Eventually, the first control points were created, from which traffic was controlled within the limits of the possibilities of the time. At first, it was the application of decentralized intelligence (together with a human operator) directly on the infrastructure (as it was for example in 1930 in Philadelphia with the placement of a ”master controller” driving the traffic light [29]), then later in the form of control centers with a centralized approach to control from the control point.

Traffic management is dependent on the acquisition of traffic data. A fundamental element is then information about traffic states obtained from sensors and detectors located on the infrastructure. Another data acquisition method collects data spatially (like Floating Car Data - FCD). Those methods of data collection, where the position in time is measured and is called a trajectory, enable visualization of the data in a space-time diagram. Traditional stationary detectors such as loop detectors or radar detectors provide point estimates of a section of a major road. Often, they keep track of essential traffic data such as speed, occupation, and flow. Measurements were conducted at arbitrary locations with sensors collecting data from connected vehicles, cars equipped with probes sending traffic data like their velocity and location, mobile network sensing, or using data from data providers like taxi or shared vehicles services. Another very important data type for traffic management and decision support systems is demand data in an O-D matrix form. This matrix describes the movements of people in a certain area, and how many people travel from their origin to their destination place. Those data are usually gathered via surveys or by using more efficient ways like floating car data, Bluetooth sensing, automatic identification, etc [30]. Estimation of O-D can be done in multiple ways, for example using gravity model [31], or clustering and other prediction techniques. O-D matrix can be used for planning purposes (like public transportation planning) or traffic control purposes including real-time operation of traffic and traffic simulation analyses and most importantly dynamic traffic assignment simulations, where the knowledge of real-time O-D is a valuable element [32].

The emerging connected (also called cooperative) vehicle technology can provide a new source of data for traffic management and open the door to new possibilities of applicable strategies or specific road traffic management capabilities. The principle of these cooperative systems is the communication between vehicles or transport infrastructure (commonly referred to as V2X - vehicle to anything) and sharing of data about their location, speed, etc. The collected information is thus very accurate and fast, which is based on the design of this concept, and thus quite precious when it comes to traffic control and management. This would allow very realistic simulations of traffic processes and traffic flow prediction. At the same time, this could lead to better controllability of the traffic flow, as the connected vehicles could act as influencing elements not only for themselves but also for the other vehicles around them. In other words, targeted relevant information for individual vehicles could be communicated through the traffic infrastructure, which is controlled by the traffic control centre, which could ultimately influence the behaviour of drivers on the road [33].

Traffic management can be differentiated according to the sphere of the management area it affects. In terms of ITS architecture, traffic management represents the highest possible form of management, which is responsible for the management of the complete traffic site of large cities and urban areas. At the urban level, the hierarchical arrangement is usually three levels:

1st level: Local traffic management

It is the lowest hierarchical level, which forms the basis for the higher layers. It is built from individual actuators and detectors placed on the infrastructure. It is therefore responsible for the collection of traffic data as well as for the transmission of important traffic information from higher levels and traffic management at the node resolution level. The layer has a primary influence on traffic management because it comes into primary contact with the traffic environment. It is further characterized by the fact that the elements have precisely defined functions and information links. This layer includes, for example:

- Traffic lights;
- Speed limits;
- Ramp metering.

2nd level: Area control

The level includes individual control systems for single areas of a larger scale. The area control focuses on area-wide systems with larger road sections around the city like:

- Coordinated traffic light signals (group of signals);
- Tunnels system;
- Variable speed limit systems;
- Coordinated ramp metering.

3rd level: Main control centre

At the highest level is traffic management in the size of cities, their perimeters, and regions. It is a central driving system that integrates the driving sub-systems of individual areas and monitors the traffic in the city, in other owrds, it integrates second-level control systems and creates a place for central traffic management. It is in charge of integrating all data into one place and evaluating it, on the basis of which it then adjusts the traffic. Another function is the evaluation of traffic excesses (i.e. incident management).

It can be noticed that as the level increases, the data required for traffic management is reduced. At lower hierarchical levels there is more data and less information. On the other hand, at the highest level, data is converted into information, and therefore work with individual data is not so frequent. With this ideology a traffic management centre concept can be introduced which integrates all functions of technologies and puts together all information from the infrastructure in an interface that allows traffic managers to make strategic decisions.

Traffic management can be further extended to real-time traffic management, also known as Active Traffic Management (ATM). ATM reacts to the current traffic situation captured by static detection and floating cars, whose data is used for strategies with resolution factors in the order of tens or even units of minutes to manage traffic. Dynamic traffic management, just like standard traffic management, is based on the use of current traffic information but also involves the close prediction of future conditions on a traffic model. For those purposes, a centre with capabilities to control real-time states and determine centrally feature solutions is needed. The main importance of building such places is precisely for this way of traffic management, where real-time traffic management consists of the actual reaction to emerging traffic problems.

2.2 Traffic Management Centre

Traffic Management Centre (TMC) buildings are the main nerve of every urban area where the city area-wide space is monitored and controlled. In simple terms, these are the physical places where all the screens and video cameras are located and where the people whose job it is to manage the traffic system are located. The range of controlled stretches differs from centre to centre but almost always major streets and highways belong to the basic control set and their operation time is 24/7. From a functional point of view, there is an integration of topological and technological layers. Ultimately, the operation of TMC should be viewed as an organ that operates in a systematic manner and also systematically integrates systems located on the infrastructure. From this one location, traffic systems are monitored like traffic signals, detector states, and road states. In addition, traffic management strategies are applied from this place aiming at congestion reduction or handling incidents and special events [34]. In [35], the role of the traffic management centre can be summarized as:

- Real-time traffic surveillance of the road network;
- Traffic state control;

- Handling of special evens, incident management and other traffic coordination;
- Road user support service and traffic information distribution to private and public sector.

World Road Association PIARC (`https://www.piarc.org/en/`) in their Guide for Practitioners [36] differentiate five main areas of road network operations:

- Network monitoring;
- Maintaining road serviceability and safety;
- Traffic control;
- Demand management;
- Traveller and road user services.

Network monitoring is referred to as monitoring of the network situation and monitoring natural events [36]. Getting to know the status of the network as soon as the situation changes is the key, but also the information needs to be of true character. For that reason, fault monitoring is also necessary. Among the information gathered are traffic conditions and information about weather detected by detectors, CCTV, probe vehicles, or other means with tools like video processing or detection algorithms [37]. The monitoring of traffic is aimed at detecting problematic conditions that differ from those normal or their prediction, and, as a secondary aim, for traffic data collection (such as speed, volume, and occupancy) [37].

Maintaining road serviceability and safety focuses on restoring the state as quickly as possible after a disturbance has occurred. The main aim of the traffic operation is to restore the road service in terms of safety and traffic flow to minimize the effect of those occurrences and the spread of traffic problems. This can be done by informing drivers about incidents ahead or managing the traffic during the disturbances [36]. This comes hand in hand with the clearance of the incident site and renewing the traffic state [36]. The road maintenance that takes place on a road in a form of road works belongs under this type of road operation and has to be planned properly and labeled as incidents with an effect on the traffic (since there is usually a capacity reduction - closed lane) [37]. Weather can significantly limit the operating conditions of roads, and therefore road management must also be concerned with informing road users of possible dangers (such as heavy rain, heavy snow, etc.), as well as providing road maintenance under these conditions [37]. When it comes to incidents, enforcement plays a big role that has an effect on drivers to obey the rules. New technologies and algorithms that automatically detect and call for emergency services on site are being used on the infrastructure and are part of this type of traffic operation [36].

Traffic control is done in time and space. Some of the principal challenges in traffic control are to optimize and direct traffic in an optimal manner with high safety priority. It is also about taking traffic flow and forecasts anticipated traffic that may occur. It identifies possible periods with higher demand for example based on the calendar day. Based on that, traffic management plans are defined as well as procedure manuals for traffic operators when that particular scenario occurs [36]. Traffic control consists of traffic measurement, traffic state estimation, and dissemination of traffic control actions to signal actuators. Special advanced control measures like integrated corridor management or strategies aiming at connected and autonomous vehicles can also be considered [38]. Road optimization can be done by traffic signals adaption (corridor or highway - ramp metering), lane use management, or speed control.

Demand management deals with exceeded demand that causes congestion. Measures taken are in a character of time distribution of vehicles or modal change support [37]. Road pricing and special road segments division can also be introduced to prefer vehicles with special requirements or accept vehicles that paid for road use.

The last element is the provision of traffic information about the traffic situation in real-time. All information for both drivers and stakeholders that affect the stability of the traffic system and the safety of road users is taken into account. In this type of management, it is not directly about correcting the traffic flow, but rather about managing traffic behaviour, where the provision of this information can change the number of trips [37]. The key element is to provide traffic information in a timely manner, in real-time, in as much detail as possible, and if possible to direct it only to the drivers to whom the information relates. At the same time, it is a matter of identifying the communication channels used to share and manage the information. Methods of information exchange include RDS-TMC (Radio Data System - Traffic Message Channel), en-route navigation, VMS, etc. Information can also be provided before the journey itself via internet information sites of traffic centres providing real-time traffic information.

Devices and technologies used on the transport network for monitoring and traffic operations could be summarized into three categories, namely: telecommunication devices, surveillance devices, and detection devices [35]. Systems used for the operation of TMC can be distinguished into systems that directly relate to the centre's purposes (traffic control, traffic monitoring, special event management, etc.), and systems that support the TMC functions (geographical information system, closed circuit television system, data processing, decision support system, etc.) [35]. Among the parts of the traffic control centre can be classified as all the equipment providing real-time traffic control responding to the needs of all road users, but also systems in charge of the management of systems at lower levels, data analysis, and, last but not least, information sharing and contact with the public [39].

In those centres, via a traffic management interface system, traffic operators can take various actions based on information from the infrastructure. These human-machine interfaces for traffic management are designed to provide operators with sufficient information in a simple but complete way, in various forms. For example, it is possible to display information on a map, verify traffic conditions of individual roads, monitor developing congestion in real-time using a CCTV system, or manage incidents using support systems for the correct decision-making of the operator when applying strategies [35]. If a situation is assessed as requiring a response, traffic operators can alter the conditions on the road and alert drivers via information panels or variable message signs. The ability to warn about some serious incidents can also be applied to other local authorities and can let notify emergency services if necessary. With all the information provided by sensors and other sources, TMCs can define weak spots in the network and come up with strategies how to mitigate the effects of those areas or help inform drivers in real-time [34]. Larger transport centres can then also be in charge of more modes of transport in the city, such as public transport.

When it comes to the needs of TMCs, having multiple sources of data is critical to their operation and the overall functioning of these centres, as they rely heavily on them. However, there is sometimes a problem with data sharing, because some providers do not allow open data provisioning, or in short, do not allow data sharing for privacy reasons. Next, there are usually different stakeholders which may exacerbate a given problem with data provisioning or with the integration of the system into the centres. Another challenge can be seen in the financial area, where costs are often very high. According to [34], the costs can vary based on the size and scope of operated area, on the facility being used for the centre, and on other factors and material costs. Other costs can be definitely seen in high maintenance level. Ultimately, the cost-effective investments put into those centres can be beneficial in the long-term period and can potentially save money from congestion and incident costs.

2.2.1 Traffic Management Approaches

High-quality data is used to manage traffic processes by estimating traffic conditions and making predictions based on this data. These states and predictions are combined with measured data and traffic models to evaluate management strategies that shape traffic. Control strategies may take the form of ramp metering, RLTC (road lane traffic control), or other types of strategies - toll, HOV, or bus line priority. Traffic management impels the traffic to shape the traffic and improve traffic volumes to not achieve critical capacity levels. Having the traffic management centre apply strategies (or by automatic means) may result in improvement in transport system quality and more efficient usage of existing transport resources. At the same time, it is important to keep in mind that by shifting the demand to different means, the new demand can be created that way that would have not been there [40].

The very basis of traffic control is (the typical) control theory. The theoretical model for control, with respect to traffic control, can be identified as simple control, feedback control, open-loop control, and adaptive control. In the case of simple control, there is only control using a model where the input of the controlled object is the output of the model, which has been calibrated from historically measured data from traffic detectors. Feedback control, on the other hand, takes the outputs from the rising object and uses them as input to the controller, which corrects the object according to the deviations from the desired value. For open-loop control, the output quantity does not affect the input meaning that the control system is without any feedback. Adaptive control is similar to simple control, but with the difference that the internal parameters of the model are changed based on the traffic situation. Most traffic control situations represent typical feedback control. The aim is to achieve optimum by feedback control corrections sent to traffic actuators and correcting the traffic by application of control actions [41].

In traffic management terminology, several types of control components can be distinguished. Generally, there are 4 basic components: a controller, an applied control strategy, the traffic system, and an estimation of the traffic state [42]. Consider a traffic system represented by actuators implemented on the infrastructure such as traffic signals, dynamic route information panels, variable speed limits, etc., that influence traffic states. The traffic state is measured or estimated and sent to the controller which reads the estimated traffic state and based on traffic models and online data estimates the future state. In other words, either manual or automatic procedure of optimizing the traffic performance is made, which results in a strategy that is applied to a traffic system and everything repeats [41].

From the time perspective, control strategies can take the form of long- and short-time horizon strategies. The time distribution can be considered when selecting control strategies, where the application of a given strategy has either short or longer-term effects. For example, a comparison can be made between the application of a city entrance fee (toll application), which has long-lasting effects on driver behaviour, and in the case of a strategy with a short time horizon, for example, changing the supply by lane closure, where it is a current response to the traffic situation and the change in driver behaviour is only short-term. Other types of control may be distinguished as:

- static (off-line) control of an area - relying on historical data,
- fixed time (static) control - time-dependent control whose input variables are time,
- traffic responsive (online) control - input from real-time measurements and selecting strategies from a database set, but the control is not optimized.

Static control uses pre-defined programs that are applied to a traffic network without any real-time management options. The only input, time, the program changes are changed based on that variable during the day. For example, at an intersection, this type of control is applied with a fixed signal plan with fixed cycle time and its 4 different versions for a different part of the day. The control is therefore based on historical data, which is an advantage for low-cost operations and simple design. On the other hand, the control is not traffic-responsive without answers to dramatic changes or events. Traffic responsive control belongs to the other side controls with dynamic responses to traffic. Sensors are used here, which can affect the traffic flow on the basis of measurements. In [43], dynamic traffic management refers to three types of management and control implementation:

- Operational - short-term decisions based on real-time measurements automatically or applied by operators.
- Tactical - control based on predefined scenarios made by traffic engineers for a traffic condition on the road (proactive approach based on available information from measured locations).
- Strategic - long-term decisions made by policy makers to mitigate negative effects of traffic (measures with proactive approach).

As can be seen above, different types of approaches can be chosen. In each case, however, it is either direct control with a relationship to supply management or indirect control that affects demand. It is also important to stress that different traffic management strategies are used for different locations resulting in control of motorways and control in urban network differentiation. Designing of the strategies is usually done by traffic experts representing some sort of knowledge base capturing general knowledge of the given issues. In [44] they present some fundamental guiding principles for optimizing networks such as:

- Manage traffic management based on movement and road category;
- High priority to road safety;
- Blend motorized road users with vulnerable road users with precautions;
- Maximize throughput of transportation;
- Balance out traffic volume over the controlled network area, etc.

Depending on which type of management is involved, we can distinguish possible strategies that have different effects on the traffic flow: diversion, harmonization of traffic parameters, information, and/or navigation. Management concepts focus on objectives that improve road conditions or the overall performance of traffic management in the form of a performance index, such as maximizing link throughput, minimizing travel time, or perhaps reducing the amount of environmental impact [7]. When all impacts of applied strategies are considered, given the fact that no new infrastructure is needed to be built, such approaches might provide the best solution to transportation problems [40]. On the other hand, it is necessary to realize that a change in traffic behaviour in one place can create a problem in another part of the city, or the problem can simply move downstream or upstream causing problems there. Thus, applying a traffic management strategy in one place can affect traffic in another place.

The following is a closer description of selected approaches to control traffic volumes.

2.2.2 Direct Supply Based Strategies - Homogenization of Traffic Flows

Traffic flow harmonization is applied to even out the traffic conditions and spread the differences in traffic variables. By doing so, traffic is more stable and more resistant to a capacity drop [7]. Capacity drop is a phenomenon that occurs on roads during congestion when capacity is reaching saturation levels resulting in capacity drop thus lower throughput conditions and incrementation in travel delay (references can be found in [45], [46], or [47]). Using direct-based strategies, once the incident happens, can also reduce the impact of this event and ease or prevent congestion. [7].

1. Ramp metering control

The use of ramp metering is a common practice in several countries, especially on the American continent. The main principle is the control of the number of vehicles on the road (highway or tunnel). With the help of a standard traffic light on the connecting ramps, access to a given section of road is regulated. The main reason for resorting to this type of control is the situation when vehicles entering the motorway do not have the chance to join the traffic flow. The aim of this approach is therefore to increase the throughput of the downstream section by avoiding the formation of shock waves. The disadvantage then arises from possible congestion forming on the connecting arm of the motorway. This is secured by the so-called capping strategy controlling the on-ramp flow by threshold. Whenever the queue is larger than the threshold, the ramp metering is useless and is switched off [48]. Another option is active ramp management, which instead of the classic ramp metering balances the merging of traffic flows by closing part of the lanes before the merging point. Different approaches can be selected - one green period per cycle or one car per green. In [49] different strategies are proposed:

- fixed-time strategy;
- reactive strategy;
- non-linear optimal strategy;
- integrated freeway network.

The ramp metering problem can be deconstructed as dynamic optimization problem with an objective of minimizing the Total Time Spent (TTS) of all vehicles in the network.

2. Road Line Traffic Control (RLTC)

RLTC is a linear traffic control, in which traffic is controlled in individual lanes of the road. For example, the speed of vehicles is regulated using the so-called Variable Speed Limit (VSL) system, where the speed limit changes depending on traffic density, unexpected events on the road, or weather. With speed homogenisation, the traffic flow is harmonised, increasing the capacity of the road (throughput) and thus reducing the risk of accidents and breakdowns. The principle consists in reducing the speed difference between individual vehicles. The data from the detectors, which are located about 150 - 200 m in front of the gantry of the variable traffic sign, are input to the traffic models upon which the system decides the optimum speed at which the traffic flow intensity will be at its maximum. This type of control increases road safety, improves environmental conditions, and increases traffic efficiency. At the same time, the system can be used as an input for incident detection [50]. To achieve these goals, different types can be implemented. The majority of the VSL systems follow a rule-based control. This type uses a decision-making algorithm that changes variable speed limit signs based on thresholds of, for example, speed or flow [51]. If the speed changes, the algorithm based on the setting of those limits decides on the speed or whether to even use this system in the first place [52]. Regarding the flow harmonization, VSL is used usually when the speed distribution is bigger or when the flow and speed levels are high and together with prediction traffic models or historical data applied, the new speed level is calculated based on an evaluation of future states [7]. Other types of VSL include fuzzy-logic-based, analytical, and control theory-based versions [42]. Several implementations have been made including in Stockholm and Germany, where the speed does not have to be followed, or in England ([53]) where, in addition, the system is used in an enforcement system [54] and the speed limit is mandatory.

Another type of control using RLTC is motorway control systems which comes with functions like lane closure, road warnings, heavy goods vehicle overtaking ban, or lane restrictions for certain types of vehicles. Different types of restrictions are used on variable message signs to control traffic flow and inform drivers. Either text or lane control signs (sometimes with pictograms) are used for this purpose. Lane management is used for example in tunnels where variable message signs close or redirect traffic flow if necessary.

2.2.3 Indirect Demand Based Strategies - Control of Traffic Volumes

These strategies aim at shifting the demand to less congested parts of the day or to distribute the demand more equally in space and time. Another aim is to promote or move people's behaviour to other travel modes of transportation. The ideology of these strategies is to prioritize people and the sustainability of cities rather than prioritize motor vehicles. More space is given to other modes of transportation such as public transport, cycling, shared mobility means, or walking). Various new mobility means can be introduced like electric or autonomous vehicles where strategies can aim at these modes and support them. This area also includes various policies from policymakers ensuring state and EU political interests. Therefore, sometimes, these strategies are implemented in the framework of national policy. The impact can be either direct on the customer or can be aimed at services that can provide customers the option to shift or change. Here are described two common approaches - redirection of traffic and tolls.

1. Redirection of traffic

Redirection of traffic comes in a form of traveller services that inform customers about their travel. This homogenization technique is also called dynamic routing and load balancing. Based on the information obtained, travelers can make informed decisions on their journey, and plan or adapt according to the actual situation. From the collected data, traffic information can be evaluated and estimates of on more feasible route for the traffic flow can be suggested [48]. They have an effect on traffic adaptability and overall performance with an effect of pollution reduction from unnecessary trip or driving excess millage. They can be aimed at individual drivers by in-vehicle routing (navigation), or on traffic flow by route choice influence (variable message signs). Generally, travel information can be static or dynamic depending on the update frequency [55]. Mentioned can be also pre-trip real-time traffic information that informs drivers about road closures, congested roads, and others (see Figure 2.1).

2. Tolls / congestion pricing

Electronic toll collection aims at traffic regulation, harmonizing the traffic, promoting the entry of private capital into transport infrastructure, and obtaining funding from foreign transport operators for the renewal of infrastructure. Other objectives may include demand management or reduction of local emissions. Various types of tolling systems are used across the world ranging from whether they are applied on the whole network (Switzerland) or just on selected roads (Italy, Czechia), city tolls, or some other types and combinations. Charged can be infrastructure usage of a particular segment (credited as a fixed amount or based on distance travelled) or access to an area (fixed amount or based on time spent inside the network). Technologies like Dedicated Short-Range Communication (DSRC), Global Navigation Satellite System/Cellular Network (GNSS/CN) - see [56] or [57], or Automatic Number Plate Recognition (ANPR) is used. More can be found in [58] or [59].

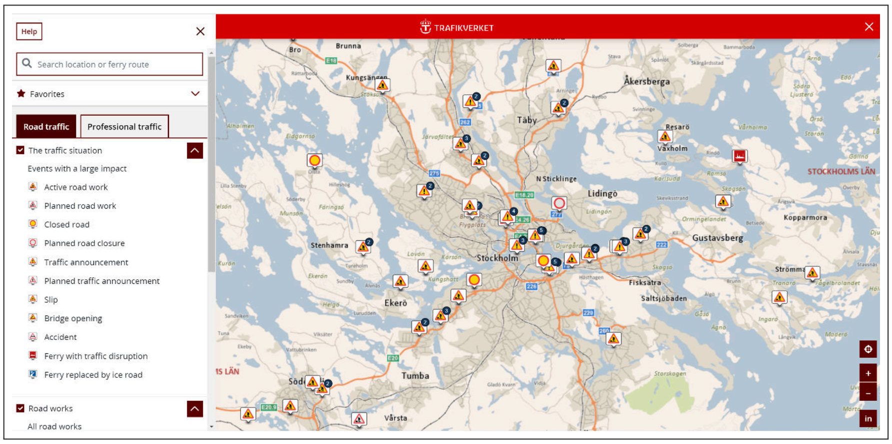

Figure 2.1: On-line traffic information
accessible via Trafikverket `https://www.trafikverket.se/trafikinformation`

Congestion pricing represents a tool to alleviate traffic congestion. The whole idea is quite simple - charges are introduced on specific segments or areas during peak hours - which has the effect of spreading the traffic into time and space. Ultimately, a traffic system can achieve change in people's decision about making the trip by private vehicle and using public transport instead. A stable and efficient transport system must be present if congestion pricing is introduced because this transition from individual to public transport can have a negative impact on other modes of transport. The charges, in some sense, represent the costs of individual traffic to society in a form of congestion, noise, air pollution, etc. The charges may be variable depending on the time of the day or congestion level in the controlled area. The implications of congestion pricing are based on the observation that people typically gravitate toward socially efficient choices when they have all the social benefits and costs of their actions in front of them [60]. The use of automatic systems detecting vehicles, and collecting the toll, respectively, is necessary for this strategy to provide its benefit [61]. The whole theoretical part of tolls application in general is a more complex puzzle. As [62] points out, it is important to make sure that all external factors (like time or place) are taken into consideration when designing the pricing policies since the pricing of congestion might not have an impact on air pollution, while a carbon tax might not have an impact on congestion given by different design methods. Real-life implementations can be found in Stockholm (since 2006), London (since 2008), and Milan (since 2012). More insight can be found in [63], [64], [65].

In a certain sense, lane demarcation is also a function of the application of the tolling system. A typical example is the driving of vehicles in designated HOV (High Occupied Vehicles) or HOT (High Occupancy Toll) lanes specially reserved for certain road users. Those additional lanes represent additional capacity that can be used before congestion kicks in. The aim is again on dealing with congestion and shifting the demand towards different modes, or towards carpooling - using the car for more than one person. The driving system allows only allowed vehicles in the dedicated lanes - public transport, fully occupied vehicles, and vehicles with a licence/permit to use the lane (chargeable). Particularly in rush hour traffic, these less congested lanes are provided to vehicles with two or more occupants or who have paid for the use. HOV is discussed in [66], [67], or in [68].

2.3 Traffic Modelling and Traffic Simulation Models

There are numerous traffic models defined over the years. The models represent to a certain level of detail the real world and their advantage is that they can be subject to testing and simulations can be made on them that otherwise would not work in the real world or would be too expensive.

With respect to traffic control management, division can be distinguished according to physical representation, degree of detail, discrete versus continuous, and deterministic versus stochastic traffic flow modelling [41]. When considering the physical representation, different approaches can be taken in the forms of what we know and how can we define the model.

Deterministic versus stochastic models differ in the way outputs can be defined. A deterministic traffic model always gives the same output when the same input is applied. That means that the input-output states are definable in the model and can be expressed, for example, by a formula. An example of a deterministic system can be to a certain extent considered a transportation system like train transportation or public transportation system. Everything in the transportation system is based on a schedule, train or bus operations follow specific pre-determined paths. Stochastic model is the opposite of the deterministic model which when all the inputs and model's conditions set are the same will never give the same output. The results are dependent on the stochastic variable and, because numerous simulations need to be usually conducted, an average of those simulations is taken [41]. Stochastic models work with probability, for example, the probability of the presence of a group of cars. An illustrative example can be considered, again to a certain extent, the traffic system. In a road traffic system, all variables represent drivers' decisions and behaviours, vehicles, and the general environment (weather, disasters, etc.) due to their unpredictability and thus represent stochastic variables in the simulation. Given the explanation of those two types, traffic flow can be thus described as a pseudo-stochastic model where some of its features have defined structure but the randomness in the form of drivers is still present and acts upon their decisions making the model unpredictable.

Traffic modelling can be broadly divided according to the level of detail to which the traffic can be modelled. As mentioned earlier in the introduction chapter, they can be divided into three groups - microscopic models, mesoscopic models, and macroscopic models. The representation of traffic flow is defined by them in a way that the more traffic flow is described in detail involving more and more vehicles, the more micro-simulation models are used. The least level of detail about each vehicle has the macro-simulation model, described by the average variables on links, and the most details about vehicle states have the micro-simulation model, having the information about the velocity of single vehicles. Macroscopic variables like speed, flow, and density can be aggregated from microscopic values [48]. All these representations of traffic allow a description of a traffic stream that can be input into ITS systems and their design, for determining the level of services, for incident detection, for analytical purposes of a traffic network, or other purposes.

Macroscopic models look at the traffic flow as a whole and describe it as such. An analogy can be found in the flow of fluids or gases. They work with aggregate quantities of the traffic flow such as velocity $V(x,t)$, density $\rho(x,t)$, and traffic flow $Q(x,t)$, and express the dependence of these quantities on each other. In other words, the parameters are averages over individual lanes. By expressing the relationship between these quantities, the evolution of the traffic flow in time and space can be described. They can be used to describe traffic states on larger sections, where these individual states can be described using macroscopic models, for example, the evolution of traffic congestion or speed in the case and space [48].

Mesoscopic models can be placed somewhere between micro and macro models and combine characteristics of both into a hybrid model. Mesoscopic models work with groups/clusters of elements. Modelled are individual vehicles but considered in a small group of vehicles. The interaction is examined between those small clusters of vehicles in a macroscopic way and their interaction between them in a microscopic way. Those clusters are defined with the same characteristics among them in probabilistic terms [69].

Microscopic approach examine particular sub-elements of traffic flow and their interaction among them. The traffic flow is described by the number of vehicles and their parameters. So, the principle lies in the modelling of individual vehicles passing a road or a segment of a network. All elements are counted in the model such as infrastructure and the means of transport. In addition, drivers' behaviour is taken into account and is included in the modelling. Input to these models has generally known parameters of all elements involved in the model such as modelled network, vehicles, road users, origin and destination of trips/network load, etc. The most known models are the headway distance model, car-following model, or overtaking model.

Several scientific papers have dealt with the topic of microscopic traffic models. To mention just a few of them, [70] introduces SITRAS (Simulation of Intelligent TRAnsport Systems) simulation system on the basis of multi-agent simulation technique in a microscopic traffic simulation and lane changing and merging algorithms developed for this model with an experiment and results upon them. Results show that the multi-agent approach belongs to the micro-simulation sphere of models and results from testing and validation of the SITRAS model showed a dominance of the model [70]. In [71] presents a new car-following model that is set on the driver's ability and own limit on when to accelerate or brake. A car-following model was also discussed in [72] or [73]. In many publications, it is referred to microscopic models as cellular automaton models implemented in them, see [74] or [75]. The main idea is that the moving of vehicles is made of 'hopps' where each hop represents moving of vehicles by a single defined smallest segment - 'cell' [41].

In addition, traffic flow models can be viewed upon the categorization of single- versus multi-lane models incorporating interactions between lanes and changes between them by application acceleration and lane-changing models. Or the diversion of traffic flow models can be looked upon their mathematical structure used for their description.

As can be seen, traffic models play an important role when considering traffic flow description or even the implementation of traffic management strategies. Especially for the second purpose, it is necessary to be able to model those instances in real-time actions and get responses as fast as possible to tune the traffic in the correct way, according to the models. Different visualizations of those models can be selected. Particularly one model important from the traffic flow perspective has to be described in more detail since it deflects most of the traffic management strategies and their approach to solving the traffic problems. Fundamental diagram is a formalized term for the transport model of a traffic flow, which is mostly used for the flow-density diagram of macroscopic models. It is a basic tool for investigating the state of a traffic flow using the expression of three traffic quantities - velocity, flow rate, and density ([76], [77]) that presume drivers will drive following similar behavioural nature of their decisions. Their further representation is in the form of velocity-density and velocity-flow models using average values. The models are always related to a specific location or segment of a given road on which, by monitoring and measuring the traffic flow, these characteristic curves can be obtained. All three fundamental quantities of the traffic flow can be read from it, where the speed is given by the slope from the origin (speed can be calculated by connecting the point where one wants to know the speed with a point of origin and measuring the angle/slope of that connection. Also, by connecting two points on the fundamental diagram, a state of the change of the traffic flow can be read - shock waves[1]. The fundamental diagram can be interpreted as when the density increases the traffic flow is also increasing

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[1] Shock wave = sudden change in density or volume upstream or downstream of the traffic flow due to a change of road conditions, change of intensity at a junction, stopping or accelerating of vehicles, or the presence of an incident in the form of a traffic accident, roadworks, etc. The slope in the fundamental diagram between two points represents the speed and direction of the shock wave

until the critical density is met. At that point, traffic flow reaches saturation, in other terms, the flow is at its maximum and flips into an over-saturation area (high amount of vehicles, slowed-down traffic). The reason for the flow being low around the point of origin is that when density is low, not a lot of vehicles are present on the infrastructure and so the flow rate is low, and, on the right side near the maximum density, the flow is low because the road segment is filled with vehicles and thus vehicles can not flow that easily. The maximum density on the right corresponds to the jam density of congested traffic.

2.4 Decision Support Tool

As a basic evaluation of a traffic stream at least historical data has to be available to reconstruct the traffic state. This can be called traffic state estimation. But, traffic is a dynamic element that changes over time and space. Traffic management needs additional information about the states in a dynamic manner so that traffic states and especially traffic management strategies can be predicted. Usually, traffic operators can achieve higher performance when they can control the traffic in time so that the traffic does not turn into congested states. Those measures thus have to be taken in time proactively throughout an interface that allows them to control the traffic. In general, what that means in practice is that there has to be a methodology applied to those control processes that follow principles of traffic control gathered over the past decades of traffic research. The operation of traffic is subject to established conventions and rules that are based on this knowledge base. Usually, a scenario/strategy is pre-defined and has historically been applied to the given incident. Provided that some control protocol has to be followed, the presence of a person or a system helping with traffic operator's decisions has to be applied to achieve the best possible traffic performance. **A decision support system (DSS)** is usually in place to give the operator support in making decisions and providing other needed support for traffic control.

The main purpose of a decision support system in a traffic management centre is to grant aid during incidents to minimize incident aftermath. DSS can be pictured as a system having an overview of everything including detector' states, actuators' statuses and conditions, data collected, and infrastructure topology, together presenting traffic state estimation but also having prediction models predicting traffic situation in the future. A traffic control strategy database including all the possible measures that can be applied to prevent and correct the traffic can be included in the DSS as well. Decision support tool can be viewed as a "superior mastermind" behind all the control that could be taken if the traffic operator finds the suggestion expedient. The human-machine interface provides enough information about the historical, current, and future traffic. Traffic models inside the system need to be responsive to all sorts of traffic states detected by sensors, process the data, and build a model of the current real-time scenario at a satisfactory level.

As for the prediction and traffic control suggestion support, DSS contains simulation module. This module represents a simulation software (or multiple) that can run multiple simulations of traffic states and applications of multiple traffic strategies, get the results like queue propagation, travel times, or speed and suggest the best possible way to take to optimize not only real-time/future traffic but also traffic control strategies themselves. The application of simulated strategies can be automatic or be approved by a traffic operator, depending on the setting or magnitude of the measure. They are specifically designed to aid traffic operators as a decision support system. The whole process is not only automatic but also traffic operators can propose an area for simulation to get the results if they need it. The results provided to the operator usually provide several simulated scenarios and are presented with a score/performance index/percentage saying how good the individual possible strategy application is. Historical scenario runs are also saved and available for evaluation enabling the operator to explore previous steps taken and fit them with current data.

Real-life implementations can be found all around the world in traffic control centres. For example, in [78] a real-time DSS was introduced aiming at providing real-time support for incident response logistics providing enhanced support for not only localizing and dispatching the emergency service but also providing the best possible routing option and on-scene management tool. An immersive survey was conducted collecting user needs from which the support system was constructed. The DSS was tested and found useful by users [78].

3 Decision Support System Architecture

In the previous chapter, a decision support system was introduced. To be able to optimize traffic flow by correcting and/or controlling strategies, a traffic state estimate has to be available with current, short- and mid-term predictions of the evolution of traffic conditions together with a possibility to run simulations with various strategies or policies to determine the best possible solution to potentially mitigate the negative impact.

In this chapter, the focus is on the decision support system's inner structure and the build of its components. An overview of DSS architecture is presented which directly describes the functionalities of each module. Those main modules, which are required for traffic management, are further characterized.

3.1 DSS Architecture

The architecture of a traffic decision support system can be perceived as a generic framework that contains different modules with relationships between them. The design of DSS architectures is evolving. Moreover, designing DSS and its architecture can be understood as a cyclical-iterative process focused on having an optimization function aimed at particular features [79]. Generally speaking, the architecture of a DSS is very dependent on the applied area of application or the principle of use of the DSS. Concept describing the composition of the architecture of a decision support system for traffic management can be found in [80].

The core architecture of most of the DSS, regardless of its usage, is composed of a database or knowledge-based system and some modelling component consisting of various models [81]. Paper [82] suggests four components of a basic DSS: a language system (all the orders/information received from users), a presentation system (output messages and information), a knowledge system (all the rules, expertise knowledge and thresholds), a problem-solver system. In the paper, the active element that makes the decision system functional in its purpose is the fourth element using the other three systems and providing the main software engine to the DSS, thus finding solutions to the given problem [82]. For traffic management, this architecture concept can be summed up into two main components - an expertise/knowledge system and a traffic simulation model. But for a true support system tool for active traffic management performance purposes, other functions must be present.

In addition to the fact that the considered DSS is a user-interactive system, it is worth mentioning that, according to [83], the reasoning behind this assumption is that there are several human-machine interactions (HMI) from many aspects that act as a cooperating assistant to the transport operator. All the messages received must be justifiable with a reasoning process of the control operation presented with a possible modifiable solution presented [84]. Moreover, the paper [84] defines 3 main components needed to be present in any DSS:

- Presentation manager - to be able to correctly understand operator's questions and provide best-possible output easily understood by an operator;
- Problem-solving medium - to be able to identify the best solution the the question using automatic tools;
- Conversation manager - middle element between presentation manager and problem-solving medium ensuring communication.

As for the main functions of the DSS from a higher perspective, [85] defines three types of question that are needed to be processed by a DSS in order to provide real-time decision support to operators ([85], [84], [86]):

1. *"What is happening?* - definition of the traffic state estimation problem;
2. *"What may happen if?* - identification and understanding the cause of imbalances between capacity and demand, as well as prediction of future traffic state;
3. *"What should be done?* - definition of subset of suggestions for network optimization.

The questions above represent the main core of decision support as they represent the characterisation of any given problem which is (1) identification and analyses of sensor data and state definition, (2) identification and understanding of imbalances between capacity and demand, as well as future prediction of traffic state with a demand model prediction and future simulation, and (3) subset of strategies available for the solution ([87], [84], [86]). As a truly first-time intelligent adaptive system for real-time recognizing traffic situations can be mentioned the SCOOT (Split, Cycle, and Offset Optimization Technique) method using the decision support model [86].

Figure 3.1 presents the conceptual scheme of the active traffic management system decision support system. It should be emphasized that the modules shown in the figure and their further definition and characteristics strongly depend on how each DSS or TMC is arranged. Therefore, the methodology behind creating real-time traffic management DSS architecture as seen in the figure comes from several assumptions:

- It is assumed that the presented architecture represents more of an ideal concept combining most of the best practices and models for traffic management control;
- Lagrangian and Eulerian sensors are available;
- Traffic centre is centralized with enough personnel to maintain and operate traffic;
- Traffic control systems (actuators) are presented on the infrastructure;
- Considered DSS is an user-interactive system: The system is completely supportive with automated process capabilities. As a result, it is purely up to the traffic operator to decide whether or not to opt for a given strategy;
- The focus is only on car-centred traffic management control where one operating agency is involved.

The DSS functions intervene in all fragments of traffic and traffic management - from data collection through traffic state estimation to the application of traffic management strategies. The system is defined by several systems and processes represented by individual modules. The environment of the system in which it is embedded concerns only these elements, the other elements are taken as the external environment of the system and are only taken as input parameters or influenced variables interacting with the defined system. The level of detail is thus given by the individual modules that define the main functions, processes, and actors of the DSS, the rest is the external environment.

Figure 3.1 can be understood as a conceptual overview for DDS introducing all the possible features (modules) that the DSS can have or have been used theoretically or practically in past use cases. The picture can also be interpreted as capturing the overall view of traffic management using DSS in the framework of a traffic centre. It is assembled from multiple concepts, that together form real-time active DSS. The concepts that inspired the creation of the presented architecture are [5], [7], [88], [89], [90], as well as university lectures. Each of those modules are explained and their basic characteristics are discussed in the section 3.2.

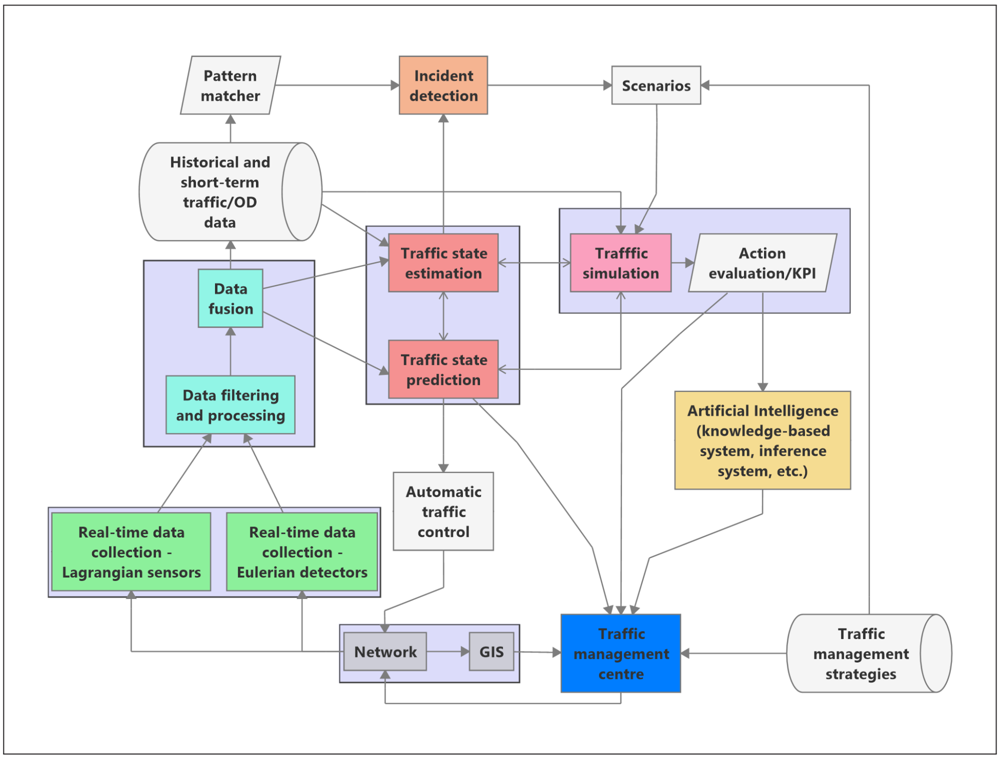

Figure 3.1: Decision Support System Architecture

3.2 Modules

In this section, each module is described. The main modules recognized for a description are:

- Traffic network;
- Data collection;
- Data filtering and processing;
- Traffic state estimation and prediction;
- Traffic simulation module;

- Incident detection;
- Artificial Intelligence;
- Traffic management decision centre.

3.2.1 Traffic Network

Network, and transport systems, respectively, can be represented by two main parts, namely physical and moving elements [91]. As described in the [91], physical elements represent individual elements that are used by elements moving on or using the traffic network, i.e. roads, road capacity, parking, but also traffic detectors, traffic lights, etc. Moving elements are for example vehicles or people. The presented conceptual architecture is oriented on the transport network on which vehicles, goods, and people move. Real-time traffic data are collected from ubiquitous detectors placed on the traffic infrastructure, as well as from moving sensors providing spatial data, from which traffic quantities can be derived. The data from these sources are transmitted either by air or by wired connection either to other systems providing communication with the traffic centre or directly transferred to this building. This transmission interface can be defined in many ways, which are not the focus of this work. Either way, the measured data is first processed in a meaningful way. For example, the data must be cleaned of outlying values and other erroneous measured data. Data processing must also be subject to the fusion between static and spatial collection methods. The amount of data is considered as big data, so an efficient way of processing them has to be applied. This is mostly concerning statistical techniques like Kalman filters or Kernel smoothing [7]. The filtered and fused data are stored in databases for future traffic state estimations based on historical data.

In the presented architecture, the network is connected with a module called GIS (Geographical Information Systems). GIS in traffic management DSS concepts is designed to provide traffic professionals with the visual support of the traffic network. They are giving operators possibilities to model areas, and segments, to see all the facilities, and also provide analysis tools. According to [92]: *"GIS assist in the preparation, analysis, display, and management of geographical data".* In the GIS implementation within DSS the GIS serves as an analysis and display utility [92]. The GIS contains a virtual representation of an area or city model o which the traffic control centre operates. Design and implementation of GIS within or even as DSS have been presented for example in [93] with an implementation in Turkey for mapping the air pollution and modelling predictions of pollutant sources representing considerable risks for cities' air quality.

3.2.2 Data Collection

Traffic data collection is a very important element for transport in general. The traffic sensor block consists of many different detectors recording important traffic data and information for other traffic systems. The data is used for the processing of key traffic-engineering variables, and therefore for the management of traffic networks and traffic correction this key element is essential. Among ather reasons is to detect travel patterns and collect statistics like average daily traffic, discover travel time trends or determine environmental effects. Different ways of measurement are used, which can be categorised into traffic detectors:

- Eulerian sensors - measurement data from static detectors placed on the relevant transport infrastructure, and
- Lagrangian sensors - measuring traffic data using spatial sensors.

Eulerian detectors are used to measure and estimate traffic variables like volume, velocity, or occupancy at the given location they were installed. The most used detector in many major roads from this category is the inductive loop sensor, video detection, radar, or infrared sensor. In turn, they are a reliable source of data and are therefore used in places with a higher frequency of traffic [7]. Parameters of such detectors can be accuracy, the aggregation level in which they record data, and the placement that also determines whether they measure one, two, or more lanes, or penetration rate. The sampling rate plays an important role when it comes to result estimation in having a problem with long-period sampling times. This causes a delay of the received signal which is relevant to the sampling time of calculated travel times [7]. That is a problem, especially for real-time management which needs to react quickly to the current situation. Lagrangian detectors, on the other hand, can provide such traffic variables as travel time or be a good source of incident detection. Measurements are done using probes present inside vehicles and capturing the vehicle's position, speed, direction of travel, and other measures. Another possible way of collecting those data is through Bluetooth or WiFi devices in cars or GPS-probes. Since the measurements collect GPS positions of equipped vehicles, fleet management is also an important source of this type of data. Fleets of taxi vehicles, vehicles of public transport, or companies operating and providing these traffic data can be a source of these data. Data can be obtained also from commercial databases like INRIX. Probe data provided by INRIX company provides location-based real-time or historical data. The INRIX dataset provides big-traffic data collecting and selling GPS data and providing their analysis [94]. Another way of their collection can be via vehicle licence plate measurement by AVI (automatic vehicle identification) or cellular network data [95]. The cellular network data enables to estimate also travel demand representing the O-D matrix and activity patterns) as well as incident detection. The collecting is advantageous in a way that it enables the collection of traffic data along the way even in areas where no static detectors are and in a possibility of measuring traffic information that has a different type of meaning for the traffic management providing more insight into understanding traffic. An important performance measure received from Lagrangian measurements is queue length reflecting both delay and travel time. Nevertheless, for queue length, it is important to also know the number of vehicles being inside the congestion which can be provided by probe data [96].

3.2.3 Data Filtering and Processing

An essential part of DSS is real-time data processing and fusion. Data processing is a need to define outliers and erroneous data that are collected on the infrastructure to improve the quality and accuracy of the traffic state representation. With more ways of measuring the traffic data and different sources, it is also necessary to be able to combine those measurements and create a picture of a current situation from all the detectors providing valuable data.

Received raw data in general terms contain error values or the values can be missing. This may be due to multiple reasons - sensor failure, measurement error, transmission error, etc. In addition, some measurements can also contain values that are not observable like negative velocity. Moreover, since the detectors are usually a matter of different companies, they can output the data in various formats. This problem is necessary to handle as well.

The cleaning methods can be based in various ways. There is usually some central logic applied to the filtered data based on logical assumptions. Data filtering usually means removing outliers and data with an error profile. Error data are replaced with estimated or computed values since they represent gaps in the measurements. Fundamental traffic models can be used for those purposes. Other methods for estimating traffic variables used are Kalman filter ([97],[98]), least square [99], neural networks [100] or Bayesian methods (for example Poisson distribution) [101]. These methods are also methods used for traffic state estimation and prediction. Given the fact that sensor data come from various locations as well, the pre-processing part contains map-mapping of the collected data. After appropriate data handling, data needs to be fused from multiple sensors.

Next, data is carefully organized in a database or warehouses in the traffic control centre. To support work with the stored data, several relational database systems can be used like

MySQL. Ultimately, those data then represent a collection of all the measurements from various sources and act as a data hub that can provide high-quality data to the traffic simulations and DSS, or other stakeholders.

3.2.4 Traffic State Estimation and Prediction

Estimating and predicting traffic states is an important feature in traffic management centres. Due to not being able to measure traffic everywhere on the network, it is needed based on the observations to estimate traffic conditions from the incoming data [102]. According to [103]: *"Traffic state estimation (TSE) refers to the process of inference of traffic state variables, namely flow (veh/h), density (veh/km), speed (km/h), and other equivalent variables, on road segments, using partially observed and noisy traffic data."*. In other words, traffic state estimation is determining the traffic state of variable X based on the measurement Y [104]. The essential part of traffic state estimation is the measured data and traffic models on traffic behaviours with two approaches - model-driven and data-driven.

Standard techniques used for traffic state estimation are the ones mentioned in the section 3.2.3, together with k-nearest neighbors, locally weighted regressing, fuzzy logic or linear time series [9]. These types of methods represent non-parametric methods mostly based on macroscopic traffic flow modelling [105]. Since the traffic state estimation includes techniques used for pre-processing the data and their filtering, one can say that state estimation and prediction may represent the same module in the figure 3.1. In the case of this thesis, it is assumed that the data are already processed and transmitted or are being processed directly in the traffic control centre. Then those data are sent to modules called traffic state estimation and prediction whose role is more about the actual determination of a current state or the state predicted. Statistical and traffic models are applied based on what is the desired goal - estimation of a current traffic state, and its short-term prediction, creation of input data into the incident management system, output data into simulation input, or directly applying any measures. The traffic estimation module determines the current network using historical, real-time data and combines it with various traffic models. It refers to estimating variables of a traffic flow based on the filtered detector data. In [106], for example, the traffic state estimation approaches are defined by the traffic flow model, estimation method, and the data measured on the infrastructure. The same description also provides paper [103]. Flow model and data measures were discussed earlier in this work as well as estimation approaches that represent either model-based or data-driven approaches to traffic estimation.

Traffic state estimation is also connected with the database with historical traffic and O-D data. Historical data in active traffic management schemes can be used as a train data set for model calibrations or for traffic models for traffic state estimation [103]. This concerns only model-driven approaches.

The traffic state prediction module predicts near-future traffic conditions. In other words, traffic state prediction predicts future states of variable X using a historical database of measured data and estimated states of variable Y [104]. Traffic state prediction is partially based on the current state estimation. Traffic state prediction can be based on data-driven and model-based approaches. In the case of the **data-driven approach** (also called non-parametric models), the models are directly dependent on traffic variables that come from historical measurements. The determination of traffic processes can thus be determined by mathematically expressing the dependence of traffic variables on each other using statistical assumptions and machine learning. The approaches that can be used to predict future states range the same methods already mentioned, for example: linear regression - [107], [108]; Kalman filter - [97],[98]; k-Nearest neighbor - [109], [110]. Their advantage is the unnecessary knowledge of deep traffic flow theory to determine future traffic processes. On the other hand, because the data come from historical measurements, the model can only be applied to situations that have already occurred or are recurring, such as congestion [7]. Another disadvantage is the impossible or very slow reaction to dynamically changing traffic situations, and therefore it is not a suitable design from the point of view of traffic management. **Model-based approach** (also called parametric models) are directly dependent on the physical properties of the real world, or rather with what detail they work and describe. Because of the nature of these models, various other elements can be added to the transport modelling. In terms of data usage, they are less demanding on the amount of input data needed, but on the other hand, they require a large amount of data during their creation/calibration [69].

As can be seen from the conceptional figure 3.1, traffic state estimation and prediction are closely connected in-between each other and data flow from both modules is present. Output from those two modules can be considered to be enough to control traffic to some extent. But, to provide proactive traffic management control and apply reasonable strategies, incident management and traffic simulation models are used. Data used in the prediction module needs to be cleaned from erroneous and missing data in order to provide substantial results. Furthermore, the prediction needs to be combined with real-time data reflecting the current traffic state. For that reason, more dynamic traffic models need to be introduced and used.

3.2.5 Traffic Simulation Module

The traffic simulation module is one of the main components for active traffic management purposes. The traffic simulation model represents software support in the shape of computer simulation programs incorporating traffic models and traffic data and providing output results of a simulated traffic reality. In DSS terms, the programs are used to simulate all kinds of situations (not only traffic related in some occasions), test strategies for negative effects mitigation, and simulate the future states [5]. It is a tool that simulates traffic on a given model that can build and run many different scenarios and evaluate various traffic conditions to provide needed decision support for traffic operators. As many different simulation models exist with multiple pros and cons, state-of-the-art simulation models usually are a combination of micro-, meso- and macroscopic models. Traditional transportation modelling in those specialized commercial software is combined together with advanced transportation planning models and with modern dynamic traffic assignment modelling [111].

Regarding real-time traffic management, a real-time O-D estimate, as well as historical patterns, must be present providing the current traffic path trends. The appropriate matrix is given by the surveillance system, after corresponding pattern matching. Pattern matching thus compares data points from the historical database with real-time data in a time domain and selects those that match.

In static models, the link is defined by inflow that is always equal to outflow meaning that the link's capacity can be exceeded [112]. For that reason, dynamic traffic modelling approaches must be selected that dynamically change traffic conditions in time with an effect that represents dynamic route choice, and dynamically changes travel demand, which is based on real-time congestion state. Traffic models are represented by dynamic demand of links on which the demand cannot exceed a given link's capacity and changes in time which results in improved captured traffic changes and the ability to model traffic peaks [113]. Dynamic traffic flow modelling in traffic simulation models is based on the Dynamic Traffic Assignment (DTA) problem. [112] defines the goal of DTA as: *"to determine the network traffic flows and conditions that result from the mutual interactions among the route choices that travelers make in traversing from their origins to their destinations, and the congestion that results from their travel over the network."* The dynamic aspect of traffic assignment modeling is the ability to describe how traffic flow patterns changes in time evolution.

DTA consists of two parts - path calculation and selection, and dynamic network loading. The first part refers to the determination of users' path choices based on travel times (or other costs) meaning assigning demand to each link based on the users' most optimal selections. The latter reflects the route costs estimation when the demand on links is known which has an effect that the greater the demand the higher the cost.Traffic assignment modelling deals with demand represented by the O-D matrix and how that demand propagates. Modelling thus recreates the demand and tries to recreate drivers' route choices when getting to their desired destination. Those decisions are usually affected by other drivers who are also moving on the road and are trying to find an optimal route to their destination. The optimum can be represented by minimum cost or minimum travel time and is based on the modelling hypothesis of Wardrop's first principle [114]: *"The journey (costs) times on all the routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route."*. This phenomenon is called User Equilibrium (UE). This means that drivers are unable to improve their individual costs by unilateral route switching [10]. Since the real-time approach is needed to be taken, UE can be also represented as Dynamic User Equilibrium (DUE). Wardrop's principle is then valid only in cases when users leave at the same time. For a DUE solution, a dynamic network loading needs to be applied to capture dynamic O-D and the arrival times at a link. It can be stated that a priori knowledge of the traffic situation plays a huge role in people's behavioural decisions during path selection. Therefore, the traffic assignment can be based on two assumptions: (1) stochastic where the routes that are being selected are based more on the user's decisions and the trips are assigned with a given probability resulting in possible UE but not necessarily, and (2) dynamic/deterministic where the paths are being selected based on the user's behaviour selection of paths that would have been normally chosen [115].

The modelling in DTA is usually done using simulation-based DTA models [116] in an iterative mode switching between route choice and network loading (where network loading refers to the traffic models used in traffic like macro- or mesoscopic, depending on the desired outcome of the simulation). This modelling approach used in DSS modelling systems enables operative real-time use for giving relevant and more accurate traffic information to the drivers or enables rerouting depending on the level of congestion. It can also serve for traffic infrastructure planning in areas where congestion is a significant element [113], as it comes from the traditional transport-planning model objectives [90]. From the traffic simulation module, the output is usually in the form of a score or some sort of key performance indicator (KPI) or its fuzzy form that describes simulated scenarios and evaluates them accordingly to the goals achieved in the simulation (fast incident clearance, minimize bottleneck effects, congestion reduction or maximizing the overall traffic performance [7]).

3.2.6 Incident Detection

The incident detection module is an important module that provides incident detection and identifies weak spots and potential incidents that occurred on the network. Then, it ensures the provision of available information about the incident giving the operator an input of the occurred incident, if available. Especially when the incident is detected in real-time, it can be a very useful tool for traffic operation managers to control traffic in unusual conditions and provide a precious timely response. [117] defines the main objectives as a more controlled and timely signal to emergency services and as a route control measure that maintains traffic system performance. Its main component working together with the incident detection module is a pattern matcher identifying sequences and repeated patterns from trained traffic models built from historical and real-time data. Incident detection does not have to be only detected from data but can also come in a way of a report from drivers using available means that enable or rescue authorities. The incident module provide input into a scenario module when it is found necessary to investigate an event or area that appears to be potential for nonrecurring congestion by the incident detection. In fact, most of the incident reports still come from manual reporting by drivers [118].

In Automatic Incident Detection (AID), fixed and probe-vehicle data are used for incident detection. Various methods and algorithms of incident identification are used [119] that are able to detect some patterns in the incident data. The detection is thus made on traffic flow variables like flow or speed. Algorithms are based on the fact an incident creates new deteriorated traffic conditions upstream of the incident creating a bottleneck in that place.

This results in a speed reduction and creation of congestion, and therefore an increase in the number of accumulated vehicles, and a reduction in the traffic flow beyond the incident location [118]. Commonly, CCTV (Closed Circuit Television cameras) are used in combination with incident detection for incident verification, monitoring, control, and during incident clearance [35].

An example of a classical AID can be represented by induction loop detectors on a road stretch collecting traffic data which are sent to the traffic management centre. Those data are processed and run by various algorithms trying to detect unusual patterns in the data [120].

The first presented incident detection algorithm used on traffic networks was the California algorithm in 1975 using a pattern recognition algorithm designed as binary decision trees [121]. The algorithm compares 3 occupancy functions from traffic detectors - the difference between two succeeding, relative differences, and 2nd detector's occupancies. If the threshold, set by traffic experts, is crossed, an alarm is generated. Many more incident pattern recognition algorithms followed like McMaster's algorithm based on the Catastrophe theory, Bayesian algorithm, or Tokyo Metropolitan Expressway (MEX). MEX is based on an analysis comparison of traffic variables from detectors located on the motorway with over 1500 detectors with a fast-paced comparison of results (1 minute) and real-time implications of traffic management detection and handling [122]. Different methods were also explored like video-based AID system [123], neural network-based AID [120], non-parametric regression [124], and others. Prediction algorithms were also introduced like the Kalman filter algorithm [125] or correlation with historical data.

All results from the incident detection module have to be first evaluated through means that check available methods of clearance of the incident and applicable strategies that provide the best KPI. A scenario is therefore prepared and sent to simulation tools to verify the correct steps that should be applied by traffic operators. Implementation of incident detection module in traffic management centre has been done, for example, in [126]. A system framework consisting of a data pre-processing module, decision support module, and monitoring module is introduced working in real-time. The first component has the traffic surveillance role of obtaining traffic data and removing erroneous records and combining various data sources. An alarm informing the traffic operator is displayed once an incident is detected in an event-driven component [126]. Information is sent to the second module called Decision support where the accurate scenario is proposed based on AI. All the possible scenarios are simulated and results in a form of performance indexes are generated and action chosen. The last module then provides supervision of applied strategy and continuously collects data for assessment.

3.2.7 Artificial Intelligence

Artificial intelligence is a computer science field and is used to represent knowledge in the decision-making process answering questions like ”What should be done?” or ”What happens if?”. Paper [127] states that using AI for decision-making has been the most important application and has always been in decision-making to either support or replace decision-makers. As mentioned, the help of systems like **advanced knowledge-based systems** and **inference systems** is used to find the best strategy for that particular scenario from the simulation results. It serves the DSS to draw on relevant procedures, historical events, and solutions and generally outlines the traffic rules and traffic behaviour observed on the infrastructure that are used to select the best strategy [5]. Finding a correct optimal strategy follows those best practices that, generally, are aimed at optimization of traffic flow at places with congestion, bottlenecks, and traffic flow patterns that have an erroneous nature and are usually the trigger of traffic problems [48].

A lot of attention has been applied to artificial intelligence (AI) and its applicability in traffic control measures and decision support systems, respectively. Mentioned can be for example one paper [128] based on fuzzy logic used for decision support for selecting the most appropriate strategies for non-recurrent congestion. Paper [129] is showing a decision-making policy framework with machine learning application in a form of a multi-agent system and reinforcement learning, to get the best optimal traffic signal control policy. After testing the framework, the paper states an advantageous situation when implemented by performance improvement observations in the simulated network [129]. Another publication [130] aims at the suggestion of an AI-based decision support system in freeway and arterial traffic management systems. The concept consisting of a real-time knowledge-based expert system is presented and described with an expansion on the notions of characteristics of this knowledge-based system for real-time decision support [130]. A large recent overview of artificial intelligence in decision-making can be found in [127].

3.2.8 Traffic Management Centre

Information from the AI module then goes through HMI to the traffic operators who play an important role in traffic system supervision. They are the ones who receive the outputs from the simulated scenarios and react to them in a module called the traffic management decision centre, which controls all the actuators situated in the network. The other option is that right from the AI module, the actions can be passed directly to the traffic management decision centre.

Based on the support from the DSS, an appropriate strategy is applied from the traffic management strategies database. The decision centre module can be understood as the final step where the operators or by automatic means apply a final strategy. The module receives commands from the traffic operator, which are in the form of suitable pre-simulated traffic management strategies. In other words, this is the control room from which traffic operators control traffic. Those applicable measures can be of type direct (measures aimed at supply) or indirect (managing the demand) depending on the desired outcome - maximizing the throughput, speed control, focusing on travel time decrement, congestion reduction, etc. Applied methods are put into operation through active elements on the infrastructure that influence the traffic flow on the transport network. The control measures are applied from the available strategy set database by, for example, the aforementioned ramp metering, lane management, or re-routing. It also receives output from traffic state estimation and prediction to be available for operators, if needed. In the automatic control measure scenario, the strategy can be applied automatically with authority supervision. Dissemination of travel and traffic information to other sub-systems is done automatically, but can also be requested by an operator.

For example, when an operator wants or needs to make a decision, DSS uses traffic models, combines them with measured data, real-time O-D matrix, and with a help of AI tools provides the operator KPI for multiple scenarios. Through visualization, the operator sees what is the prediction and possible aftermath for all scenarios and sees the results of different usage of strategies. Based on that support from DSS the operator decides and selects one solution for the given traffic problem by applying the given strategy through the available means.

4 Simulation Tools

Simulation tools were defined as being one of the key components in the decision support systems due to their ability to provide answers to difficult problems to the given input. Their development is aimed to help traffic experts with planning the traffic, traffic modelling and for traffic control for the evaluation of different traffic scenarios [131] and management of road traffic. As the computer power increases over time, the ability to test scenarios in a computer environment gives traffic engineers an option to test experiments that would have been impossible or very difficult to conduct in the real world. The benefit of being able to simulate traffic phenomena and study how they disperse in time and space makes this approach of traffic analysis one of the most commonly used methods today.

Different actions can be taken under traffic simulation. They can be used as an off-line evaluation tool for assessing and evaluating concepts before their implementation since they can predict what can happen to some extent. In the sense of real-time traffic management usage, they have become a mandatory feature not only for simulation purposes but more recently also for other things like data processing, traffic model calibration, incident detection, and others. Some of the tools thus can also include other modules from the scheme presented earlier (see DSS architecture figure 3.1). In both cases, off- and online, using simulation models enables traffic experts to obtain knowledge about complex traffic systems that the simulation tool provides and understand the interactions among all elements. Nowadays, the market features an extensive range of traffic simulation software leading, as an important aspect, to the importance of the selection of a correct SW for traffic management purposes.

More need for a solution where the traffic in the simulation models can be simulated under operational conditions made the research look for more dynamic approaches. That relates to the dynamic distribution of demand and dynamic representation of a traffic link with an ability to model non-recurrent events like traffic incidents that DTA models can provide. More specifically, mesoscopic DTA models are capable of capturing the macroscopic level and provide benefits in providing a simplified view of a model, as well as give the simulation necessary microscopic abilities for traffic simulation giving it a more detailed description of vehicles' movements and more detailed simulation results [132]. In other words, recognizing the design compromise between the simplicity of modeling from both levels, they represent a suitable solution for large metropolitan areas for online predictive simulation. Hence, DTA models with a mesoscopic simulation combination are capable of capturing dynamic phenomena observable in the time domain like real-time traffic control or queuing with both levels of details, which has been a focus of more and more traffic simulation SW vendors. Nevertheless, it must be mentioned that the latest state-of-the-art design of simulation software usually provides a hybrid combination of the aforementioned simulation modelling approaches.

When considering a decision support system, the simulation-based approach is usually part of the concept as one of its modules/features providing microscopic or mesoscopic models for predictions. To use the simulation software inside a DSS the SW is required to replicate everyday conditions happening on the infrastructure and replicate traffic phenomena occurring there including non-recurrent and recurrent congestion [133].

In the previous chapter, it was described what is the purpose of a simulation module in the DSS architecture. It has been shown that simulation SW are part of DSS itself. Before showcasing the practical use of one of the software, Dynameq, ways of different implementation of the simulation tools and a description of how the features are being implemented in various simulation software available on the market are presented here. The aim is to provide a deeper understanding of various modules used in current software tools and discuss their differences and approaches taken within that software. In particular, a basic comparison is made among software that was found to support the concept of real-time traffic simulation and/or was considered suitable for DSS.

4.1 Previous Research on Software Comparison and Case Studies

Usually, traffic simulation software work with a computer model that represents a conceptual model of a system (in this case a traffic system). Simulation can be described as recreating a system's processes and relationships among its components under complex mathematical model constructions which are studied through simulation examining the performance results of a given input to the system [134]. As described in the previous chapters, the model contains all the components of the real world with all the assumptions based on the model categorization (microscopic, mesoscopic, macroscopic). Therefore, many research papers dealing with traffic simulation models, in general, distinguish traffic simulation models into three categories according to the traffic modelling approaches.

Many studies contribute to the problem of different software availability and deal with the selection of a suitable software for particular problems by comparing software with one another. Like [135] that presents a research comparison of 4 simulation tools, namely Matsim, SUMO, Aimsun, and PTV Vissim. The study presented in the paper compares the aforementioned software in terms of different criteria such as operating system portability, whether the software is open source or freeware, graphical point of view, or what simulation outputs particular software can provide. The result claims positive feedback on SUMO, Aimsun, and Vissim as they could provide the most reasonable performance across all other competitors [135]. Another conclusion was found to be knowing the data and the needs of the traffic network used inside of simulation software as a necessary piece of information for software selection. Similar research was done in [136] with the same criteria compared between six SW. In addition to the previous simulation tools, new ones were considered namely Quadstone Paramics Modeller, Treiber's Micro-simulation of Road Traffic, Trafficware SimTraffic, and CORSIM TRAFVU. Their findings reflect a problem with the necessity of deciding on whether to use a macroscopic or microscopic model and its connection to the computer's CPU power where based on the modelling level the performance of the simulation changes. For large-scale models, and especially for real-time traffic control, it is important to choose the appropriate modelling approach and a powerful computer wisely, as results should be obtained with the least time delay [136]. However, as is stated in [137] for microscopical traffic simulation models, once the model is well calibrated they are more or less equal giving similar performance results regardless of the type of the simulation model.

To help with the correct selection of a traffic simulation SW, paper [138] comes with a systematic simulation evaluation procedure developed for that reason. Based on the user's requirements and needs for a simulation SW, the procedure presented in the paper helps with the selection. That procedure is based on their qualitative and quantitative approach that assigns users' weights to individual modules of SWs. Evaluated features were in a form of functional capabilities, characteristics of input/output, level of required knowledge, or accuracy. The method was tested with the pool of two SW tools - AIMSUN and VISSIM but it is claimed that the selection pool can consist of many other options (not just two). Both SW were evaluated following the procedure presented in the work and found their capability in traffic modelling with similar accuracy and provided features. In addition, [138] declares a need for a data processing tool enabling a data format conversion within the SW. It is also stressed that the selection process reflects subjective factors affecting the overall score, which, however, contributes towards the most appropriate selection of users as the needs are always different for different projects [138].

A large comparison of 17 simulation SW was made in a paper [131]. An evaluation process was done based on literature and available specifications and reviews together with interviews of simulation tool developers, product managers, traffic managers, or engineers to provide their insights on traffic simulation in the context of traffic management. The comparison was done based on many factors like modelling approach, model design capabilities, testing various ITS scenarios (V2V, adaptive cruise control, public transport, etc.), or real-time data processing and analysis. The comparison detected how some of the SW has developed at a fast pace [131], especially in the ITS area whereas others have not. The interview provided some answers to the concept of traffic management, for example, on the requirements that one can have on those SW. Since the usage of traffic simulation SW is claimed by many different fields of transportation, the functionalities (or modules, as it is called in this thesis work) vary from product to product. Even within the product, it is possible to customize the solution since some functions are just unnecessary for some application fields. Moreover, in the future, it is expected that those platforms (software) will become a general element for traffic management and transportation areas like public transport, emission, or energy consumption simulation [131]. Regarding the traffic simulation software in the real-time domain, the authors state that it is necessary to have good models that represent the behaviour of the drivers and traffic processes in general, as well as some prediction algorithms. Also, those real-time requirements need the modelling approaches both from micro and macro perspectives, thus creating a demand for mesoscopic solutions capturing just the right amount of dynamics on the network [131]. Further, they characterized also other trends in simulation SW like GIS component or model calibration option.

Another extensive comparison was made in [139] comparing 29 different SW from different aspects of traffic flow scenarios. In the article, they focus on different features when considering the differences between individual tools and presented the viability of each SW based on the road infrastructure categorization (intersection, highway, freeway, etc.). One of the statements in the paper is that driver's traffic behaviour should be based on the driver's origin or country in the SW since divergent behavioral natures come with different countries [139]. Next, the differences in traffic simulation software are very large and there is no software better than others although there can be seen some performance differences in various scenarios where one SW can simulate the case better than other [139]. Lastly, the most important aspects that should be considered for SW selection are mentioned: traffic behaviour, traffic models, project type, and calibration [139].

Other interesting comparisons of traffic simulation software can also be found, for example, in: [140], [132], [141].

When looking at the practical use of simulation tools in DSS projects, many different use cases, research papers, and projects dealing with this topic can be observed. For example, a project within the EU created an architecture named MOTIC-SMC (MObility and Traffic Information Centre - Strategic Management Centre). The architecture was built on AI components that are combined with traffic simulation models (based on AIMSUN2) providing the traffic operator assessment and evaluation of strategies before their implementation

[142]. DTA simulation approach is introduced in [43] presenting a decision support system with real-time models that instead of loading new demand on routes it uses a ”rolling horizon”. This method takes up to 5 minutes of a previous assignment and uses it as an initial value for network loading resulting in pre-occupied routes eliminating the warm-up phase [43]. In the final report of the Florida Department of Transportation document of the transportation corridor program called Integrated Corridor Management (ICM) Systems Initiatives under the U.S. Department of Transportation, the simulation modules were used for offline and online use cases of decision support tool applications [133]. Among the considered modules of DSS in the project, a simulation-based predictive engine in different forms (based on the corridor) was used for real-time DSS management. This DSS with simulation SW was implemented on three corridors in San Diego, namely I-15 (with a predictive engine AIMSUN microscopic simulation model), US-75 (using mesoscopic simulation-based modelling tool DIRECT), and I-210 (incorporating two different simulation models - one macroscopic invented by the University of California of Berkeley and the other applying macroscopic Aimsun simulation tool) [133]. The document also includes many more implementations of DSS, in both online and offline versions, and research towards the applicability of DSS as the key component in ICM is analysed. In a case study of Madrid in Spain [88] a decision support system was implemented as part of a project to develop a real-time traffic management system. The simulation program used within the project was AIMSUN microscopic simulation model which in an incident case would automatically run multiple simulations with various strategy scenarios in simulation software. Based on the simulation, the results would then be provided to the traffic operator in a variety of ways [88].

4.2 Traffic Simulation Comparison

A comparison of different SW found on the internet is done and a brief overview of each one is given. The selection of compared simulation tools followed research papers that had done similar comparisons, as well as their assessments presented in the previous section. Discussed simulation SW are reviewed in terms of functionality and usability within the DSS concept, what can the product offer or is currently offering for traffic management, how had they been used to support decisions, how they work, etc. Features and techniques were searched in research papers found online, from manuals, documentation, and official websites of each SW.

4.2.1 Mezzo

This mesoscopic event-based[1] traffic simulation open-source software is managed by Royal Institute of Technology (KTH) Stockholm. It is a discrete-event traffic simulation model where speed is a function of density on the link with a queue-server paradigm which enables accurate simulation of bottlenecks and on-/off-ramps [143]. It can be used with a hybrid model representing a microscopic traffic simulation SW to obtain both vehicles’ movements and aggregated driver’s behaviour [144].

The network is represented by nodes and unidirectional links. Links are made of two parts - running and queuing, where the running part is used for vehicles on their way without any delay by, for example, traffic lights, thus the thresholds between those parts vary over time [143]. It is further capable of analysing shock waves or queue formation and dissipation simulation. Traffic demand is defined by the O-D matrix specified for each time slice. Different vehicle types can be simulated. Route choice in Mezzo SW is based on two approaches - pre-trip route choice and en-route-switching. For more information, a detailed description can be obtained in [143], [139], or on the official website `https://www.kth.se/ctr/research/model-development/mezzo-mesoscopic-traffic-simulator-1.726113`.

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[1] Event-based simulation is a type of simulation where the state of traffic is computed at the ”change” of the system and not with fixed-time intervals (for the Mezzo case, those changes can represent a new vehicle being entered into a link or transfer of a vehicle from one link to another) [143]

4.2.2 PTV Optima

PTV Group provides numerous traffic software products for different areas of transportation and logistics. They specialize in software development in traffic and transportation, but also logistics and mobility fields. The variety of products they offer contains many simulation tools. One of the products is called PTV Optima aiming at real-time traffic management. The tool provides useful features that are directed toward road authorities and traffic operation centres providing various crucial functionalities necessary for real-time traffic handling. As claimed by the company and seen in the presented use cases on their websites, the product is a modulable solution which focuses on different use cases in different solutions and provides different features for different traffic fields. The main concept is the incorporation of several PTV products into one new UI, which brings all the features of the other products, and in addition, provides additional functions and features for the provision of traffic information and traffic decisions. Moreover, other ITS solutions can be incorporated into the SW resulting in overall control of any ITS solution and applying SW functions and model calibration based on these solutions too. This creates from PTV Optima a SW for traffic entities providing several functions.

Considering just basic key real-time traffic management features, Optima can serve for:

- Traffic information

  Collection of data from the network from different sources like fixed and spatial sensors with an option of adding new ones. At the same time, a real-time data integration process is applied fusing different data sources. The data collected are also combined with traffic data providers like INRIX, Here, and TomTom and fused together with the live feed from sensors on the network. Several sources of data can be processed such as DATEX II (for events), GTFS (for public transport events) or OCIT-C, etc. The fusing is done by one module that cleans the data from outliers, corrects and adds missing or corrupted data and when more data are coming from the same place, the module fuses them.

  All the data sources can be visualized and controlled/monitored throughout this SW at any time giving additional needed information about the source of the collected data to the operator.

- Traffic propagation

  Traffic simulation on different levels gives the operator knowledge about the interaction of all road users. The traffic propagation is estimated through a dynamic traffic equilibrium model (which is based on macro-mesoscopic simulation) and available data making data-driven traffic estimation.

- Traffic forecast

  Prediction is provided for the entire network (or for the selected use case scenario) even where is no sources of data. To do this, a prediction is made using a dynamic model with machine-learning techniques [11]. PTV Optima can provide a forecast for up to an hour depending on the given supply and demand to the model.

- Decision support

  DSS tool uses all knowledge from all the strategies, AI, and previous actions taken and utilize that for traffic simulation of scenarios giving the operator a final KPI score of different alternatives. Scenario evaluation is enabling traffic operators to simulate multiple strategies and evaluate them thus selecting the most appropriate one for the current situation. That is done by combining real-time traffic data and multiple traffic models. Incident detection is present in the DSS helping with timely reactions to unforeseen events.

- Strategy distribution

  With all these functions traffic information can then be transmitted to the road users informing them about traffic conditions, and path navigation and applying other strategies for traffic state optimization. PTV Optima also enables the traffic centre to set up automatic control measures and automatic warnings. The communication is with available traffic infrastructures like sensors, VMS, traffic lights, or other actuators in the network that can influence drivers on their way. Other PTV software can be used as modules in PTV Optima for this function such as PTV Balance (corridor management solution used for PT priority, green force enforcement, etc.) or PTV Epic (representing an adaptive traffic light control system).

Areas and use cases where PTV Optima can be implemented or used are for example traffic capacity analysis, dynamic traffic simulation modelling, data processing, fusion, and their validation, traffic prediction, bottleneck analysis, queue detection, traffic signal status and plans, model self-calibration and more. Solutions that PTV Optima provides can be (among several other implementation versions) based on road micro-dynamic or dynamic-macro traffic model in PTV Visum that is combined with real-time traffic data and provides decision-support based on those real-time predictions from those modellings. In the core of the SW, there is a model-based approach that provides the ability to make traffic estimations, forecast the traffic conditions, and apply scenario evaluation within DSS [11].

Since the PTV Optima is software built from modules that represent various functions, one of them is called PTV Optima Micro and is aimed at bringing real-time operational DSS advantages, that the PTV Optima has, together with planning modelling features simulated in PTV Vissim. The simulation model used in PTV Optima consists of a macroscopic approach that is used for the provision of operational decision support in real time. It checks all alternatives in the simulation environment for the next x minutes when an incident happens. The software is able to gather crucial data in the forms of offline (supply and demand) and online (flows, speeds, incident information - supply change) inputs to the traffic simulation. Those data are sent and used by PTV Vissim which represents a microscopic planning decision support tool that enables short-term planning prediction, as well as the model, which can be used as an offline tool for planning purposes. This microscopic model is useful for additional traffic understanding and examining of applied strategies or new strategies that are being developed for real-time traffic management so that the traffic operator can visualize them and potentially re-plan them if found as being not optimal. When those two key simulation approaches are combined, they represent a tool that combines those two outputs into a decision support system that the operator can base their decisions on or can be used for re-calibration of existing strategies. Optima consists of two parts - offline and online. That correlates to the above-mentioned approach of PTV Optima Micro where the offline section works with PTV Visum and the online part is responsible for PTV Optima.

More information can be found on the official websites `https://www.myptv.com/en`, or in one of their webinars on YouTube: [11], [13], [12].

4.2.3 SUMO

SUMO (Simulation of Urban MObility) is an open-source software for microscopic traffic simulation. Because of its open-source option, the tool is well-studied and described within the traffic engineering community, and used in various projects worldwide. The implementation is in C++ which has the advantage of the software is highly modifiable [135]. SUMO's main features are more like applications that are being used in the software for traffic simulation performance. Simulations are performed with time-discrete and space-continuous vehicle movements [139]. Simulated can be all sorts of multi-modal scenarios [139] with features like large-scale network microscopic simulation, DTA simulation, evaluation of surveillance systems, V2X communication, emission, and noise modelling, or traffic management strategies simulation, traffic lights, vehicle behaviour, and many others. The network is imported to the SW from external sources (like VISUM, Vissim, OpenStreetMap, or XML road network graph representation) because SUMO does not include network editor [90]. O-D matrix cannot be directly used in sumo, instead, the tool OD2TRIPS needs to be used to convert the O-D matrix into individual trips, or get the traffic demand from agent-based model [139]. Traffic flow modelling in SUMO can be defined by flow and turning ratios, flows, by origin-destination matrices, or manually as a sequence of particular routes/edges, which results in different principles (user equilibrium, stochastic UE or the fastest route for a given departure time) [139]. Microscopic simulation models presented in the SUMO SW are car-following (a modified version of the car-following model by Krauß) and lane-changing (the current version of the lane-change model is SL2015). For the DTA simulation currently implemented SUMO uses an algorithm by Gawron and a c-logit algorithm, both representing dynamic user assignment iterative method. SUMO can generate various outputs defined by the user and can have a form of information about each vehicle, the simulation states, network performance measures, placed detectors and so [135].

For the application areas, there is a list of use cases and projects that used SUMO simulation software on the official SUMO web pages `https://www.eclipse.org/sumo/`. Mentioned can be, for example, a use case of traffic management simulation software for traffic monitoring and real traffic simulation in a virtual Traffic Tower developed by DLR Institute in Germany [145]. Real measurements are used for traffic forecast and control measures are simulated as a reaction to the situation in different scenarios. Another project named iTETRIS integrates a simulation platform with wireless communication modelling and creates a simulation platform aimed at traffic management centres for cooperative ITS applications optimization [146]. Within this platform, cooperative ITS traffic management applications can be applied and simulated before their real implementation. More examples of use cases involving SUMO can be found in [147] or in [148].

4.2.4 AIMSUN

This software developed by the Department of Statistics and Operational Research is a solution for simulating real-world traffic conditions. AIMSUN Next (the current version of the simulation software's name) is a traffic simulation package that involves static traffic assignment at all three aggregation simulation levels, as well as a hybrid approach [132]. Besides static, as many other mesoscopic SW, AIMSUN's mesoscopic simulation is based on dynamic traffic assignment with both stochastic route choice and equilibrium-based route choice assignment [132]. It enables the modelling of all sorts of traffic flow models including car-following, lane-changing, or gap acceptance models. A graphical editor of the road network is available in AIMSUN providing tools for network definition and adjustment. Through an extension, the software is fully controllable throughout external user-defined API with other control interfaces, tools, or software [138]. Another add-on extension that can be used within AIMSUN is an incident modelling module and traffic management module able to model different strategy scenarios.

The simulation itself is very detailed providing a detailed look at the traffic flow, which can be modelled with different transport modes, and various demands. Different traffic controls can be modelled with fixed or adaptive and dynamic control [138]. Measured traffic simulation values can be of many different simulation measurements using different types of detectors in the network at all aggression levels [135].

AIMSUN can be applied to offline and online traffic engineering solutions as a planning simulation tool for long-term strategic planning and also for real-time traffic management as a decision support system [149]. As mentioned, the software can be used as decision support for traffic operators since it provides all the necessary modules. This version of the Aimsun product is called Aimsun Live (originally Aimsun Online) which is a traffic prediction tool for traffic management combining AI techniques and real-time simulation to help traffic operators make their decisions. The traffic management strategies can be evaluated in real-time to react in real-time to all conditions on the road network that can be of non-recurrent and recurrent character. The product is advertised with the following functions: incident management, traffic flow modelling on highways, emission modelling, complex DTA, real-time data versus historical data comparison, traffic management strategy and policies simulation, and many others [150]. The Aimsun Live concept is meant for traffic management centres as a solution to be implemented together with other ITS infrastructure and available detectors placed in the network to provide featured functions for the whole city. Traffic data from detectors can be collected, processed, filtered, and evaluated in the SW. Historical traffic data databases are also available within the solution to provide more detailed and accurate traffic state estimation and prediction.

Just like in the PTV Optima case, AIMSUN Live is a very modulable solution and the final product can vary based on the application area. There exist many different use cases where Aimsun live (or just Aimsun) was applied. Just to mention, for example, in the Grand Lyon Opticities pilot project the use of Aimsun Live was aimed at real-time traffic management prediction for traffic operators to react to the forming congestion [151]. When the traffic prediction is made, traffic operators then can test different strategic scenarios depending on the current situation, compare them and select the best possible one, which is the general idea behind the concept of DSS. In the city of Singapore, the application of Aimsun Live was used for real-time traffic management simulation and prediction of traffic conditions with a DSS potential implementation for the Land Transport Authority of Singapore [152]. The last example of a use case that showcases the traffic management solution with the Aimsun application is the project on M30 in the Madrid control centre. In this use case, Aimsun Live was used to produce short-term predictions of traffic congestion and provide results on the performance indicators of the future state. A set of possible actions could then be simulated and provided to traffic control centre operators to apply suggested measures or automatically put them into practice [153].

The possibilities of simulation and applicability of Aimsun solutions include the possibility of incorporating and exploring autonomous vehicles and cooperative systems within virtual environments with the possibility of evaluating the results to identify potential weaknesses or shortcomings in this area. For more details about the SW or other use cases visit the official website `https://www.aimsun.com/`, or see comparison studies conducted in [138], [131], or [132], or see a more in-depth description of the SW modelling and approaches in [90].

4.2.5 SimMobility

SimMobility is an event-based simulation software using an agent-based approach to integrate traffic model simulations. The simulation tool simulates land use, traffic interaction, and their communication. It can be used for testing and predicting various future mobility scenarios of applied strategies on the network with an assessment impact, evaluating ITS systems or emissions evaluation [154]. The agent-based technique here represents a very broad range of decisions made by all the components ("agents") in the simulation that all aim for their own set goal. This can affect the behaviour of a person, for example, to choose a mode of transport, what path to choose, or driving behaviour, and they are based on MATSim probabilistic model [154].

The simulation tool incorporates all three traffic modelling approaches from micro- to macroscopic models. The simulation approach in SimMobility is divided into three levels each representing different time horizon simulation resolutions, and correspond to the traffic conventional modelling approaches [155]. Short-term simulator (seconds) represents a microscopic approach and simulates drivers' decisions and travel behaviour (speed, acceleration, car-following, lane-changing) in a small time step [155]. The model is based on the microscopic traffic software MITSim with some modifications to the agent capabilities. The mid-term simulator (seconds to minutes) is categorized as a mesoscopic simulator and simulates what route to take, what is the destination, or what mode of transport to use [155]. Last, the long-term simulator represents a simulation of land development. Those three types of simulators share one database sharing all states and results within each other and co-existing simultaneously at all times.

For more information about the software see [156].

4.2.6 CUBE Dynasim

CUBE Dynasim is a microscopic traffic simulation software that enables examining multimodal transportation systems and ITS applications [157]. SW provides solutions for planning purposes helping traffic planners with analysing the effects of applied changes to the traffic network or travel demand, or changes to the traffic policies supporting decisions on planned use cases [158]. Another feature is called scenario management. The simulation is event-based producing stochastic and dynamic outputs [158]. The software enables working with imported data files from CAD or GIS and other analysis programs [158]. In addition, the presence of a data management module provides a tool for easy handling of data, their management in the database, and thus also their editing and visualization. Traffic parameters can be modified within the SW and calibrated. There is no option to modify reaction time, acceleration, or deceleration in CUBE Dynasim SW, which affects the simulation results to some extent.

Besides CUBE Dynasim, also other versions of the SW are available. Introducing, for example, the mesoscopic simulation model CUBE Avenue provides DTA methods for understanding the knowledge of the city traffic. It allows the modelling of queues and delays, which can be then further simulated with an application of operational strategies and assessed. Another SW version is called CUBE Boyager provides a macroscopic view of the transportation system with some traffic state prediction abilities. It also allows testing scenarios and evaluating them.

CUBE systems were used in the Western Cape province in South Africa Cape Town. The project aimed at developing a system for the estimation of paths selection, for goods movement, and developing a model for land-use modelling and interactions among road users [157]. More information regarding the use case and other software information can be seen on their official web pages `https://www.bentley.com/software/cube/`.

4.2.7 DYNASMART-P

Traffic simulation software with dynamic traffic assignment approach originally developed by the University of Maryland but currently managed by Federal Highway Administration (FHWA) through McTrans in 2007 [139]. Simulation software enables operational traffic planning. It combines two approaches - DTA models used for demand forecasting, and traffic simulation models used for traffic flow analysis [159]. Another feature uses scenarios to accurately simulate used paths in DTA and drivers' response to Advanced Traveller Information Systems (ATIS) [140]. The tool generates optimal paths throughout the network that can be advised to drivers to take which comes is tightly connected with state estimation and prediction of traffic flow [140]. The network is represented by links and vehicles that can be described by velocities, evaluated can be queues, travel times, or traffic management [160]. The optimum obtained from the simulation is used as the benchmark on which the route guidance is based for ATIS.

4.2.8 MATSIM

This open-source system uses modules with specific functions that can be integrated into the SW. Similarly, as it was with SUMO SW, the great advantage is that the source code of the software is freely available, which allows great modifiability and adaptability to the user's use case. Another advantage of this SW is in its fast-pace simulation calculation and fast vehicles' routing during the simulation, which has a drawback in a very simple representation of traffic network [140]. The simulation is agent-based so the route choice depends on each "agent's" departure time, mode of transport and its surrounding spatial information [161]. This solution provides tools for transportation planning or congestion analysis, as well as traffic flow, demand, and various mobility solutions simulation[160]. It can incorporate real-world data into a comparison of the simulation results [160]. However, its disadvantage is in basic traffic flow behaviour simulation [161]. All necessary information can be found on their website `https://www.matsim.org/`.

4.2.9 Paramics Discovery

Paramics Discovery (S-Paramics is the original version) product is a microsimulation 3D simulation software used for transport design, assessment, and analysis of detailed interactions among vehicles in the network [139]. It is claimed that the functions provided by this tool are brought by a variety of planning features enabling testing of new infrastructure, traffic signal control, traffic event planning, or public transport operation, all in a simulation environment. The SW includes a network editor for creating and editing road networks. Traffic data can be used as input to the model for calibration.

The core of Paramics simulation is in parallel microscopic road traffic simulation. It provides a tool to examine congestion and demand, as well as evaluation of actions taken in the forms of traffic control strategies, investigation of driver's behaviour and the effects of information systems on them [162]. The presence of the interface between Paramics software and ITS traffic control systems gives the overall overview of the whole city's network with simple or sophisticated traffic scenarios for traffic management and incident management [90].

The vehicles in the model move on links with respect to the road parameters. The route choice is based on the destination that vehicles need to achieve their goal most effectively while respecting the rules of the road and other vehicles in the simulation [90]. Demand is represented by OD matrices used for network loading. Traffic flow can be adjusted by controlling the departure time profile with the effect on demand, releasing vehicles in a time step interval [90].

Ultimately, it is a very complex simulation software, which allows a wide range of modifications of the whole simulation and its elements. From the traffic management perspective, it also includes necessary functions and tools used in traffic management centres with a possible extension to automated traffic management, which has been used in a real-world use case in London on M25 incorporating variable message signs. For an in-depth description of the traffic simulation and all the parameters, or other use cases, visit official websites `https://www.paramics.co.uk/en/`, or see [90].

4.2.10 Others

Here are presented SW that were not found important from the traffic management perspective or are not used for DSS.

AnyLogic provides a hybrid multi-agent simulation tool with its road traffic library that provides options to plan, design, and simulate traffic flow. The library consists of multiple traffic-engineering algorithms that are applied on vehicles each defined by behavioral models build with flowcharts. Simulation is capable of reproducing dynamic traffic modeling, lane merging, or driver behaviour. Use of the tool can be for planning purposes and optimization by simulation of bottlenecks and regarding congestion, traffic lights, and traffic flows, and visualize it all together with a statistical output [139]. Road traffic modelling was performed in [163]. More information can be found here [164].

OpenTrafficSim provides macro- and micro-simulation that works on an open-source licensing [165]. The simulation can represent multi-modal traffic and their movement and interactions between them. Their movements are based on movement description, which follows some tactical planner whose goal is to accomplish a given overall strategy. Those goals may be defined as destinations, departure times, and mode choices. The simulation logic uses a driver who has set a goal on a road stretch and tries to achieve it by its inner sensing the surrounding environment traffic conditions [166]. After obtaining that insight from other vehicles around, instantaneous state variables are used to make a decision on a short-path selection [166]. The traffic flow is simulated in terms of car-following and overtaking models. This approach can thus simulate drivers' behaviour and decision-making process which is quite useful in combination with a simulation engine called DSOL (Java-based event scheduling package) on which OTS is built [165].

TransCAD is a transportation planning software that works on a GIS basis developed by Caliper. Data can be displayed, analysed, and worked with thanks to the connection between GIS systems and traffic modelling. It enables multi-modal modelling with application tools like routing, estimation of travel demand and traffic, public transport, or territory management. Its main advantage lies in tools provided by GIS giving high precision of the traffic network and spatial analysis of the given traffic data. The usage of this SW is claimed to be advantageous as a decision support tool because of its multi-modal approach and data handling and visualization. More information also about use cases can be found on their websites `https://www.caliper.com/tcovu.htm`.

Synchro/SimTraffic (with the combination of SimTraffic application) is a microscopic 3D traffic simulation software with options to model aerial roads, signalized intersections, and roundabouts [167]. It serves traffic engineers for traffic analysis and also for optimization and simulation of various applications with a scenario management tool. Those applications are separate modules that add functionality to the simulation like traffic signal evaluation, trip generation calculations, or TransModeler application for traffic planning and modelling purposes [139]. The software can be used for the examination of traffic flow dynamics and assessing overall network performance. Travel demand forecasting is available through another module used within the SW enabling evaluation of traffic demand simulation [139].

Their official website could not be found, see other scientific articles instead, like [167] that worked on a comparison between SimTraffic and VISSIM. Or [168] dealing with traffic control through Synchro and SimTraffic.

UrbanSim is a software for planning purposes that provides tools for the evaluation of different traffic scenarios of urban areas and evaluate them. The software is designed to help the planning traffic authorities with future land-usage modifications analysis. The simulation models are based on transportation and macroeconomic inputs simulating interactions of traffic, land-use approaches, and environmental aspects[169]. UrbanSim is available with different packages each developed for different purposes like dynamic traffic assignment models, activity-based modelling, emissions, etc. [139]. It is possible to create scenarios with various transportation or policy measures which enable testing them in the simulation environment.

For in-depth information about the software see [170] with an aim on decision-support usage of this software. See also their official website `https://urbansim.com/home`.

CityTrafficSimulator is a microscopic traffic simulation SW for small area networks. It uses an "intelligent driver model", which is a car-following model [139] based on the scheme presented in `traffic-simulation.de`. The software is capable of simulating a number of traffic scenarios on the defined network. Traffic flow modelling including car-following and line-changing models are presented. For more information see `https://www.cszb.net/index.php/menu-citytrafficsimulator`.

Dracula is a dynamic traffic micro-simulation model which aims at the in-depth study of the interaction between supply and demand [90]. The simulation approach is in running the simulation with an evolutionary state from day to day where each day is simulated in detail with all the traffic flow simulation concepts and when the simulation is ended the next day is modelled but with the knowledge from the previous day. In the end, after many iterations of between-day evolution, the demand and supply interaction is derived and can be examined. The simulation process is thus a learning process where at the end of a day the experiences of each entity are stored and have some impact on the next day's choices [90]. It allows setting options of many different aspects of simulation such as route choice and also its assessment [139]. The architecture concept of Dracula SW is made of different modules representing different aspects of the simulation software and describes the dynamic evolution approach for the evaluation of demand and supply evolution. Those modules include, for example, DTA for route assignment and departure time based on their previous experiences, demand module representing varying day demand, or data collection module having the task of collecting the measured data [90]. More information about the models and use cases can be found in [90] and [171], SW's official website could not be found.

Emme is developed by INRO company, the same company as Dynameq. Emme is presented as a multi-modal transport planning tool enabling forecasting of traffic for planning purposes (see official website `https://www.inrosoftware.com/en/products/emme/`). The software is working with multi-modal static equilibrium incorporating all modes of transport to further replicate the real scenario. The tool is mostly used for assessing the impact of transit services and finding more optimal routes for transit services [172]. Simulation software includes a graphical interface with network adjustment tools. All the input values, calculations, and model parameters need to be input manually by functions representing algebraic expressions [172]. Travel demand is assigned based on frameworks of various methodologies [172]. Simulation with Emme provides a static equilibrium assignment and thus has the goal of finding a network equilibrium state and the output can thus be used to determine network performance or can be used for other planning purposes (HOV lanes, new roads suggestions, etc.) [172].

4.3 Dynameq - version 4.4.0

Dynameq ("DYNAMic EQuilibrium") is a mesoscopic and microscopic traffic simulation software produced by INRO Consultants, Inc. It is a simulation-based software providing traffic flow modelling and dynamic traffic assignment simulation model. The simulation structure of the DTA model is based on dynamic user equilibrium assignment. Simulation is event-based meaning that the traffic simulation solution is not time-step-wise, which makes the simulation faster [173]. The model of the simulation is made of a traffic flow simulation (how vehicles interact with each other on the network) and a routing model (representing route choice model) both representing driver behaviour modelling aspects [90]. The simulation involves behavioral interactions among vehicles with models like car-fallowing, gap-acceptance, or lane-changing. The lane-changing process is done before the vehicle enters the following link which allows the modelling of each lane's flow and thus replicates traffic paradigms like queues or congestion [133]. The behaviour on the link is set on the free-flow speed of individual links and also interaction with other vehicles [140]. Interaction between vehicles on the traffic network, where a vehicle has to change its original speed to the speed of the preceding vehicle, causes a time loss for that vehicle, i.e. a delay, which Dynameq can model accurately because of that precise lane flow modelling. The microscopic approach in Dynameq is used for the path choice of each driver that is pre-determined before the flow assignment (before the vehicle's departure) and is not changed en route to the destination within an iteration, which is relevant for short- and long-term operational planning traffic state prediction [90].

The simulation run is in iterative steps until user equilibrium is met or any other suitable solution is achieved. This is a representation of the real-world scenario where drivers learn from everyday traffic and use that knowledge again every time they make their next trips. When there was a path that, for example, took more time to complete, the next day is the driver trying to find another better path that will be more convenient for them in any expanses costs. In other words, each iteration represents one day that drivers are assigned to the network, experience different traffic conditions, and use their learning process from their previous experiences to try to find a better path to their destination [173]. Iteration is then one cycle. For the first run, the vehicles take the shortest path [133]. When all the paths are said to be the best option for all drivers, it means that the simulation model found an equilibrium and has converged. The results are collected from each iteration including all the movements, links, and lanes. The principle of Dynameq simulation can be seen in figure 4.1. Moreover, the resulting equilibrium state can be re-used as a starting point for the next scenario using an option called ”warm start”. This way, incident scenarios or changes to the network can be tested on the current working city model and compared to the effect of those on the converged model.

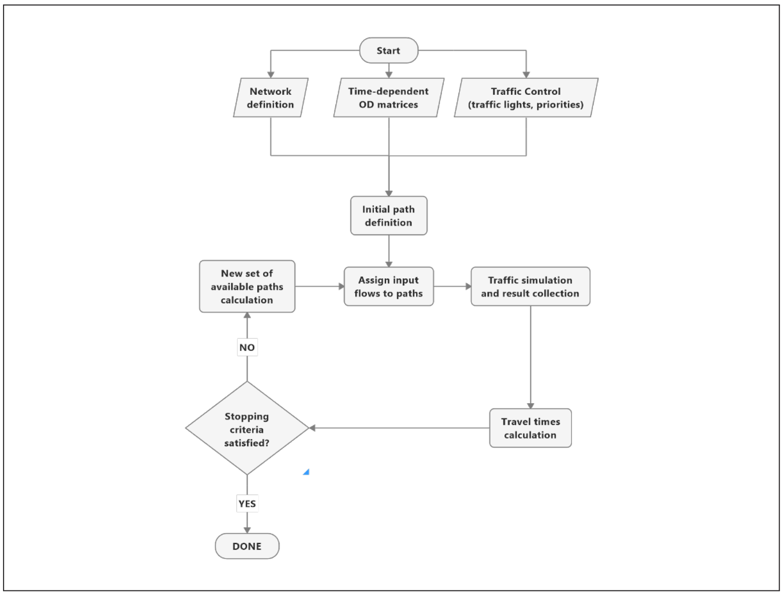
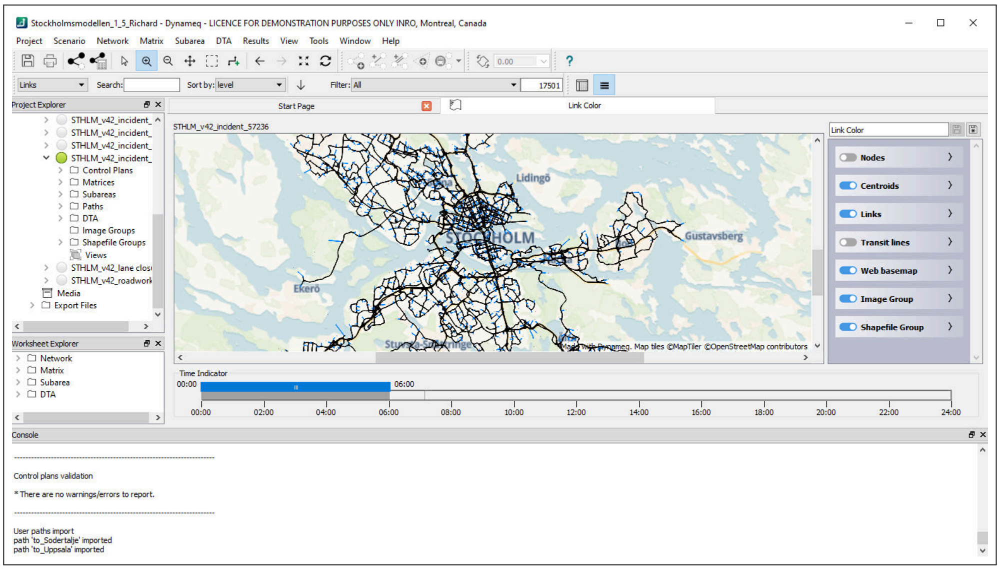


Figure 4.1: Dynameq principle
Inspired by [90]

The graphical user interface can be seen in figure 4.2. It consists of the network model with the road model representation, general toolbar menu, Project Explorer with all projects, Worksheet Explorer with the simulation results and map features for visualization, analysis, and data record, and the Console [173].



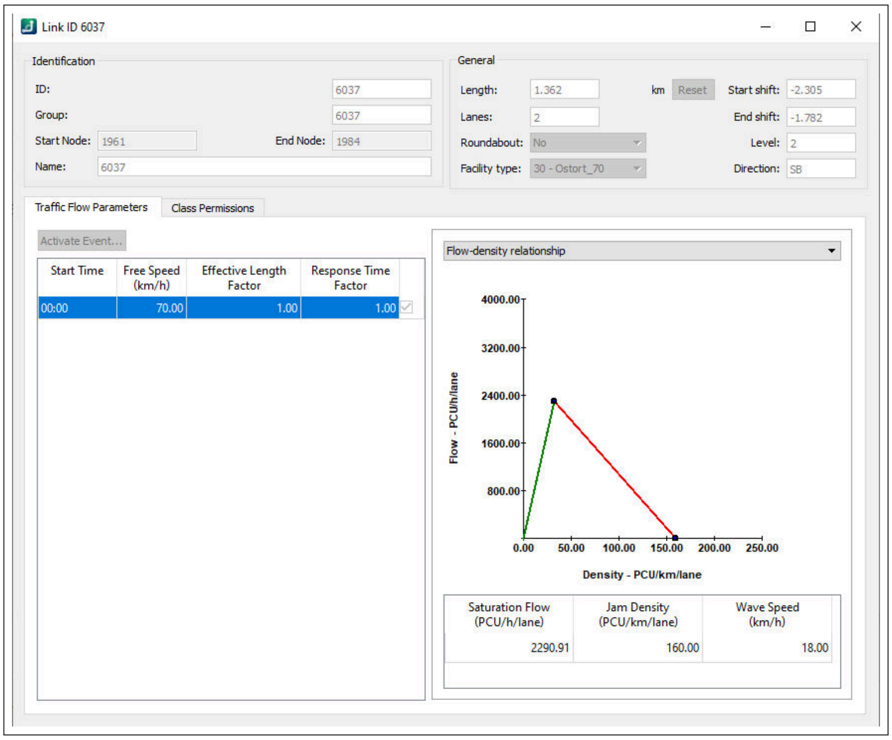
```
------------------------------------------------------------------------

Control plans validation

* There are no warnings/errors to report.

------------------------------------------------------------------------

User paths import
path 'to_Sodertalje' imported
path 'to_Uppsala' imported
```

Figure 4.2: Dynameq graphical-user interface

The project settings allow users to control all the general settings and default parameters for the project. Parameters for the network editor can be adjusted, signal control parameters set, or default values for DTA defined.

Input data into the simulation is defined as the network and its definitions, signal traffic control plans, an O-D matrix, and also defined generalized cost function (an expression of the added sum of a link and movement costs - like tolls, distance or time) [173]. Output data can be represented in many different ways, but the main outputs are represented by vehicle trajectories, simulation results, transit line results, path-based results and matrix results [173]. The simulation results are divided according to the different aspects of the modelled elements - network results, link results, movement results, node results, centroid results, and lane results, which means that they can be collected for each of these elements and evaluated. Depending on the type of results such as matrix results of travel time, delay, or vehicle trajectories, they can be visualized, statistically analysed, and animated within the interval specified by users. Users can also specify their own attributes after their definition.

A network in Dynameq is defined as individual lanes. A network editor is included in the software as well as a tool for network import from another simulation SW. Specified can be a turning shape of the link, the level on which the link is situated, what facility type the link represents, free-speed, and other parameters. Links are described by a fundamental diagram modifiable with free-speed parameter, number of effective length and response time (see figure 4.3). Each link can also be characterized by the number of lanes that are available for cars and how many are restricted, which is expandable to the vehicle classes as well. Different vehicle classes are used to represent the traffic flow in the model. Lane width cannot be modelled.



ID: 6037
Group: 6037
Start Node: 1961
End Node: 1984
Name: 6037

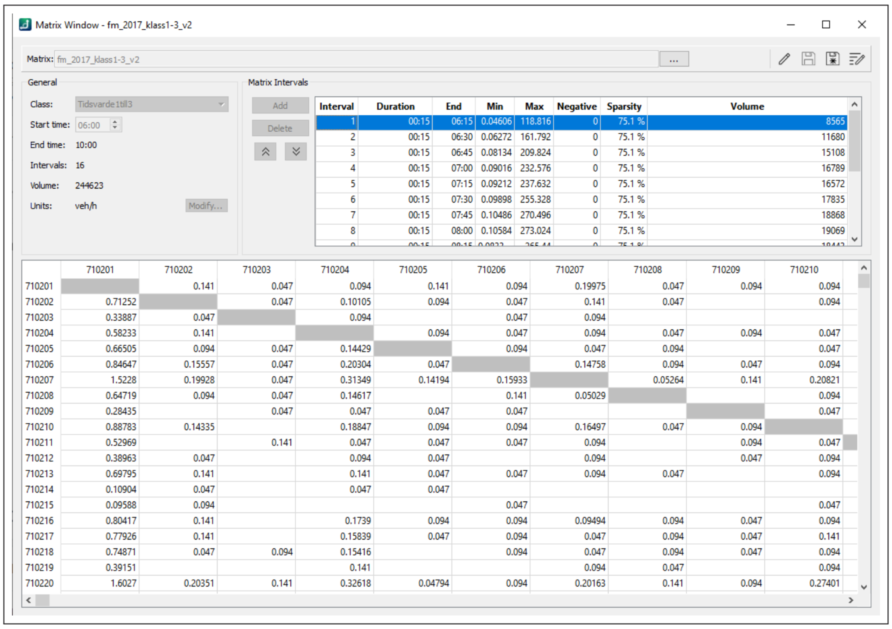
Length: 1.362 km
Lanes: 2
Roundabout: No
Facility type: 30 - Ostort_70
Start shift: -2.305
End shift: -1.782
Level: 2
Direction: SB

Start Time	Free Speed (km/h)	Effective Length Factor	Response Time Factor
00:00	70.00	1.00	1.00 ☑

Saturation Flow (PCU/h/lane)	Jam Density (PCU/km/lane)	Wave Speed (km/h)
2290.91	160.00	18.00

Figure 4.3: Link parameters

Traffic demand is represented by an origin-destination matrix (see figure 4.4). Vehicle classes can be specified by various vehicle types defined by their physical parameters and also driver's behaviour such as response time, speed limit acceptance and by the highest achievable speed [173].



Matrix: fm_2017_klass1-3_v2

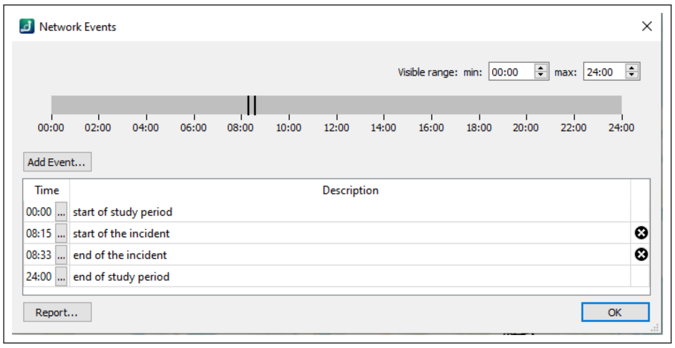
Class: Tidsvarde1till3
Start time: 06:00
End time: 10:00
Intervals: 16
Volume: 244623
Units: veh/h

Interval	Duration	End	Min	Max	Negative	Sparsity	Volume
1	00:15	06:15	0.04606	118.816	0	75.1 %	8565
2	00:15	06:30	0.06272	161.792	0	75.1 %	11680
3	00:15	06:45	0.08134	209.824	0	75.1 %	15108
4	00:15	07:00	0.09016	232.576	0	75.1 %	16789
5	00:15	07:15	0.09212	237.632	0	75.1 %	16572
6	00:15	07:30	0.09898	255.328	0	75.1 %	17835
7	00:15	07:45	0.10486	270.496	0	75.1 %	18868
8	00:15	08:00	0.10584	273.024	0	75.1 %	19069

	710201	710202	710203	710204	710205	710206	710207	710208	710209	710210
710201		0.141	0.047	0.094	0.141	0.094	0.19975	0.047	0.094	0.094
710202	0.71252		0.047	0.10105	0.094	0.047	0.141	0.047		0.094
710203	0.33887	0.047		0.094		0.047	0.094			
710204	0.58233	0.141			0.094	0.047	0.094	0.047	0.094	0.047
710205	0.66505	0.094	0.047	0.14429		0.094	0.047	0.094		0.047
710206	0.84647	0.15557	0.047	0.20304	0.047		0.14758	0.094	0.047	0.094
710207	1.5228	0.19928	0.047	0.31349	0.14194	0.15933		0.05264	0.141	0.20821
710208	0.64719	0.094	0.047	0.14617		0.141	0.05029			0.094
710209	0.28435		0.047	0.047	0.047	0.047				0.047
710210	0.88783	0.14335		0.18847	0.094	0.094	0.16497	0.047	0.094	
710211	0.52969		0.141	0.047	0.047	0.047	0.094		0.094	0.047
710212	0.38963	0.047		0.094	0.047		0.094		0.047	0.094
710213	0.69795	0.141		0.141	0.047	0.047	0.094	0.047		0.094
710214	0.10904	0.047		0.047	0.047					
710215	0.09588	0.094				0.047				0.047
710216	0.80417	0.141		0.1739	0.094	0.094	0.09494	0.094	0.047	0.094
710217	0.77926	0.141		0.15839	0.047	0.094	0.047	0.094	0.047	0.141
710218	0.74871	0.047	0.094	0.15416		0.094	0.047	0.094	0.047	0.094
710219	0.39151			0.141			0.094	0.047		0.094
710220	1.6027	0.20351	0.141	0.32618	0.04794	0.094	0.20163	0.141	0.094	0.27401

Figure 4.4: O-D matrix

Dynameq allows the creation of different scenarios where each scenario contains always one transport network and defined input parameters for the given scenario (see figure 4.5). Within those scenarios, events can be created that represent a change in the network's parameters. This feature is quite essential when it comes to real-world incident simulation when traffic supply can be changed at a particular moment. The traffic control centre can then test those scenarios and prepare better in advance. It is also suitable for traffic congestion and the occurrences of bottlenecks, or for congestion spillback investigation. Traffic management strategies aiming at traffic lane management can be easily simulated with scenarios defined by time events at specific time points closing lanes, prohibiting vehicles on selected links, etc.



Visible range: min: 00:00 max: 24:00

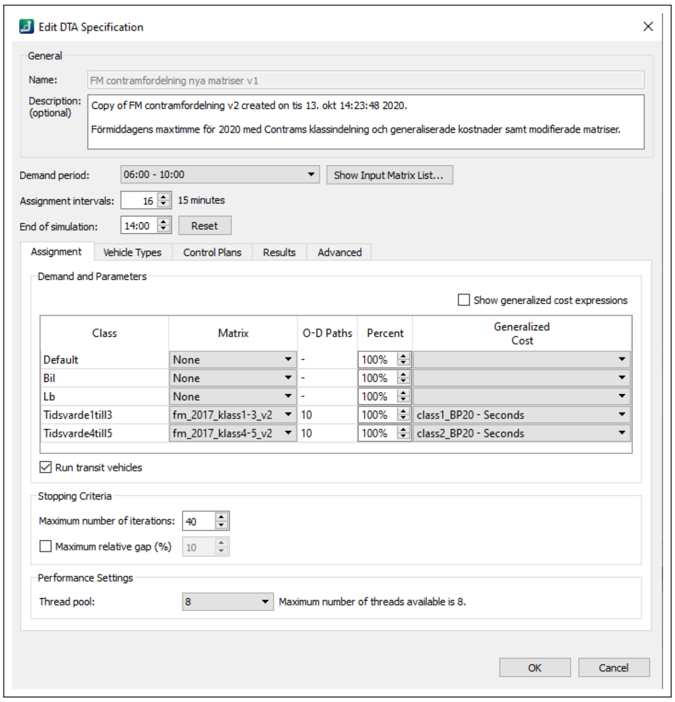
Time	Description
00:00	start of study period
08:15	start of the incident
08:33	end of the incident
24:00	end of study period

Figure 4.5: Network event definition window

In figure 4.6 is shown a DTA specification window example. DTA is described by the input demand, assignment intervals, and the length of the simulation. The assignment interval represents time periods with the given set of paths that remain constant and on which the demand volumes from the O-D matrix are assigned [173]. The maximum number of iterations can be chosen or equivalently a limit to the maximum percentage relative gap[2]. Dynameq allows you to run more DTA simultaneously and get results from multiple DTAs at once.

---

[2] Relative gap tells how much converged DTA is, thus how close can reach equilibrium



Name: FM contramfordelning nya matriser v1

Description: (optional) Copy of FM contramfordelning v2 created on tis 13. okt 14:23:48 2020.

Förmiddagens maxtimme för 2020 med Contrams klassindelning och generaliserade kostnader samt modifierade matriser.

Demand period: 06:00 - 10:00

Assignment intervals: 16 15 minutes

End of simulation: 14:00

Demand and Parameters

☐ Show generalized cost expressions

Class	Matrix	O-D Paths	Percent	Generalized Cost
Default	None	-	100%	
Bil	None	-	100%	
Lb	None	-	100%	
Tidsvarde1till3	fm_2017_klass1-3_v2	10	100%	class1_BP20 - Seconds
Tidsvarde4till5	fm_2017_klass4-5_v2	10	100%	class2_BP20 - Seconds

☑ Run transit vehicles

Stopping Criteria

Maximum number of iterations: 40

☐ Maximum relative gap (%) 10

Performance Settings

Thread pool: 8 Maximum number of threads available is 8.

Figure 4.6: DTA specification window

Use case scenario available on Dynameq website can be mentioned `https://info.inrosoftware.com/dynameq-case-study`. The domain of implementation of the Dynameq software was traffic simulation and the DTA model for transportation planning from the perspective of a multi-modal system in the city of Edmonton, Canada. Dynameq helps the city with operational prediction. Dynameq software application can be found in [174]. Dynameq software sensitivity analysis from 2011 was done in [175]. For a more detailed look and description of modelling approaches visit the official web page `https://www.inrosoftware.com/en/products/dynameq/` and user manual (accessible only with licence number) [173], or see [90] and [176].

5 Simulation Case Study

The Swedish Transport Administration (Trafikverket) provided a **Stockholm model** which is a DTA type of model built and calibrated in Dynameq software by an internal team from Trafikverket, but only for planning purposes. The main question was whether the model is reusable also for traffic management purposes. Previous chapters dealt theoretically with the question of decision support systems and traffic management in general. In this chapter, a simulation case study is chosen to determine whether the decision support system in a form of Dynameq software is suitable for traffic management or not. For all study cases, this model is used to understand what can be done with it using Dynameq and what is needed for traffic management support.

A method of scenario-evaluation is applied which is a method comparing two states - before the incident and after when a lane is closed and capacity is reduced. First, in order to understand the provided model in Dynameq and its usability for DSS, the Stockholm model is described. Second, the data used for the simulation is described. Afterward, the model is described in terms of calibration and simulation parameters. Next, in form of scenarios that represent specific real traffic incident that had occurred in Stockholm with available incident data is simulated in Dynameq. The ability of Dynameq to simulate the incident and provide relevant results is assessed.

This part has the major goal of answering research question 4 which is aiming at evaluating the current version of the planning model of Stockholm and its usage for traffic management purposes based on simulation scenarios evaluation with decision support system functionalities that Dynameq can offer.

5.1 Stockholm Model Description

The Stockholm model is a virtual representation of the Stockholm network of the major roads and adequate O-D matrices with the traffic demand (see figure 5.1). No detailed information was provided by Trafikverket thus all the description is based on the available analysis of the model.

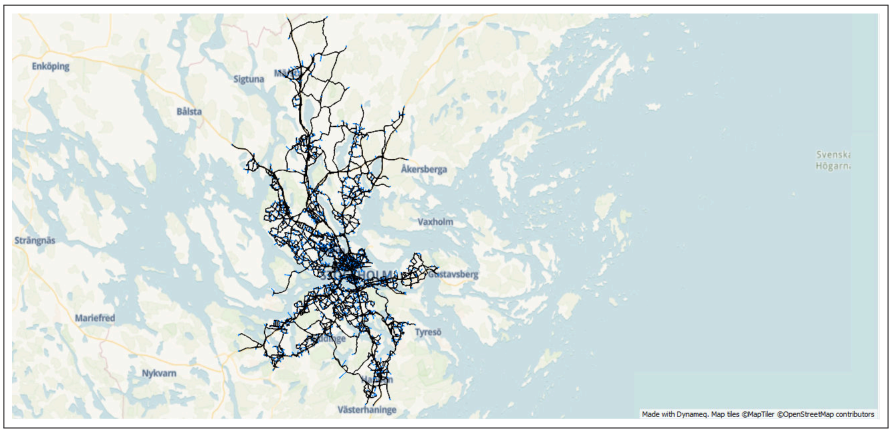


Figure 5.1: Road network in Dynameq

As seen in the detailed picture in 5.2, the model consists of the Stockholm network built with links and link nodes. Links can be divided into regular links used by vehicles to move around and then entering and exiting connectors connecting centroids and regular links. Centroids with O-D values are situated in the model and modelled as red points (see figure 5.3). The O-D matrix represents a demand of a typical day. Both signalized and unsignalized intersections are presented and priorities are defined. The majority of intersections in the model are without any determined priority, followed by roundabouts and signal-based rules.

Figure 5.2: Detailed look at the network

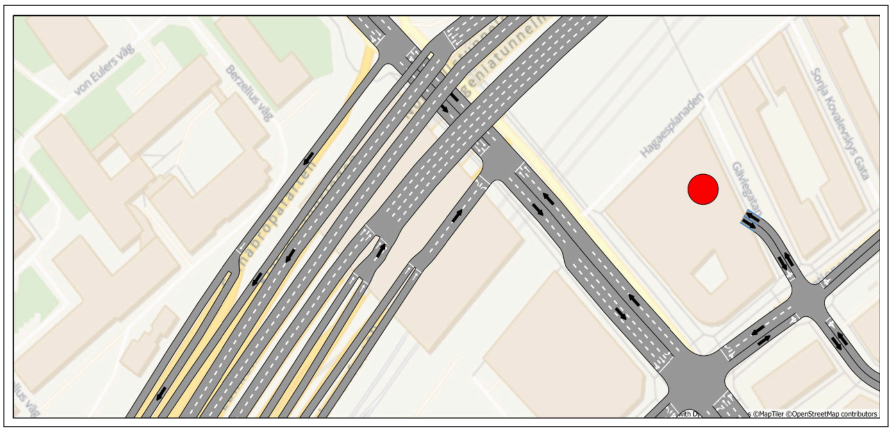


Figure 5.3: Centroids containing O-D values (red dot)

All links fall under different facility types with the majority of them being within the 50km/h speed limit and 30km/h. The motorway ring around Stockholm is mostly represented by 4 lane segments with a free flow speed set to 70 km/h. Aerial highway connectors in the direction to Uppsala or to Södertälje have a free flow speed set to 80 km/h. Driving is on the right side.

A passenger car is defined with an effective length of 6.25 m, maximum speed is set to 200 km/h. Response time is set to 1.25 seconds and represents the duration of how long it takes for a driver to react and change the vehicle's speed, trajectory, etc. For the other vehicle considered in the model which is a transit vehicle has its effective length set to 12.5 m with the same speed as for the passenger vehicle. The reaction time is set to 1.5 seconds.

Visual comparison was made consisting of comparing the Stockholm model with other map providers. Dynameq model uses the OpenStreetMap map base. Links modelling is not as detailed as in Google maps, for example. The model replicates the main roads and transit lanes in Stockholm like freeways or arterial but does not show all the local or collector and distributor roads. From the comparison of the Dynameq model network with Mapy.cz and Google Maps network, it can be stated that the main roads and motorway are relatively similar to the real-world situation, again without showing all the local roads.

5.2 Data

Linköping university have provided access to their database with traffic data for the Stockholm area (LiU database). Traffic data were of two types, probe FCD data measured using probe devices and MCS data measured with static detectors on the infrastructure in Stockholm. The LiU database contains GPS probe data, road network data, incident data and radar data that is used in the thesis. The GPS probe data was measured during Autumn 2019 in September and October, and is provided by INRIX, see [177] for more detailed information. Radar data from the Motorway Control System (MCS) is provided by the traffic management center in Stockholm. About 1485 placed detectors are located around Stockholm city (see figure 5.4). The static detector data (MCS data) were used to determine what the link flow and speed are upstream of the incident to check upstream demand. The probe data was used for incident analysis purposes (speed, queue length, incident analysis), if Dynameq can model the effect of the incident. The question was then whether the usage of probe data can provide all the necessary information for the comparison of incident simulation results with probe data. The initial answer was believed to be positive because of the nature of the INRIX data used for this work, but the hypothesis had to be still tested. Incident data is provided by the traffic management center in Stockholm. Incident data contained incident descriptions like the date and time of an incident, duration of an incident, strategy applied to that particular incident, notes further describing an incident, or their location. These data are used to visualize incidents on the map and to define use cases on them. Road network data is from Openstreetmap (available from www.openstreetmap.org).

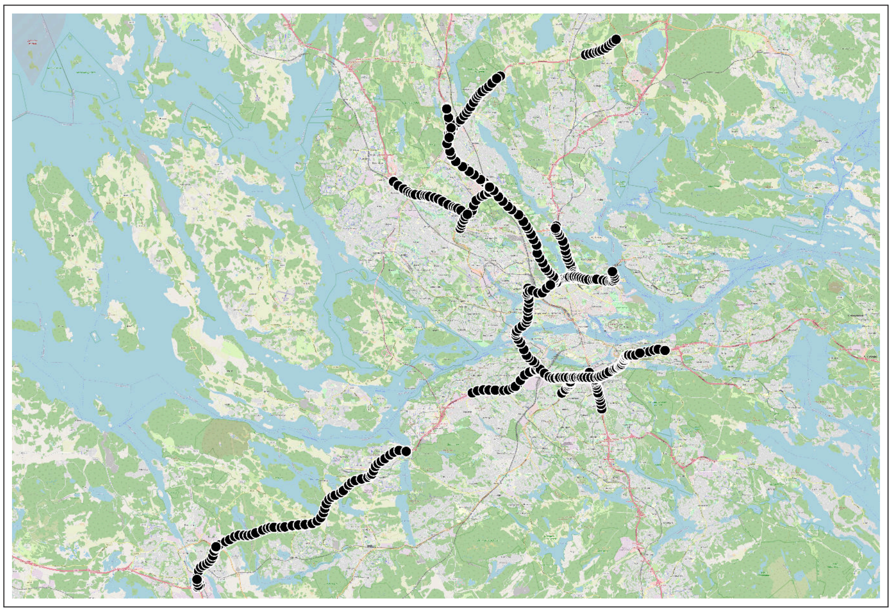


Figure 5.4: Map with detector locations

5.3 Use Cases Selection

Traffic events such as car accidents, roadworks, or events such as road closures have a significant effect on traffic creating problems with capacity reduction, and queues, and may lead to an overall breakdown in the event area. Different types of events can occur on the infrastructure having different severity. The main classification of the incidents can be described as planned and unplanned events. Both have an impact on surface traffic, but the difference is in their unpredictability.

Planned events are usually connected with areas where multi-use venues are typically located and come at an exact scheduled time, duration of an event, and location [178]. The demand is highly affected before, during, and after the event, or the capacity can be reduced due to closed lanes or event facilities. This work does not focus on these events and instead works with unplanned events. Unplanned events are situations that occur after accidents and non-predictable cases. These incidents are unforeseen, not reoccurring situations that create bottlenecks. Traffic flow is affected in that area where capacity, and supply, respectively, are usually smaller which subsequently leads to a queue spill-back and eventually results in congestion.

In addition, a use case where reoccurring congestion happens is not part of traffic incident management because even though the queue is formed at a location where nothing, in particular, is happening (no accident, bottleneck, etc.), the problem can be solved by better traffic planning (by structural modification, change of right of way, etc.). For that reason, this type of incident is not simulated.

In both cases (planned and unplanned) there is a significant effect on the road network. In [179], the authors described what traffic engineering parameters are tightly connected to the investigation of traffic incidents describing their characteristics:

- Road capacity - is effected by the incident that changes the original number of lanes thus reducing the number of vehicles that can use the incident segment;
- Speed - in a form of free flow speed representing an average of a non-congested condition with vehicles flowing in a free-flow speed that is affected by an incident usually due to the driver's caution;

- Critical density - is an important parameter that describes how likely, with the current amount of vehicles per kilometer, the queue spills-back from the incident segment upstream
- shock wave speed describes speed of the congestion travelling upstream or downstream (in incident scenario usually upstream/backwards).

The selection of use cases for the simulation in Dynameq followed several steps. Each use case was selected to represent the most common typical **unplanned incident** that occurs the most often on the Stockholm network. First, incident data was loaded into QGIS from the database and visualized. Before incidents were further filtered, a heat map was created containing all the available incidents data from the database (see figure 5.5).

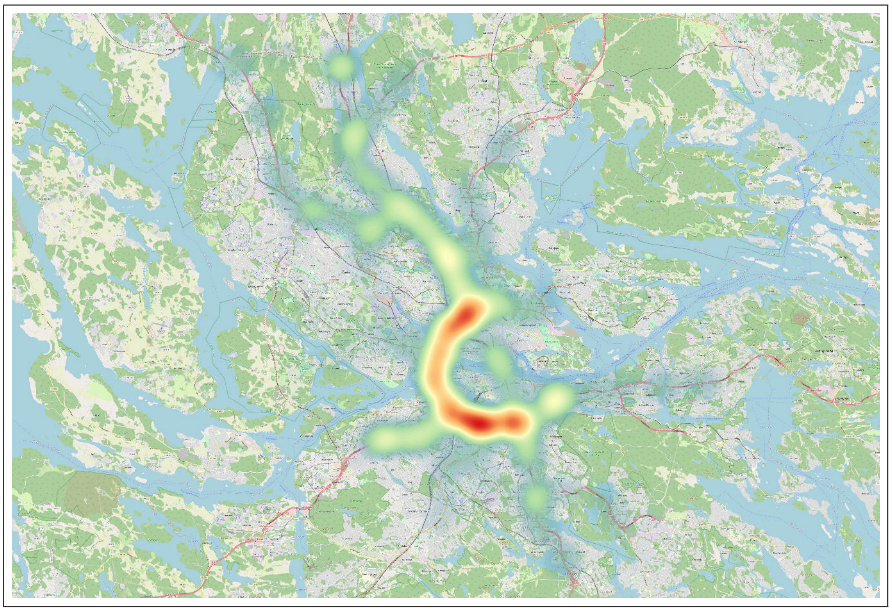


Figure 5.5: Incident heat map

As can be seen from the picture, most of the incidents happened on the main motorway ring around Stockholm. For that reason, the use case selection was based on these roads. More specifically, after closer examination of the incident data, it was decided to work only with the west stretch of the E4 motorway in both directions from Södertälje to Uppsala (and vice versa), as can be seen in the figure 5.6. It is therefore only the route that runs north/south along E4 **without** the influence of inflow from on-ramps and the influence of out-flow on off-ramps.

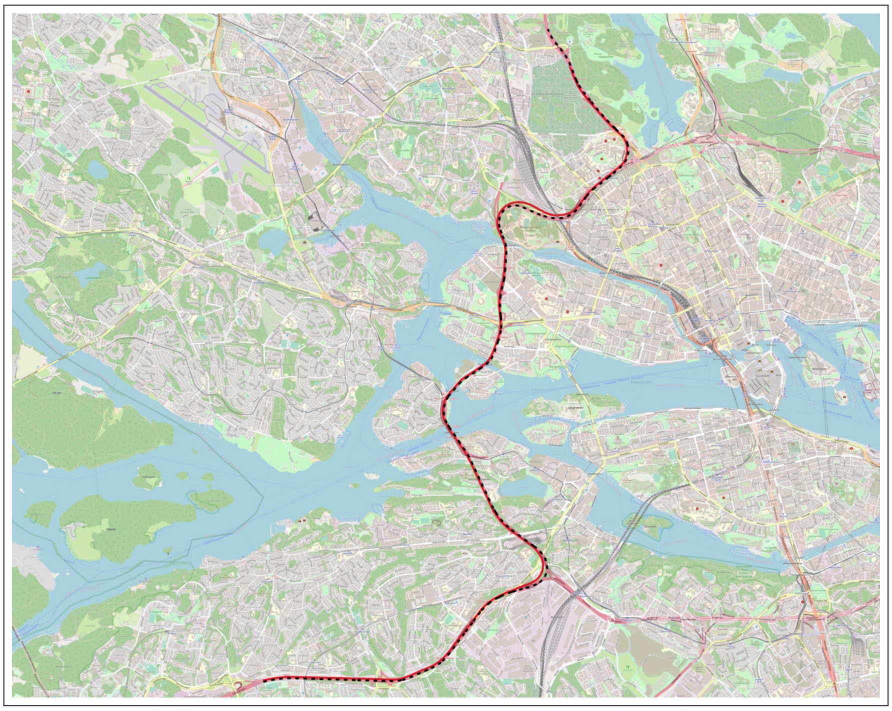


Figure 5.6: Two roads considered for this work
Red full line represents used segments in the direction from Södertälje to Uppsala, black dashed line represents used segments in the direction from Uppsala to Södertälje

A list of most occurred incidents was created. The top three incidents were identified as standing vehicle followed by accident and object on the road.

No.	incident	count
1	stationary vehicle	25,329
2	accident	5,512
3	object on the road	5,096
4	slow queue	744
5	closed tunnel	653
6	towing	637
7	animals on the road	455
8	traffic signals malfunction	278
9	major event	264
10	people on the road	230

Table 5.1: Most common incidents in Stockholm

The top three types of incidents were selected for further incident filtration since they happen most often and so it is important to test whether the software is able to detect and recreate them. That is also important from the traffic management point of view as those incidents have to be dealt with most often. Simulation of these three types of incidents in the Dynameq software cannot be directly represented since Dynameq does not enable simulation of an accident or a standing vehicle. Therefore, the use case incidents were simulated using an indirect method by changing traffic parameters at the time of an incident: changing capacity by closing a lane. The fundamental diagram of the incident link was maintained.

Therefore, the initial demand and supply also needed to be known as important inputs for the simulation [179]. In the case of supply, the initial available values from the model were used, as it reflects the reality, which is the maximum capacity of a route/segment. As for the demand, which can be understood as all the expected or planned trips that people want to do, the one from the calibrated model was used. The demand in the model is set for a typical weekday with no specific day.

On all incidents, a query was then applied to filter out incidents according to the following specifications:

- Incident in the period starting 16.9.2019 till 21.10.2019 for which the measured data was available in the database;
- Incident that happened during the morning peak from 6AM to 8AM;
- Only incident that happened during workdays (no weekend days);
- Incident that lasted for more than 15 minutes;
- Incident that was one of the three most common types of accidents;
- Incident situated on the main city's motorway network around Stockholm and its main connections and/or transit lines - E4, 75, E20.

Although the model also contained an afternoon demand (O-D matrix), morning O-D was selected as the best option for simulation, as the model was better calibrated for that time period. To evaluate the model, no weekend day was selected since the traffic is usually calmer in comparison with weekdays. The location of incidents had to be selected on the main roads because of the availability of the traffic data only on those links. Additionally, these roads are essential from the traffic management center point of view. The minimum duration of the incident was set to represent more serious incidents that lasted longer. The resulting data output from the database showed about 78 incidents (see figure 5.7).

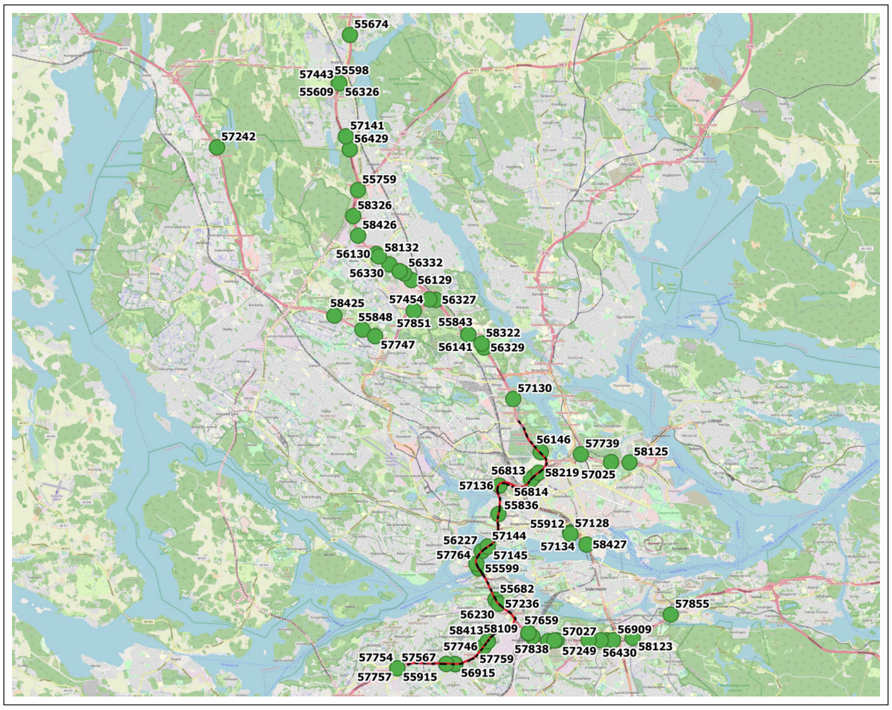


Figure 5.7: Incidents after simple filtering

Next, all the incidents were examined one by one, and determined whether the incident could represent a use case scenario that is interesting to simulate. This selection was based on factors like incident location, additional notes from the incident database and the amount of available data. Because the filtering could not be specified for cases where the incident happened in a tunnel, each incident was evaluated manually in that sense and if it was found being in a tunnel, the incident was excluded. The reasoning behind removing those incidents is that special conditions apply to traffic while travelling in tunnels, so it was decided to not use them within this work.

At the end, 5 incidents were chosen for further examination as potential use case incidents (see figure 5.8).

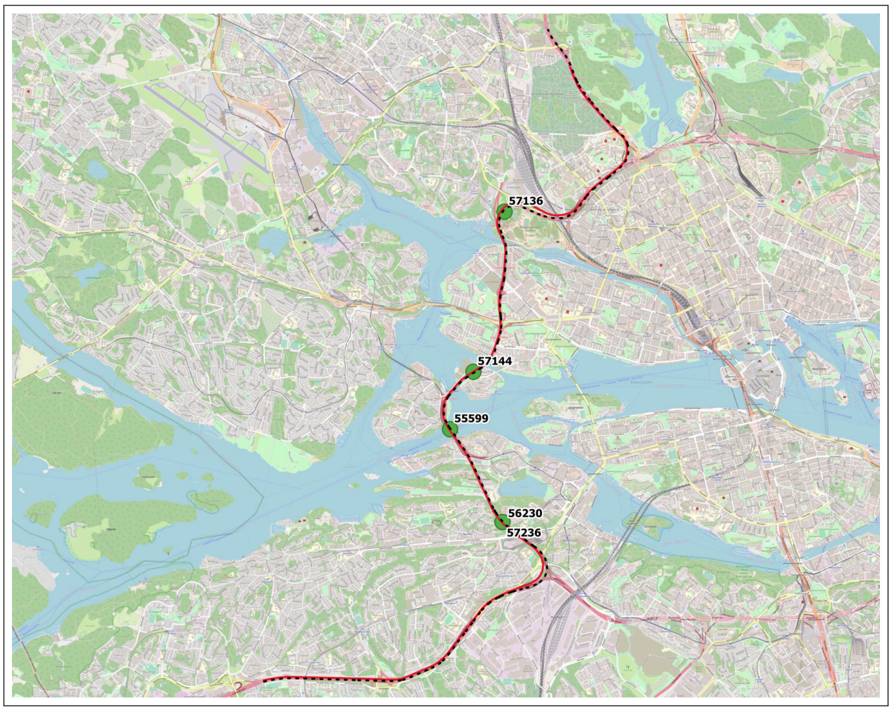


Figure 5.8: Selected 5 incidents for further examination

One hour of traffic data before and after the accident plus the duration of the incident was visualized for each of the 5 incidents. INRIX probe data were filtered for that specific incident day and time was selected from 6:00-10:45 AM to correspond to Dynameq's model demand assignment period with an extra 45 minutes to capture some time after the end of demand assignment as well. Probe data was visualized on a map basis with a 1 km radius around all incidents (see figure 5.9). The visualization was supplemented with speed coloring. The individual points represent the probe data and the measured speed at a given moment. Probe data was then counted to determine which incident has the most available data. An example with 2 incidents and filtered probe for this incident can be seen in figure 5.10 and 5.11. The count of probe data can be seen in the table 5.2.

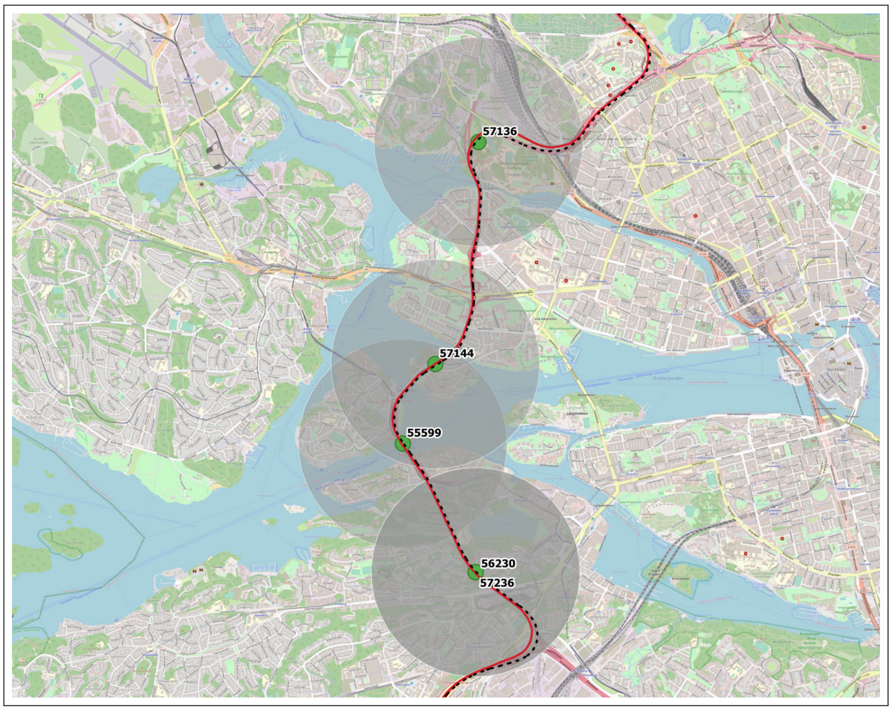


Figure 5.9: 1km radius around each incident

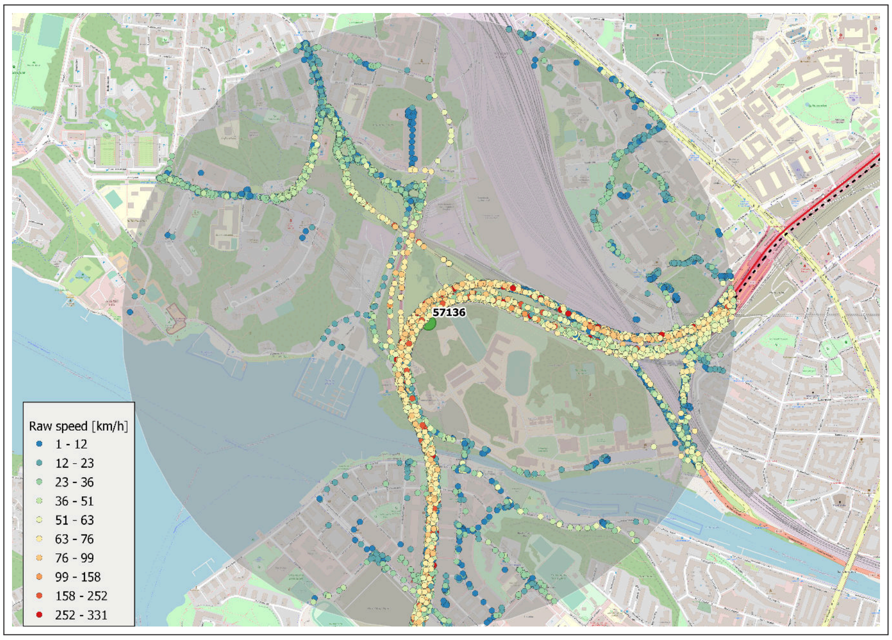


Figure 5.10: Speed coloring of probe data for incident 57136

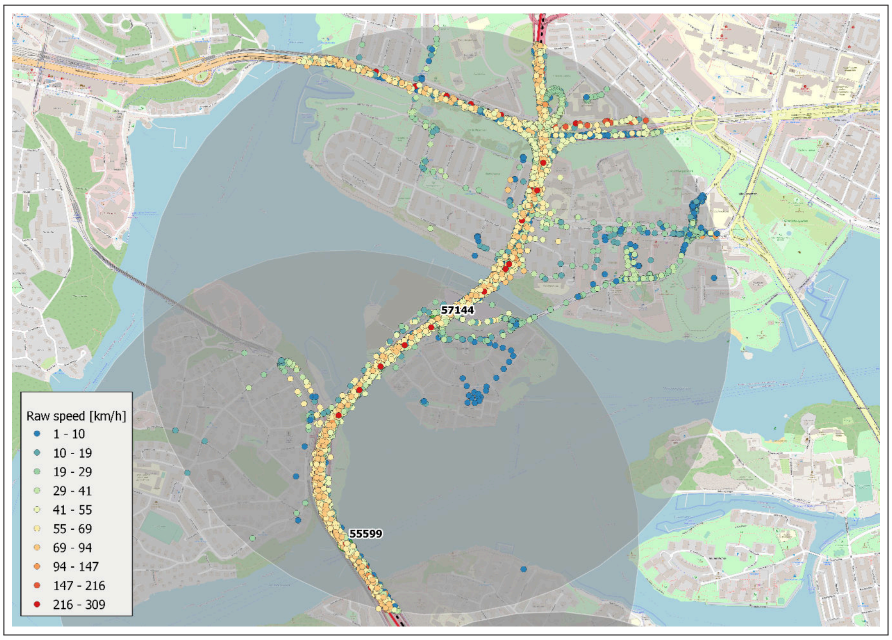


Figure 5.11: Speed coloring of probe data for incident 57144

Incident No.	probe data count
56230	8,538
57136	8,369
57144	7,045
57236	6,015
55599	4,244

Table 5.2: Probe count for final 5 incidents

In the following step, the selected incidents were deeper characterized and analysed. A description of each incident with a short characterization is presented. Considered incidents were also represented by the space-time diagram constructed with INRIX probe data. **The space-time diagram was chosen** for the evaluation because it can be used to observe the variables (queue length, speed over space and time) that are used in this work to assess the state before and after the incident. For each use case, the start and end of the incident is marked in the space-time diagram, along with the location of the incident on the considered stretch. The INRIX probe data was selected for the space-time diagram after their aggregation into 15-minute intervals.

Incident 56230

Incident 56230 is an incident representing a stationary vehicle on the road. A passenger car was stationary at E4 between Nybohov E4N km 52,535 and Nybohov E4N km 52,745 towards Uppsala (see figure 5.12). The location of the incident was recorded by detectors placed upstream of a 4-lane segment 16885360_0, right before the on-ramp (see figure 5.13), with a free flow speed at 70 km/h. The incident happened on 24.9.2019 at 6:45 AM on Tuesday. The duration of the incident was 32 minutes during which the incident blocked 2 lanes. From the incident data, it could not be specified which lanes were blocked.

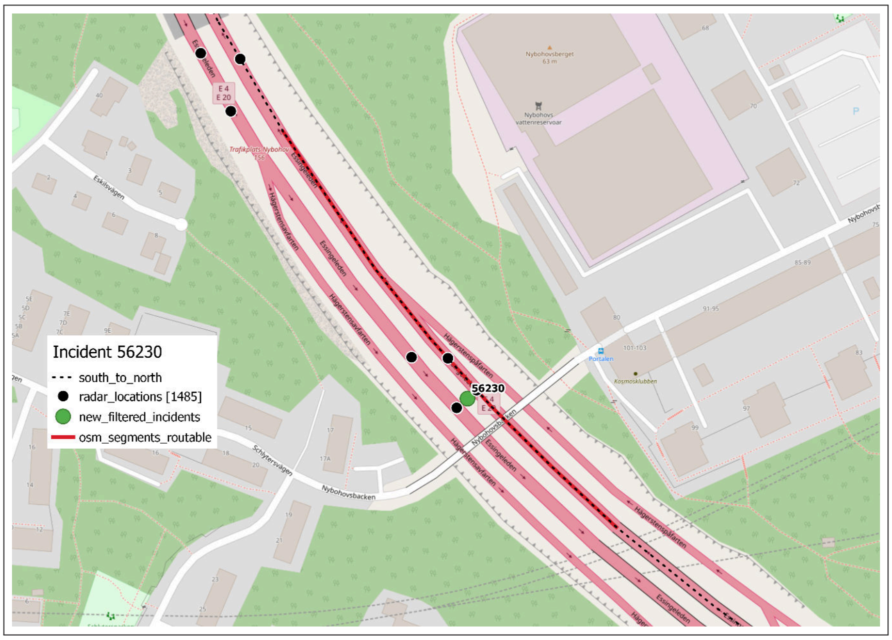


Figure 5.12: Location of incident 56230

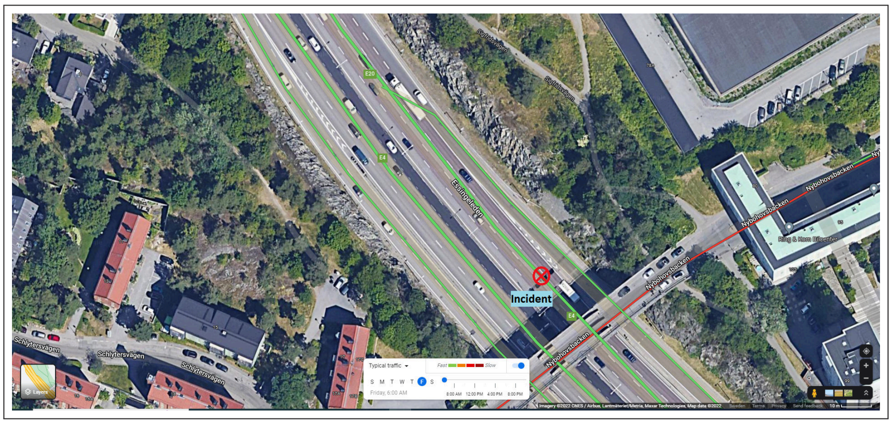


Figure 5.13: Satellite Google maps view of the location of the incident 56230

The Space-time diagram can be seen in figure 5.14.

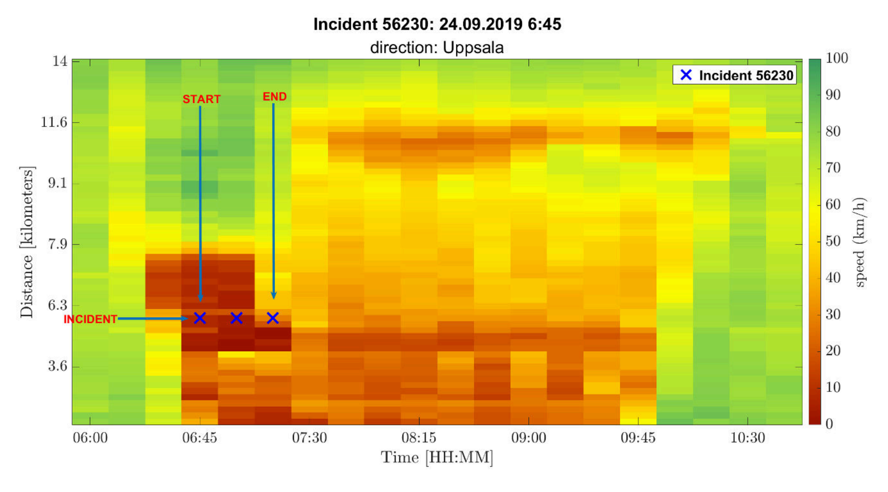


Figure 5.14: Space-time diagram for incident 56230

Incident 57136

This car accident incident involved two passenger cars and one light truck. The location of the incident was localized at E4 from Tomteboda towards Uppsala between E4N km 57,195 and km 57,305. The accident happened on 03.10.2019 at 7:30 AM on Thursday and lasted for 27 minutes. The incident segment 39041069_0 has 4 lanes in a curve profile with a free flow speed set at 70 km/h. During the incident, 2 lanes were blocked.

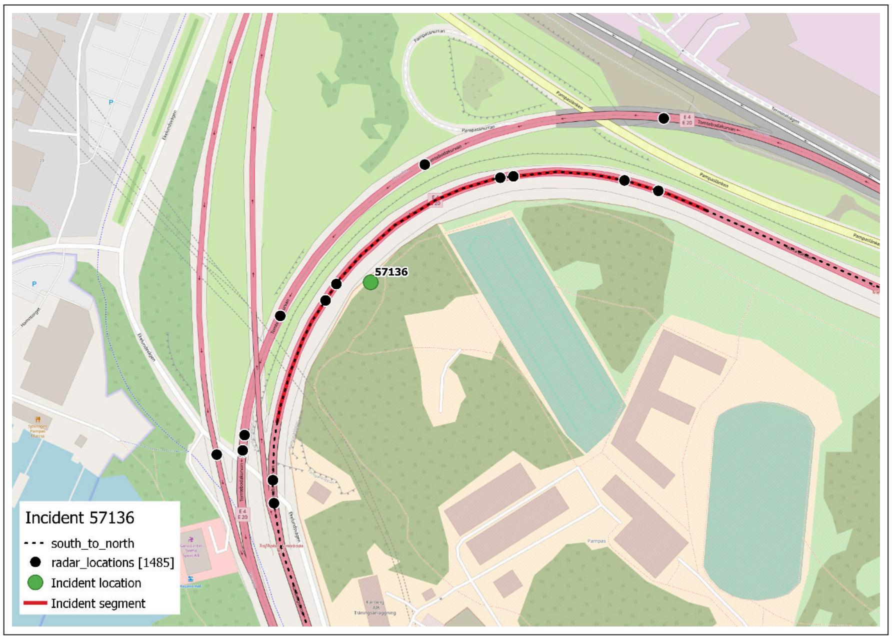


Figure 5.15: Location of incident 57136

Figure 5.16: Satellite Google maps view of the location of the incident 57136

The Space-time diagram can be seen in figure 5.17.

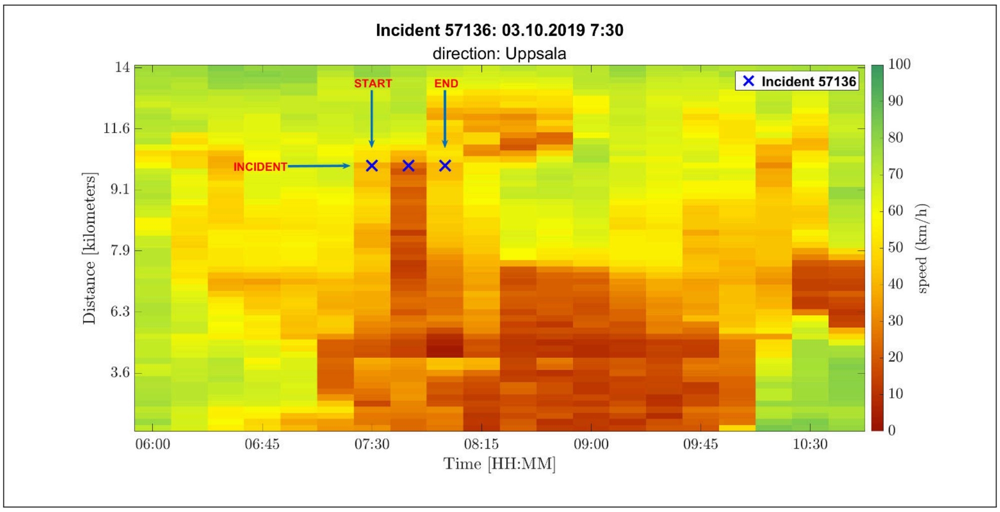


Figure 5.17: Space-time diagram for incident 57136

Incident 57144

Traffic incident 57144 represents an accident of three passenger vehicles in the left lane and a passenger vehicle in the right lane. The accident happened on 3.10.2019 on Thursday at 8:15 AM, the same day as the previous incident 57136, but different direction. Conditions were disturbed for 18 minutes on the motorway E4 at Lilla Essingen between E4S km 54,880 in the direction of Södertälje. The incident link 205889183_0 consists of 4 lanes with a free flow speed of 70 km/h.

Figure 5.18: Location of incident 57144

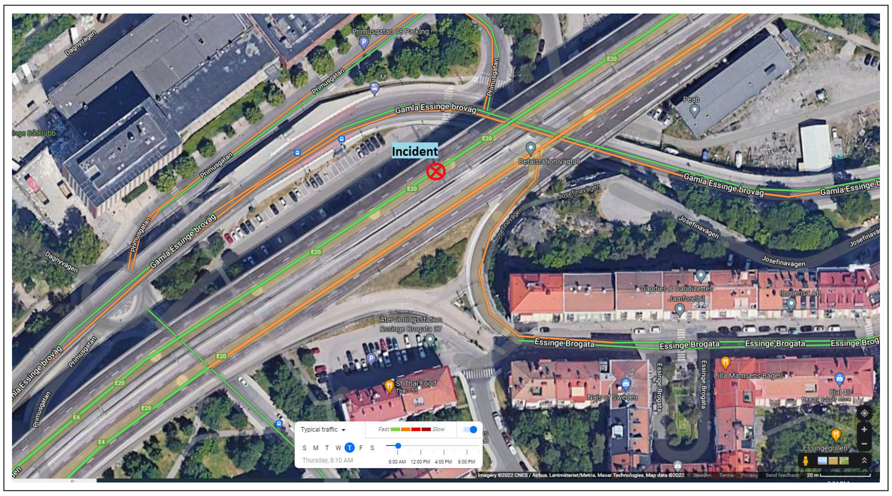


Figure 5.19: Satellite Google maps view of the location of the incident 57144

The Space-time diagram can be seen in figure 5.20.

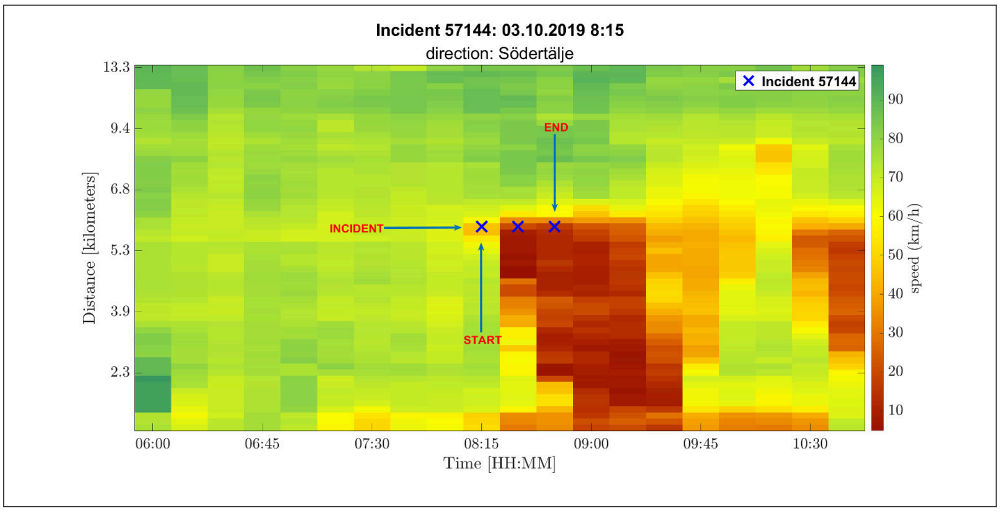


Figure 5.20: Space-time diagram for incident 57144

Incident 57236

Incident 57236 is an incident involving a stationary vehicle located at the on-ramp at E4 at Nybohov. Road assistance was presented on-site during the incident as well. According to the notes for that incident, the detection was made at E4N km 52,535 in the direction of Uppsala on a road segment with the detectors, not on the on-ramp. The incident happened on 4.10.2019 at 6 AM on Friday and lasted for about 1:09 hours during which the incident occupied 2 lanes. From the database and the location of the incident, it was not possible to determine which lanes were affected and where exactly the incident happened. In the end, the incident segment was selected the segment on the main road 16885350_0 with a free flow speed of 70 km/h where 2 lanes were blocked. Those two lanes were selected closer to the on-ramp since the incident was supposed to happen there.

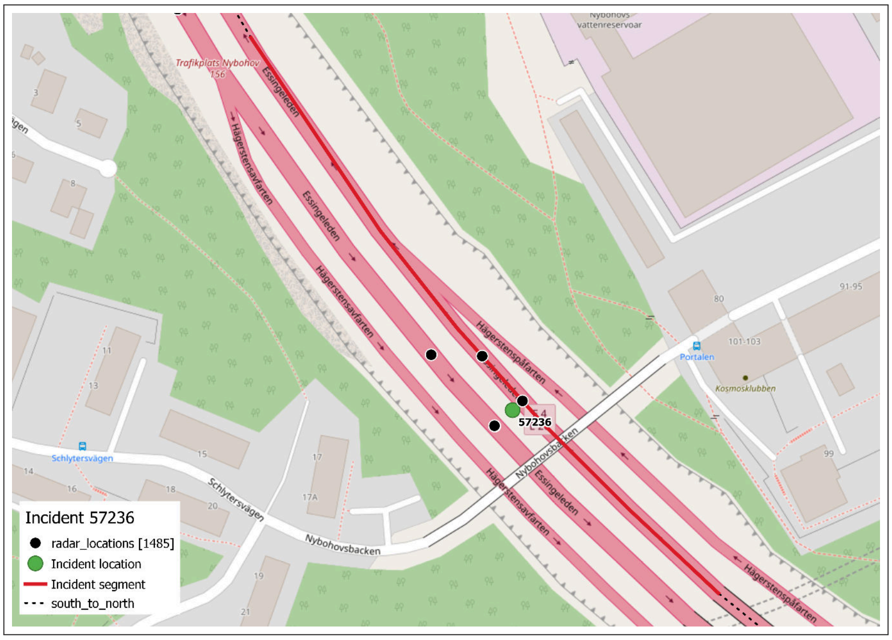


Figure 5.21: Location of incident 57236

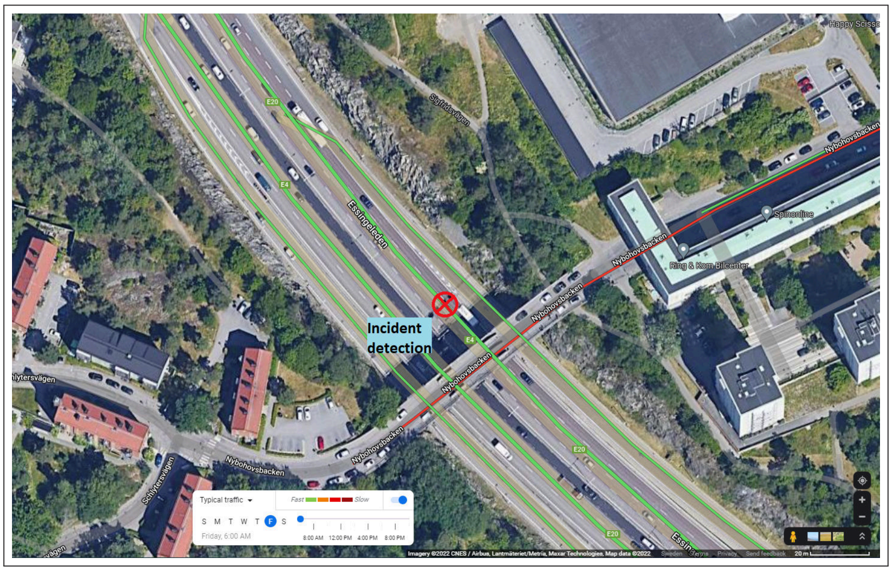


Figure 5.22: Satellite Google maps view of the location of the incident 57236

The Space-time diagram can be seen in figure 5.23.

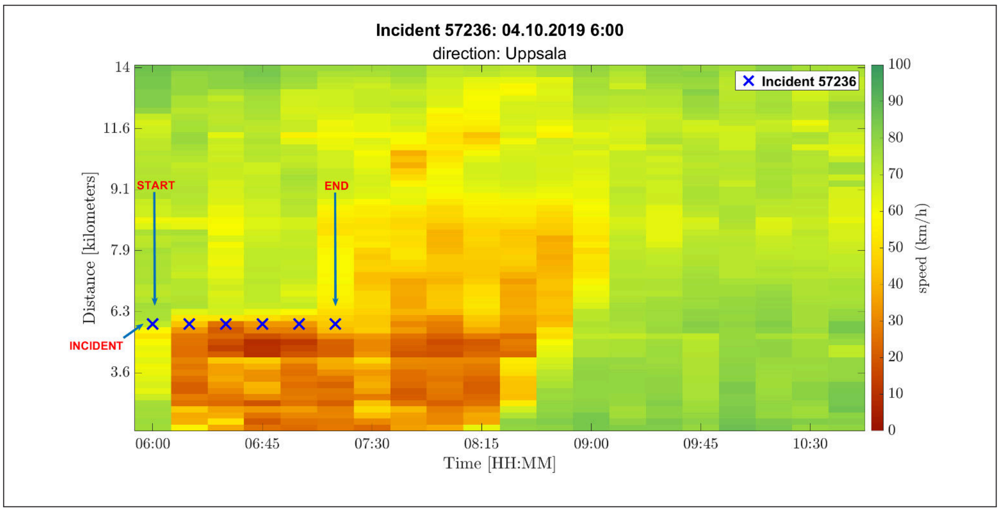


Figure 5.23: Space-time diagram for incident 57236

Incident 55599

The last incident happened on Gröndalsbron on the E4 motorway at Stora Essingen with a free flow speed of 70 km/h. The incident segment 45049310_0 with its exact location at E4N 53,955 towards Uppsala was a place of an accident of a passenger car. The accident happened on 16.9.2019 on Monday at 6:15 AM and lasted for 26 minutes. During the incident, two out of 5 lanes were affected.

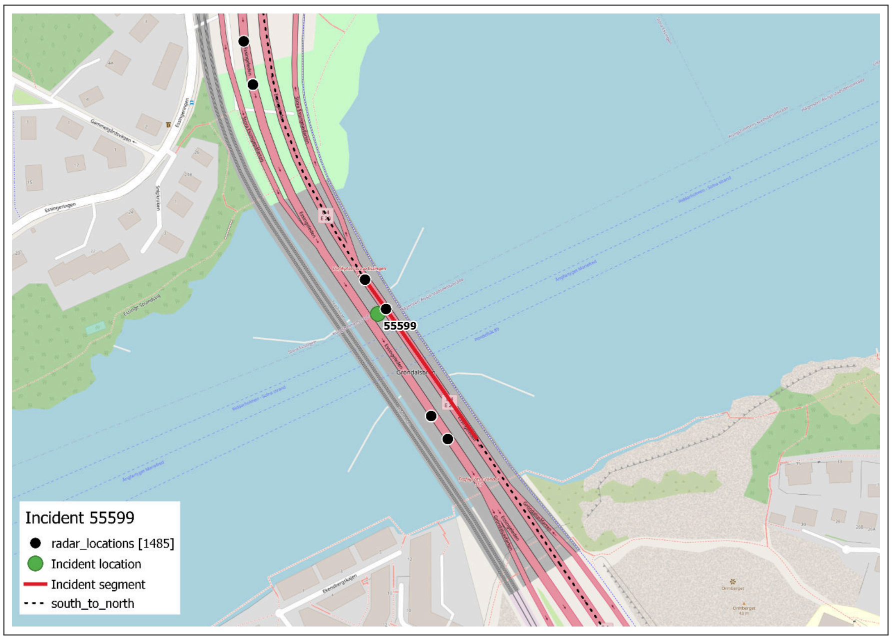


Figure 5.24: Location of incident 55599

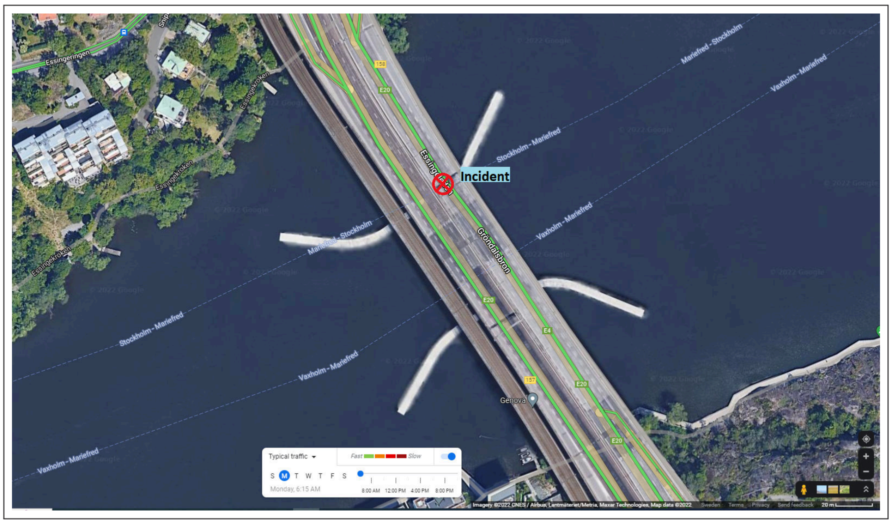


Figure 5.25: Satellite Google maps view of location of the incident 55599

The Space-time diagram can be seen in figure 5.26.

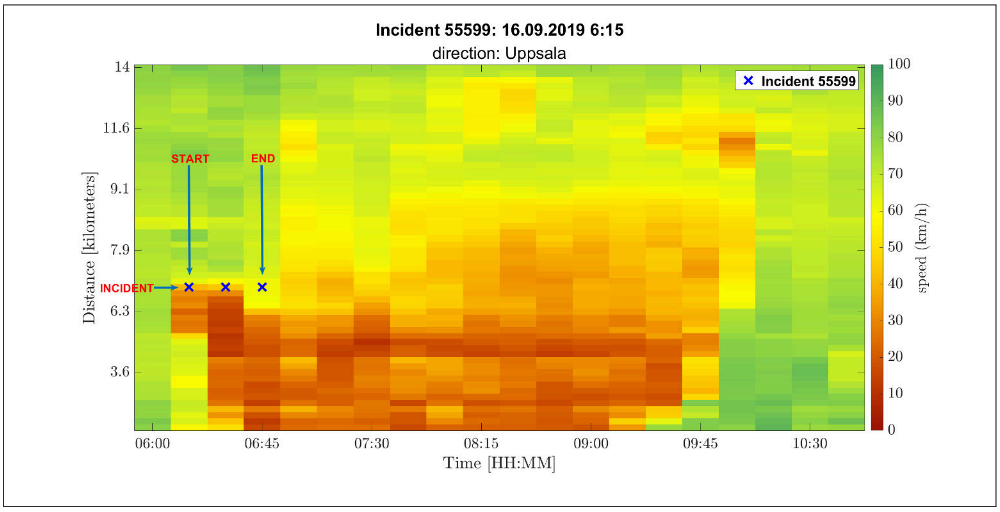


Figure 5.26: Space-time diagram for incident 55599

A summary of all incidents can be seen in Table 5.3.

Incident	56230	57136	57144	57236	55599
Date	24.09	03.10	03.10	04.10	16.09
Incident time	6:45	7:30	8:15	6:00	6:15
Duration [min]	32	27	18	69	26
E4 location [km]	52,535	57,305	54,880	52,535	53,955
Direction	Uppsala	Uppsala	Södertälje	Uppsala	Uppsala
Type	stat. vehicle	accident	accident	stat. vehicle	accident
Affected lanes/available	2/4	2/4	2/4	2/4	2/5

Table 5.3: Summary of 5 incidents

5.4 Use Cases Simulation

To evaluate the Dynameq model and thus the software as a DSS, a set of use cases is defined, and simulations are conducted. The simulation case study is done purely on the Stockholm model and the Dynameq software with its corresponding traffic network and defined paths southbound and northbound (see figure 5.27). The input to the use cases is set on the methodology of use case selection and data presented earlier in this work. Individual use cases represent 1 selected incident. After analysing all five incidents from the previous section (see Table 5.3), it was decided that all 5 incidents will be simulated.

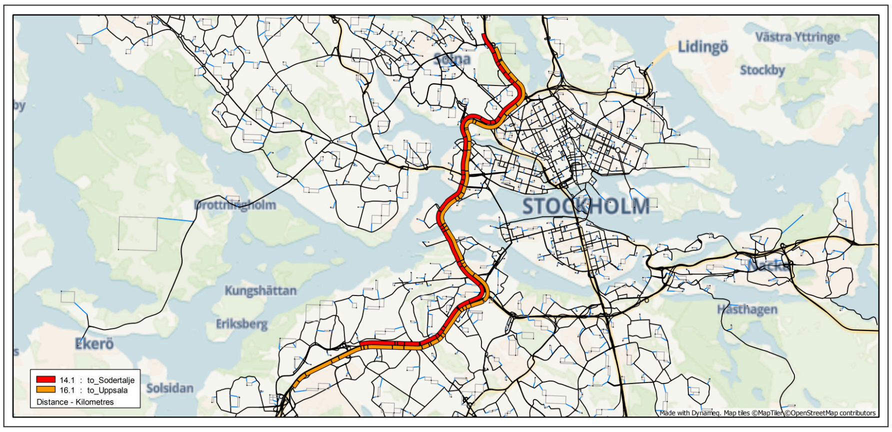


Figure 5.27: 2 paths in Dynameq

To analyse the given model and simulate use cases, specifications of DTA simulation parameters have to be presented. Those settings represent the ”original” model that was provided by Trafikverket and no changes to the model or the simulation were applied. As can be seen in the following points, the model is run with 40 iterations. For more details about what an iteration is see Chapter 4. The DTA specification was set up as follows:

- demand assignment is defined from 6:00 to 10:00 - morning peak;
- assignment intervals are set to 16 intervals (1 interval is 15 minutes);
- simulation starts at 6:00 and ends at 14:00;
- two types of demand matrices are used - one with lower and second with higher cost function which represents different costs for different vehicles (when some vehicles are delayed, the generalized cost is higher due to their higher overall cost like public transport vehicles, transit vehicles, etc.), which corresponds to two different vehicle classes used in the simulation (passenger car and transit vehicle);
- O-D paths set to 10 which represents a number of possible re-routes between an origin and destination (maximum number of paths that can be used within as assignment interval);
- transit vehicles are simulated. They represent, for example, public transport vehicles moving around the network with the same assignment rules and interactions among vehicles as normal vehicles;
- The number of iterations is 40 - the number of cycles that the simulation is run for

The general idea of the experiment is a comparison between:

1. Traffic demand and speed from Dynameq simulation of Stockholm model with demand and speed from MCS detectors for the southbound direction (to Södertälje) of the incident 57144
2. Dynameq 40-iteration model results with results from a Dynameq simulation with an incident implementation
3. Dynameq simulation with an incident implementation results with probe data from a given incident day

The first mentioned comparison provides an indication of how well the Dynameq model is calibrated and set up with the O-D matrix and other simulation parameters from Trafikverket. Investigated can also be an input flow to incident 57144 from the simulation and measured data. The second comparison compares the simulation of an incident with a simulation without an incident. Model behaviour can also be observed, how the Dynameq model reacts or changes according to the particular incident use case simulation. The third comparison is made with the incident simulation results from Dynameq and probe data regarding each incident day.

Therefore, the simulation part consists of:

- Simulation with given parameters and O-D matrix of the **”original” model** - using Dynameq with a given O-D matrix and given set of simulation parameters (see above) from Trafikverket, the simulation is run, and results from the simulation are gathered (performing 40-iteration simulation);
- Simulation of an incident - using Dynameq with the simulation result from 40-iteration simulation as a starting point for **one iteration simulation** with an implementation of an incident;
- Simulation of an **incident with 40 iterations** - an incident is simulated and the number of iterations is set to 40 (as the number of iterations of the original model) to see how the travelers adapt to the incident in the model.

In other words, after an initial simulation where the Dynameq model was simulated and equilibrium was found (for more information about equilibrium state see 4), an incident was then simulated using the last iteration with the same route choices from the 40th iteration, and results were compared. A warm-up start feature was used that enables the usage of the last iteration of the selected scenario as a base for the new one. Each incident use case simulation thus started with the 40th iteration taken from the ”original” model with a set sensitivity of the warm-up start. The sensitivity parameter is defined in the manual [173] as *”Parameter that influences how much traffic will be moved between paths by the traffic assignment algorithm in response to path measures (travel cost) in the warm start DTA,”* and can be set from 0 to 1. For the incident simulation, the number of iterations parameter in Dynameq DTA settings was set to perform only a **one-shot simulation** to perform a Stochastic Traffic Assignment (STA). This allowed to understand how the typical travel pattern on a specific link for a specific incident (represented by the 40-iteration simulation) is affected by introducing an incident into the model. This one iteration simulation thus represents a simulation of an incident that the drivers are introduced to for the first time.

Next, the same incident was simulated 40 times, and results were collected. Simulated was thus a case where examined was drivers’ behaviour and their route choice as if the incident was happening there every day, almost creating a reoccurring bottleneck. The analysis is just visual, for comparison with the one-shot simulation. No rerouting was further investigated. Simulation with 40 iterations of the simulation with an incident was performed to see whether the traffic condition could return to equilibrium.

Simulation results were also compared in terms of travel times, but **only for simulation outputs**. The outputs were taken from the 40-iteration simulation without an incident and from the 1 iteration incident simulation. Real travel times from probe data were not plotted. All the generated results from simulations were collected by the Dynameq software and then either evaluated using MATLAB or build-in analysis functions in Dynameq.

As mentioned earlier in this work, network representation is not fully considered meaning that modelling on- or off-ramps is not applied. This is believed to not be a problem when determining whether the simulated model can give a representative result on applied incidents. Another important disclaimer applies to plots that compare the speed-contour plot from simulations with plots from probe data. Because the representation of the individual segments in the Dynameq model does not exactly match the representation of the individual segments from the available data in the database (mainly in the link attributes like lengths and lane separation), it is important to note that the y-axes from the simulation and probe data do not match. The y-axes in the probe data plots represent the distance from the start of the considered stretch and because the segments are represented by different lengths, the y-axis also does not scale properly (with a fixed space interval). However, graphs from the simulation show an area for which no probe data have been aggregated. This marking of the segment in the simulation graph which is not included in the probe output should then lead to a possible comparison of the two graphs, although incidents may appear to be marked in different places. The position of an incident in each graph was always checked to make sure that the incident is at the right spot. The difference in sections between the Dynameq model and the probe data can be seen in Figure 5.28 and 5.29.

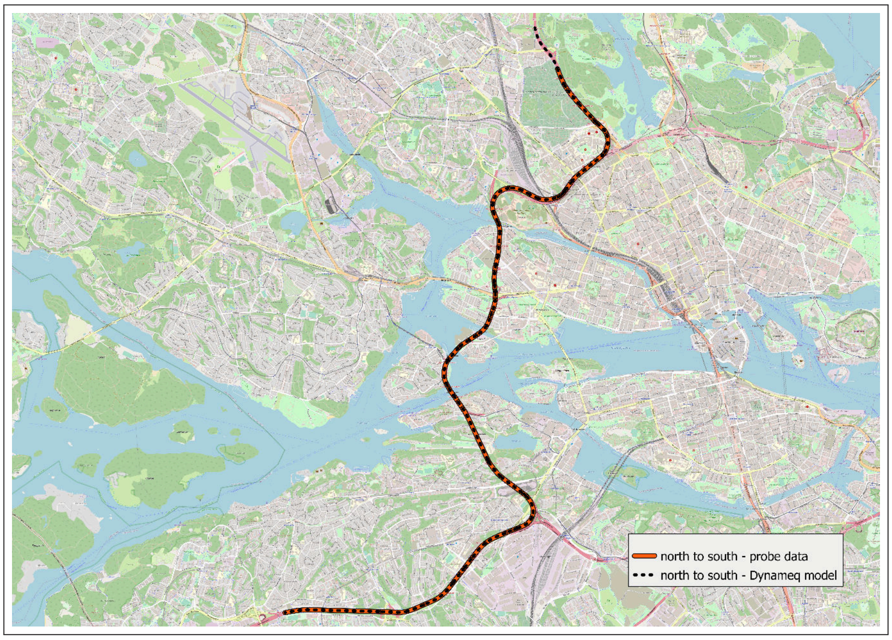


Figure 5.28: North to south stretch difference

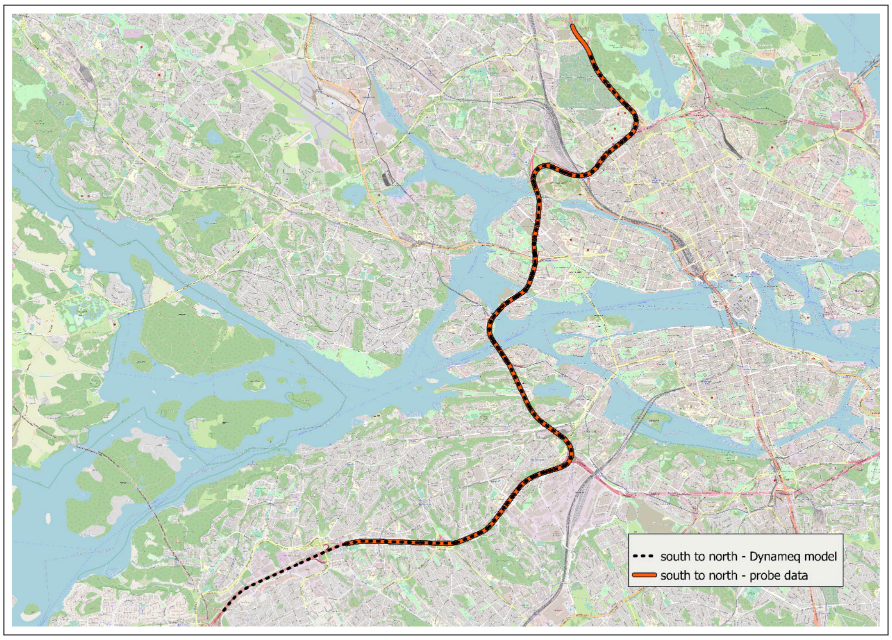


Figure 5.29: South to north stretch difference

5.4.1 Upstream Flow and Speed Comparison

Initially, upstream flow and speed of the Dynameq model from Trafikverket is evaluated. **The results** from the simulation can be seen in figures 5.30 (direction: Uppsala) and 5.31 (direction: Södertälje). As can be seen in the first case, the plot shows congested traffic of a morning peak in the northbound direction on E4. Two bottlenecks can be observed - one at km 4.5 and the second one at km 10. The two independent congested areas start at about 6:45 when bottlenecks are activated. Traffic breaks down at those bottleneck places and traffic congestion starts forming upstream. One of the possible factors is starting morning peak causing high traffic load. The smaller bottleneck is formed after an on-ramp, right before the free-flow speed reduction from 80 km/h to 70 km/h. The congestion starts to build up more at 7:30h, reaches its peak at 8:15, and is dissolved before 9:00h. The larger congestion appears at Lilla Essingen right after Essinge Brogata on-ramp. The congestion appears right before a tunnel which might have an effect on this bottleneck.

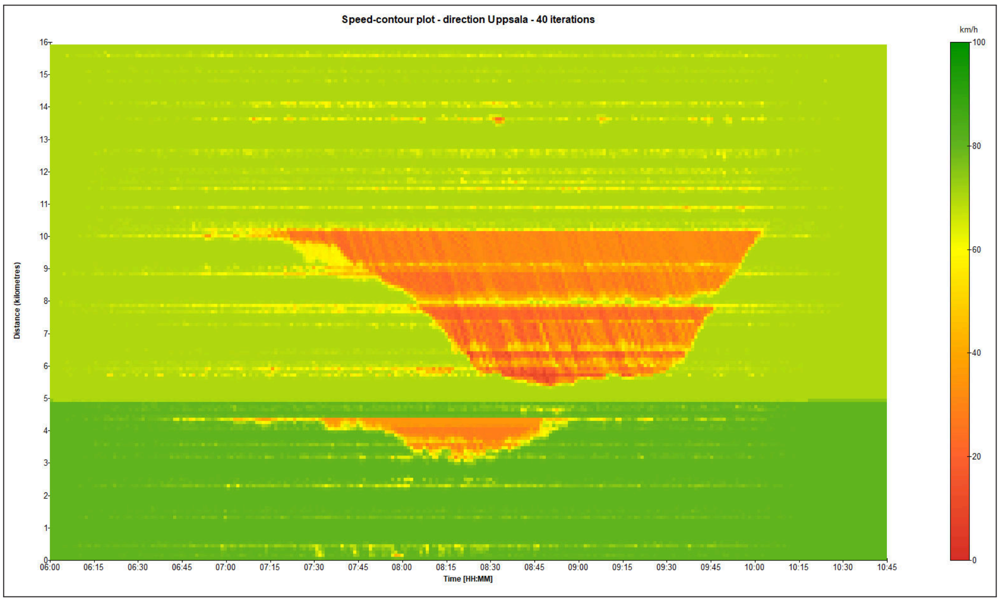


Figure 5.30: Dynameq original model simulation output - space-time diagram for the direction to Uppsala

What can be observed in the second case of the Södertälje direction is that no congested areas are created in the southbound direction. Some areas signal that there is a presence of a starting bottleneck, but the sufficient capacity and a level of incoming demand do not activate any bottlenecks thus no congestion is formed upstream.

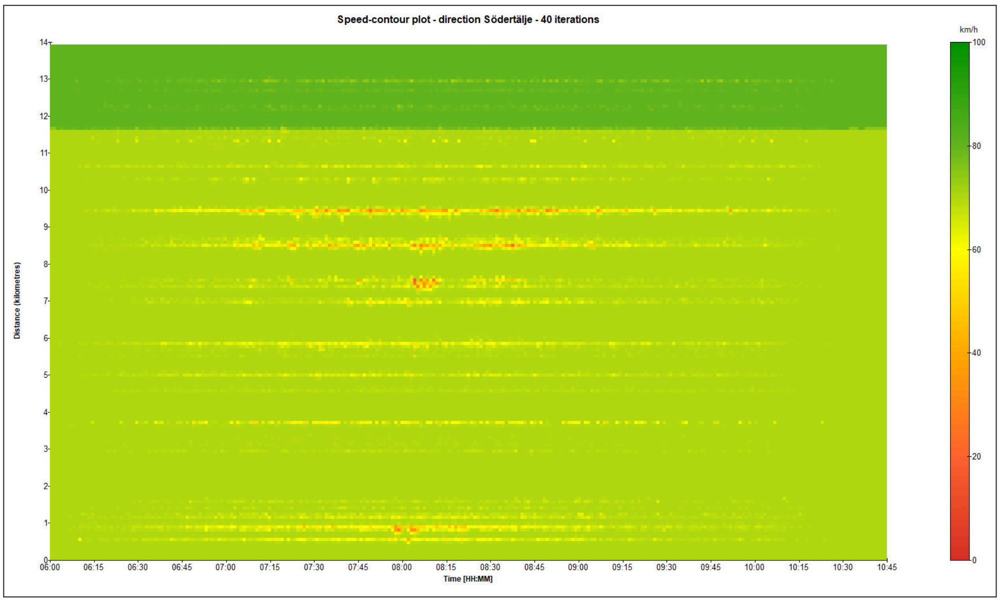


Figure 5.31: Dynameq original model simulation output - space-time diagram for the direction to Södertälje

Next, incident 57144 was selected for a comparison between traffic demand from the simulation and demand measured with MCS detectors. Compared was flow from Dynameq model incident simulation for the time period from 6 to 10 AM, and Stockholm's measured flow data from MCS sensors for the incident day and the day before (October 2 - October 3). The flow from the simulation results is taken from the incident link where the incident happened averaged across all four lanes per one hour. In the case of MCS data, the flow was taken from the upstream detector E4Z 55,210 for all four lanes where the detector collects data. The MCS flow data was smoothed across all four lanes with a 20minutes window and summed. MCS detectors located on transport infrastructure in Stockholm measure the speed and flow of all lanes and the location of the considered MCS sensor as well as the location of the incident can be seen in figure 5.32. Lane numbering is selected to be from left to right in the direction of travel (most-left lane is number 1, second most-right lane number 2, etc.).

Figure 5.32: Location of selected incident 57144 and MCS detector for the flow and speed data

Figure 5.33 presents Dynameq simulation flow upstream of the incident (blue dashed line), and flow observations upstream of the incident on the same day as the incident happened (orange line) and one day prior (blue line). The result from the day before can be considered as a typical since normal morning and afternoon peak hours can be observed. The peak starts around 6:30 AM where the demand was around 5500 veh/h. Then it grows up to almost 6000 veh/h, where the demand starts to decrease, and at 11 AM is flow at its local minimum.

When analysing the incident day MCS flow values, a rapid drop in demand after 8 AM can be seen. Shortly before the incident happened, the demand went down to the value of 4000 veh/h. The demand goes back up again at 9AM but some fluctuations, especially, when compared to the typical flow day before were detected.

From the Dynameq simulation (blue dashed line), it can be observed that the flow dropped down after the incident had occurred and kept on decreasing. In terms of an inflow to the incident, Dynameq modelled flow reached almost the same value as the typical day flow. Especially in the early morning hours, it can be well observed that the demand from Dynameq and from the MCS typical day flow are almost equal where Dynameq at 6 AM has a flow of 3217 veh/h while MCS typical flow at the same time has a flow of 3289 veh/h. Even after the incident flow at 9 AM is quite similar to the real observed flow (Dynameq flow is 4696 veh/h and MCS typical flow is 4899 veh/h). Demand is not met at the end of the simulation with the typical flow. What can be observed is that the demand is perfect on the onset, but it decreases rapidly right after the incident and keeps on decreasing. The Dynameq flow from the incident 57144 simulation is higher and does not represent the MCS data from the incident day. Fluctuations observed in the MCS data do not represent the simulation output since the simulated demand is dropping down while the measured MCS flow rises.

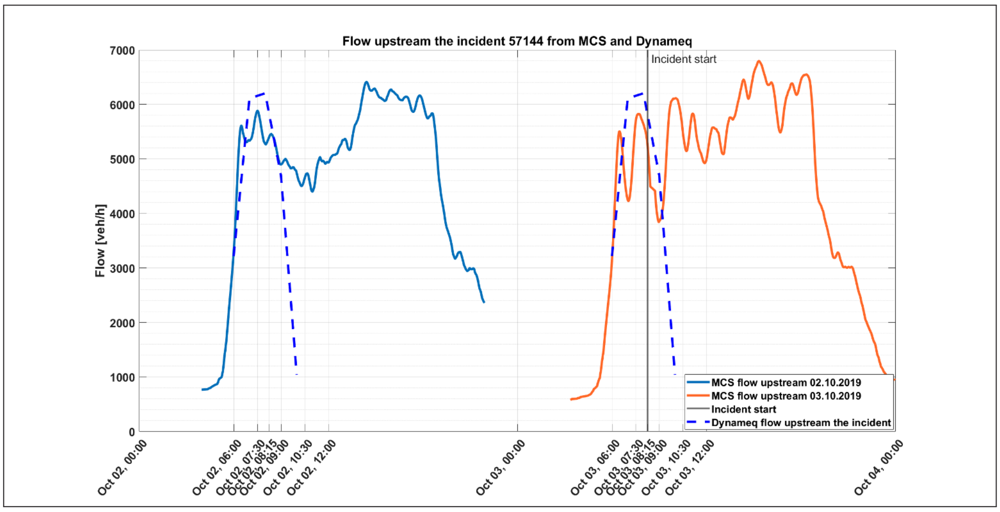


Figure 5.33: Flow observations uplink the incident location from MCS detector and Dynameq simulated flow observation

Speed was compared as well for the incident and MCS data. The speed data was obtained by the same upstream detector for each lane, but only for the incident day from 6 to 10:30 AM. Speed results from the simulation were collected within the same time window from the upstream link before the incident link at the bottleneck place where the queue was forming. The speed is represented by the blue line as an average from all lanes of MCS data.

In figure 5.34, a rapid drop in speed can be observed right after the incident happened in the case of MCS data. The problem lasted until 9:20 AM when the speed increased again. However, the speed did not recover back to its normal values even after 10:30 AM.

In the case of Dynameq, the speed started at the value of free flow speed and slowly decreased over time as the morning peak appeared. The speed was, however, lower than what was observed in the MCS data. In addition, the speed on lanes 2 and 3 began to drop to the incident speed limit even before the incident began. In the case of lane 1, the speed was decreased when the incident started. After the incident ended, traffic conditions went back to normal in terms of speed.

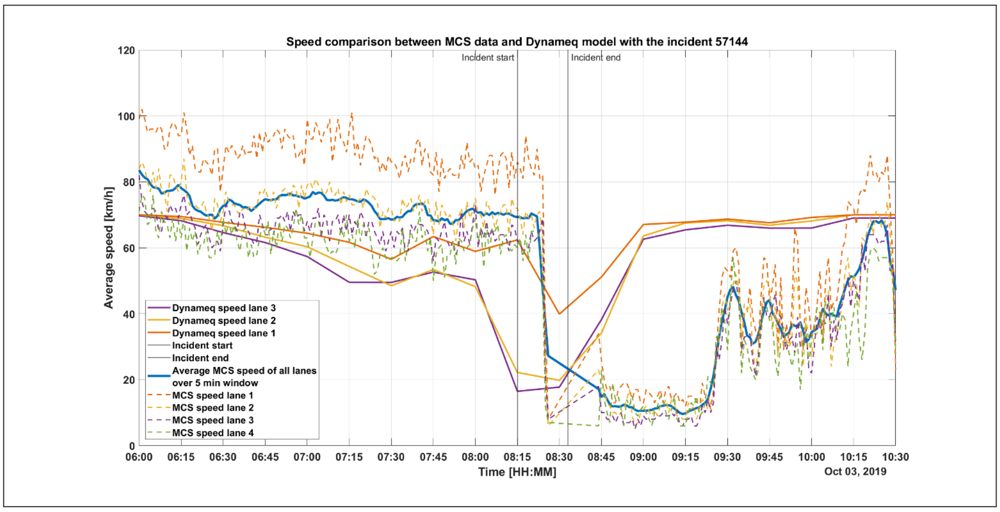
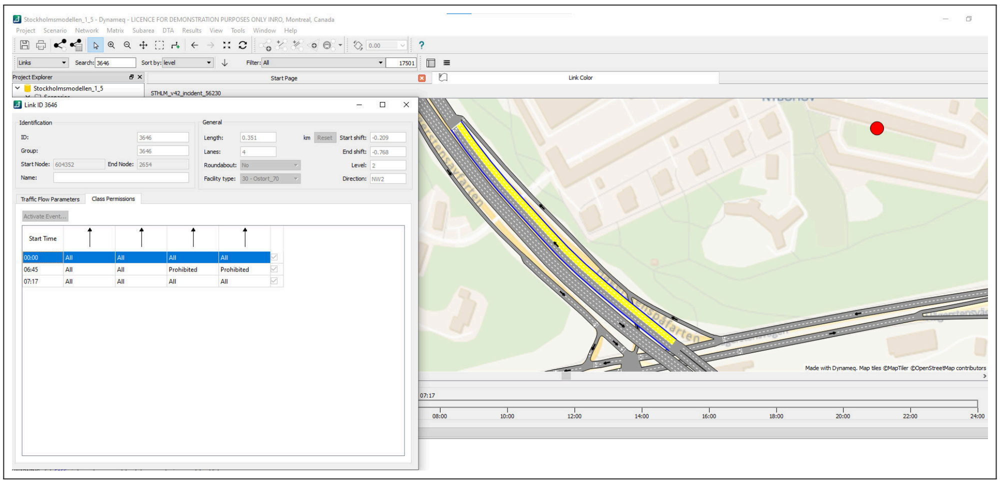


Figure 5.34: Speed observations uplink the incident location from MCS detector and Dynameq simulated speed observations

5.4.2 Use Case 1 - Incident 56230

Incident simulation of a standstill vehicle was performed in Dynameq by network modification of the incident segment (see figure 5.35). Two rightmost lanes were closed at 6:45 for the incident duration. The warm-up start was set up using the original model from Trafikverket (after 40 iterations) and the sensitivity of the ”warm-up start” was set to 0.05.



Links Search: 3646 Sort by: level Filter: All 17501

ID: 3646
Group: 3646
Start Node: 604352 End Node: 2654
Name:
Length: 0.351 km
Lanes: 4
Roundabout: No
Facility type: 30 - Ostort_70
Start shift: -0.209
End shift: -0.768
Level: 2
Direction: NW2

Start Time	↑	↑	↑	↑	
00:00	All	All	All	All	☑
06:45	All	All	Prohibited	Prohibited	☑
07:17	All	All	All	All	☑

Figure 5.35: Network modification for incident 56230

The resulting space-time diagram can be seen in figure and figure 5.36. Traffic conditions were affected by the bottleneck from the two-lane closure. A queue propagation can be observed propagating backward which causes congestion. From figure 5.36, it seems that this incident just amplified the re-occurring bottleneck and activated other bottlenecks on the observed stretch. The sequence of events then led to the overall breakdown of the traffic affecting traffic flow to the very beginning of examined stretch. The incident area seems to be completely blocked since the speed is very low. The speed of the queue propagation is also very fast during the incident duration since it propagated back up to the 4th kilometer in just 30 minutes, where it activates another bottleneck and congestion started to spread there.

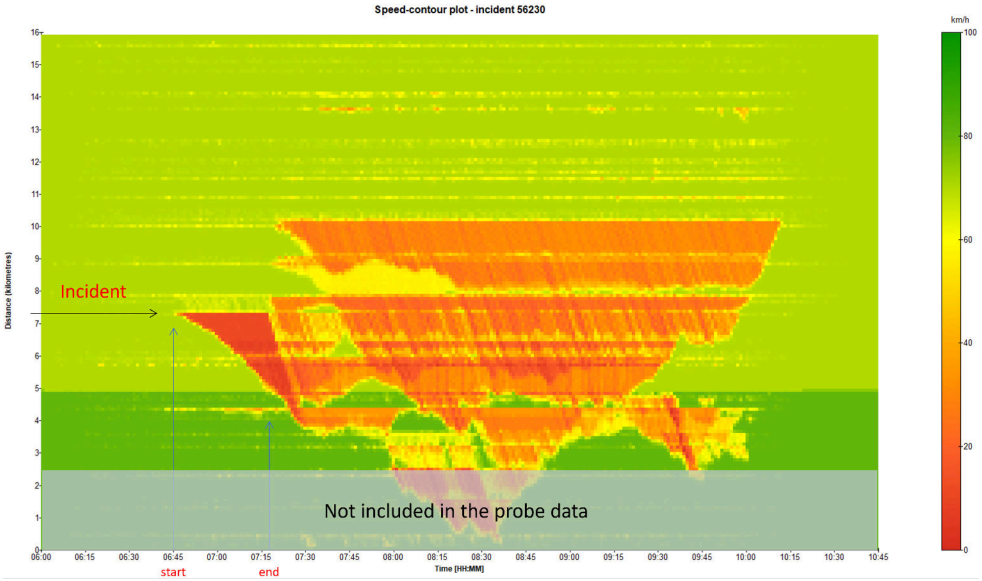


Figure 5.36: Incident 56230 simulation

Next, a Dynameq incident simulation comparison with real-measurement probe data was done (see figure 5.37). Probe data show that the bottleneck furthered along the stretch and approximately 15 minutes earlier than what the incident data say. This could mean that the traffic breakdown was not caused by the incident itself but rather by some other circumstances. Nevertheless, the appearance of the incident definitely did not help the situation and made it worse, or could have caused more disruptions since the incident location in the figure seems to create more speed reduction than the previous/further one. The right side of the probe data plot corresponds to the modelled output where the right side of the queue main tail ends at 10:15h in both cases.

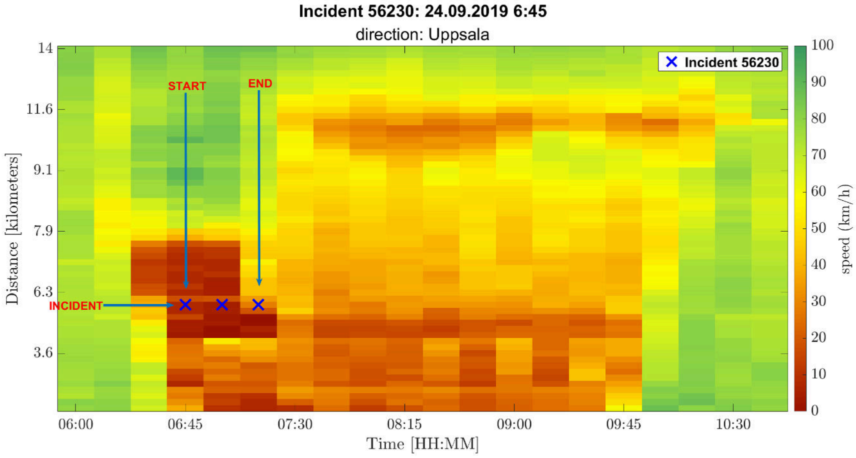


Figure 5.37: Probe data output - incident day 24.09.2019

In figure 5.38 travel time of the incident from the simulation with the simulated original model after the equilibrium was found can be seen. The incident's travel time copies the original model's travel time in the beginning and then around the incident time starts growing which would indicate some disruptions caused by the incident which corresponds with the case as observed from the speed contour plot. The overall travel time is since the incident is higher then what the equilibrium model's travel time is.

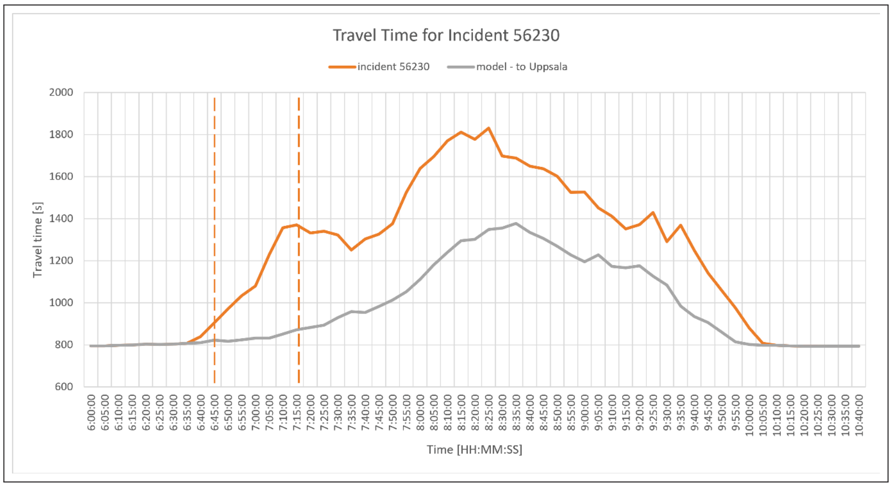


Figure 5.38: Travel time for incident 56230

As can be seen in the figure 5.39 a new equilibrium was found when compared to the previous simulation result. At the incident location, it can be observed that the queue propagation is much smaller than in the case of 1-iteration incident simulation which indicates that some rerouting had been done. The bottleneck area thus does not propagate up-link which means no other bottleneck areas were activated.

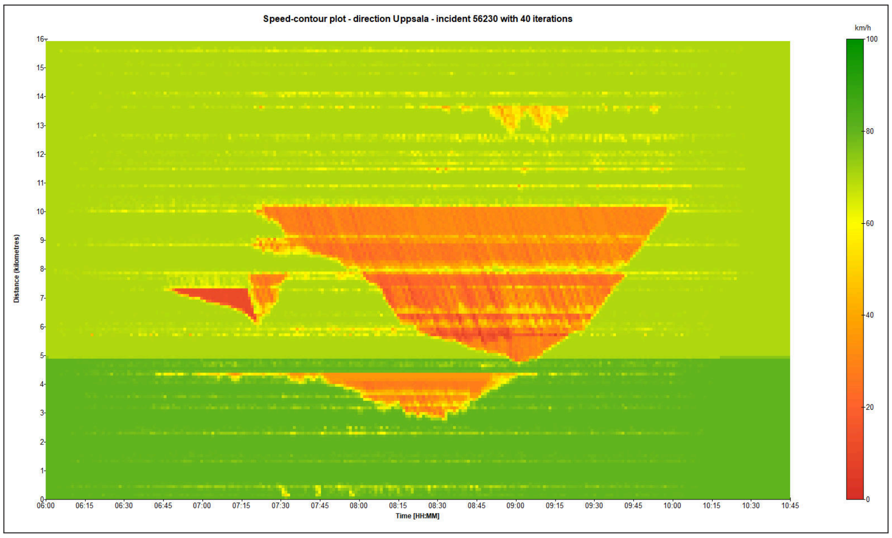
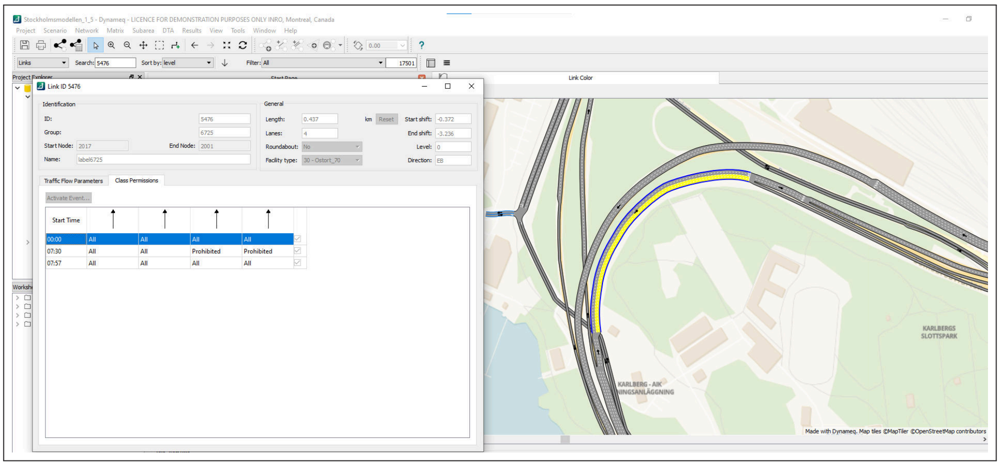


Figure 5.39: Incident 56230 after 40 iteration simulation

5.4.3 Use Case 2 - Incident 57136

The second incident simulation was performed by closing two right-most lanes of the road segment (see figure 5.40) representing a car accident of two passenger vehicles. The DTA was set with the same parameters just as in the previous use case. The lanes closure was set to 7:30h and lasted for 27 minutes after when the road capacity was restored again.


Stockholmsmodellen_1_5 - Dynameq - LICENCE FOR DEMONSTRATION PURPOSES ONLY INRO, Montreal, Canada

Search: 5476 Sort by: level Filter: All 17501

Link ID 5476

Identification

ID: 5476
Group: 6725
Start Node: 2017 End Node: 2001
Name: label6725

General

Length: 0.437 km
Lanes: 4
Roundabout: No
Facility type: 30 - Ostort_70
Start shift: -0.372
End shift: -3.236
Level: 0
Direction: EB

Start Time	↑	↑	↑	↑
00:00	All	All	All	All
07:30	All	All	Prohibited	Prohibited
07:57	All	All	All	All

Figure 5.40: Network modification for incident 57136

Resulting illustration traffic conditions of the incident can be seen in a space-time diagram in figure 5.41. The figures show that no queue propagation was caused and observed in both situations - the converged model and model with the incident. During the period of the accident, the traffic conditions were only affected by a local reduction in speed. Otherwise, no effect was observed.

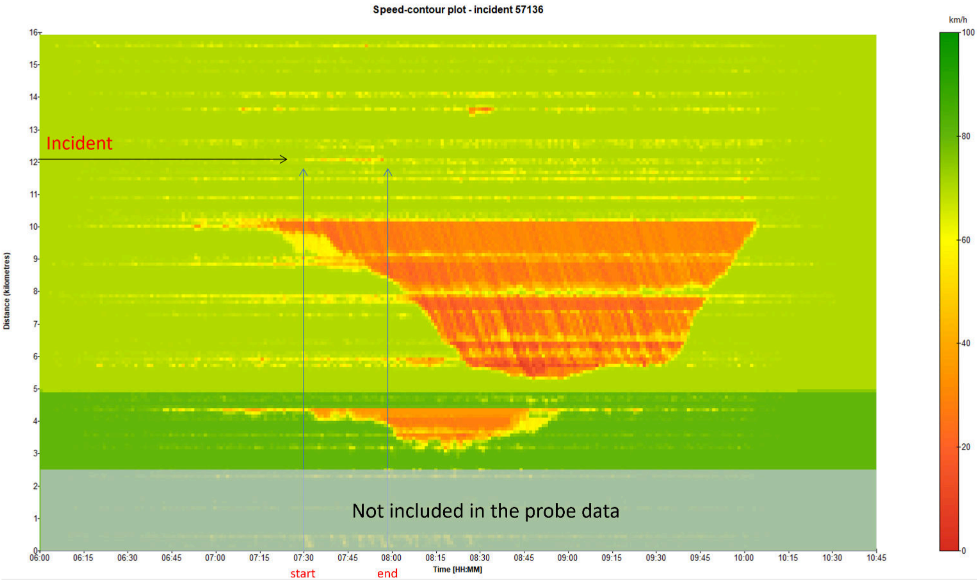


Figure 5.41: Incident 57136 simulation output

When compared to the probe data (see figure 5.42, it can be seen that in reality there was a queue propagating upstream, most likely caused by the incident. The queue propagation then reached the bottleneck at 10th km.

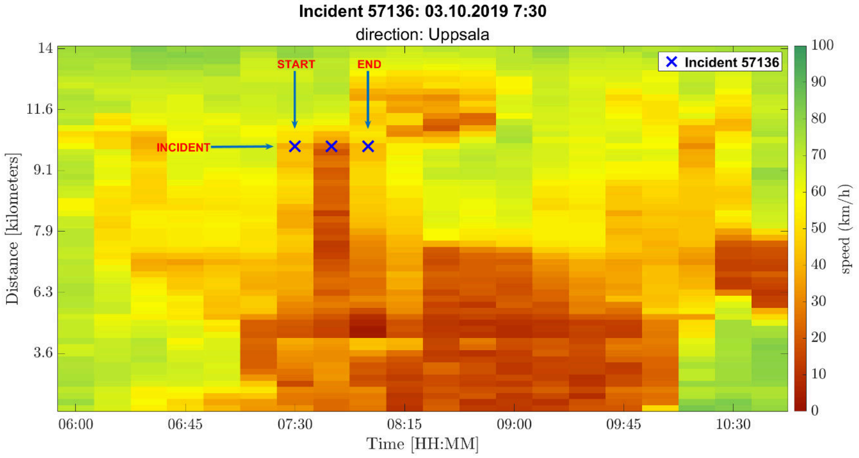


Figure 5.42: Probe data output - incident day 03.10.2019

The resulting travel time from the simulation in figure 5.43 confirms that the disturbance caused by the accident did not have any effect on the traffic performance since the line follows the 40-iteration model's travel time.

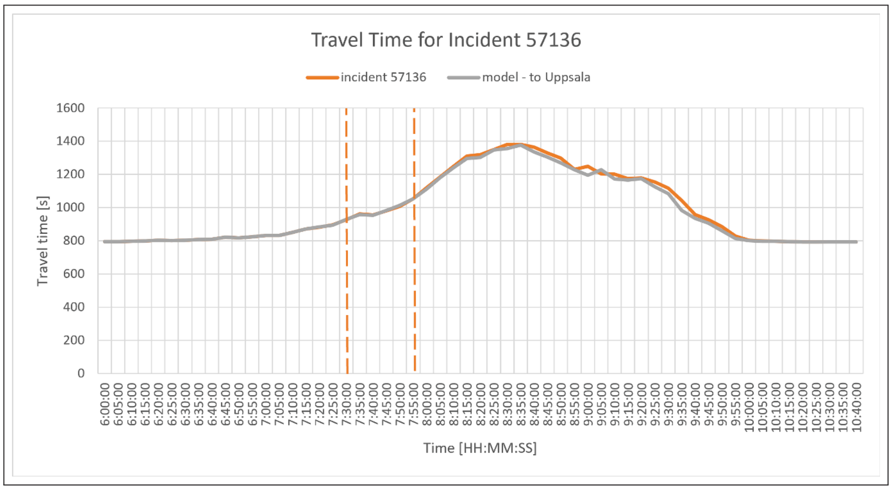


Figure 5.43: Travel time for incident 57136

Figure 5.44 provides a view of 40 iterations with the incident simulation. Comparatively, the plot looks almost the same just like the plot with one iteration. The incident area is affected in the same way as well. What it seems is that right before the 14th kilometer at 8:30, there is a small congested area that is larger than the one in the one-iteration simulation case.

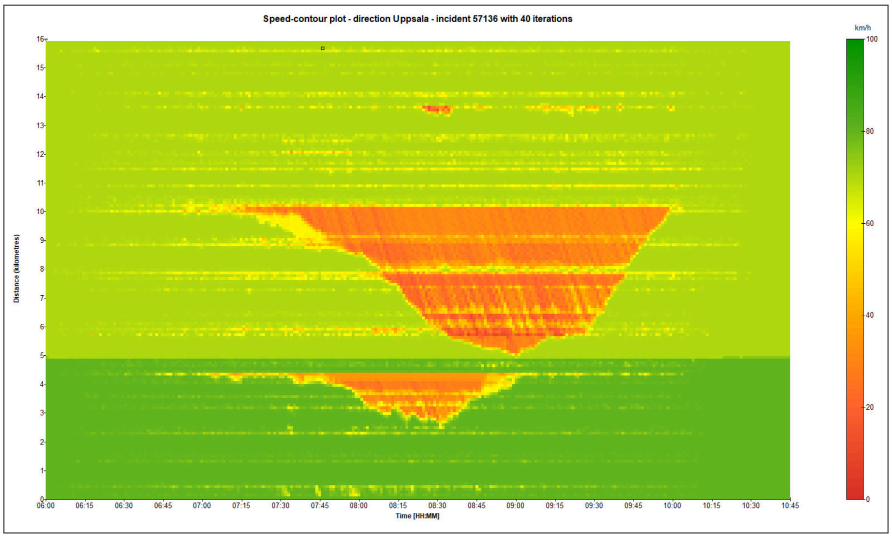
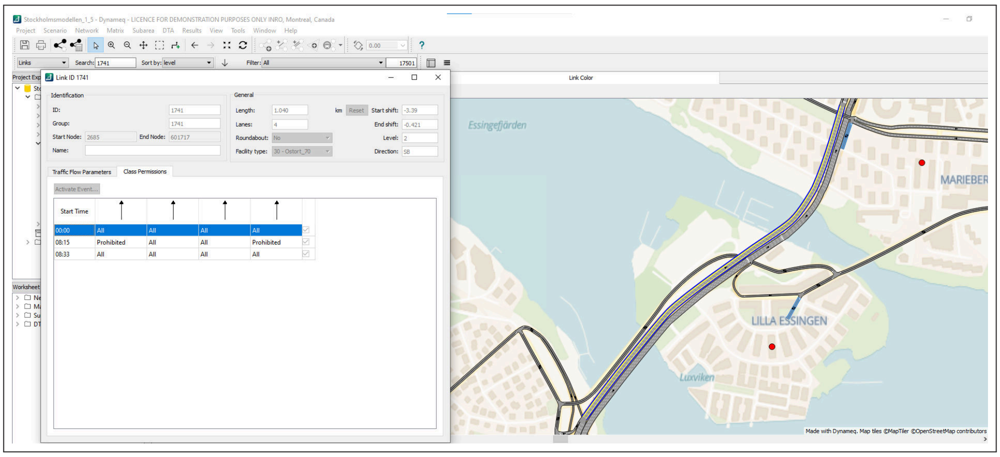


Figure 5.44: Incident 57136 after 40 iteration simulation

5.4.4 Use Case 3 - Incident 57144

The third incident simulation which was a 3-passenger car accident in the left and one lorry and passenger car in the right lane occurred in the area of Lilla Essingen of southbound direction (see figure 5.45). Therefore, the most-left and most-right lanes were closed in the simulation during the morning peak hour from 8:15 to 8:33.



Links Search: 1741 Sort by: level Filter: All 17501

Identification

ID: 1741

Group: 1741

Start Node: 2685 End Node: 601717

Name:

General

Length: 1.040 km Start shift: -3.39

Lanes: 4 End shift: -0.421

Roundabout: No Level: 2

Facility type: 30 - Ostort_70 Direction: SB

Start Time	↑	↑	↑	↑	
00:00	All	All	All	All	☑
08:15	Prohibited	All	All	Prohibited	☑
08:33	All	All	All	All	☑

Figure 5.45: Network modification for incident 57144

In the simulation output in the space-time diagram congestion appears caused by two lanes blockage (see figure 5.46). Before the congestion spreads it almost completely dissolves. The peak of the congestion can be found at the end of the incident duration when the queue length reaches almost 2 km. After that, the traffic conditions are getting back to the original non-congested state.

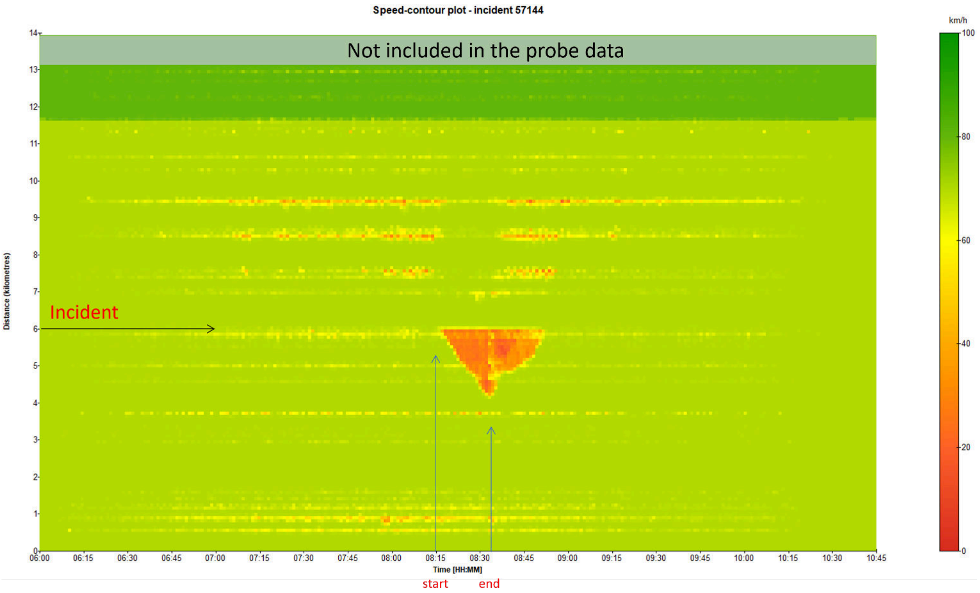


Figure 5.46: Incident 57144 simulation output

A very similar outcome provides probe data which can be seen in figure 5.47 where can be observed a queue propagation caused by the incident at the same time. The incident length from probe data suggests that the duration was longer than what the simulation result shows. The one-shot simulation indicates that the overall traffic conditions were affected only until 8:50, but in reality, the incident seems caused more serious traffic disruptions. This may indicate that the simulation model underestimates the real impact of the accident, or that the accident was not well represented in the simulation. Another bottleneck appearance can be seen on the bottom part of the plot which is not present in the simulation case.

The incident can also be compared with the presented flows and speeds from the model evaluation in the previous section 5.4.1. The demand in the probe data goes back at 10 AM. That is also represented in the flow comparison in the MCS data in figure 5.33, where the

MCS demand reaches its normal value at 10 AM, which can be also observed in the probe L-t diagram (see figure 5.47). The congested area in the probe data dissolves at around 10 AM in a short time period, just like in the case of MCS flow build-up. However, the recovery is not full, which can also be observed in the speed and flow MCS plots. This may indicate that even if the demand is correct, the capacity is a little bit low as well because in the probe space-time diagram 5.47 the congestion propagates all the way back, but in the simulation, it propagates only until 8:50. This can be seen also in the speed data plot.

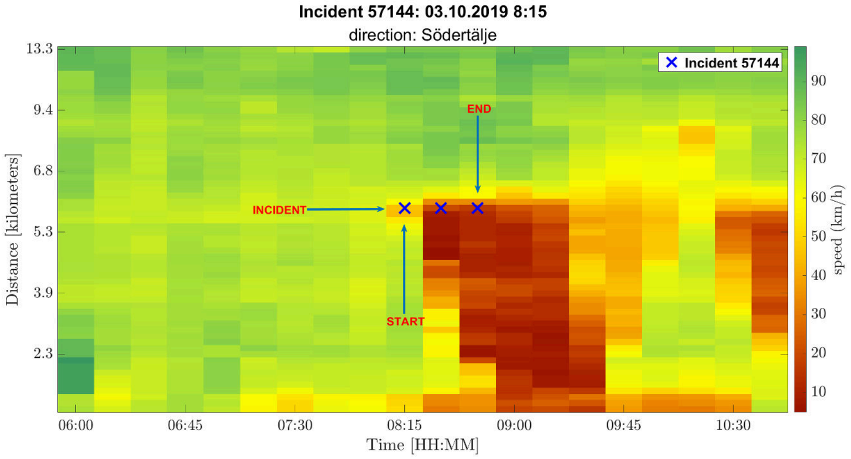


Figure 5.47: Probe data output - incident day 03.10.2019

When examining the travel time in figure 5.48, the effect of the accident is evident, which resulted in an increase in the travel total time for travelling a given route.

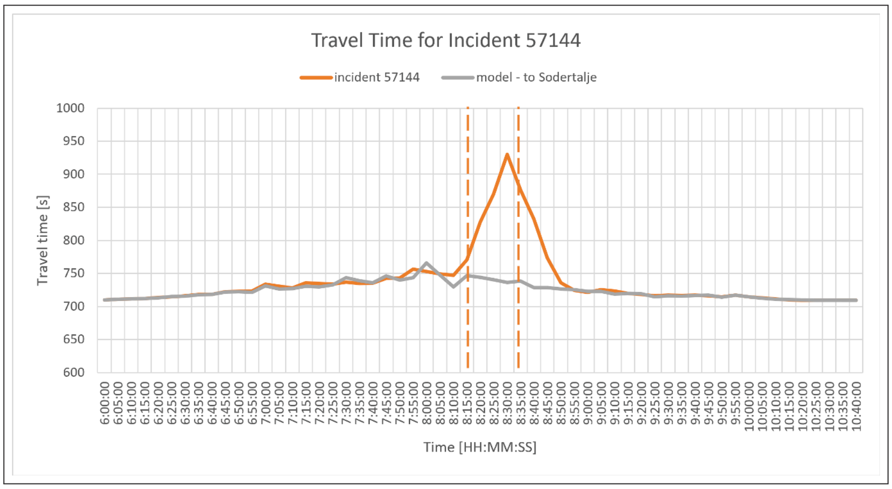


Figure 5.48: Travel time for incident 57144

With 40 iterations, it seems like the queue propagation is even larger than in the case of one-shot simulation (see figure 5.49). Another interesting aspect of the 40 iterations plot is that another small congested area appears at 8:45h before the 8th kilometer of the stretch that did not occur before. This may indicate that the demand in more than one iteration is larger and thus creating a bottleneck at that point that had not been recorded in the single shot simulation.

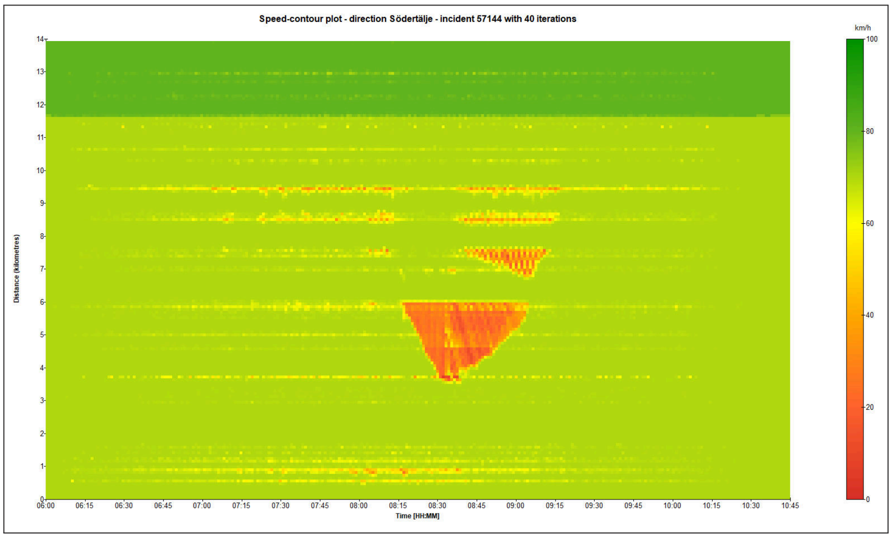
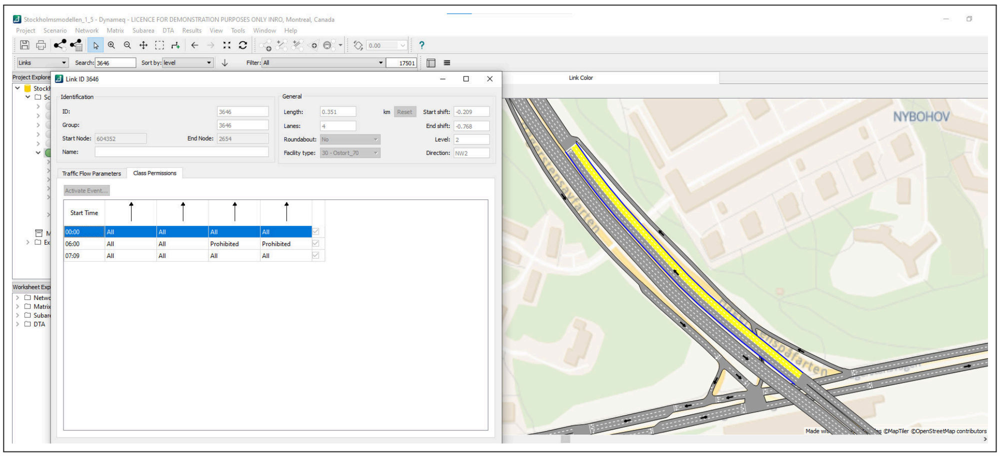


Figure 5.49: Incident 57144 after 40 iteration simulation

5.4.5 Use Case 4 - Incident 57236

Fourth incident simulation corresponds to the same location as for the first use case. Two lanes were closed during the incident period from 6:00h for 1:09 hours and the simulation ran (see figure 5.50). This simulation result can provide a comparison for the first use case simulation since they both happened at the same location and thus only the incident input is different. The DTA's warm start sensitivity is set to 0.05.



Search: 3646
Sort by: level
Filter: All
17501

Link ID 3646

Identification
ID: 3646
Group: 3646
Start Node: 604352
End Node: 2654
Name:

General
Length: 0.351 km
Lanes: 4
Roundabout: No
Facility type: 30 - Ostort_70
Start shift: -0.209
End shift: -0.768
Level: 2
Direction: NW2

Start Time	↑	↑	↑	↑	
00:00	All	All	All	All	☑
06:00	All	All	Prohibited	Prohibited	☑
07:09	All	All	All	All	☑

Figure 5.50: Network modification for incident 57236

As can be seen from **the resulting speed contour plot** in figure 5.51 from the simulation, the incident did not have any effect whatsoever on the traffic since the demand was meeting the network's capacity. Just at the same time as the congestion started in the first use case, an incident started to have an impact in a form of a queue build-up which showed at 6:45h creating a bottleneck. The overall length of the queue spill back is smaller than in the first use case; the queue does not extend upstream that much.

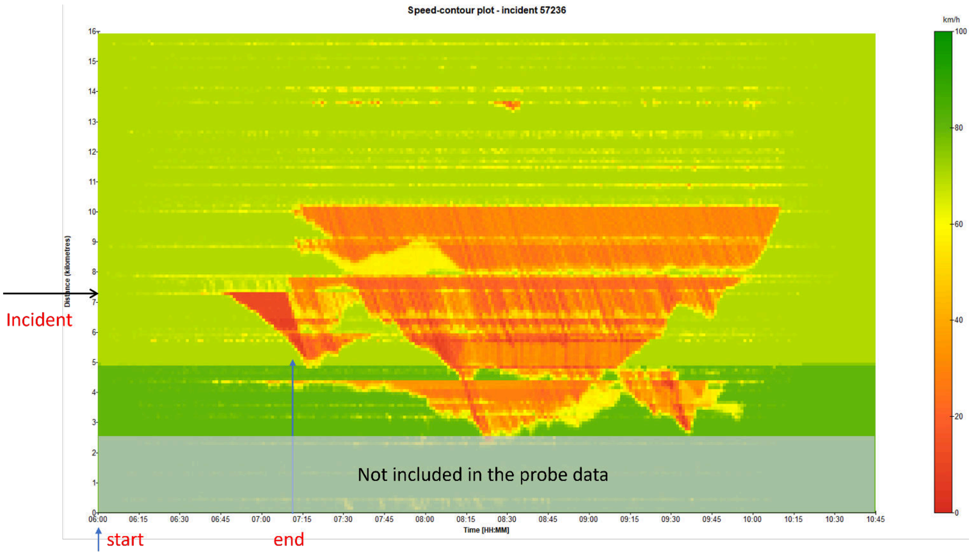


Figure 5.51: Incident 57236 simulation output

In the case of real probe data, a bottleneck is created almost right in the beginning. The queue starts to propagate upstream creating congestion that lasts more than 2 hours. The cause of this bottleneck could be created by the incident. When the simulated plot is compared with the probe data plot, the plots quite match the early morning hours, but then the congested state in the simulation lasts and stays congested for the whole morning, which is not the in the probe data case.

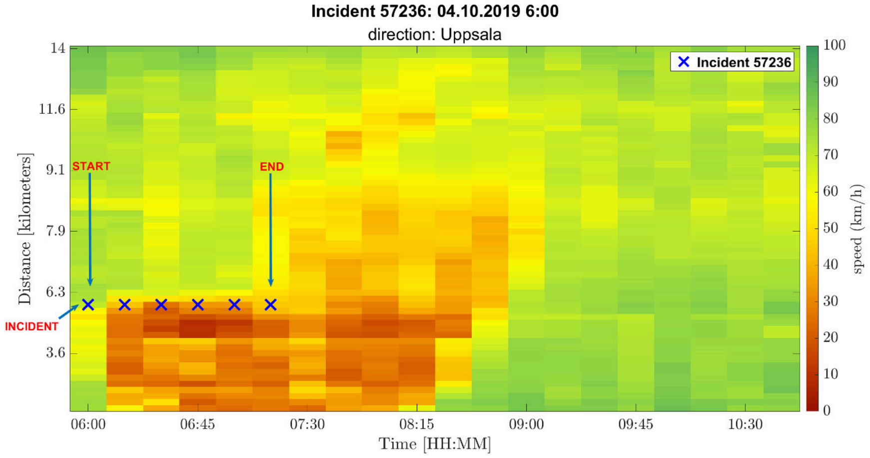


Figure 5.52: Probe data output - incident day 04.10.2019

Travel time indicates that the incident might had an effect on the traffic since the travel time is shifted from the original model's travel time (see figure 5.53). It also shows that the congestion in the simulation had a big effect on the traffic performance since the travel time got back to normal after 10:00 AM.

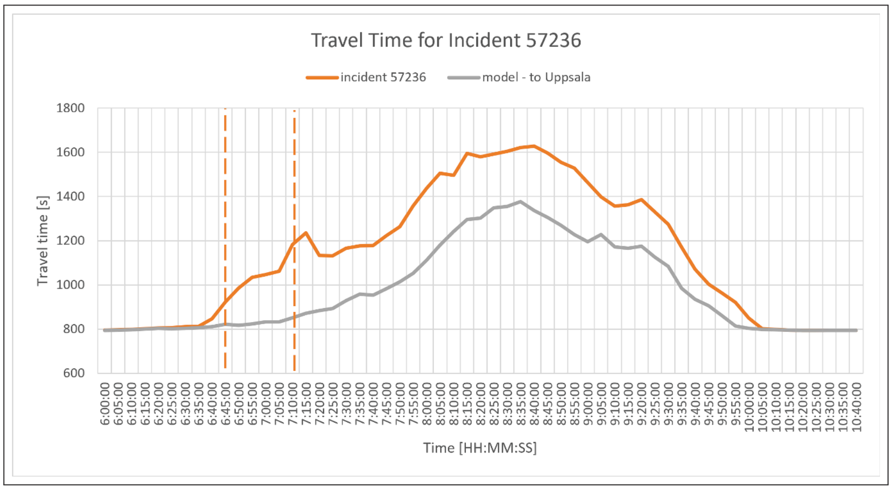


Figure 5.53: Travel time for incident 57236

Figure 5.54 shows this incident under 40 iterations. The congested area is again quite similar to the original congested area size. Only at 6:45 AM, there seems to be a smaller congested area right at the incident location. This congested area is shortly after dissolved with no other effects on the network's performance.

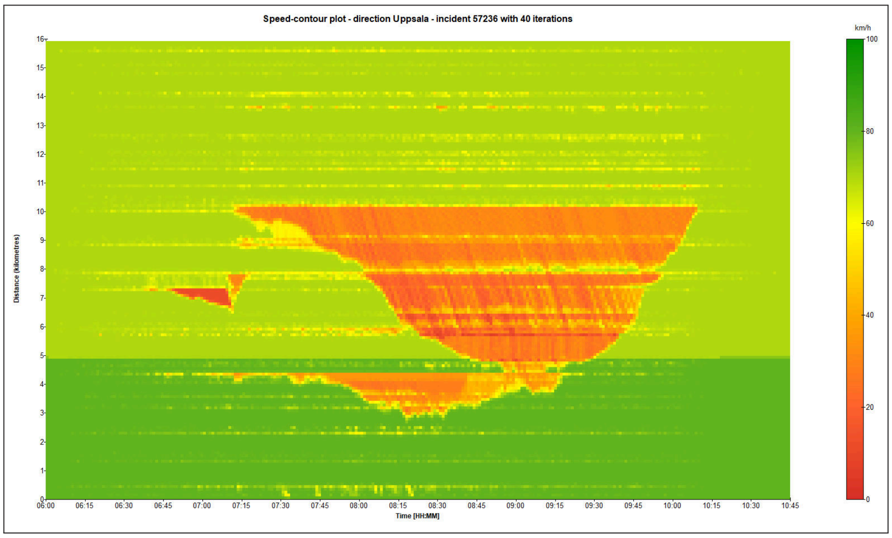
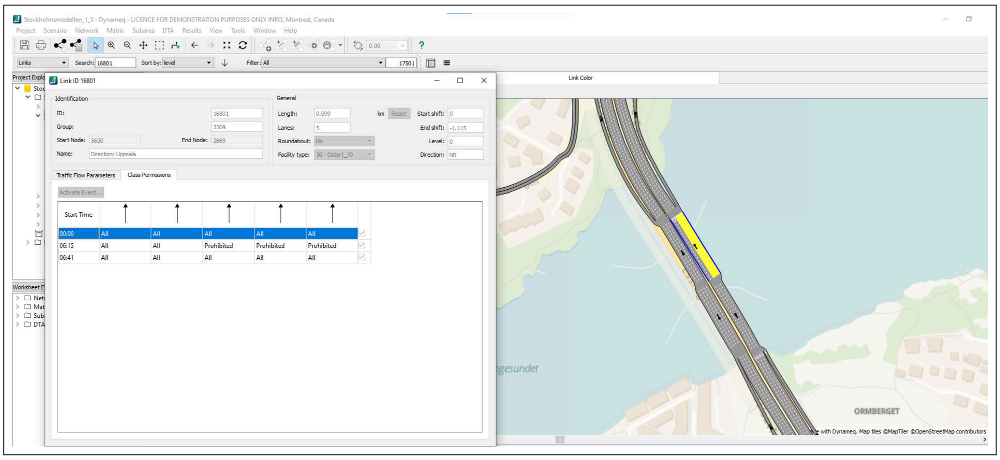


Figure 5.54: Incident 57236 after 40 iteration simulation

5.4.6 Use Case 5 - Incident 55599

Last 7th incident simulation represented an accident that had an effect on 2 right-most lanes. However, in the simulation three right-most lanes were closed to see whether the incident simulation will be closer to the actual simulation from probe data or not. Three links were thus closed at 6:15 for 26 minutes and the DTA was run with the same sensitivity setting of 0.05 like in previous cases (see figure 5.55).



Stockholmsmodellen_1_5 - Dynameq - LICENCE FOR DEMONSTRATION PURPOSES ONLY INRO, Montreal, Canada

Links | Search: 16801 | Sort by: level | Filter: All | 17501

Link ID 16801

Identification

ID: 16801
Group: 3369
Start Node: 5630
End Node: 2669
Name: Direction: Uppsala

General

Length: 0.099 km
Lanes: 5
Roundabout: No
Facility type: 30 - Ostort_70
Start shift: 0
End shift: -1.115
Level: 0
Direction: NB

Traffic Flow Parameters | Class Permissions

Start Time	↑	↑	↑	↑	↑	
00:00	All	All	All	All	All	☑
06:15	All	All	Prohibited	Prohibited	Prohibited	☑
06:41	All	All	All	All	All	☑

Figure 5.55: Network modification for incident 55599

Incident simulation result presented in figure 5.56 show that at the beginning of the incident there was a response in a form of a small bottleneck that propagated a bit upstream, but without any serious consequences. The congested area reached its peak at the end of the incident simulation and shortly after dissolved. This could mean that the demand was not that high since no spillback can be observed, even though there were 3 lanes closed. More interestingly with a one-shot simulation, there can be observed a huge congested area that starts at the same incident location but outside of the incident boundary conditions. It seems like the incident does not affect the later condition although it might had been a needed element for the traffic to break down. The bottleneck at 7:30 between the fourth and fifth kilometer starts as usual but is connected with the propagating queue from the bottleneck downstream.

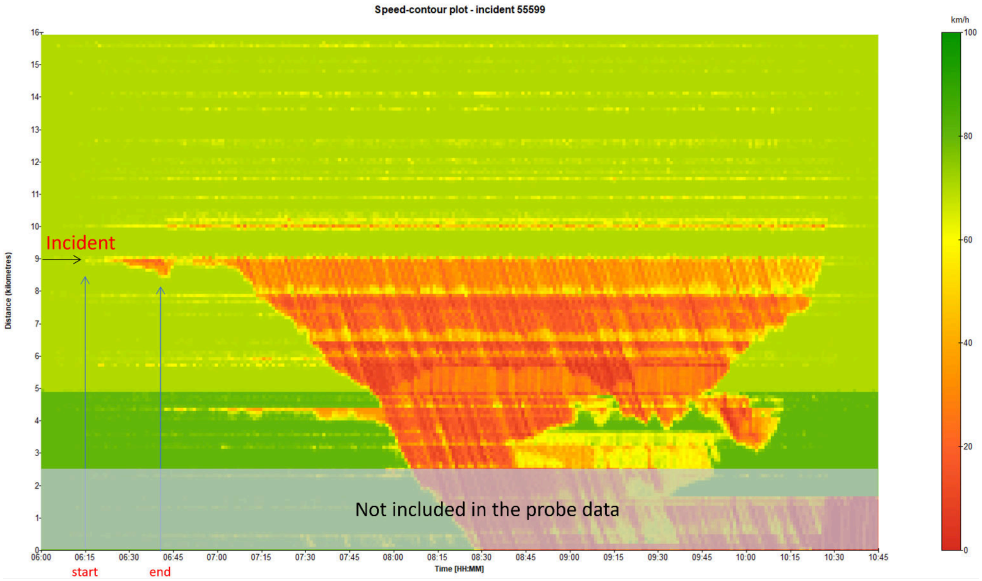


Figure 5.56: Incident 55599 simulation output

Observations from the probe data plot indicate that right after the incident occurred, there was traffic congestion with a queue spillback. However, the probe data do not quite match the simulated outcome in terms of the morning hours in the MCS data plot. The incident seems had an effect that created a traffic breakdown upstream which is not the case in the simulation plot.

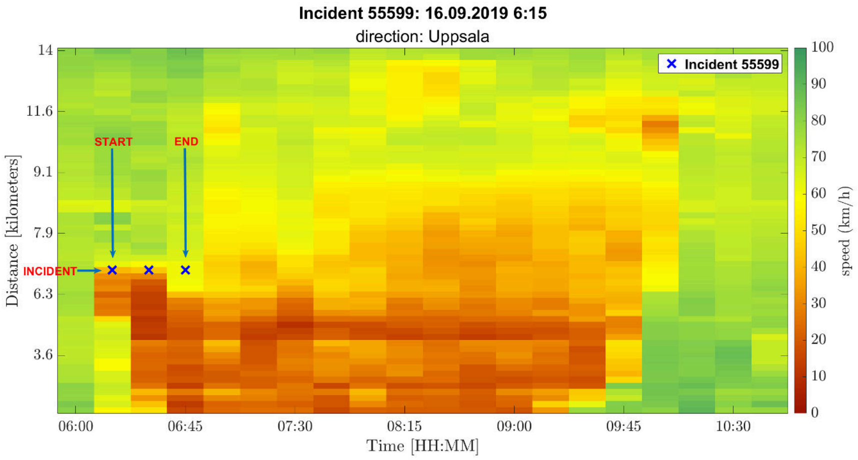


Figure 5.57: Probe data output - incident day 16.09.2019

In figure 5.58 travel times are compared which clearly indicates that the disruption in the simulation case was not that high. The graph also shows how was the traffic effected in the highly congested state later in the morning.

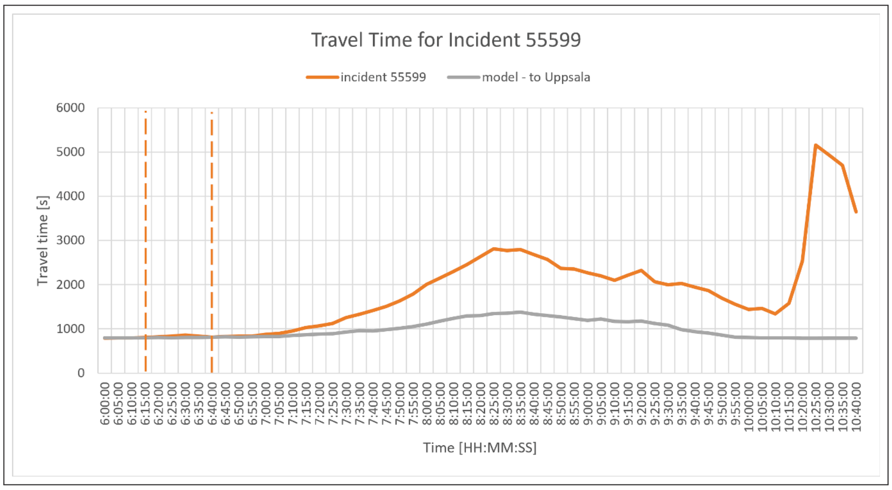


Figure 5.58: Travel time for incident 55599

40 iterations did not change the occurrence of the small bottleneck at the incident location to disappear, as can be seen in the figure 5.59. The traffic condition got back to the normal scenario observed in the original model, however. No other effects did the incident have in this case on the traffic performance.

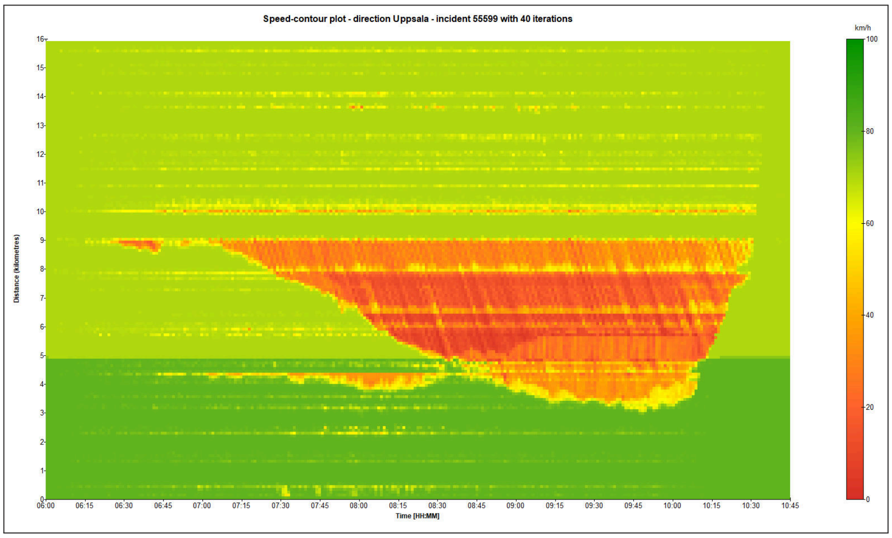


Figure 5.59: Incident 55599 after 40 iteration simulation

6 Discussion

This thesis presents an analysis of model-based decision support systems, their individual components, and functions related to traffic management, focusing on the simulation software Dynameq, which is used here for the proposed use cases based on non-recurring traffic congestion in the city of Stockholm. Ultimately, the use of Dynameq software on selected use cases was tested through incidents simulation and evaluation of measured results.

Four research questions were formulated and the proposed methodology in this work was used to find the answers to them. The methodology part consisted of two separate parts each focusing on different aspects of traffic management and DSS found in the literature with a final step of using Dynameq simulation software for defined purposes found throughout the work in a study-based simulation experiment. The following section provides a discussion of key findings in the literature overview and best practices with findings from the simulation case study to answer the following research questions.

RQ1 What are the characteristics of different traffic simulation software for traffic management?

RQ2 What main modules in a decision support system are needed for traffic management?

RQ3 What decision support system functionality does Dynameq software provide for analysis of traffic management scenarios?

RQ4 How suitable is the Dynameq model for traffic planning usable for traffic management in Stockholm?

6.1 Results of Literature Overview

The conducted qualitative analysis showed a greater benefit when the traffic is controlled in any manner that has an effect of mitigating traffic congestion and creating a more efficient transport system. Traffic management and traffic control are used in many cities today to respond to traffic situations that arise in an effort to mitigate the negative impacts of these incidents. The main pillar in traffic management and subsequently in DSS can be seen as traffic data, their collection, processing, and use for traffic models or traffic planning and management. From studied use cases from literature in this thesis, it was found that a significant improvement of strategies application is achieved with the acquisition of real-time data from traffic infrastructure, which can then provide the possibility to predict the traffic situation to a certain extent and proactively manage traffic. Acquiring up-to-date and relevant traffic data is thus an important part of traffic management, which can ultimately represent a digital twin suitable for traffic simulations if enough data is collected and relevant tools are available. The collection of detailed data with the use of new approaches such as FCD or autonomous vehicles can then help in this area for traffic management and control in the future if one considers the fact that the data provide information in detail of individual traffic lines and, in combination with other traffic data sources, an overall detailed view of the traffic situation is possible.

From the literature studied, the areas in which traffic management intervenes were identified, namely real-time monitoring of the traffic situation, traffic flow management, traffic distribution and control during special events, including incident management, and last but not least, traffic information sharing. Traffic strategies through on-road infrastructure or various forms of applied policies are used for this purpose. The concepts based on feedback or adaptive control are used for this purpose. Traffic models to which traffic data are applied are an integral part of these strategies. In the context of this work, model-based traffic models are based on this principle. However, as it was found from the literature review, the use of data is essential in their creation and calibration, but they are less demanding on the amount of input data needed. Several research papers were studied in terms of different traffic modeling approaches from micro- to macroscopic. The main models identified from the literature include the LWR model and its discretized version, the Cell-Transmission Model (CTM) in the case of macroscopic models, or car-following and lane-changing models in the case of microscopic models.

A Decision Support System has been identified as an important component for traffic management and control for traffic control centres utilizing all the incoming data and traffic models to provide support for traffic operators. The support provided within those systems is in a form of continuous observation of the network and evaluation of traffic performances where, if some facts indicate that the traffic situation may deteriorate in the next time horizon, provision of applicable strategies as a preventive measure against potential disruptions by the usage of simulation, analytical functions, and artificial intelligence approaches. A large variety of DSS concepts were found providing the necessary support on both levels - online for proactive traffic management, but also offline as a planning tool for a longer-term focus. These support systems are usually represented as modular solutions, where each module represents a given function.

The research on DSS architecture has shown the great dependence of these systems on the applied environment, which can significantly affect the composition of the support system itself. Another observation is that most DSSs use some form of database or knowledge bank and traffic-simulation models for their principle. These elements can therefore be considered essential modules for the use of tools with the purpose of application in the field of traffic management and control as DSS. Among other key modules that were found and included in the conceptual architecture figure 3.1 included the following:

- Traffic network;
- Data collection;
- Data filtering and processing;
- Traffic state estimation and prediction;
- Traffic simulation;
- Incident detection;
- AI;

- Traffic management decision centre.

The module-based architecture can also be found in most of the simulation software tools for simulation and/or decision support found in the literature of information provided on the official websites. Over the years, there were many papers created with an aim of a simulation SW overview where most of them usually compare them not in a relation to the DSS functionality or applicability. In total, 18 traffic simulation software were described (including Dynameq) and their basic characteristics for traffic management were presented. It has been found that the software is mostly not represented as a DSS tool, but rather consists of single modules, which differ in the case of each applied use case. State-of-the-art software solutions include AIMSUN Live and PTV Optima, which provide features directly referencing all the necessary traffic management functions and offer all the necessary modules for a decision support system implementation to the traffic centres. Mostly observed traffic simulation modelling approaches identified were mesoscopic with DTA models providing perspective from macro- and microscopic models enabling those software static and dynamic travel analysis at multiple levels.

Since Dynameq uses DTA models as a modeling option, a question was whether the software provides a solution to simulate traffic events and create scenarios to test different strategies. The Dynameq software is presented in the researched literature and from the available information on the internet as a model for traffic planning and simulation using dynamic user equilibrium. The ability of Dynameq to simulate traffic behaviour is achieved with the event-based simulation approach which enables fast computing times and correct representation of traffic phenomenons in the forms of traffic events. Simulation runs in iterations which stand for ”one day” during which the demand is assigned and paths between origin and destination are performed. The number of iterations can potentially be used to test a variety of strategies ranging from short-term to long-term applications by changing the number of iterations to 1. Additionally, Dynameq enables to define a specific time window that can be used to introduce a traffic incident to the network at the selected time and duration. The ability to use a warm start can also help to simulate incidents that are close to reality. However, this is depending on the quality of calibration of the traffic model. If the model is not well calibrated in the first place, the results cannot be considered creditable.

In terms of other DSS functions identified in Dynameq from the architecture figure 3.1, it must be stated that Dynameq provides limited options to be considered fully as a decision support system tool capable of providing all of them. It contains the main modules for network representation and the data can be loaded. Input data has to be filtered and processed beforehand since no tool has been identified for that in Dynameq. Traffic state estimation and prediction can be considered as present in Dynameq, as well as the traffic simulation module. Scenarios can be created and incidents, when correctly defined, simulated. Evaluation and result representation is included in Dynameq software making it possible to visualize simulated use cases. On the other hand, one key function is missing which is the actual support operating automatically and providing recommendations for operators based on real-time traffic conditions. As stated, Dynameq is a planning model which is capable of providing solutions in the long-term future. It can also provide solutions in a short-term period, but the other features that PTV Optima or AIMSUN Live provide, and what makes them more like a support system for operators, are missing. In addition, the possibility to implement various traffic management strategies, or simulate an incident with greater specifications was not found. Moreover, Dynameq can be hardly seen as a software running in real-time since the simulation run took a lot of time to complete. This is quite essential when it comes to active traffic management. The average time to run one iteration of the simulation was around 5 minutes. Hence, Dynameq could be considered useful software for a decision support system with the combination of other implemented tools and software in the traffic management centre.

6.2 Results of Simulation Case Study

The quantitative analysis was carried out in the form of a simulation case study in Dynameq software aiming to test whether the current version of the Stockholm model provided by Trafikverket can be used for traffic management. The conducted Dynameq model evaluation was performed using the original model adopted from Trafikverket, which was compared with the selected incident 57144 to indicate what could be the reason for that specific incident, and how well the Dynameq software can represent demand and speed.

The conducted analysis considered the selection of 5 different historical traffic events observed on the Stockholm network which were then applied to the Dynameq simulation and evaluated in the forms of effects they had on the traffic performance. Incidents were selected from real-world incidents that had happened during the Autumn 2019 based on many different criteria. The approach taken for the selection of appropriate incidents discovered the absence of more quality data on traffic incidents in the database and their amount. Especially, the lack of more detailed information like the number of effected lanes, what lanes were blocked during the incident, the exact location of the incident site, the number of emergency vehicles at the incident location, or more descriptive details about vehicles involved or weather. General conclusions of the selected use case scenarios are hard to get seeing that most of the incidents were not properly described. In this context, the results can be affected by the limiting factor of the incident data since only a few of them could have been used at the end. Therefore, the incident selection presented in this work could be considered as a separate methodology on its own.

From the evaluated results of the traffic flow and speed measured using MCS detectors placed on and upstream of the incident site, it can be concluded that the incident happened on that day sometime around the incident time. Both speed and traffic demand showed unusual traffic behaviour that was not representing the typical morning traffic pattern, observed the day before, for example. Oscillations can be observed in the demand case which had been probably caused by the traffic build-up during the incident. Simulated flow from the incident 57144 decreased sharply in the second half of the simulation resulting in the peak being a little bit too short, which could have affected the result. The incident demand in Dynameq was not thus quite representative since also the demand was higher, which could mean that the capacity is overestimated in Dynameq. On the other hand, the simulated incident demand was relatively matching with the MCS typical day demand.

The speed analysis of MCS data and Dynameq simulation of the selected incident suggests that the speed was a little bit lower than the actual observed speed during that day. A possible underestimation of the network's capacity in Dynameq could be the reason. It can be also concluded that after the traffic was restored due to the blocking incident, the actual traffic conditions were not immediately what they appear to be from the simulation perspective. As can be seen, the speed was still limited in the MCS case even one hour after the incident had officially ended (regarding the incident data), whereas in the simulation case the speed was already restored to its original state. This may indicate that Dynameq is underestimating the real traffic situation after the congestion was formed, or that there was still an incident in the real world after the incident or other additional influences at the scene that were limiting drivers from reestablishing the speed limit. Moreover, from the comparison of the probe speed contour plot and speed MCS data from the incident 57144, it can be stated that both sources represent the same traffic behaviour (oscillations). This could mean that the use of probe data was good and their use did not have a negative effect on the evaluation, because some parts of the probe data can be observed in the MCS data plotting or the speed contour plot from Dynameq incident 57144.

Thus, the different behavioral patterns observed in Dynameq simulation results in comparison with the real-world representation may represent three limitations of the results - first, that the capacity during the incident (the simple modelling of the incident) is misrepresented, second, that the demand in Dynameq is not representative, or third, that the definition of the incident in terms of incident duration is wrong. The demand in Dynameq has a very good start but decreases fast in comparison with MCS data, which could indicate that the capacity was lower than expected in the simulation. This could be an explanation for the fact that in the space-time diagram for the incident using probe data, where a queue is propagating upstream, but not all the way back to the starting point of the considered stretch as in the real-world case of probe data (meaning that the queue length does not reach the same length). Eventually, it may be probably due to both factors combined - incorrectly estimated capacity during an incident and the demand matrix not accurately represented in the simulation since it has a steep drop down. Another possible representation of that demand drop could be the averaging of the results over one hour window from the simulation. In the aforementioned case, when the capacity is wrongly represented in the simulation, it is usually difficult to correctly represent what happened in real life in the simulation environment, unless there is a special feature in the software available for that purpose. Nevertheless, quality incident data for that purpose is needed since the capacity factor depends on various parameters that can be represented by the fundamental diagram or just simply by the capacity of each lane, by the number of vehicles disturbing the traffic, rubbernecking, for example, etc.

The analysis of the results of the selected use cases represents three above-mentioned limitations for all simulated incidents. It was shown that the Dynameq software can reproduce the incident to some extent. It was possible to detect a queue build-up and congested areas as a result of an incident. However, when compared to the probe data, the results differ in some cases. The first use case showed more or less similar results for both simulation and probe result plots. Even after the incident, the traffic state simulated in Dynameq relatively represented the traffic state from the real-world scenario. In the second use case, no congestion was observed in one iteration nor 40 iteration simulation, although traffic behaviour was affected by the incident from the probe data clearly because of the incident. Incident 57144 which was investigated also with the provided insight into flows and speeds going to the incident showed the most prominent results out of all 5 incidents. When the incident was introduced to the one-iteration simulation, the response appeared in a form of congestion. As described earlier, even though Dynameq recorded congestion, the analysis of the probe and MCS data shows that the simulation could be affected by the mix of wrong capacity representation, demand calibration, and incident duration. This conclusion can be applied also to the fourth and fifth use case where the simulated space-time diagram did not match the probe data in any way.

Simulation with 40 iterations of the simulation with an incident was performed to see whether the traffic condition could return to equilibrium. The results showed that most of the incidents generated changes in routing.

7 Conclusions and Future Work

The present thesis aims to investigate different traffic models and provide their analysis in context to traffic management decision support tools and evaluate the potential application of Dynameq software as a decision support system (DSS) in Stockholm. A literature study, as well as a simulation case study, was used to meet the aim of the thesis. The main arguments for DSS were described in the context of traffic management centres. The key features of the DSS were presented and discussed in an architecture framework. Once the main modules of the DSS were identified, they were described. Traffic models and their relation to traffic simulation modeling were described. In total, 18 traffic simulation tools were described and their applicability as DSS was assessed. Next, Dynameq traffic simulation software was examined both from the literature perspective and in context with the traffic simulation case study. The aim was to describe Dynameq software and its functionality in terms of a DSS. Last, 5 incidents representing typical non-recurring congestion in forms of traffic incidents historically occurred during the Autumn 2019 were simulated and responses from Dynameq model were examined along with an investigation of a provided Stockholm traffic model in Dynameq. Limiting factors for the simulation results include the traffic data used, limited literature available for traffic simulation software, and the quantity and quality of available incident data.

RQ1: What are the characteristics of different traffic simulation software for traffic management?

A large number of traffic simulation software (TSS) has been developed focusing on different aspects of traffic simulation. TSS for traffic management is represented by different models, most often a mesoscopic model in combination with dynamic traffic assignment models. Cases, where micro-, meso-, and macroscopic models are combined into a hybrid model in one TSS, were also found. An important factor is the use of quality traffic data, which is either modified in the software or can be pre-processed elsewhere and then imported. Most of the identified TSS for traffic management in this work is based on a modular architecture. Each module represents a specific function of a given software that is used within a use case. Some of the software is focused on real-time traffic management like PTV Optima and AIMSUN live but also can be used for planning purposes. They differ from the other studied tools in the way they work with traffic data and how they integrate them. They also provide decision-support functionality and enable their operation in real time. Dynameq can potentially also be categorized into this group of software, however, there is not much literature on how it can be done. From the rest of the software, they can potentially also be used for traffic management as well like CUBE Dynasim, SUMO, or SimMobility. However, some of them were found to be focused only for planning purposes and thus not suitable for traffic management purposes.

RQ2: What main modules in a decision support system are needed for traffic management?

DSS modules intervene all parts of traffic management. DSS should be able to provide support to traffic operators for their decisions in a relatively short time. These modules were identified, as part of the presented DSS architecture in this work, to be the different main components for real-time DSS - traffic network and GIS, real-time traffic data collection, filtering and fusion, traffic state estimation and prediction, incident detection, traffic simulation, AI system capable of supporting the decision-making process, and visualization features providing bridging between the decision support and the traffic operator in a form of HMI. Each module can in some way contribute to understand the traffic system and to support decisions for network optimization taken by the traffic operator. In order to have real-time decision-support functionality for traffic operators, the DSS needs real-time data otherwise the purpose of the DSS can be seen as an offline evaluation tool capable of providing inputs into decisions as well, but not from the real-time DSS perspective. For full support, however, DSS should ideally be able to cooperate with other traffic management software and systems too. Finally, it is concluded that from the studied literature and research papers, research of DSS deals with the topic of applying DSS to TMC, but overall conceptual architecture view of the DSS concept and implementation in TMC is not discussed in detail. This work thus offers one possible view of the architecture of these systems.

RQ3: What decision support system functionality does Dynameq software provide for analysis of traffic management scenarios?

Dynameq is a planning software that enables setting up individual scenarios and running multiple simulations at once. Various traffic phenomena can be modelled and simulation of traffic incidents can be implemented. The model is able to be run with the incident scenario where the running of the model took on average 5 minutes. That of course may differ from the size of the model and the used hardware. Given a reasonable demand and a calibrated model, traffic state estimation and prediction results using the model can be obtained. Scenarios can be compared, and KPIs can be obtained and also compared for those scenarios in terms of travel times or total delays. Scenarios and simulation results can be visualized to provide visual support for the traffic operator's decision. To the best of the author's knowledge, any way to provide support to handle real-time data within the tool was not found. The data must be cleaned and processed elsewhere before their input to Dynameq. Also, no predefined way of modelling incidents was found. Dedicated support for managing traffic incidents by strategy application through the software, as seen in PTV Optima or AIMSUN live, was not found. When compared to other traffic simulation tools, Dynameq is not equipped with some of the modules for DSS that, for example, PTV Optima or AIMSUN live provide. Features not presented in the used version of Dynameq can be however implemented in the future.

RQ4: How suitable is the Dynameq model for traffic planning usable for traffic management in Stockholm?

Traffic incidents were able to be simulated and compared with real measured data from the network. For some of the simulated incidents, the prediction was reasonable showing some effect when an incident started. Some of the results from the incident simulation were represented with large deviations from the measured probe data results. The sources for those erroneous results can be seen in demand estimation, in the way of modelling the incident, or in the calibration of the model. For the first reason, the model used demand that represented a typical day. To improve the prediction, the ability to feed the model with real-time data should be considered. The second reason express a possible way of wrongly handling the modelling of incidents. The implementation of incident simulation was done by closing lanes. To understand how one can model an incident in more details in Dynameq it still has to be investigated and more time needs to be spend on the research. Thirdly, the calibration of the model still needs to be worked on, for example, a representation of model capacity. But, it is more likely that a combination of different error sources had an effect on the simulation results. More work needs to be conducted to see how the different error sources can be improved or done using Dynameq. The thesis also shows that it is possible to analyse model performance during incidents with GPS probe data.

7.1 Future Studies

The limiting factor in this work was the amount of data that the incident data set represented. Therefore, more information about incidents is needed to draw more conclusions on the comparisons between simulated and observed traffic states. One possible future project could concern the conversion of text description of an incident into changes in the model, as for some of the incidents in this work it was not clear sometimes what is meant by their description. Travel time could also be included in the future analysis comparing travel times observed from the probe data and from the incident simulation results from Dynameq.

A potential analysis of rerouting during incidents can be included which would provide more information about the effect of a traffic incident, how was the reaction of drivers. Incident representation in simulations should also be researched, how to represent a car accident or how to model standing vehicle incident properly using Dynameq. This could be done by changing the parameters of the fundamental diagram of the incident link.

Dynameq was used with the calibrated origin-destination matrix for the morning peak. Used demand in Dynameq thus represented a typical day that is used for planning purposes by Trafikverket. The future research should consider having real-time estimation of demand data and therefore running the simulation also in real-time. That goes along with working with more real-time traffic data sources since only some MCS and probe data were used that had been measured historically.

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