Dipl-Ing. Christina Presinger (née Flitsch)

Calibration and Validation of Mesoscopic Traffic Flow Simulation

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Supervisor

Univ.-Prof. Dipl-Ing. Dr.techn. Martin Fellendorf
Graz University of Technology, Institute of Highway Engineering and Transport Planning

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Second supervisor/evaluator:
Prof. Dr. rer. nat. Peter Wagner
Technische Universität Berlin, Transport Systems Planning and Transport Telematics
Third evaluator:
Prof. Dr.-Ing. Uwe Plank-Wiedenbeck
Bauhaus-Universität Weimar, Transport System Planning

Preface

Shortly after I have started working on the project EVIS.AT, I have discovered the complexity and the large effort behind the development of real-time-traffic data. Not only, I realised the importance behind the co-working of different fields of knowledge within a team, but as well the challenge to handle large data sets. The motivation to find a way to adjust a large scale traffic simulation of Upper Austria, with as little effort as possible and to provide some structure for others was there soon.

Undertaking this thesis has been an invaluable learning experience. I have gained some understanding of the nature of research and the need to combine various fields of knowledge. I have learned, that working with large data sets can bring one to one's limits (like computer capacity, limits of statistical programs etc.) and that there is a need to think outside the box to solve these issues. The most important rule is to know the structure behind the data and to understand the data.

I want to thank my supervisor Martin Fellendorf, who gave me the opportunity to work on this topic and pointed me into the right direction. I appreciate Peter Wagner for undertaking the role of the second supervisor and giving me new inputs. I want to thank Uwe Plank-Wiedenbeck for taking the time to evaluate my thesis.

I am grateful to have received the full support of Matthias Neubauer, without whom it would not have been possible to finish this thesis. To create the optimal working conditions he helped me not only to receive the financial support, but also has stood by my side for any kind of concern and always had my back.

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Abstract

Real-time traffic information systems are an established part of today's society. Individuals and organisations apply these systems on a regular basis to plan routes and navigate from A to B. Typically, various sensors gather the underlying data of real-time traffic information systems. The sensor data needs to be evaluated and combined to achieve high data quality. However, there is still one major problem: gathering near-real-time data for complete road network is challenging and data gaps can appear. To fill these gaps, various solutions may be applied: One possibility is to fill data gaps with historical data or calculations, another one is to use traffic simulations for gap filling. Hybrid solutions provide the possibility to re-calibrate traffic simulation models with historical sensor data. Moreover, hybrid traffic information systems need to meet two requirements: firstly, they need to be near-real time and secondly it should be possible to re-calibrate the simulation (online) fast. Using a mesoscopic simulation model has the advantage to work 100 times faster than a microscopic model and returns a more detailed level of information than a macroscopic model [1].

However, also filling data gaps with models can be challenging. The quality of traffic data, generated by traffic simulation models, depends on different aspects, such as the parameter settings of the simulation tool, or the data used for the calibration and validation of the traffic simulation model. In general, the development and maintenance of such traffic models requires a significant amount of work for developers. Developers are usually challenged when it comes to the availability of data, data selection, the selection of adequate parameter settings, the evaluation of the impact of changes in a model, etc. Further, developers need to gain a deep understanding of the system behind the model they are working with.

The overall goal of this thesis is an approach for efficient development and validation of mesoscopic simulation models for large road networks.

In this thesis two research questions are addressed:

1. How can mesoscopic traffic models for road transport networks be adjusted efficiently?
2. How can mesoscopic traffic models for large road networks be validated efficiently?

The first research question explores relevant elements for the valid development of mesoscopic traffic models. Doing so, state of the art approaches for providing real-time traffic data are analysed with respect to suitability, requirements and challenges. In the available data set, data gaps are still an issue. An approach to find similarities between traffic behaviour is developed within the thesis applying an ANOVA and Cluster analysis based on historical speed profiles. The results can be used for data gap filling and moreover to reduce a large network in a manageable number of behavioural patterns with relation to road characteristics. In addition, finding the right parameter settings is crucial for developing valid traffic models. For this reason, the effects of mesoscopic settings are analysed using a One-At-A-Time Sensitivity Analysis as well as a combination of multiple variables. The approach aims to support developers to configure parameters adequately and evaluate different parameter settings.

The second main research question addresses the validation of mesoscopic traffic simulation

models. In this context, the selected data for the validation and calibration of traffic models will influence the model quality. In order to be able to improve/to ensure model quality, requirements related to data sets and a procedural model for the data selection are presented. Finally, a validation procedure, based on the combination of the simulation goal and on the correlations between traffic behaviour and road characteristics, for mesoscopic traffic simulation models is presented, which aims to help developers to efficiently discuss changes in large networks.
In this thesis, a mesoscopic traffic simulation for Upper Austria was used, which is implemented in the SUMO (Simulation of Urban Mobility) software tool. An extensive set of historical traffic data, gained with loop detection and floating car data is used for the data analysis. The data set supported to gain insights related to finding similarities in traffic behaviour. Within an additional test-network the effects of model parameters are analysed. Furthermore, the Upper Austria model allowed to test and apply the developed procedures for efficient model calibration and validation.

Kurzfassung

Echtzeit-Verkehrsinformationssysteme sind ein fester Bestandteil der heutigen Gesellschaft. Privatpersonen und Organisationen nutzen diese Systeme regelmäßig, um Routen zu planen und von A nach B zu navigieren. Üblicherweise werden die zugrunde liegenden Daten von Echtzeit-Verkehrsinformationssystemen mithilfe unterschiedlicher Verkehrssensorik gesammelt. Die Sensordaten müssen ausgewertet und miteinander verschmolzen werden, um eine hohe Datenqualität zu erreichen. Eine flächendeckende Erfassung kann auf großen Straßennetzen eine Herausforderung darstellen, wodurch es zu Datenlücken kommt. Um diese füllen zu können, gibt es unterschiedliche Methoden. Einerseits können Datenlücken mit historischen Daten oder Berechnungen gefüllt werden, andererseits können hybride Ansätze mit einer Verkehrssimulation angewandt werden. Hybride Ansätze bieten die Möglichkeit, Verkehrssimulationsmodelle mit historischen Sensordaten zu kalibrieren. Diese müssen echtzeitnah sein und schnelle, online, Rekalibrierung der Simulation muss möglich sein. Die Verwendung eines mesoskopischen Simulationsmodells hat den Vorteil, dass es 100-mal schneller arbeitet als ein mikroskopisches Modell und einen detaillierteren Informationsstand liefert als ein makroskopisches Modell.
Allerdings kann auch das Füllen von Datenlücken mit mesoskopischen Modellen eine Herausforderung darstellen. Die Qualität der, vom Verkehrsmodell erzeugten, Verkehrsdaten hängt von verschiedenen Aspekten ab, wie z. B. den Parametereinstellungen des Simulationsprogramms oder den Verkehrsdaten, welche für die Kalibrierung und Validierung des mesoskopischen Verkehrssimulationsmodells verwendet werden. Im Allgemeinen erfordert die Entwicklung und Wartung solcher Verkehrsmodelle einen erheblichen Arbeitsaufwand für die Entwickler. Herausforderungen für die Entwickler stellen unter anderem die Verfügbarkeit von Daten, die Datenauswahl, die Wahl geeigneter Parametereinstellungen, die Bewertung der Auswirkungen von Änderungen im Modell und vieles mehr dar.
Das übergeordnete Ziel dieser Arbeit ist ein Ansatz zur effizienten Verbesserung und Validierung von mesoskopischen Simulationsmodellen für große Straßennetze.
In dieser Arbeit werden zwei Forschungsfragen adressiert:

1. Wie können bestehende mesoskopische Verkehrsmodelle für Straßenverkehrsnetze effizient verbessert werden?
2. Wie können mesoskopische Verkehrsmodelle für große Straßenverkehrsnetze effizient validiert werden?

Die erste Forschungsfrage untersucht relevante Elemente für die valide Entwicklung von mesoskopischen Modellen. Dabei werden Ansätze zur Bereitstellung von Echtzeit-Verkehrsdaten auf ihre Eignung, Anforderungen und Herausforderungen analysiert. In der verfügbaren Datenmenge sind Datenlücken ebenfalls relevant. Im Rahmen der Arbeit wird ein Ansatz entwickelt um Ähnlichkeiten im Verkehrsverhalte zu finden, indem eine ANOVA und eine Clusteranalyse auf Basis historischer Geschwindigkeitsprofile durchgeführt wird. Die Ergebnisse können einerseits zum Füllen von Datenlücken und andererseits zur Reduktion eines großen Netzes in eine überschaubare Anzahl von Verhaltensmustern in Abhängigkeit von Straßeneigenschaften

verwendet werden. Die Wahl der passenden mesoskopischen Parametereinstellungen sind ebenfalls entscheidend für die Entwicklung valider Verkehrsmodelle. Aus diesem Grund werden die Auswirkungen der mesoskopischen Einstellungen mit Hilfe einer Sensitivitätsanalyse analysiert. Der Ansatz zielt darauf ab, Entwickler dabei zu unterstützen, Parameter passend zu konfigurieren und verschiedene Parametereinstellungen zu bewerten.
Die zweite Forschungsfrage befasst sich mit der Validierung von mesoskopischen Verkehrssimulationsmodellen. Die ausgewählten Daten für die Validierung und Kalibrierung von Verkehrsmodellen beeinflussen die Modellqualität. Um die Modellqualität verbessern bzw. sicherstellen zu können, werden Anforderungen an die Datensätze und ein Vorgehensmodell für die Datenauswahl diskutiert. Schließlich wird ein Validierungsverfahren für mesoskopische Verkehrssimulationsmodelle vorgestellt. Dieses berückisichtigt die Ziele der Verkehrssimulation sowie die Erkenntnisse der Datenanalyse. Ziel des Verfahrens ist, Entwickler dabei zu unterstützen Änderungen in großen Netzwerken effizient zu identifizieren und analysieren.
In dieser Arbeit wird eine mesoskopische Verkehrssimulation für Oberösterreich verwendet, die in dem Softwaretool SUMO (Simulation of Urban Mobility) implementiert ist. Für die Datenanalyse werden historischer Verkehrsdaten verwendet, welche auf Dauerzählstellen und Floating Car Daten basieren. Für die Analyse der Auswirkungen von Modellparametern wird ein zusätzliches Testnetzes erstellt. Darüber hinaus können am oberösterreichischen Verkehrsmodell die entwickelten Verfahren zur effizienten Modellkalibrierung und -validierung getestet und angewendet werden.

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1. Introduction

Traffic simulation models are used to address different research questions. Depending on the scope, different simulation levels, microscopic, mesoscopic and macroscopic, can be applied. A traffic model of high quality should be able to reproduce a typical day of traffic behaviour in the certain area. The state-of-the-art research shows a research gap in the calibration and validation of large mesoscopic traffic simulation. The goal of this thesis is on the one hand to investigate well-fitting parameters and on the other hand to develop a procedural model for validation of large networks. Taking into account the integration of historical real-time data into the processes the research gap can be filled.
This thesis is built on an existing mesoscopic traffic simulation model for Upper Austria. The continuous collection of real-time data and the ongoing expansion of sensor technology allows to gather data sets throughout Upper Austria. An overview of various intelligent transport systems (ITS)-data sources is provided at the beginning of this thesis. Based on an exploritative data analysis the complexity in the network is reduced and a validation procedural model is developed. The parameters are investigated within a One-at-a-time-sensitivity analysis. A first validation is performed using the selected real-time data of the current state. Afterwards the re-calibration can be carried out based on the parameter investigation. The effectiveness of the calibration is evaluated by the previously defined validation process. A focus is set on commuter traffic and areas around the city centers.
The used mesoscopic traffic simulation is built with the open source program SUMO and was developed in the project EVIS-AT. In the course of the EVIS-AT project, traffic information and traffic forecasts for all of Austria are created in real time. Together with RISC Software GmbH, FH OÖ uses a hybrid calculation approach to create the real-time traffic information for Upper Austria. This means that real-time traffic data, such as permanent counting stations and Floating Car Data (FCD), is used together with a traffic simulation. Depending on the data source, it can be challenging to receive enough data for real-time traffic information service. One possibility is to fill these data gaps by including a traffic simulation. The demand model of the simulation is based on the Upper Austria household survey data of 2012 and the network on the Graph Integration Platform Austria (GIP-AT). Due to the constant development of transport and supply infrastructure not only the demand model is outdated, but also an update of the route selection has to be done. The existing simulation model can be used as a testing environment for this thesis. Also, it is possible to use the historical real-time traffic data sets for the validation process.

1.1. Research objectives

This study is limited on the calibration and validation of large traffic models with ITS purpose. The overall goal of this thesis is defined as: *"An approach for adjusting and validating mesoscopic*

simulation models for large road traffic networks efficiently." From the research goal and limitation of this thesis (compare section 1.2) it is possible to derive two main research questions. These questions are split into further questions (modules), which will be answered in the individual chapters of this thesis. The research questions are answered on the basis of literature and with the use of various statistical methods. The main research questions and the modules provide the structure of this thesis. In the following, each question is explained.
The first main research question is:
How can mesoscopic traffic models for large transport networks be adjusted efficiently?
To answer this question seven modules are defined. The answer to the first main research question is provided by the combination of each individual answer from the modules.
The first research question investigates mesoscopic parameters for large transport models. To understand which output is needed, the traffic variables need to be defined for further work (module 1.1 *"What are relevant traffic variables and data sources for ITS purposes?"*). This is accomplished in chapter 2, where an understanding for ITS data is provided by literature research. To be able to handle large data sets, an analysis to find similarities in traffic behaviour is carried out in chapter 3. In this chapter the module 1.2 *"How can data gaps of speed-over-time-profiles be filled?"* is answered by an explorative analysis using Analysis of Variance (ANOVA) and carrying out a cluster analysis. To investigate the influence of mesoscopic parameters (sub-research-question 1.3) a testing network based on the similarities of traffic behaviour found in chapter 3 is built. The module 1.3 *"How can the influence of mesoscopic parameters on different road characteristics be recognised without the need of several re-calibrations of the model itself?"* is answered by testing the influence of various mesoscopic parameters using a One-at-a-time-analysis Sensitivity Analysis (OAT). The influence is compared by using fundamental diagrams and relevant traffic variables. The impact is depicted by casual loop diagrams. These provide the answer of module 1.4 *"What impact do different parameter settings have on the simulation model?"*.
The modules 1.5/2.1, 1.6/2.2 and 1.7/2.3 are needed for the first research question as well as for the second research question.
The second main research question is:
How can mesoscopic traffic models for large road networks be validated efficiently?
A part of the answer to this question is connected to the first main research question. Three modules are needed to answer both questions. The module 1.5/2.1 *"Which data sources are suitable for the validation and calibration of large traffic models?"* is answered in chapter 5 where a procedural model is designed to find the fitting data sets for various simulation models. Using this model should help to decide which data sets can fit. Within the module 1.6/2.2 *"How can the Level of Fitness of a traffic model be determined?"* a quantitative validation model is designed. For this, Measurement of Performance (MoP) need to defined, which answer the module 1.7/2.3 *"Which methods of performance measurements are suitable for determining the Level of Fitness of mesoscopic traffic models?"*. To find weak points in large networks without the need of investigating each edge, similarities in traffic behaviour are used, which are calculated in chapter 3. This answers the modules 2.4 *"Which data can be used to find similarities in traffic behaviour over large networks?"* and 2.5 *"Which characteristics of roads do have a significant influence on traffic behaviour?"* in which traffic data and road characteristics are investigated.

1.2. Structure of the thesis and research focus

Research focus

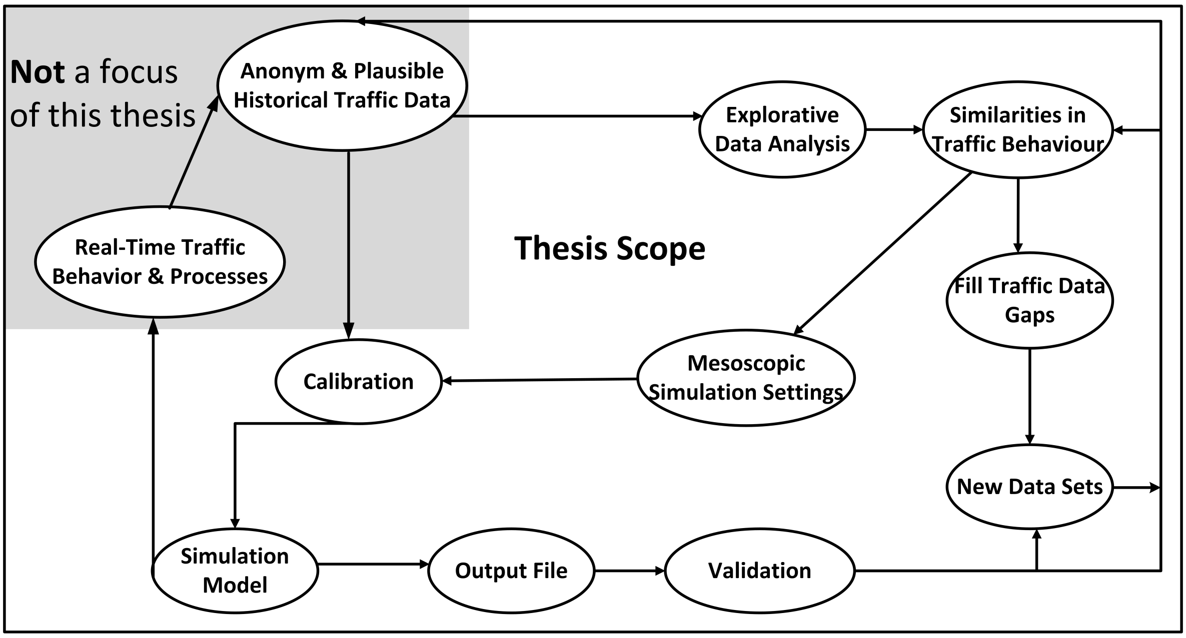

Figure 1.1.: Thesis scope

Mesosopic simulation models are built upon traffic data and demand for adequate data (pre-)processing. In order to be able to efficiently develop and validate such models, knowledge related to the underlying data basis is vital. As pictured in figure 1.1 the preparation of the data basis is not a focus in this research.
However, to be able to understand the provided data basis and settings, background knowledge of real-time traffic information and how the data is gained by sensor types is provided in chapter 2. Further, the requirements on formats and standards of traffic data in ITS are explained. Additionally, the anonymisation and plausibilisation processes are described. It is not a focus of this thesis to improve or to change the settings noted above.
Because the used network is very large, similarities in traffic behaviour are investigated to reduce the complexity of the network. An additional focus is set on commuter traffic. To accomplish finding these similarities an exploitative data analysis and data mining are carried out. Mesoscopic simulation settings are investigated to adjust and re-calibrate the model, the output data is validated afterwards. The similarities in traffic behaviour are used to find weak points in the simulation output.
By setting a limitation to the above mentioned tasks only a part of possible calibration and validation processes are discussed. The thesis focus relies on efficient processes for large traffic models with the special aspect of the further application in a real-time traffic information service.

Structure of this thesis
The first chapter "1-Introduction" and the last chapter 7 "Conclusion" provide an overview of the thesis content, results and conclusions. In chapter 2-6 the research questions are answered.

The connection of each chapter to other chapters is pointed out in this section.
In the second chapter “2-Real-time-traffic-data” an overview of different ITS initiatives and providers as well as the study area of this thesis is presented. In this chapter the module 1.1 is answered by literature research. It provides a necessary basis regarding further chapters, such as basic information about the model, data sources and traffic variables.
The third chapter “3-Similarities in traffic behaviour” focuses on finding similarities in traffic behaviour depending on different spatial conditions. Three modules (1.2, 2.4, 2.5) are discussed within this chapter. The analysis considers various road characteristics, which are tested regarding their significant influence on speed profiles. To find similarities in traffic behaviour, a cluster analysis is carried out. A focus is put on commuter traffic and the areas around cities, because it is an important aspect for ITS proposes. Therefore, an additional analysis is carried out as well. An approach to calculate inbound and outbound directions is proposed and similarities are calculated for each direction. The results can be used for two purposes: Data gaps can be filled with the results of the clusters or the network can be reduced to a manageable number of areas, which is used for the validation process (compare chapter 6).
The focus of the fourth chapter “4-Mesoscopic settings” relies on understanding the influence of different (mesoscopic) settings on models with different road categories. In this chapter two modules are answered (1.3 and 1.4). Using the results of the cluster analysis a test model is developed. Various parameters are changed by a *One-at-a-time* analysis or combined with further variables. The influence on the output data is compared to the output of the same model simulated on a microscopic level using fundamental diagrams and key traffic variables. The influence is depicted on an impact diagram (casual loop diagrams). These findings are used to re-calibrate the current Upper Austria model. The impact is validated in chapter 6.
The fifth chapter “5-Data selection for validation and calibration processes” provides a procedural model for selecting data sources for validation and calibration purposes. Within this chapter the modules 1.5/2.1 are answered. Various requirements that should be set in advance are discussed based on literature research. Defining these requirements can help to search for well-fitting data sources with a high quality. The procedural model is carried out for speed validation. With this the data sources for the validation in chapter 6 are set.
The sixth chapter “6-Validation of large models for ITS use cases” focuses on validation of models for ITS use cases with large networks. The modules 1.6/2.2 and 1.7/2.2 are addressed in this chapter. To handle the validation of large networks first a literature overview is provided with various approaches. Based on these a validation process is designed for the present model approach. The focus relies on quantitative model validation. Measurements of performance are determined to carry out the evaluation. To be able to compare the results more easily an approach for determining the Level of Fitness is provided. The validation is compared for various road characteristics as well as for the different cluster classes. Using the approach of cluster classes it is possible to find weak points in the simulation. Combining the knowledge of the model fitness with the impact of parameter settings it is possible to adjust the model up to a certain point.
In the “Conclusion” (chapter 7) a summary is provided and limitations of this thesis as well as future work is pointed out.

2. Real-time-traffic-data

2.1. ITS-solutions

All over the world different initiatives are set up to provide real-time-traffic-information for individual traffic as well as for public transport. Individual users and companies are in charge of efficiently timing departures as well as correctly estimating travel and arrival times. An incorrectly planned arrival time can result in high costs for logistic companies. For commuters, avoiding traffic jams results in higher leisure time, less stress factors and as a result a higher quality of life. However, not only for citizens traffic information is important. In case of an incident or emergency the government is responsible to prevent traffic jams and to handle traffic. Additionally, traffic management is an important initiative to reduce emissions by re-routing and providing recommendations for other modes of traffic. Traffic information is not only necessary for route planning, but also for future initiatives in the field of connected intelligent transport systems (C-ITS) such as automated and connected driving.
In exchange to receive the customers position information in real-time companies offer different applications (e.g., navigation systems)[2]. The European government supports the development of traffic information with intelligent transport systems (ITS) on international level to provide free of charge traffic information. This includes the support of ITS development by individual countries over transnational information systems as well as the development of formats, standards and interfaces to share collected information on a transnational area [3], [4], [2].
In the following it is explained how commercial providers gain traffic data and how they provide the information. Furthermore, international and cross-boarder initiatives are explained and national actions of different countries are discussed. Eventually, an overview about ITS activities in Austria is provided.

2.1.1. Commercial traffic information initiatives

Due to the requirement of precise travel and arrival time planning the need of traffic information is saturated by a large market of different commercial offers. They also offer real-time-traffic-information, traffic prognosis and provide information about traffic patterns. The European commission[3] provides an overview of available commercial traffic data for each country. The market leader are *HERE*, *TomTom* and *INRIX*. In a few countries the service of *Be-Mobile* is available. A frequently used app is *Google-Maps*. Further commercial providers and smart phone applications are available, but their services are not offered in several countries.
Table 2.1 shows an overview of the available services and update intervals of the mentioned commercial traffic information providers. Table 2.2 gives an overview of their data sources and table 2.3 summarises in which transmission formats and standards the data is available. In the following each provider is explained in detail.

HERE collects traffic information with FCD, Floating Phone Data (FPD), portable navigation devices, road sensors and connected cars. The information is available in around 100 countries all over the world, even though not every functionality is supported in all countries. The live traffic information is updated every minute by *HERE*. Real-time-traffic-data is provided by Extensible Markup Language (XML)-data scheme, as well by different formats e.g., Transport Protocol Experts Group (TPEG), RDS-TCM, Alert-C. Datex-II is also available (compare 2.2). It needs to be noted, that not every format might be available for every country. To ensure high data quality, the data is tested against historical data records and government sources. The basis for alternative routes and driver time prediction is provided by traffic patterns in 15 minute intervals. Further, traffic analysis of speed data is offered in over 57 countries with a coverage of 100% of the roads [5], [6], [7].
TomTom provides traffic information for portable navigation devices, in-dash car systems and solutions for fleet management. Real-time-traffic information is available in over 80 countries and the data is updated every 30 seconds. Service for fleet management is available in over 150 countries. The data is gathered by Global Navigation Satellite System (GNSS) measurements and mobile data, provided by government and private sources, as well as field analysis. Fleet management functionalities for tracking, routing and route optimisation are offered as well as additional information for logistics, speed profiles and address points. The data is provided by TPEG, DATEX-II (compare 2.2) and Protobuf [8] [9]. Protobuf is a standard configuration offered by TomTom. The product can be adjusted to certain needs, though when it is implemented once it can not be changed anymore [10].
INRIX is supported by various companies for example IBM, BMW, Microsoft as well as the United States Department of Transportation Federal Highway Administration. INRIX develops traffic data, travel time, trip analysis, parking data as well as a connected car platform. An artificial intelligence (AI) algorithm is used to predict traffic state, speed and calculate arrival times. Traffic data is gained by different FCD fleets (e.g., cars, trucks, taxis) and FPD. The data is updated every minute in around 30 countries. INRIX delivers data as JavaScript Object Notation (JSON), XML, RDS-Traffic Message Channel (TMC) or TPEG [11], [12].
Be-Mobile offers traffic information for traffic management, tolling, logistics fleet management, travel information (e.g., real-time-traffic information, connected vehicle information) and different mobility payments. Traffic information is provided for over 32 car-manufactures and in over 30 countries. A daughter company of Be-Mobile is *Mediamobile*. The information is transmitted by RDS-TMC, DAB-TPEG or CONNECTED (compare 2.1.2). The data is mainly sourced by FCD, but also from mobile phones, surveys, sensors, cameras and public transport. Traffic prediction is available in 15 minute to 30 minute intervals [13], [14].
Google collects traffic information either by enabling GNSS on the phone or the pattern of the wireless access points near the phone so that positions from millions of users are gathered all the time. Google receives the speed information via telephones movement. The gathered information of different people and their traffic state as well as their travel time are sent back to Google maps meaning that the data is gathered by crowdsourcing on the road [15]. Google collects comprehensive traffic data for over 200 countries and territories and advertises within a 99% coverage of the world. The data is also created for china, but the access in china might be difficult (i.e., a VPN is needed) and the information has a higher error rate. The inaccuracy is due to a different geographic position standard (e.g., not the same GNSS is used). This means, that a shift in the data accures. The reason is, that there are various geodetic datums available and in contrast to other countries, where usually WGS84 is used, in china GCJ-02 is the national standard [16],[17]. With one billion users every month, they are able to provide 25

million updates every day. Data can be collected as JSON-files (routes and distance matrix) or XML (distance matrix only). The data is collected for different traffic modes as well as different types for prognosis. The application of Google-Maps for individual use is free of charge, though for using a high amount of data, for example for different applications or as historical data, it can get expensive. Additionally, different fee-based services for companies are offered [18], [19], [20].

Table 2.1.: Overview of the available products and the update interval from different commercial providers

	Update interval	**Traffic prediction**	**Other products**
HERE	60 sec	X	X
TomTom	30 sec	X	X
INRIX	60 sec	X	X
Google	N/A	X	X
Be-Mobile	60 sec	X	N/A

X...product available
N/A...information not available

Table 2.2.: Overview of the various used traffic sources from different commercial providers

	Traffic Source				
	FCD/ GNSS	**FPD**	**XFCD**	**road sensors**	**field analysis**
HERE	X	X	X	X	N/A
TomTom	X	X	N/A	X	X
INRIX	X	X	N/A	N/A	X
Google	N/A	X	N/A	N/A	X
Be-Mobile	X	X	X	N/A	X

X...traffic source used
N/A...information not available

Table 2.3.: Overview of the available formats from different commercial providers

	Format					**Further**
	TPEG /GSM	**RDS-TMC**	**Datex II**	**XML**	**JSON**	**Formats**
HERE	X	X	X	X	N/A	X
TomTom	X	X	X	N/A	N/A	X
INRIX	X	X	N/A	X	X	N/A
Google	N/A	N/A	N/A	X	X	N/A
Be-Mobile	X	X	N/A	N/A	N/A	X

X...format available
N/A...information not available

2.1.2. Cross-border and national European ITS initiatives

Within European ITS Directive 2010/40/EU the Delegated Regulation (EU) 2017/1926 instructs all European Union (EU) Member States to provide traffic data for multi-modal travel information services. The purpose of this regulation is to make cross-border traffic information available. Harmonised interfaces, standards and formats need to be adopted to meet these requirements [4]. Too many private ITS providers lead to different levels of quality and missing harmonisation. End-users and data recipients are confronted with different services and user-interfaces. If the data is not created in a traceable way and is difficult to access, the value of the data is low. As a consequence, if public data is not used, the prices of commercial providers will rise. Therefore, it is necessary to support the development of cross-border real-time traffic data and traffic standards. In the trans-European transport network (TEN-T) corridor specifications were adopted for cross-border usage [21]. Following outstanding cross-border projects and national initiatives are explained.

Cross-border initiatives:
To meet the goal of cross-border data sharing, different projects are supported. The project *Crocodile* and follow up project *Crocodile 2* focus on the data exchange based on Datex-II. Highway operators, ministries and public authorities of 13 European Member States use the infrastructure for cross-border data exchange with the goal to provide harmonised traffic information. Their focus relies on safety and truck parking information [22].
To provide cross-border traffic information the project *Intelligent Transport Systems in South East Europe* (ITS-SEE) was carried out between 2012 and 2014 to maximize benefits from ITS deployment in the area of South East Europe. The focus was on the identification of definition gaps in ITS, as well as the optimisation, harmonisation and cooperation between independent Intelligent Transport Systems of this area. They concentrated on optimal use of road, traffic and travel data, on traffic and freight management ITS services and on ITS road safety and security applications. Core partners from different EU states were involved: Greece, Italy, Romania, Hungary, Bulgaria and Slovenia. Strategic partners from Italy, Greece, Hungary, Croatia and Albania were included as well [23].
Within the project *Linking Danube* a concept is build to connect different traffic information

systems from different countries (Austria, Czech Republic, Romania and Slovenia) with the goal to provide international multi-modal traffic information with route planning [24].
In the Mediterranean area the project *MedTIS* France, Italy, Spain and Portugal try to solve the challenges of cross-border traffic information together. They work on merging data sets for road safety solutions, traffic management service, impact evaluation and traveller information service [25].

National European ITS initiatives:
With the support of the EU Member States a national access point for ITS-data is developed. *National Access Points* provide a data-basis to find open ITS-data in each country. 13 members developed specifications as well as Key Performance Indicator (KPI) for ITS-data. For urban mobility a special action plan is provided by the European government. Cities have high demands on ITS systems due to different transport modes and technical and political issues. In the following a few examples for different national ITS-initiatives in Europe are provided. Following national ITS projects in Austria are explained [21].

MDM: In Germany the national project *MDM* (mobility data market place) gathers information from different providers. With this national access point the possibility to search as well receiving ITS-data is given. The recommended sharing format is DATEX II. The first data consumer of MDM is INRIX [26], [27].

ITS-UK: In the United Kingdom different providers gain data for traffic information. The "National Traffic Information Systems (NTIS)" are responsible for traffic data on highways over the whole country. For the Scottish area "Traffic Scottland Information Service (TSIS)" provides traffic information, in Wales it is the "Welsh National Traffic Data System", in North Ireland "Trafficwatchni.com" [28].

NDW: The Dutch National Data Warehouse (NDW) was the first nationwide ITS implementation in the world. NDW provides traffic information gained by different sensors. Using video sensors, Bluetooth-sensors, GNSS-data, loop detectors, radar detectors, floating car data and third-party data a wide range of traffic information can be gathered. Around 10 million traffic data updates are received over the complete country every day which covers nearly 10.000 km of highways, national and urban roads [29].

Austrian ITS initiatives
The government of Austria passed a law for the implementation of ITS [30]. Three important projects to build a basis for ITS are currently in progress. First, a high quality street-network is needed. The basis for this is the "Austrian Basemap". The project "Graph Integration Platform Austria (GIP-AT)" provides a new network every two months. To provide routing information for end users, in the project "traffic information Austria (VAO)" real-time information of current traffic, public as well as individual, is provided and the best route will be suggested to the user. Gaining and providing the individual traffic data is realised in the project "Realtime Traffic Information Austria (EVIS.AT)". In the following, these projects are presented.
Mobilitydata.gv.at: The Austrian National Access Point "Mobility-Data" provides an overview about public and privately generated data sets which are listed in the directive and delegated regulations of ITS [24].
basemap.at: With information from provinces and cities, an internet compatible open-data base map is created and constantly updated. It can be used as well on-line as off-line and offers a 24h service management. The map is provided by the public administrations, who are responsible

for its quality. To create an homogenised map a minimum quality was defined, which is available all over Austria [31], [32].
Graph Integration Platform Austria (GIP-AT): To provide intelligent traffic systems all over Austria, initiatives have been started. One important basis for all projects is the GIP-AT [33]. It is developed by the Austrian federal states, ASFINAG and public authorities, for example BMVIT. The graph is used as a basis for current and future mobility projects, traffic information systems, traffic planning and new modes of traffic, e.g., autonomous vehicles. One main advantage is, that the network is independent from commercial data sets. The graph is updated every two months, because by continuously including changes, the quality can be increased.
Traffic information Austria: The *traffic information Austria (VAO)* (German:"Verkehrsauskunft Österreich") is an inter-modal traffic information data hub, which is based on the GIP-AT. Individual traffic data is received from different providers all over Austria. In addition, live data is received from public transport providers. Combining the data route information, travel time, estimated arrival time and prognosis for inter-modal traffic is provided to the user. In the future VAO will receive individual traffic data directly from the Realtime Traffic Information Austria (EVIS.AT) data-hub.
Realtime Traffic Information Austria (EVIS.AT): One of the largest projects for the development of real-time-traffic data in Austria is *EVIS.AT*. 14 project partners, representing the Austrian federal states and different research institutes, are working together to develop real-time-traffic-information. The Austrian highway authorities ASFINAG are leading the project. Over 60 months, from the end of 2015 till the middle of 2021, the partners are working on a national-wide system to provide traffic information for Austria. A service for public traffic information will be offered by *VAO*. Other companies and research institutes can obtain both real-time data and daily curves for a small fee [34].

During this project interfaces and standards are developed to gain traffic data from different sources together and provide information including planned and unexpected event information. Traffic information is provided by five different institutions using different approaches to develop. Considering the requirements of the EU (compare section 2.2) as well as various providers delivering data the following challenges need to be solved:

1. Standardisation and harmonisation of traffic variables
2. Definition of provided attributes and data sets
3. Development of formats and interfaces

2.2. Requirements and challenges for real-time traffic data

To provide traffic data for large areas with a qualitative high standard the government and companies are confronted with different challenges. The cost of data collection and digitalisation of data lead to a lack of data. The lack of co-operation between providers and stakeholders and the lack of physical access to the data as well as the framework conditions for usage and re-use leads to the problem that data is not shared. As well, the lack of set quality requirements and regular data updates results in the problem of insufficient data quality. Further, the lack of harmonised standards and insufficient use of existing standards leads to data, which can not be merged easily. From the EU government point of view these problems lead to the overall problem: that there are no harmonised and available data across the EU [3].

For providers, which try to provide traffic information for a large area, the first problem "lack of data" is in the center of the focus. To gain real-time traffic data different possibilities are usually used: road sensors and GNSS-sensors. The goal is a wide range of sensors to receive necessary geographical and critical time coverage of traffic information [29]. Road sensor technology is usually installed and provided by authorities. The infrastructure can be used for traffic management, traffic information, traffic planing and in the future for autonomous vehicles. Different road sensors can be loop detectors, traffic cameras as well as Bluetooth-data [20].

Road-sensors

Inductive loop detectors: Next to microwave radar detection, inductive loop detectors are the most common traffic sensors. They are positioned next to crossings, for advanced signal traffic control systems, or on roads with a major traffic management importance. In the second case, the loops are used to gather vehicle type, speed and traffic volume. An induction loop are one or more turns of wire embedded in the asphalt. When a vehicle passes over it, it will be detected. When too loops are positioned in a small distance next to each other, it is possible to measure the speed. One advantage of inductive loops is the ability to deliver a certain number of vehicles compared to other sensor types, though they are vulnerable for errors and malfunction, because of their positions in areas with a large traffic volume. Additionally, their information is limited to the coverage area, which means a certain point on a road. The installation, which is quite expansive, requires lane closure and modifications to the road. They are provided by the government or highway authorities [35], [36], [20].
In case that two loops are available it is possible to calculate travel times between these. It should be kept in mind, that the information can be calculated within statistical methods if there are no exits or entries (e.g., vehicles within section) and as well information about the vehicle needs to be delivered (e.g., length, type, number of wheels) [37], [38], [39], [40].
Microwave radar detectors and infrared sensors: Radar detectors are detection sensors, which are positioned on the structure over or to the side of a road. This is a large benefit compared to inductive loop detection because the installation is easier and cheaper. With electromagnetic waves they have the ability to detect traffic under nearly all weather conditions, except heavy sand storms. Problems can appear, when tall vehicles pass and cover the sensor, which can reduce the accuracy. Infrared sensors can be active or passive detectors: passive detectors detect the energy, which is reflected from vehicles or other objects. They are able to detect different traffic information, though their accuracy is weather-sensitive. Active sensors release an energy that is reflected back from the vehicle. They have a high accuracy in controlled environments e.g., tunnels [36].
Bluetooth-detectors: Bluetooth-data for traffic information systems and traffic management has been used since approximate 10 years and is not as popular as FCD. Bluetooth-Senors deliver time stamps when a vehicle passes the installed sensor. If a vehicle passes two sensors, then the travel time between them can be calculated. The vehicle coverage is, compared to data from detection loops, at around 12% to 18%. Because car industry is producing an increasing number of vehicles with Bluetooth sensors, the tendency is that the amount increases [41], [42], [2], [20].
Traffic cameras with AI: To gather real-time-traffic-data traffic cameras can be used. With an artificial intelligence it is possible to measure the amount of vehicles and the vehicle-type. Disadvantages from cameras can be lighting conditions, camera movements, camera positions

and visibility problems caused by weather influence. Advantages are the tracking of vehicles as well as lane changing [43].
Further road-sensors: There are further sensors types available, in this paragraph three are listed. Ultrasonic detectors transmit pressure waves, though they are weather-sensitive. Acoustic sensors detect traffic with microphones, recognising different sounds of vehicles by the increasing of sound energy when it passes. Magnetometers are similar to inductive loop detection. They measure the change in the magnetic field resulting of the presence of vehicles [36], [43].

Floating-Car-Data
Floating Car Data (FCD) are able to deliver travel speeds and travel times by a GNSS-signal [35]. They are installed in vehicle fleets or individual cars, for example taxis, vehicles of public transport, emergency cars and trucks as well as cars of different (logistic) companies. Using FCD brings some challenges with it: the need of anonymity and plausibility checks. Not only it is necessary to ensure a well done map matching, but also to generate plausibility checks for vehicle types (taxis, public transport, emergency cars). The position of a vehicle is delivered in an interval from 3 to 45 seconds, when it is moving. A benefit of investing into FCD instead of vehicle detector loops, is that these can provide data over a large area, though, the coverage is depending on the area where the vehicles are driving. Due to the driving habits, the coverage can be higher in urban areas and on main streets through the province. Gaining traffic data by floating cars in rural areas and municipal roads can be challenging, because a lot of fleets use streets with a higher-order [2] [20], [44].

Floating-Phone-Data
For traffic information with FPD accurate positions can be used to collect speeds and as a result calculate the current traffic state. The precise GNSS-Positions depend on the telephone provider. To generate accurate positions technical effort is needed. One advantage is, that more vehicle trajectories are available. With FPD reasons for route-choice can be analysed and origin-destination matrix can be build [45], [43]. The coverage is around 2% to 5% of all vehicles [46]. The positions can be collected within GNSS data points and wireless access points. Within the wireless sensor network vehicle flow and speed are measured by the disturbances in geomagnetism. A protocol is implemented to communicate between data nodes. In the future 5G, as well as 4G, will become relevant for C-ITS and mobility management. It is already investigated within various projects (i.e., 5G-connected mobility) [47], [48], [49].
One advanced type of FCD is Extended Floating Car Data (XFCD). For example BMW already equip their vehicles with sensors, to have the possibility to provide their own traffic information system – not only with FCD but also with XFCD. XFCD provides more information for traffic, for example ice on the street or measurements of fog [50].

Traffic simulation
Because real-time data does not always cover the complete network, alternatives are used. Different applications are available to predict traffic behaviour for data gaps with simulations. A basic model provides a basis for the online-calibration, which needs to be up-to-date. Because of this, it is elaborate in maintenance. For online-calibration real-time data is needed, to recalibrate the model (see section 2.3).
Various tools are available: Simulation of Urban Mobility (SUMO) offers an on-line-recalibration tool (*TraCI*) for microscopic and mesoscopic models called *TraCI*. The traffic simulation can be recalibrated every 5 minutes [20], [44]. PTV Optima offers an implementation for microscopic models. It is currently used by *ITS-Vienna Region* (partner of EVIS.AT), the city of Erfurt

and the Direction des Routes d'Île-de-France (highway authority of Paris) for real-time traffic information [51]. Aimsun.live offers a live prediction for the next hour with a re-calibration of 2-5 minutes. Amisun Live is used for real-time traffic forecasting in the project *Calle 30 - Madrid*, for urban areas in the project *Opticities - Grand Lyon* and different projects for Air Quality [52].
Tables 2.4, 2.5 and 2.6 provide an overview and summary of the different data sources.

Table 2.4.: Overview of sensors and data for traffic information: costs and output

	Output				
	Local speed	**Traffic volume**	**Travel time**	**Route choice**	**Vehicle type**
Inductive loop detectors	X	X	X*	/	X
Radar & infrared sensors	X	X	c2	/	X
Traffic cameras	X	X	c2	c2	X
Bluetooth sensors	c	/	X	p	/
FCD	X	/	X	X	p
FPD	X	/	X	X	p
Traffic simulation	c	c	c	c	c
Statistical methods & AI	c	c	c	c	c

c2... calculation between 2 sensors
c... calculated
p... gathering possible
X... information gathered
/... not directly possible
*... some companies offer additional functions for calculation using 2 sensors

Table 2.5.: Overview of sensors and data for traffic information regarding coverage and quality

Data source	**Coverage**	**Quality**
Inductive loop detectors	100% on the segment	high
Radar & infrared sensors	100% on the segment	high (depending on position area)
Traffic cameras	100% on the segment	high-medium (depending on algorithms)
Bluetooth sensors	∼12% between 2 sensors	high-medium (depending on poition area)
FCD	area depends on the path of vehicle fleets, higher in urban areas and important streets; 2% of traffic volume	high-medium (depending on algorithms)
FPD	area depending on people using the device; 3-5% of traffic volume;	high-medium (depending on amount of users)
Traffic simulation	hole network	depending on model quality
Statistical methods & AI	depends available historic data	depending on historical data

Table 2.6.: Overview of sensors and data for traffic information regarding advantages and disadvantages

Data source	**Advantage**	**Disadvantage**
Inductive loop detectors	high quality for traffic information	
Microwave radar detectors and infrared sensors	high quality for traffic information	
Traffic cameras with AI	larage number of vehicles detection possible	lighting conditions;
		camera movements; camera positions; visibility problems;
Bluetooth sensors	route choice between two or more sensors can be detected	quality and measurement depends on the lenght and amount of crossings; interpretation mistakes possible; no large scale traffic information
FCD	coverage also in low-ranking network-possible	plausibility checks are needed
	distinction between cars and trucks possible (depending on the fleets)	equipment of vehicles with GNSS is a great effort
FPD	information can be gained for route choice, O-D-matrix;	high technical effort;
	many trajectories	GNSS-positions are not precise; quality depends on telephone provider
Traffic simulation	can be used when data is missing	the model needs to be well calibrated elaborate in maintenance
Statistical methods & AI	it is possible to fill data gaps or predict	can have a high error rate;
		needs a large data basis

Formats
To transfer real-time-traffic data different international standards are available. As pointed out in section 2.1.1 and above one major problem is that the lack of harmonised data sets and formats lead to the problem, that data can not be combined easily. Different available formats are explained below.
DATEX II: Since the early 90s different stakeholders, highway authorities and governments work on an electronic language to share and exchange traffic information. After discovering that DATEX I was not up-to-date for current technical concepts, DATEX II followed. The focus is set on the standardisation for transferring and receiving traffic data independently of the written or spoken language. New inventions, for example autonomous vehicles, bring new requirements to this standard, which means that it has to be extended. The European Commission supports and invests in the development of a harmonised data-exchange format.

As already pointed out in section 2.1.2 DATEX-II is used and improved in various projects. DATEX II contains standards for safety related messages, parking, traffic signal status and traffic data for different vehicle types. Datex II can be transmitted in XML, Unified Modeling Language (UML)2 and XMI2.1. The second formats ensure a faster and more user-friendly transmission [53].
Traffic Message Channel (TMC) is a specific application of FM RDS (Radio Data System) used for broad casting real-time-traffic data and weather information. The program works with normal FM radio transmissions, which can be received by antenna or radio. The TMC-equipped navigation system receives traffic information and decodes it. In a next step, the driver receives then a typically dynamic route guidance with alternative routes. Advantages of the TMC formats include updated traffic information in real time, immediate information about accidents, roadworks, traffic jams and information in the users' language [54].
TPEG: Transport Protocol Experts Group is a traffic industry standard for transmitting traffic data independent from client type, location or delivery channel type. It is independent from the transmission by ultra short waves. This means, that TPEG can be transmitted by internet, mobile communications as well as television. TPEG offers a high number of standardisations to reach more users. Every TPEG-service is identified with a unique Service ID (SID) worldwide. TPEG is supported by the EBU (operating eurovision and euroradio) [55], [54], [56].
CONNECTED is a fast technology to transmit TPEG or XML formats with personal content over the smartphone [13].
TN-ITS: The previous explained standards and formats are for dynamic traffic information. TN-ITS is a standard with the focus on the exchange of static data, for example speed limits. It is necessary for all ITS-applications to have an up-to-date digital map. The data is provided from governments and road authorities [57].

2.3. Study area of this thesis: ITS-Upper Austria

This section presents the underling approach of this thesis, which is the study area.
Within the project *ITS-Upper Austria (ITS-Upper Austria (ITS-UA))* and the follow-up project *ITS-UA2* RISC Software GmbH and the Logistikum - University of Upper Austria provide real-time-traffic-data with a hybrid approach for the area of Upper Austria, without highways. The projects are supported by the government of Upper Austria. Under consideration of using harmonised standards, formats and interfaces defined in EVIS.AT (compare section 2.1.2) traffic information is sent every minute to data recipients. The data is matched onto the graph of *GIP-AT*. Currently the data is sent directly to VAO as well as to the EVIS.AT-data hub (see section 2.1.2).
The goal is to develop high quality traffic data with short proceedings times. A high level of network coverage for FRC 1-4 should as well be reached. Within this project three different traffic data sets are provided:

1. Real-time-traffic data
2. Short term prognosis for the next 75 minutes
3. Long term prognosis

Though, every sensor type delivers different traffic information a structured combination of different data can lead to a solution to achieve high quality and network coverage. The system includes the following sensor types:

- Inductive loop detectors and radar detectors
- Bluetooth-sensors
- FCD

If no current traffic information is available, the gaps are filled with *a mesoscopic model*. In the following, the data management of Upper Austria is explained. Additionally, information of the available sensors are given. Further, the mesoscopic model is explained and how it is used to assist in the creation of real-time traffic situations.

Data management:
Granted that, real-time traffic information is provided constantly, different steps are required in data management. In figure 2.1 the process from gaining real-time-traffic data and developing the simulation until the output data arrives at the recipients is depicted.

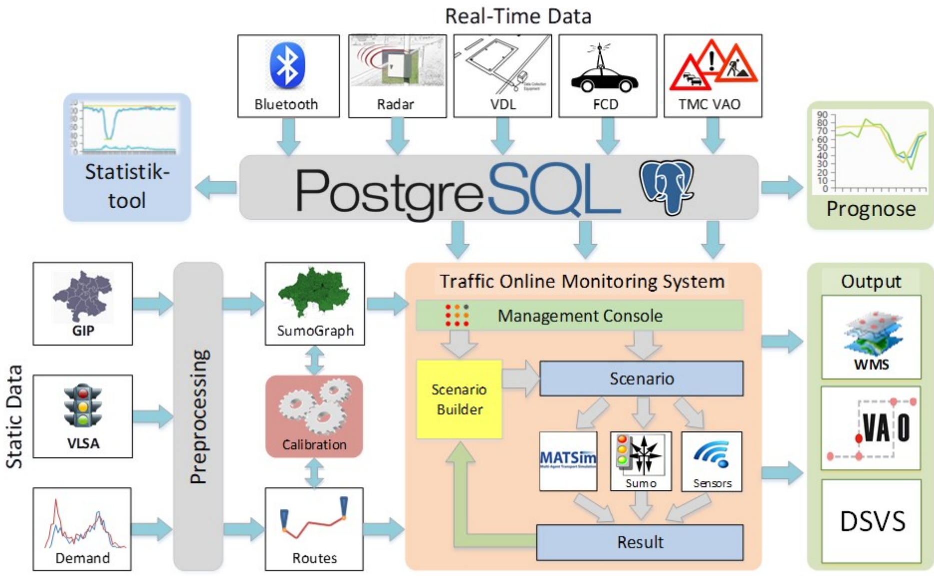

Figure 2.1.: ITS-Upper Austria data fusion (update figure compare [44])

The data is divided into *real-time-data* and *static data*. Real-time data includes all data received by different sensors as well as event messages. The historical data is stored in a "PostgreSQL"-data base. For real-time-traffic information it is forwarded and statistically stored to the Traffic On-line Monitoring System, which is called the "Management Console (MC)". The MC is the controlling part of the system, where all ITS-processes are developed, parameterised and controlled. For example, from the MC the simulation can be started and communication mechanisms between the sensors and online simulation are integrated. For traffic simulation a graph (GIP-AT), traffic signal plans and a demand model is needed. With the scenario builder *TraCI*, which is located in the MC, an on-line calibration is carried out. The scenario builder consists of the programs Simulation of Urban Mobility (SUMO), MATSim and the sensor-data. These steps are explained in detail below. In the Traffic Evaluation Statistic System (TESS) the data can be used for further analysis and data quality checks. Additional short term prognosis is calculated parallel to the real-time data. For long term prognosis speed-over-time-data are calculated. These can additionally be calculated in *TESS* for specific time intervals. Finally, traffic information is sent to Web Map Service (WMS)-layers, *VAO* and the EVIS.AT data hub [44].

Gaining traffic data:
Inductive loop detectors and radar detectors:
Currently there are around 90 detectors installed in Upper Austria, which are on-line-capable [58]. They are mainly installed on road sections that are important from a traffic management point of view, such as access roads to cities. Measurements, vehicle types and speed data is gained in real-time (compare section 2.2) [2], [20]. The data is sent to the ITS-UA system with a short transmission time.

Bluetooth-Data:
Currently around 50 Bluetooth-Sensors are installed in Upper Austria and since spring 2019 the data is collected. The vehicle coverage is, compared to the amount of vehicles from detection loops, around 12 % to 18 %. To gain data with a high quality, a filter algorithm is programmed by comparing Bluetooth-data with historical loop detection data, FCD speeds and travel time over the segment. Vehicles that choose a different route, but pass through both sensors, can be identified [2], [20] (compare section 2.2).

Floating-Car-Data:
The main data source in ITS-UA is FCD, which is already quite popular for traffic information systems(compare section 2.1.1 and 2.1.2). In Upper Austria, data is triggered from taxis, vehicles of public transport, emergency cars and trucks as well as cars of different (logistic) companies. The position of a vehicle is delivered in an interval from 3 to 45 seconds, when it is moving. The coverage depends on the catchment area of each fleet (compare section 2.2) [2], [20]. In figure 2.2 the average FCD coverage for September 2019 is depicted in relation to communities of Upper Austria. In urban areas over 18 vehicles per hour can be detected between 6 am and 8 pm, in rural and suburban areas the coverage is less. Gaining traffic data by floating cars in rural areas and municipal roads can be challenging, because a lot of fleets drive on streets with a higher-order. To ensure the data protection law, automatised anonymisation processes are implemented. This means, that every time a vehicle is started a new, random ID is assigned for the journey. In the case, that the vehicle does not move for a specified time interval (e.g., the transmitted GNSS-position does not change) the route is considered as completed. When the car starts moving again, a new, random ID is assigned. To guarantee the plausibility of the data, different algorithms for vehicle types are implemented. For taxis and buses separate lanes as well as stops are stored for plausibility checks. In addition, information gained from emergency cars is only added when they are not driving with flashing blue light.

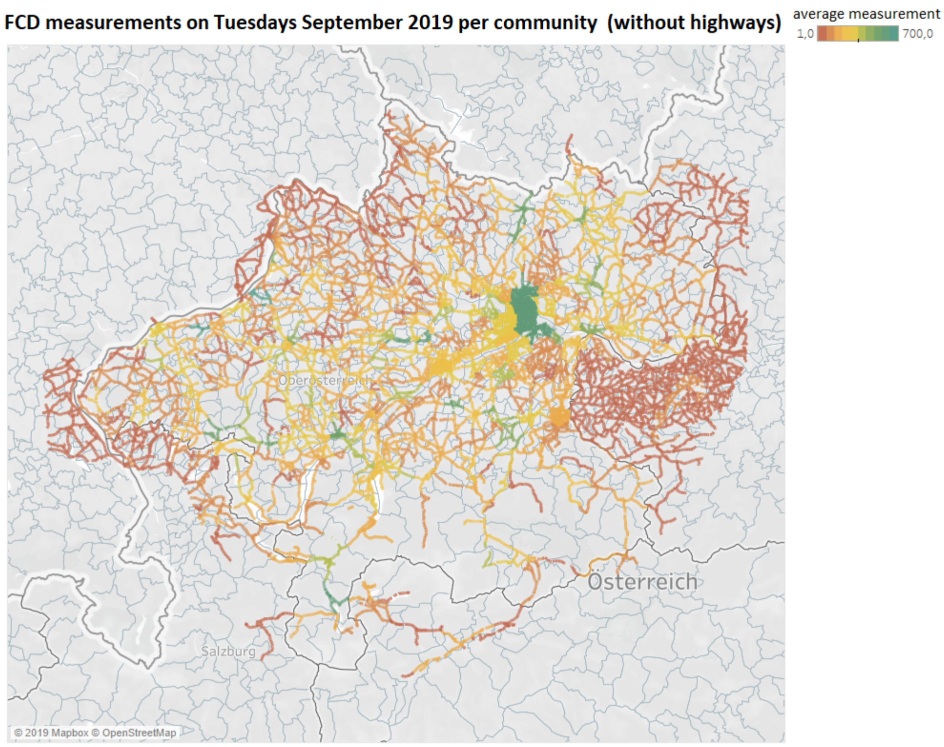

Figure 2.2.: Floating car data coverage on Tuesdays between 6am and 8pm

To generate traffic information "virtual" measurements are calculated based on transmitted trajectories: When two measurements are obtained on different edges, there may be occasions when another edge is in between without any measurement. This is due to the transmission interval. In this case the information is calculated and a "virtual" measurement is saved (compare figure 2.3). The calculation is carried out with time stamps and GNSS-positions, which are used for the calculation of the distance between the measurements. The average speed is calculated and stored for the intermediate link. Notably, validations have shown that the "virtual" measurement fits compared to real-time-traffic [20].

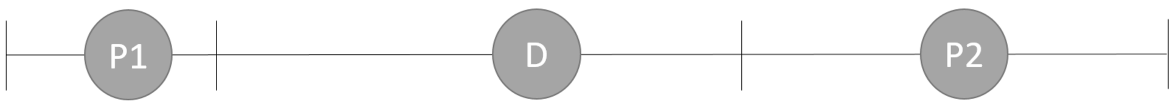

Figure 2.3.: Example for creating a virtual measurement FCD [20]

Traffic simulation:
As may be inferred from figure 2.2 a large area is not covered all the time by the available sensors. Because of this, the simulation is chosen as an additional possibility for developing efficient traffic information. The current model is simulated with a mesoscopic traffic simulation of SUMO developed by German Aerospace Center (DLR) [59]. SUMO is an open source program, which is constantly further developed by the developers themselves as well as by users. One important feature for the application regarding real-time traffic information, is the

on-line-capable calibration. With current real-time detection loop information, the model can be re-calibrated faster than real-time and the output, which is used for the traffic information, is adjusted to the current traffic situation. In order to fill gaps in the traffic data, a prognosis can be simulated. Though, this is an important feature, it is still necessary to work with a near-real-time model as a basis, because there are not enough loops all over the network available to re-calibrate the model in every area. In the following an overview is provided about:

- Why a mesoscopic model is needed
- How the "off-line" model is created
- How the "on-line" simulation works

Mesoscopic SUMO model: For a real-time traffic simulation SUMO is interesting, because the free open-source framework enables further development by the users. Albeit, with large computing power microscopic simulations can be used for large networks and/or real-time models, challenges with microscopic models for this application need to be solved, these concern, among others, the network, the routes as well as the complexity of the simulation. SUMO as well offers a mesoscopic simulation which can speed up the model between 50 to 100 times. Given that, a microscopic input is available, it can be used as a basis, but it needs to be noted that adjustments need to be done. Because of this major advantage, a mesoscopic model is chosen for ITS-UA [60], [44], [44]. The mesoscopic SUMO model and it's functions will be explained in chapter 4.
The "off-line" model: The simulation is based on the *GIP-AT* network. With the conversion to a network file for the simulation some streets with less significance for traffic are filtered. The filter is carried out under consideration of streets which are relevant for traffic, as well as edges which are needed to generate a network without gaps between the edges. One disadvantage is, that the start of trips needs to be adjusted. Because starting roads may be not included in the simulation network, there is a need to insert vehicles on road segments. This can lead to congestion or a high number of vehicles waiting to be inserted. The network can be created either with SUMO or with MATSim.
In 2012 a household survey was conducted in Upper Austria. From this survey it is possible to create origin-destination matrix for traffic simulations. This matrix was created in 2013 with VISUM under the authority of the Upper Austria government and the file forwarded to the ITS-Team to work with it as a basis for the model. The O/D-matrix should reflect the traffic behaviour during a usual working day. The trips are summarised for each hour. Based on the O/D-matrix routes are computed with a fast Dijkstra algorithm and alternative routes are as well stored. To create a better model alternative routes can be chosen or vehicles can be shifted temporarily. The "off-line" calibration is carried out in steps. SUMO runs repeatedly until 8pm for each hour at least 30 times. If there are less than 1000 vehicles arriving late, the next time end is chosen and SUMO runs again with the new stored route file. A vehicle is considered to be delayed if the average speed is too low compared to historical data [60] [44], [44].
In recent years, various people have worked on the simulation. The simulation shall be validated and calibrated to a near real-time basic traffic model. These topics are explored in the chapters 4 and 6.
The "on-line" model: After calibration of the "off-line" model, for ITS-proposes an "on-line" calibration is performed. The mesoscopic model runs parallel with the MC, the controlling environment (compare above), of ITS Upper Austria. Coupled with the MC, the sensor data is collected and traffic information calculated. Every 6 minutes the simulation is stopped and a current state of the simulated network is created (called "netstate-dump"). The output returns

values for vehicle speed (m/s), flow (vehicles/hour), occupancy (%) and the number of vehicles that pass as well as have entered but did not pass the detector. The data is compared with the current real-time information from loop detectors. The program "TraCI" returns the deviation to SUMO. The simulation will calibrate the next 6 minutes with the new input. With this output data gaps in the traffic information system are filled. ITS-UA has build a TraCI for the mesoscopic SUMO-simulation based on the TraCI for microscopic simulations. The feature was added by German Aerospace Center (DLR) at the beginning of 2020 [20].

Figure 2.4 provides an overview of the different model characterisations of the used off-line and on-line model. The influence between the offline model is depicted by the arrows in the chart.

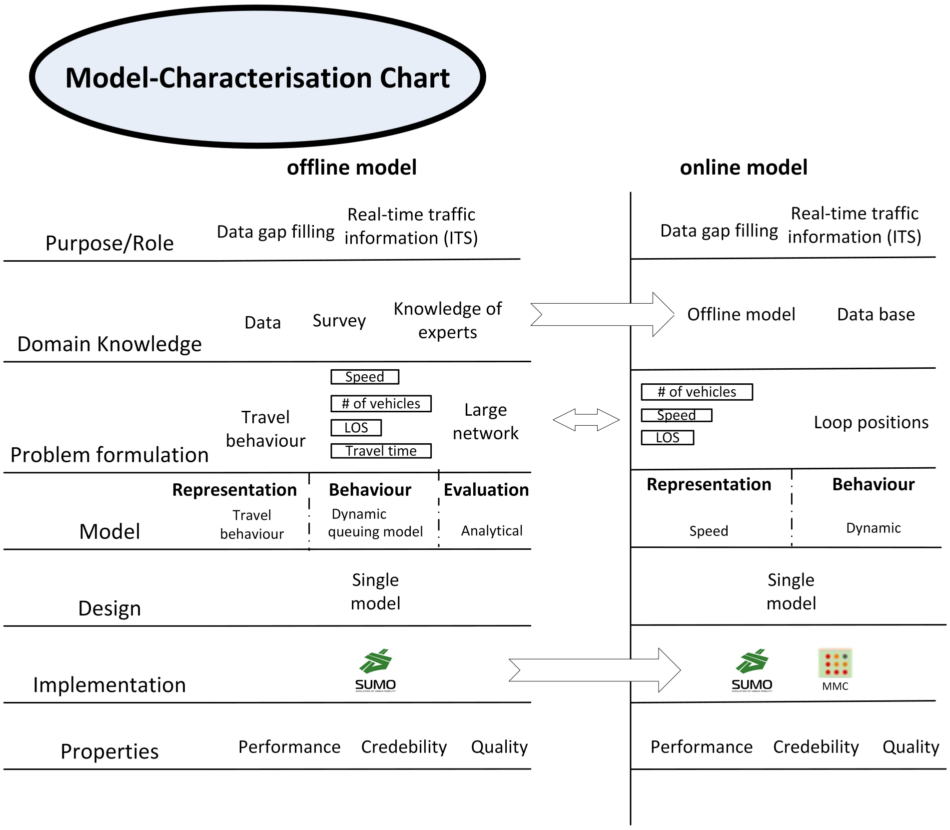

Figure 2.4.: Overview of the ITSUA model characterisation

2.4. Summary

To provide ITS Systems various data sets are available. The challenge is to gain enough data 24 hours a day for real-time-traffic information. In larger networks the coverage on main streets and urban cities is higher. Gaps can be filled with traffic analysis or traffic simulation. One objective of the EU is to support the provision of data across borders. To fulfill this goal, standards for harmonisation need to be defined. With National Access Points it is possible to provide an overview about open source ITS data in each country. However, this does not provide any information on the quality of the data.

In Austria, the *EVIS.AT* project attempts to fulfill these requirements and provide harmonised traffic information throughout Austria. The approach for ITS-Upper Austria is to gain traffic data by loop detectors, bluetooth-detectors and floating car data. To fill data gaps, a mesoscopic traffic model is provided. The goal is that the basic model reproduces typical traffic behaviour. With a tool for online calibration it can be adapted to the current traffic situation. In figure 2.5 it is depicted how the simulation model influences the data base for real time traffic information. This real-time information is used for traffic management as well as by individual users. The knowledge of traffic behaviour, travel times and routing influences the reality again. For the purpose of ITS a re-calibration of the on-line and off-line model is needed.

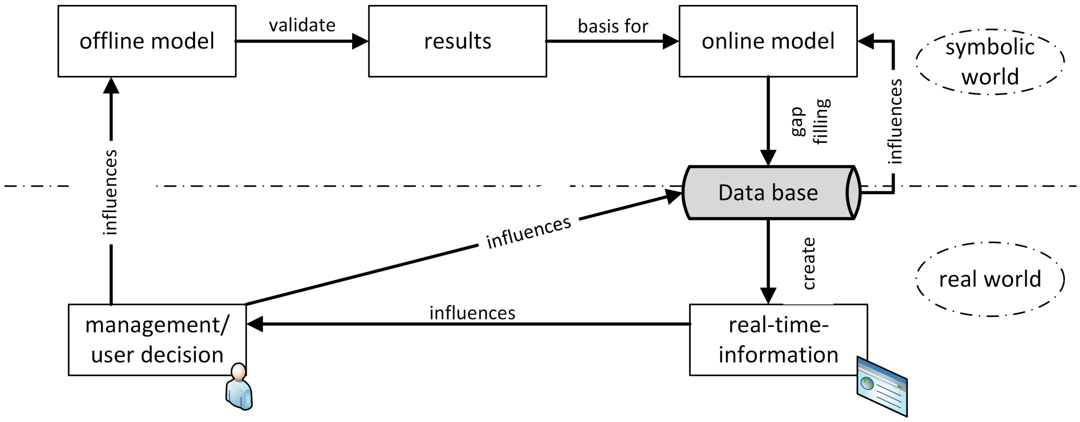

Figure 2.5.: Relationship between model and reality

3. Similarities between historical traffic data

3.1. State of the Art

It is possible to apply various methods for data analysis, therefore in this section an overview of selected, successfully conducted studies is provided. Firstly, selected research with variance analysis is presented, then the literature on cluster analysis in the transport context is addressed.

Variance Analysis of speed traffic data
ANOVA and Tukey's honestly significant difference test (Tukey's HSD test) are applied in various studies, a selection is presented in this paragraph. Xu et al. [61] have used ANOVA to explore the impact of traffic behaviour, gathered by a house holdsurvey regarding transport emissions. A one-way ANOVA test is applied to identify significant household characteristics regarding emission classes. Alonso et al. [62] have investigated the correlation between socio-demographic characteristics and aggressive traffic behaviour by using ANOVA and Tukey's HSD test. For the comparison a significance level of 0.05 is used. Peng et al. [63] have tested the influence from bad weather onto traffic situations. The analysis is applied on speed over time data with weather conditions using ANOVA.

Cluster Analysis of traffic data
Relationships of traffic data can be identified by applying a cluster analysis.
Antoniou et al. [64] uses event data from emergency vehicles, based on floating phone data, to calibrate a simulation model for a small road network with the results of a cluster analysis. With the cluster analysis it is possible to detect abnormal behaviour, which accrues in case of an emergency. A model-based cluster analysis, which includes a hierarchical clustering, expectation-maximization algorithm (EM algorithm) and Bayesian information Criterion (BIC) are used for selection of mixture models and number of classes.
Shafei et al. [65] have applied a cluster analysis to compare continuous counting points (loop detectors) with household data and to improve calibration and validation processes. With a k-means algorithm clustering and classification is applied on fundamental diagrams for dynamic traffic assignment.
Kessler et al. [66] have compared the measurement results of continuous counting points in the area of congestion zones with floating car data by cluster analysis. The results show that FCD and loop detection speed data are comparable. FCD return smaller congestion clusters than calculated with detection data.
Rahman et al. [67] have used a cluster analysis in different regional areas to determine similarities between times of day and the days of the week. The analysis is applied to various spatial conditions. The effect of marketplaces next to the roads are analysed as well as intersections. Additionally, it is analysed how factors of land use influence the traffic congestion.
Hertkorn [68] has used the cluster analysis to classify time-of-day-dependent traffic routes

(combination of route purpose) from diary data. Before the cluster analysis is contributed, a classification of the survey attributes is carried out. Applying an agglomerative clustering method (hierarchical clustering), similarities in the traffic routes, based on the classified survey attributes, are investigated.
Jeon et al. [69] has used different analysis methods to show the relevance of the influence of different urban areas. Information for more extensive network sizes is stored and analysed according to different areas. The study identifies different traffic behaviour in different urban areas as significant.
Russo et al. [70] has analysed the influences of the radius of roads in rural areas on the V85. The cluster analysis is carried out for tangent segments, circular curves and over the complete data set. For the separate analysis 10 clusters are detected, for the complete data set it returned 16 clusters. Additional filter criteria are applied before working with the results.
In summary, related studies (see table 3.1) show that cluster analysis in traffic is a proven way to reveal similarities in traffic data. On the basis of different sensor data correlations between times of day and days of the week as well as in combination with road structure similarities can be identified. The combination of a cluster analysis with pre-classification (compare Hertkorn [68]) is as well one possible approach.

Table 3.1.: Summary of selected cluster analysis literature regarding traffic behaviour

Author	**Data basis**	**Topic**	**Cluster method**
Antoniou et al. [64]	FPD emergency vehicles	calibration small simulation model	model-based cluster analysis (hierarchical clustering)
Shafei et al. [65]	loop detectors/house hold survey data	calibration/validation	k-means
Kessler et al. [66]	loop detectors/FCD	analysis if speed output data is comparable for congestion areas	algorithm for congestion cluster
Rahman et al. [67]		analysis of the impact of regional areas regarding times of day and week	agglomerative clustering method (hierarchical clustering)
Hertkorn [68]	diary data	classify time-of-day-dependent traffic routes	agglomerative clustering method (hierarchical clustering)
Russo et al. [70]	V85 different travel directions	influences of the radius of roads in rural areas on the V85	k-means

3.2. Road characteristics

Before running a cluster analysis, significant road characteristics are identified. This step has three benefits:

1. Reducing the amount of data: The speed data sets, specially with 15-Minute intervals, are large. In order to reduce the amount of data, to need less computer power and less calculation time, identifying (significant) road characteristics is one possible approach.
2. Knowledge between traffic behaviour and road characteristics in the calculated clusters (e.g., traffic categories) is gained.
3. The output of the analysis is independent from Edge-IDs and can be matched on different/updated networks if the road information is available.

In table 3.2 the available road characteristics and how the data is gained is summarised. In the following an overview of each attribute and their definitions is provided.

Table 3.2.: Overview of data source and road characteristics

Data source	**Road characteristics**
GIP-AT	FRC, Form of Way (FOW), street categories
External calculation	curvature of the road, crossing type, incoming lower and higher priority, free-flow speed
Statistic Austria	type of region
additional calculation	road direction

3.2.1. Road characteristics provided by external data sources

Road characteristics provided by GIP-AT
The graph of GIP-AT (compare chapter 2) provides *edge*-IDs and *link*-IDs for segments of a network.
An *edge* is a road segment whose geometry returns the middle of the road. For routing the edge is not usable, due to the missing information of direction. A benefit of using the edge is that the ID is more stable over different network versions (e.g., when the GIP-AT changes some IDs change).
The *link* is defined by the geometry of the middle of the road. In contrast to the edge it is split at the crossing with another link. A link always consists of two *nodes*: A start node, the *from*-node, and an end node, the *to*-node, which defines the driving direction. Each node is defined by the geometry (i.e., latitude and longitude). With this information it is possible to use links for routing.
The data set of GIP-AT includes numerous attributes. In the following selected attributes, which are used in this thesis, are explained.
Functional Road Class (FRC): the attribute defines the relevance for traffic of the segment regarding traffic planning and network related logic, where FRC 0 represents highways and 1-4 the relevant transit network. Using the GIP-AT for traffic models it is recommended to use the FRC 0-8 to receive a complete network.
Form of Way (FOW): The FOW provides information of the structural characteristic (for example: highways, roundabout, parking space) of the segment.
Street category: This attribute returns the street category defined by the street system of Austria. Relevant categories are community lanes and national street classes.
Urban: It defines if the segment is in urban or rural areas and is used additionally in chapter 6.
Regional-Code: this attribute represents the regional administrative allocation of the edge or

link, in detail it is a sequence of digits to identify communities and cities. This will be used for joining the regional structure, provided by *Statistic Austria*, to the GIP-AT data set for the upcoming analysis [71], [72].

Regional structuring by *Statistic Austria*
For regional structuring of a network various definitions are available. The most popular is the Nomenclature of territorial units for statistics (NUTS) defined by the EU, where the European Commission divides the economic territory into three different classifications. The classification in Austria consists of 35 units, in which different communities are combined [73].
In Austria two further spatial classifications are available: one defined by the ÖROK, the Austrian spatial planning conference [74], the other defined by *Statistics Austria* [73]. Due to the coarse deviation in human behaviour, *Statistics Austria* provides a categorisation for rural and urban areas under consideration of economic characteristics and population. Four main units can be derived:

- Urban Centers
- Suburban Areas
- Regional Centers
- Rural Areas

The units suburban areas, regional center and rural areas can be divided into further categories like central, intermediary and peripheral. An urban center can be divided into small, medium or large center [75].
If only one federal state is analysed, the economic characteristics are more detailed than the NUTS and in addition they take commuter traffic into account, which is relevant for Upper-Austria (compare section 3.2.2). Because of these advantages the areas are added to the GIP-AT data set, using the *Regional-Code* (compare previous paragraph).

External calculation of road characteristics
Within the project ITS-UA additional road characteristics are calculated for each GIP-AT-link. A benefit of these attributes is that they return more information about each link, which can have an impact on finding similarities of traffic behaviour. The following attributes are calculated:
Intersection type: This attribute provides information about the type of intersection at the end of a road. It is distinguished between *priority lane*, *traffic light*, *right-before-left* and *dead end*. A *priority lane* is not crossed by a higher priority lane, a link with crossing type *traffic light* has a traffic light at the *to*-node and the crossing type *right-before-left* is a crossing without a traffic light. The *to*-node of an *dead-end*-lane is not a *from*-node from another link (e.g., The road ends at the *dead-end*-lane).
Incoming lower/higher priority: This attribute is needed additionally for the crossing type. It defines how many lanes with lower or higher/same priority cross the lane. If neither a lower nor higher/same priority lane is returned (e.g., the number in both attributes is zero), no lane crosses. In this case the intersection type "*priority lane*" is returned. The crossing type *right-before-left* in combination with the attribute *incoming lower/higher priority* shows whether a vehicle on this link has priority or not.
Curvature of road: The speed of a vehicle depends on the curvature of the road (compare 3.1). To be able to take this behaviour into account the curvature of road is calculated. It is divided into *curvy*, *slighly curvy*, *straight*, *double-curvy* and *tight curves*.
Free-flow speed: The allowed speed in the GIP-AT - network is invalid for many links. To

supplement the road characteristics with a speed-attribute in the further analysis the rounded free-flow speed is used as an additional character. In general, the free-flow speed is defined as the average speed of a driver if there is no congestion [76]. In the project EVIS.AT the V85 is used for the free-flow speed.

3.2.2. Additional calculation: inbound and outbound direction

In this thesis special attention is given to the commuter traffic, due to the fact that in Upper Austria 2011 already 64,1% of all inhabitants commuted to work to a different community every day, which has an impact on the traffic in Upper Austria. The three main cities with incoming and outgoing commuters are Linz (∼108.000 commuters), Wels (∼30.000 commuters) and Steyr (∼16.000 commuters) [77].
To be able to consider jammed streets in the morning and evening the direction of the road is needed. The GIP-AT returns information about the direction by the supplementary *from* and *to* in the link-ID, though this supplementary does not provide the information if a link direction is inbound or outbound. It provides the geographic information of each *from*-node and *to*-node for each link (compare 3.2.1). With an additional attribute *direction* this information is added to the dataset and supports the correct aggregation of the traffic data. For the three cities with large commuter traffic (i.e., Linz, Wels, Steyr) a central point, with the geometry of each *center* (C), is defined by local knowledge, which is a manual step. Alternative ways to define a centre are the calculation of the centre of the polygon of the boarders of each city or using a polygon as a central area instead (e.g., automatised calculation). If the inbound or outbound direction for further cities or communities is needed the calculation algorithm can be extended.
To avoid overlap in the calculation of directions due to the geometrical proximity of the cities, a catchment area is determined for each city. Additionally, links which are far apart to the urban area, are excluded and assigned as *not calculated*.
In order to identify, if the link is directed inbound or outbound, the distance (D_{CF}) between the central point (C) and a *from*-point (F) is calculated, as well as the distance (D_{CE}) between the central point (C) and *to*-point (T), within the *Haversine* formula 3.1. It returns the great-circle distance between two points, which are defined by longitude and latitude [78].

$$d = 2r \sin^{-1} \sqrt{\sin^2\left(\frac{\varphi_C - \varphi_N}{2}\right) + \cos(\varphi_N)\cos(\varphi_C)\sin^2\left(\frac{\psi_C - \psi_N}{2}\right)} \tag{3.1}$$

d : distance
r : radius of earth
C : Center Point
N : Node of Link
φ : longitude
ψ : latitude

In the following step the direction is calculated. If D_{CF} is higher than D_{CT} it means, that the *from*-node is farther away from the center than the *to*-node. The direction of the link is defined as *inbound* (compare formula 3.2). If D_{CT} is higher than D_{CF} it indicates, that the *to*-node is farther away from the center than the *from*-node. The direction of the link is defined as *outbound* (compare formula 3.3).

$$Inbound = D_{\mathrm{CF}} > D_{\mathrm{CT}} \tag{3.2}$$
$$Outbound = D_{\mathrm{CF}} < D_{\mathrm{CT}} \tag{3.3}$$

D_{CF} : Distance between Center Point and From-Node calculated with 3.1
D_{CT} : Distance between Center Point and To-Node calculated with 3.1

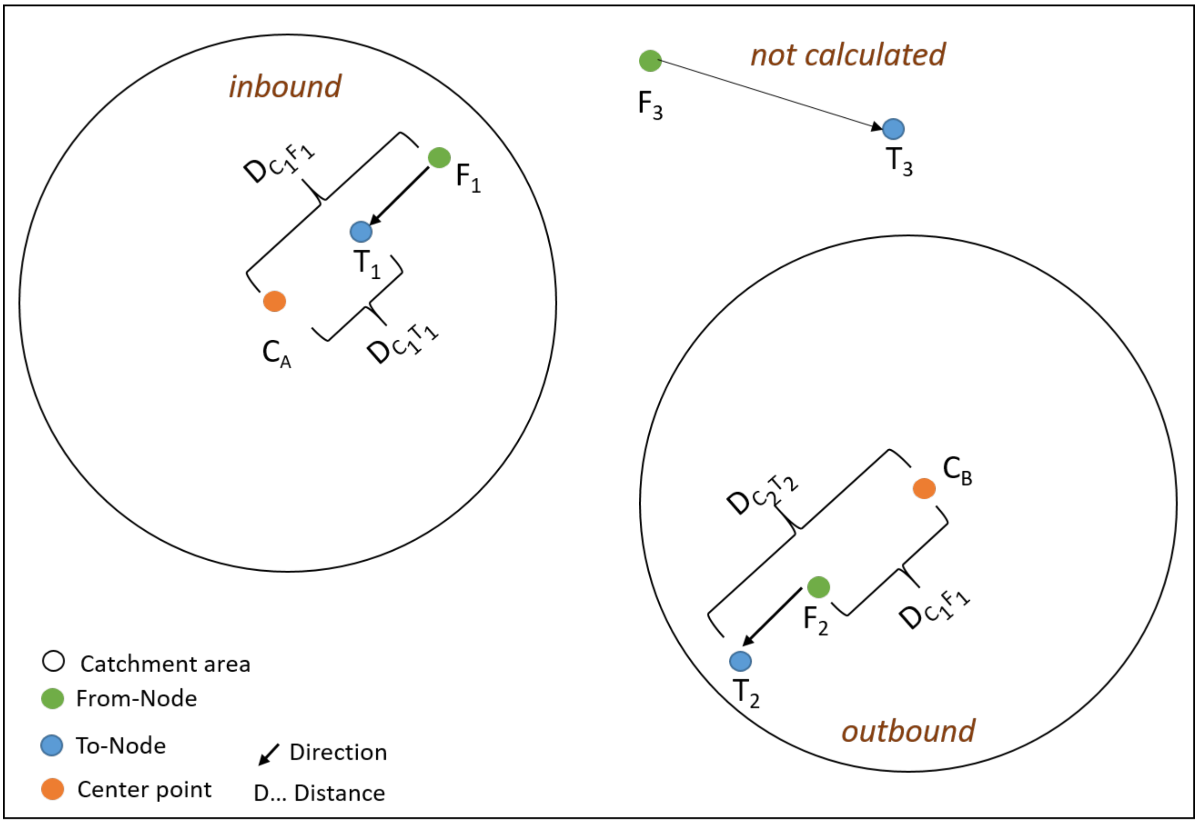

Figure 3.1.: Example for inbound/outbound calculation

In Figure 3.1 an example for the calculation of the direction is depicted. At the left the distance between the center point of city “A” (C_A) and the from- and to-node of link 1 (F_1 and T_1) is calculated. The direction is defined as *“inbound”*. Between the center of city “B” (C_B) and the link 2, with the from- and to-node F_2 and T_2, the distance is as well calculated. Using formula 3.2 and 3.3 it returns that the direction is *“outbound”*. Around every city a catchment area is determined and the link 3 is outside of the catchment areas regarding city “A” and “B”. The direction of this link is not calculated.

A quality check is carried out with Bluetooth-routes to ensure that the calculation of the direction is right. The routes of the Bluetooth consist of numerous links. The inbound and outbound of each Bluetooth-route is documented. The links of the Bluetooth-routes are used for comparison and the quality check returns that the allocation is defined realistic. A difficult example for calculation would be a ring-road around a city. It needs to be noted, that such a road might be divided into multiple edges. Each edge will receive one characteristic. In this case an additional characteristic could be added to point out the error-proneness. For example defining a minimum variance between the calculated distance of the from and to point to the center point (i.e., in a ring road the from-point and to-point might have nearly the same radius around the defined center). Though, the test returns that the calculation algorithm works, there might be a chance that errors accrue due to asymmetries.

In table 3.3 the attributes and their characteristics, which are used in the following analysis, is presented.

Table 3.3.: Spatial and structural attributes and their characteristics

Attributes	**Characteristics**
Functional Road Class (FRC)	1: freeway 2: streets of the central network 3: streets of the urban network 4: community connecting road
Form of Way (FOW)	2: divided roadway (no freeway) 3: undivided roadway 4: roundabout 10: turning lane
type of region	urban centre (UC): high, middle, and low level regional centre (RC): central, intermediary rural area in surroundings of centers (RAS): central, intermediary, and peripheral rural areas (RA): central, intermediary, and peripheral
type of street curve	curvy slighly curvy straight double-curvy tight curves
street categories	B: national street class B L: national street class L G: community lane
intersection type	priority lane traffic light right-before-left dead-end
incoming lower priority lane crossing	ILP0: no lower priority lane is crossing ILP1: one lower priority lane is crossing ILP2: two or more lower priority lanes are crossing
incoming higher priority lane crossing	IHP0: no incoming higher priority lane crossing IHP1: one higher priority lane crossing IHP2: two or more higher priority lanes crossing

Table 3.4.: Additional attributes and their characteristics

Additional attributes	**Characteristics**
free-flow-speed	between 30 and 100 km/h
direction direction	inbound outbound

3.3. Methodology and statistical analysis

Based on the State-of-the-art (compare 3.1) and technical conditions a combination of data exploration and cluster analysis is used, to detect similarities between traffic behaviour and the road network. The description of (available) road characteristics is provided in section 3.2. By performing an ANOVA and a Tukey's HSD test the significance of road characteristics regarding speed values are investigated. Combining significant characteristics of a link and speed values a new data set is build on which the cluster analysis is contributed. After identifying clusters, it is possible to assign each link to a traffic category. In the following, the methodology for the significance test as well as the cluster analysis is explained.

Influence of spatial and structural information on traffic speeds

In the following, it is distinguished between attributes and characteristics (compare table 3.3), which means, that a character is a value of an attribute.

To analyse the influence of attributes and characteristics on speed data two hypotheses are tested (compare [79]):

- H0: spatial and structural attributes and their characteristics (table 3.3) do not have an influence on travel speed
- H1: spatial and structural attributes and there characteristics (table 3.3) do have an influence on travel speed

In order to identify the significant attributes, an analysis of variance, using ANOVA, is carried out. Therefore, a Bartlett-Test is performed in advance, to prove the admissibility of ANOVA. If a correlation between the attribute and the speed-data is returned the Tukey's HSD test is conducted to investigate the correlations of each characteristic. In case, that the Tukey's HSD test indicates, that two characteristics are not correlating it is possible to join them. If the Tukey's HSD test indicates, that a characteristic has a significant influence it will be added to the link. Finally, every link has an assigned combination of significant characteristics. The test is carried out with a 95% confidence interval on speed-over-time-profiles is tested for V85 and median driving speed on a link (V50), once for the complete day and once for 15 minute intervals between 6 am and 8 pm.

The following findings are received:

Region type: All region types indicate a correlation with the speeds of the daily curves. Though, analysing V85 and V50 it is discovered that the suburban area is not significantly different to the rural area (V50 p=0.99 and V85 p=0.65). One reason for this effect could be that both directions of streets could influence the analysis by balancing the data.

FRC: The analysis of the FRC shows, that for the speed V85, V50 the characteristics are significant different.

FOW: The analysis of the FOW for V85 and V50 indicates that FOW10 and 2 are not significantly different to each other. Additionally, for V50 FOW4 is not significant different to FOW10 and FOW2. As a result, FOW10 and 2 are combined.

Crossing type: The test returns dead-ends are not significant different to traffic lights for V50.

Curve type: The Tukey's HSD test returns that the characteristics “small curves” and “curvey” are not significant different for V85 and V50 to each other. The characteristics can be combined.

Higher priority lanes crossing: The data set is adjusted before the calculation, because there were too few data record entries with more than three higher priority lanes crossing. The Tukey's HSD test indicates that all characteristics are significant.

Lower priority lanes crossing: The test results return that there is a significant difference between no lower priority lane crossing and the amount of lanes crossing.
Street categories: the data set shows that all characteristics of the attribute street categories are significantly different from each other.
To sum up, the ANOVA Analysis indicates that all attributes are significantly different regarding diverse tested speeds. Within the Tukey's HSD test it is possible to combine various characteristics, which are not significantly different. The above defined hypothesis *H1: spatial and structural attributes do have a significant influence on travel speed* is verified. A classification with all the characteristics for each link is received. In total 948 classification categories are created. Determining significant street characteristics for V50-speed 636 street-categories can be identified (compare B.1). For every classification category the max. V85, min. V85 and median of V85 over all links is calculated. In case of the speed-over-time-data-set the V50 is used.

In the following table 3.5 six examples of classification categories are depicted (compare [79]). Analogous to the V85 a data set is created for speed-over-time-data and with the additional attribute "direction". The results for the first 6 street categories for the first two intervals (e.g., 6:00 am till 6:30 am) are depicted in the appendix B.

Table 3.5.: Example for classification categories with V85

Street categories	**Max. V85**	**Median V85**	**Min. V85**
R-B-FRC1-FOW3-priority-Curvey-ILP0-IHP1	68	66	63
R-B-FRC1-FOW3-priority-Curvey-ILP1-IHP1	77	63	47
R-B-FRC1-FOW3-right_before_left-Curvey-ILP0-IHP1	83	59	36
R-B-FRC1-FOW3-right_before_left-Curvey-ILP0-IHP2	68	68	68
R-B-FRC1-FOW3-traffic_light-Curvey-ILP0-IHP1	39	35	31
R-B-FRC1-FOW3-traffic_light-Curvey-ILP1-IHP1	39	35	31

Cluster analysis
In order to identify similarities between speed data and road characteristics a cluster analysis is carried out, which is an unsupervised Machine Learning technique. In general, data points are assigned to one group, if they have similar behaviour/characteristics, while data points, which are quite different to this group, should be in another group [80].
Over the last years various methods to carry out a cluster analysis are proposed. In statistic books, for example in Backhaus et. al. [81] and Fahrmeier et. al. [82], classic algorithms (e.g., *K-means*, *Agglomerative Hierarchical Clustering*, *Single-linkage*, *complete-linkage*, *average-linkage*, *Ward-Method*) are explained. In the working paper regarding data mining in transport management and transport planning different approaches for clustering are presented. It is distinguished between hierarchical clustering, prototype based clustering (e.g., k-means, Fuzzy-c-means), density based clustering (e.g., DBCAN) and self-organizing feature maps [83].
Seif [80] explains the difference between five famous cluster algorithms (e.g., *K-means*, *Mean-Shift Clustering*, *DBSCAN* and *Agglomerative Hierarchical Clustering*). He points out, that the advantages of Hierarchical Clustering are defining the number of cluster. In addition, that it is

not sensitive to the density matrix as well as it is possible to receive a hierarchical structure. Other algorithms have the advantage of not being as time complex as the hierarchical clustering. In contrast to the hierarchical clustering, DBSCAN is very sensitive to the method behind the density matrix. DBSCAN has the advantage of identifying the noise in the data set and does not require the number of clusters in the beginning. K-means clustering is a very time efficient clustering method, though it has some disadvantages: the number of clusters needs to be set in advance. Additionally, it starts with a random choice of cluster center. This can lead to a different result within every run of the analysis [84], [80].
As can be seen, various methods for cluster analysis, with different advantages and disadvantages are available. These methods are heuristic, which means that receiving an exact solution regarding large clustering problems is not possible [85]. The data analyst faces the challenge to decide, which method should be applied.
In this thesis, a hierarchical clustering is carried out using the Ward method (see formula 3.5) with the euclidean distance matrix (see formula 3.4). This method is selected, due to the possibility to investigate the optimal number of clusters. The implemented R-Code is depicted in the appendix A.

$$d\left(x,y\right)=\left(\sum_{n=1}^{d}\left(x_{\mathrm{j}}-y_{\mathrm{j}}\right)^{2}\right)^{1/2} \tag{3.4}$$

d : distance
x : j coordinate of first data point
y : j coordinate of second data point
j : coordinate

$$D_{\mathrm{w}}\left(C_{\mathrm{j}},C_{\mathrm{k}}\right)=\frac{n_{\mathrm{j}}n_{\mathrm{k}}}{n_{\mathrm{j}}+n_{\mathrm{k}}\|\bar{x}_{\mathrm{j}}-\bar{x}_{\mathrm{k}}\|^{2}} \tag{3.5}$$

D_{CF} : Distance between Center Point and From-Node calculated with 3.1
C_{j} : object or cluster group j to match
C_{k} : object or cluster group k to match
n_{j} : amount of objects in group j
n_{k} : amount of objects in group k
x_{j} : arithmetic averages of all objects in group j
x_{k} : arithmetic averages of all objects in group k

Joining data points and clusters is contributed in the hierarchical cluster analysis until all are in one cluster. The term *Cluster validity* defines the procedure of evaluating the result of a cluster analysis [86]. The Cluster validity is usually validated running a *cluster validity index.* The quality of the result of the cluster analysis depends on the number of clusters. The analyst has to decide which number of clusters is the most suitable [87]. It is possible to choose the optimal number of clusters either manually or semi-automatic. For large data sets the manual (e.g., visual) selection is too complex, because too many branches in a dendrogram appear confusing. A semi-automatic selection returns the number of the optimal cluster without the

need of analysing dendrogram.
In the last 30 years various cluster validity indexes were developed to find the right number of clusters. For example, Miligan et al. [88] propose 30 different procedures for selecting the number of cluster groups. Rousseeuw developed the "silhoette statistic" [89] which returns a validity index for the cluster.
Charrad et al. [87] has implemented the most relevant 30 methods to compare the results of each one. This means that it is possible to investigate the recommended number of clusters for each method. To choose between the proposed number of clusters Cherrad et al. suggest two possibilities: the majority rule or by choosing one of the best recommended indices (by Milligan et al. [88] these are for example CH index, Duda index, Cindex and Beale). Applying the majority rule means to choose the number of clusters which is statistically the most recommended one.
In this thesis the approach from Charrad et al. is applied and with additional quantitative and qualitative validation steps the chosen number of clusters and the output of the cluster analysis is validated:

- quantitative validation:
  - investigating the mean, maximum and minimum speeds of each cluster group
  - investigation of the amount of different road characteristics in each group
- qualitative validation:
  - create speed-over-time-profiles based on the cluster groups (except for V85)
  - depicting the cluster groups on the map (validation with local knowledge)

In the following section the results for the applied cluster analysis are presented.

3.4. Results

To fill data gaps and to reduce the complexity in large networks, the V85 as well as the speed-over-time-data-set is analysed within the methodology explained in the previous section 3.3. This means, that the cluster analysis is carried out on the significant road characteristics, due to the benefits noted in 3.2.
The V85 is calculated between 6:00 am and 8:00 pm. The speed-over-time-data-sets contains the V50 in 15 minutes intervals between 6:00 am and 8:00 pm. The data set contains data transmitted by FCD and permanent counting stations (compare chapter 2.3). To ensure that sufficient measurements are included in the calculation, it is specified that at least 5 plausible measurements must be available in each 15 minute interval. This means that if less than 5 measurements are available, no information for speed is received (i.e., there is a data gap for the time-stamp). The calculation is done with data from June 2018, which was free of holidays and of bank holiday. For the following calculation the data set for Tuesdays-Thursdays is used to find similarities in traffic behaviour for a typical work-day.
In this section, the analysis is first carried out on the V85 and then on the speed-over-time-data-set. Due to the focus of this thesis on suburbs, the second analysis compares the influence of the attribute *"direction"* on the results as well as the investigation of each characteristic itself.

3.4.1. Clustering V85

Within the majority rule 7 clusters are proposed by 7 indexes (compare table 3.6 in the *appendix*), 6 indices propose 5 cluster groups and 4 indices propose 9. Comparing the recommended indices shows that the *CH index* proposes 7 clusters, the *Duda index* indicates 9 clusters and the *Beale index* proposes 6. The *Cindex* proposes 17 clusters, which is not implied by further indices. Due to the majority rule and the output of the recommended index 7 and 9 traffic categories are compared to each other by matching the results on the network.

Quantitative validation
To compare the speed values in each traffic categories the average of maximum V85, median V85 and minimum V85 is calculated (see table 3.6). The average median V85 speed in traffic categories 1, 4, 5 and 6 does not differ much from the average minimum and maximum speed V85 (∼5 km/h), though the speed values in traffic categories 2, 3 and 6 spread more. The values for 9 traffic categories are compared to the 7 traffic categories and indicate that the clusters with lower speed maximum values do not spread as much as clusters with a higher maximum spread value. For the value range of V85 7 cluster return better results than 9 clusters (compare [79]).

Table 3.6.: The calculated 7 traffic categories with V85-speed

Cluster index	Δ Max. V85	[km/h] Δ Median V85	Δ Min. V85
1	77	74	71
2	90	66	45
3	87	58	31
4	39	35	31
5	48	45	43
6	69	51	31
7	55	53	50

Following the characteristics in each traffic category are investigated, to understand the traffic category itself. The tables are depicted in the appendix B. For this, to each link the traffic category is added. The distribution of the individual characteristics over the transport network shows that the most links are in class 6 (∼48 %), 2(∼15 %) and 3(∼18 %). Compared to the previous analysis this shows that these are the traffic category classes in which minimum, maximum and mean value differ the most.
In addition, the comparison of the number of classifications (subsection 3.3) in each traffic characteristic returns that 21 % are in traffic category 6, 18 % in traffic category 5 and 17 % in traffic category 7.
Comparing the FRC in the different traffic categories, returns that traffic categories 1 has nearly 70 % FRC 3, which are streets of the urban network and 26 % community connecting roads. Traffic categories 4, 5 and 6 have around 80 % of all edges in these traffic categories are FRC4 and around 10-15 % are FRC3. The other types are less than 10 %. Traffic categories 3 and 7 are distributed more even over all FRC. In the traffic categories 1, 2, 5 and 6 the Form

of Way is detected for over 90 % as a divided roadway or turning lanes. 2/3 of edges in traffic category 3 are divided roadways or turning lanes, around 1/3 are undivided roadways. In traffic category 4 around 60 % are divided roadways or turning lanes, around 25 % are undivided roadways and around 15% are roundabouts. In traffic category 7 82 % are divided roadway or turning lanes, 15 % are undivided roads and 3 % are roundabouts.
Analysing the urban type, most edges (more than 78%) in traffic category 2, 3, 4 and 6 are in rural areas, 60% of all edges in traffic category 6 are in rural centers and 72% of the edges in traffic category 1 are in urban centers. It needs to be noted, that the rural area and the suburban areas are joined as one character (compare 3.3).
The road radius is distributed evenly in traffic category 3 and 7, in traffic category 4 around 60 % are straight roads. Between 75 % and 90 % of all edges in traffic category 1, 2, 5 and 6 are characterised as straight and are evenly distributed between curvy and winding segments.
More than 85 % of all edges in traffic category 2, 3 and 6 are characterised with a right rule crossing at their end. In traffic category 1 and 5 a quarter of all edges are priority lanes and three-quarter are right rule crossings, traffic category 4 has over 60 % of edges characterised as priority lanes and 20 % have a right rule and 18 % a left rule at the end.
Nearly all edges in traffic categories 1 and 6 are national streets "L", in contrast to traffic category 2 where 97 % of the edges are characterised as are national streets "B". Over 50 % of all edges in traffic category 4 are commuter lanes.
Table 3.7 provides an overview of the quantitative analysis regarding the major characteristics for V85. It can be noted, that the traffic categories 2, 3 and 6 are in rural areas. Traffic category 4 has the most edges in rural areas, but the analysis returns that there are community lanes and roads with a traffic light as well included. The reason for this can be that the rural area is joined with suburban areas, due to the significant test (see section 3.3). Traffic categories 5 and 6 are as well traffic categories for urban edges.

Table 3.7.: Summary of major characteristics in the V85 traffic categories

Traffic categories	**Street category**	**Intersection type**	**Urban type**
1	L	RBL/P	UC
2	B	RBL	RA
3	B/L	RBL	RA
4	G/L	RBL/P/TL	RA
5	B/L/G	RBL/P	RC
6	L	RBL	RA
7	B/L/G	RBL/P/TL	RA/UC

B...national street class B
L...national street class L
G...community lane
RBL...intersection controlled with right-before-left rule
P...priority lane
TL...intersection controlled with traffic lights
RA/RAS...rural area/rural areas surrounding
UC/RC...urban center/rural center

Qualitative validation
Additionally, the traffic categories are investigated by local knowledge, which helps to understand the validity of the traffic categories. The matching of the traffic categories onto the network is depicted in figure 3.2. Traffic category 6 (green) represents rural areas, in contrast to traffic category 2 (red), which contains important traffic routes through Upper Austria. This is as well valid for Traffic category 1 (pink), though there are fewer roads in this group. The visual analysis indicates that Traffic category 4 (yellow) mainly contains streets in urban centers, in contrast to traffic category 3 (grey) includes suburban areas and areas around rural centers and 5 (black) is spread on links all over the network. Traffic category 7 (blue) is mostly in urban areas and rural centers, thought there are not as many links as compared to number 4 (yellow) (compare [79]).

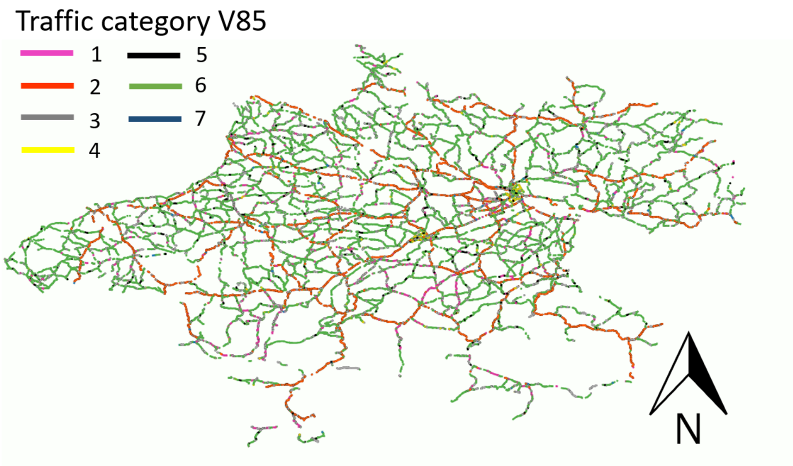

Figure 3.2.: Traffic categories for V85 matched on the network (compare [79])

The visualisation indicates that the traffic categories fit quite well to real-traffic behaviour. Within the summary of the quantitative analysis it is possible to understand the characteristics in each traffic category at first sight.

3.4.2. Clustering speed over time

In the following the results of the determined traffic categories for three different data sets are provided:

- Complete network without *direction*
- Complete network with *direction*
- Inbound/outbound lanes

Inbound/outbound lanes are analysed separately due to the focus of this thesis. Returning the results separately for each direction improves the traffic categories for these areas, which can be used for the validation in chapter 6 or for gap filling.
The number of traffic categories are determined for each cluster analysis, based on the majority rule and summed up in table 3.8. For the complete network without *direction* the ideal number

of traffic categories is seven, in contrast to the complete network with *inbound and outbound direction*, where the best number is seventeen.
For the inbound and outbound lanes the analysis is carried out for the complete network, suburban and urban areas, where the number of categories is recommended to be between six and seven.

Table 3.8.: Overview of the optimal number of traffic categories for each area

Area	**Optimal number of traffic categories**
Complete network without *direction*	7
Complete network with *direction*	17
Inbound complete network	7
Outbound complete network	6

Quantitative validation - speed values
Complete network without "direction"
To be able to understand if the results react sensitively regarding day times of the speed data, not only the traffic categories for the complete data set are investigated but as well for three different time periods: morning hours (am) (6 am till 8 am), during the day (DD) (8 am till 4 pm) and evening peak (pm) (4 pm till 8 pm). The results regarding the complete day are depicted in in figure 3.3 with an median speed for each time-stemp (15 minute interval) and indicate the following:

1. The calculation of the median speed for each traffic category and time-stamp indicate realistic results.
2. The comparison of the results of the cluster analysis for morning, evening and the complete day shows that the median speed does not differ significantly if the data set is split up for the different day times. This indicates that the results do not react sensitive regarding the day times and the cluster analysis can be carried out for the complete data set.

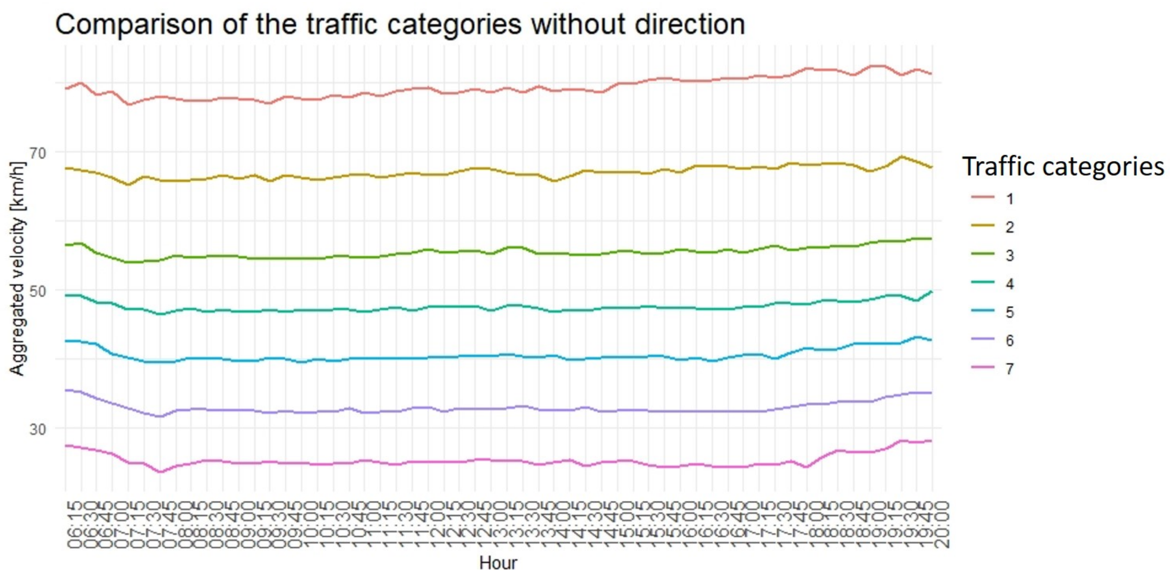

Figure 3.3.: Calculated traffic categories for speed-over-time-data without direction for the complete day

Complete network with "inbound/outbound direction"
The values of the data set returns traffic categories with clearly recognisable peaks. In 7 traffic categories the values do not differ much from each other, in these categories speeds are up to 50 km/h. In the speed range of 50 to 80 km/h as well 7 traffic categories are identified by the cluster analysis. At least one category has a wide range between the values over the complete day and a significant evening peak can be identified. Three traffic categories return speed values over 80 km/h.
In figure 3.4 aggregated speed values for each cluster are depicted, which means, that the speed values only indicate the range of each cluster (e.g., in the data set lower and higher values are possible). Generating the upper and lower quantile this range can be investigated. The figure shows, that two traffic categories return a significant evening peak and at least one a morning peak.

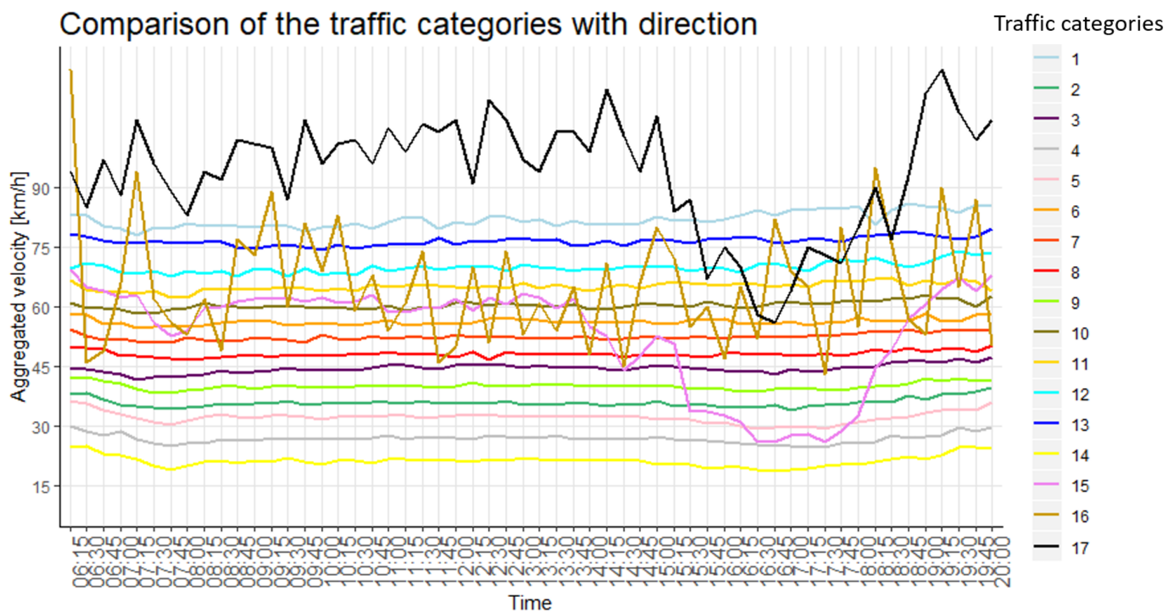

Figure 3.4.: Calculated traffic categories for speed-over-time-data with direction

Inbound/outbound direction
Investigating the speed-values in the separate inbound and outbound direction a difference between the speeds can be identified: the inbound direction has five traffic categories with values between 20 km/h and 50 km/h, compared to the outbound direction where 4 categories are in this range.
Summary
Within the attribute "direction" more clusters are recommended compared to the analysis without direction. Due to the aggregated speed values, this can have a benefit in the results. If the speed-values of each cluster is analysed, it can be noted, that many clusters are created where the aggregated speed does not scatter much. In case of the analysis with "direction" some clusters are returned with a significant peak.
Compared to the inbound/outbound direction only, the peaks are more significant in the cluster within all data sets.

Quantitative validation - characteristics in each cluster
Complete network without "direction"
The traffic categories are matched onto the GIP-AT network, where 214.093 edges can be defined by the traffic categories.
The proportions of the traffic categories on the edges are evenly distributed for five of the seven traffic categories. Traffic categories 4 and 5 represent a clear minority with 1 and 6 percent.
The FRC 1 is less than 5 % in every traffic category, in contrast to FRC 4, which dominates each traffic category. In traffic category 4 and 5 three quarters of the assigned edges are FRC 4.
Traffic categories 1, 2 and 3 are assigned to a quarter to FRC 2 and 3, and categories 6 and 7 are assigned one sixth to FRC 2 and 3.
In the next step the free-flow speed of each traffic category is compared. 99 % of edges in the first traffic category return a free-flow speed of 80 km/h, compared to traffic category 2, which

represents edges with an higher free-flow speed (90-100 km/h). Traffic category 3 represents edges with an free-flow speed around 70 km/h. Traffic category 4 represents slower streets with 30 to 40 km/h, as well as category 5, which is is assigned to edges with 40-50 km/h free-flow speed. 90 % of the edges in traffic category 6 return an free-flow speed of 50 km/h.
The most edges in each traffic category are assigned to FOW 3, though FOW 4 can only be found in traffic category 4 and 5. Between 8 % and 12 % of all edges in traffic traffic category 4, 5 and 6 have the characteristic FOW 2/10.
The validation regarding incoming lower and higher priority lanes returns that most edges of each traffic category have one lane with an higher priority crossing (e.g., do not have an lower priority lane crossing). In traffic category 4 and 5 around 80 % of the edges have a higher priority lane crossing and in these traffic categories around 11 % of the edges are crossed by two or more lanes. Between 7 % and 9 % of edges are not crossed by an higher priority lane, which is represented again in the validation for lower priority lanes crossing. In traffic category class 4, 5 and 6 edges with lower priority lanes are representative.
In traffic category 1, 2, 3 and 7 more than 50 % of all edges are in rural areas and between 20 % and 30 % of edges in these groups are in rural surrounding areas. In traffic category 1 and 2 less than 10 % of edges are in rural centers or urban center, in contrast to category 3, where 21 % are in rural and urban center. Traffic category 7 has 30 % links in urban/rural center. In traffic category 4, 5 and 6 37-40 % of edges in these groups are in rural areas, 5 % of edges of traffic category 4 are in rural surrounding areas and 54 % in urban center and traffic category 5 and 6 have 11-15% of edges in rural surrounding areas and around 40 % to 46 % in urban center.
The investigation of edges with different crossing types returns that in each group most edges have a right-before-left crossing at the end node. Over 90 % of edges in traffic category class 1, 2, 3 and 7 have a right-before-left crossing at the end, compared to category 4 and 5, where 50-60 % of all edges have an right-before-left crossing at the end node. Around 23 % of edges in these traffic category are assigned as priority lanes. Between 15 % and 24 % of all edges in traffic category 4 and 5 have an traffic light at their end node, in contrast to category 6, where 19% of all edges are priority lanes and 78 % have an right-before-left crossing at their end node.
The investigation of the road characteristic *curves* returns that most edges in each group are either straight or winding. A very low amount of curvy (less than 10 %) edges are in every traffic category and 10 % of all edges have the characteristic slightly curves in traffic category 5.
As well the street categories, provided by GIP-AT are analysed. In traffic category 1, 2, 3 and 7 around 70 % of all edges are national streets class L and around 30 % are national streets class B, in contrast to category 4, 5 and 6, in which the types are more mixed (48-59 % “L”, 18-22 % “B” and 18-34 % community lanes).
The results are listed in the appendix B.

Summary of speed-over-time traffic categories

The speed-over-time traffic categories can be calculated with the data set between 6 am and 8 pm. Dividing the day into three time periods does not significantly increase the quality of the results. The validation of the results using the median speed returns that the traffic categories fit well to real speed-over-time curves, but the peaks are not significant enough.
The investigation of each traffic category for different road characteristics return that the free-flow speed, the urban type and the street category provide information about each traffic category group. The number of incoming higher and lower priority lanes indicate that traffic category 4, 5 and 6 include around 20 % edges with an lower priority lane or more than one higher priority lane crossing. The results for the FOW and FRC show that these characteristics are mixed in each group. In table 3.9 the major characteristics of each group is listed.

Table 3.9.: Summary of major characteristics in the speed-over-time traffic categories

Traffic categories	Freeflow [km/h]	Lanes crossing type	Street category	Intersection type	Urban type
1	80	H	B/L	RBL	RA/RAS
2	90-100	H	B/L	RBL	RA/RAS
3	70	H	B/L	RBL	RA/RAS
4	30-40	L/H	B/L/G	RBL/P/TL	UC/RC
5	40-50	L/H	B/L/G	RBL/P/TL	UC/RC
6	50	L/H	B/L/G	RBL/P	RA/RAS-UC/RC
7	60	H	B/L	RBL	RA/RAS

H...higher priority lanes crossing
L...lower priority lanes crossing
B...national street class B
L...national street class L
G...community lane
RBL...intersection controlled with right-before-left rule
P...priority lane
TL...intersection controlled with traffic lights
RA/RAS...rural area/rural areas surrounding
UC/RC...urban center/rural center

Complete network with "direction"
Over 570.000 edges are allocated to traffic categories, which is compared to the analysis without direction much more, even if the "outside" edges are not considered. Traffic category 11, 6 and 2 are each allocated to over 10 % of all edges, compared to the categories 15, 16 and 17 which are allocated to less then 1000 edges.
Traffic category 15 only consists of FRC1, compared to traffic category 16 and 17 which return only FRC4. In other groups over 50 % of all links are defined as FRC4 except for 5 categories. FRC 1 to 4 are evenly distributed in these traffic categories.
The free-flow speed of traffic categories 1 and 17 is equal or greater than 100 km/h, and traffic category 16 returns a free-flow speed of 90 km/h. Traffic categories 2, 5, 10 and 14 have free-flow-speeds between 40 and 60 km/h and category 4 between 30 and 50 km/h. Traffic categories 10, 11, 12 and 13 are distributed between 70 and greater than 100 km/h.
The higher/lower lanes return that traffic category 16 only has edges which are categorised as "IHP0: no incoming higher priority lane" and category 17 is allocated to streets with one incoming higher priority lane as well as 0 lower priority crossing lanes. Traffic category 15 has one or more incoming higher priority lane and category 14 as well as 4 is allocated to all possible types. The other traffic categories are mainly matched to edges with 1 (or 0) higher priority crossing lanes.
The traffic categories 15, 16 and 17 have straight roads, in contrast the categories 1, 2, 4, 6 and 10-14 where over 50 % are allocated as edges with a small radius.
The edges of traffic categories 2, 4, 14 - 17 are located in urban centers, in contrast to the other

categories which are allocated also to edges in other areas.
The street categories of traffic category 15 and 16 are defined as national street class B, category 17 is defined as community lane. Traffic categories 1, 3, 6-8, 10-13 are matched to edges of national street class B and L.
Due to the consideration of inbound and outbound lanes, the distribution in each cluster is analysed. The statistical analysis returns that eight traffic categories are mostly allocated to outbound directed lanes, seven of the 17 categories are mixed and two are for the most amount of lanes inbound directed (e.g., over 60 %). In table 3.10 the major characteristics of each group is listed. The individual results for each category are listed in the appendix B.

Table 3.10.: Summary of major characteristics in the speed-over-time traffic categories within direction

Traffic categories	**Freeflow [km/h]**	**Lanes crossing type**	**Street category**	**Intersection type**	**Urban type**	**Direction**
1	100+	H/L	B/L	P/RBL	RA/RAS/UC/RC	I
2	40-60	H/L	B/L/G	P/RBL	UC/RC	I/O
3	50-70	H/L	B/L	P/RBL	RA/RAS/UC/RC	O
4	30-50	H/L	B/L/G	P/RBL/TL	UC/RC	I
5	40-60	H/L	B/L/G	P/RBL/TL	UC/RC	I/O
6	60-80	H/L	B/L	P/RBL	RA/RAS	O
7	70-80	H/L	B/L	P/RBL	RA/RAS	O
8	60-70	H/L	B/L	P/RBL	RA/RAS/UC/RC	I/O
9	40-60	H/L	B/L/G	P/RBL	UC/RC	O
10	70-100+	H/L	B/L	RBL	RA/RAS/UC/RC	I/O
11	80-100+	H/L	B/L	RBL	RA/RAS	O
12	80-100+	H/L	B/L	RBL	RA/RAS	I/O
13	80-100+	H/L	B/L	RBL	RA/RAS	I/O
14	30	H/L	G	P/TL	RA/RAS	I/O
15	80-90	H	B	RBL	UC/RC	O
16	90	H	B	RBL	UC/RC	O
17	100+	H	G	RBL	UC/RC	O

H...higher priority lanes crossing
L...lower priority lanes crossing
B...national street class B
L...national street class L
G...community lane
RBL...intersection controlled with right-before-left rule
P...priority lane
TL...intersection controlled with traffic lights
RA/RAS...rural area/rural areas surrounding
UC/RC...urban center/rural center
I...inbound direction
O...outbound direction

Inbound and Outbound direction in urban and suburban areas
Around 18.500 edges are matched as inbound directions in urban and rural areas, 19.000 are calculated as outbound.
The validation regarding the FRC returns similar results to the speed over-time curves without direction. Analysing the results for inbound direction, the most edges of each traffic category are characterised as FRC4, except for cluster 3 and 5, where the edges are distributed equally to each FRC. This is valid also for the outbound direction.
In this analysis only the suburban and urban areas are analysed, which means that the inbound edges can be in either of these areas. The analysis returns that the traffic categories 2, 3 and 7 inbound are over 89 % allocated to urban centers. Traffic categories 5 and 4 are allocated equally to urban and suburban areas, in contrast to categories 1 and 4, which are matched mostly to suburban areas. Regarding outbound direction the analysis returns that two traffic categories are allocated to suburban areas, two to urban areas and the other two are spread over both areas.
Investigating the edge characteristics regarding inbound directions returns for traffic category 1, 4, 5 and 6 that most edges have a right-before-left intersection rule at their end node, in contrast to traffic categories 2 and 7, which indicate a mix of all intersection types. In category 3 around 60 % of all edges are priority lanes and 35% of edges have a right-before-left intersection rule at their end node. Traffic category 1, 5 and 6 outbound directed are matched to most edges with an right-before-left rule intersection, compared to edges in category 2, which mixed with all intersection types. In the categories 3 and 4 most edges return a right-before-left rule or are defined as priority lanes.
In inbound direction over 80 % of the edges in category 4 and 6 are characterised as national streets “L”, the edges in traffic category 1 and 5 are either national streets “L” or “B” and the edges in category 2 and 7 are categorised as community lanes. The edges of cluster 3 have various characteristics.
Traffic categories 2 and 3, outbound directed are mainly characterised as community lanes, traffic categories 1, 4 and 5 the edges are either national streets “L” or “B” and in category 6 the most edges are national streets “L”. In the tables 3.11 and 3.12 a summary of the results for each direction is presented. The individual results for each category are listed in the appendix B.
The traffic categories are very similar for inbound and outbound direction.

Table 3.11.: Summary of major characteristics in the speed-over-time traffic categories with inbound direction

Traffic category	FRC	Freeflow [km/h]	Street category	Intersection type	Urban type
1	1/2	100+	G/B/L	RBL	RAS
2	4	40	G/B/L	RBL/P/TL	UC
3	4/1/2	50	L	RBL/P	UC
4	4	50-60	B/L	RBL	RAS/UC
5	1/2/3/4	60-70	B/L	RBL	RAS/UC
6	4/3/2	70-80	L	RBL	RAS
7	4	30-40	G	RBL/P/TL	UC

B...national street class B
L...national street class L
G...community lane
RBL...intersection controlled with right-before-left rule
P...priority lane
TL...intersection controlled with traffic lights
RA/RAS...rural area/rural areas surrounding
UC/RC...urban center/rural center

Table 3.12.: Summary of major characteristics in the speed-over-time traffic categories with outbound direction

Traffic category	FRC	Freeflow [km/h]	Street category	Intersection type	Urban type
1	2/4	70-100+	G/B/L	RBL	RAS
2	4	30-50	G/B/L	RBL/P/TL	UC
3	4	40-50	L	RBL/P	UC
4	4(1-3)	50-60	B/L	RBL/P	RAS/UC
5	1/2/3/4	70	B/L	RBL	RAS/UC
6	4/3	80	L	RBL	RAS

B...national street class B
L...national street class L
G...community lane
RBL...intersection controlled with right-before-left rule
P...priority lane
TL...intersection controlled with traffic lights
RA/RAS...rural area/rural areas surrounding
UC/RC...urban center/rural center

3.5. Summary and conclusion

In this chapter historical traffic data sets are investigated to find similarities between speed behaviour. One condition is that it should be possible to reuse the results on updated graphs. In other words, the results should be independent from edge-IDs. Therefore, significant road characteristics are identified and connected with speed data sets.
Literature shows, that clustering traffic data with road characteristics and considering different spatial areas is a proven method. To be able to find similarities regarding commuter traffic additionally the direction of relevant edges is needed, therefore a calculation method is presented in this chapter.
Applying a cluster analysis, similarities between three different traffic data sets are identified: the free-flow speed (V85), speed-over-time curves and speed-over-time curves with direction.
The results show that the best number of traffic categories for all data sets is 7 or 6 for V85 and for speed-over-time-analysis without direction, in contrast to the analysis with direction, where 17 traffic categories are identified. The indices, which propose the number of traffic categories, mostly determine the maximum value regarding the number of traffic categories.
Calculating speed-values for each traffic category return realistic curves/data sets, though a weakness in the output of the speed-over-time results is that the speeds in the morning and evening peak do not collapse strongly enough, which is due to the missing inbound/outbound direction.
Adding inbound/outbound to the data basis the results return this behaviour.
The analysis for each characteristic, in each category, returns that usually not only one characteristic is allocated to the clusters, which indicates the not only one characteristic can identify the similarities between speed data, e.g., a mixture of various characteristics is necessary.
The characteristics free-flow speed, street category and intersection type return information to be able to use the traffic categories in further analysis, for example validation of traffic models (see chapter 6).
Comparing the State-of-the-Art with the results of this chapter returns that classification is an important step at the beginning of the analysis (compare Hertkorn [68]). Jeon et al. [69] and Rahaman et. [67] al. investigate the influence of different regional areas and urban areas. In the validation of the results it turns out that this information has a major influence on the cluster structure. Adding the information of direction to the road characteristics changes the cluster results. Not only the values in the speed-over-time curves return a better fitness, but also the proposed best number of traffic categories vary. Russo et al. [70] investigates the influence of different V85 data with different travel direction regarding the radius of roads in rural areas, though various number of cluster for each curve type is tested. The results of the cluster analysis in this thesis show that the radius type has a significant influence on the speed-data set. However, the individual traffic categories can not be identified only by the radius type. The validation shows that the combination of curvature with other road characteristics has the strongest influence on cluster formation.
In this chapter three modules are worked out.
"Which characteristics of roads do have a significant influence on traffic behaviour" is discussed in section 3.3. Finding significant characteristics depends on the speed-data set, these are explored using ANOVA and Tukey's HSD test.
The sub-research question *"How can data gaps of speed-over-time-profiles be filled?"* and *"How can a large network be reduced depending on traffic behaviour?"* is investigated by using cluster

analysis (Ward-Method). For the first question speed values of each cluster is investigated with a qualitative and quantitative validation. The quantitative validation returned for the speed-over-time data sets that an additional information is needed: the direction of each edge. The results for inbound and outbound direction are better fitting.
With these results it could be possible to fill missing data sets if needed. One need for this could be that there is no free-flow speed available and it is necessary for the simulation network.
The second module is answered as well: it is possible to find similarities in different speed-data sets by applying a cluster analysis. The investigation of the results for each cluster show that the results are realistic and that each cluster concentrates on some road-characteristic combinations. For each cluster it is possible to develop representative speed-over-time curves. These results indicate that the cluster can be used for validation of large simulation models regarding speed output.
Additionally, this analysis provides results which are independent from the basic network. Regarding this thesis, the benefit is that the used network of the GIP-AT is changing multiple times and it is possible to work with the traffic categories independently of the current network. Of course all, significant, characteristics are needed for map-matching. It would be possible to match these traffic categories as well on other networks, if the characteristics are available.

4. Mesoscopic settings

4.1. Introduction

Mesoscopic simulations of different companies differ in their mode, depending on the implemented algorithms. An overview of selected open source mesoscopic simulations is provided in table 4.1. Further mesoscopic simulations are available, e.g., DynaMIT, DynaSMART, Dynamo and hybrid combinations like Mitsim combined with Mezzo or Vissim. In this thesis the mesoscopic simulation model SUMO is used.

Table 4.1.: Overview of selected open source mesoscopic simulations

Software provider	**Algorithm**	**Short description of the meso mode**
AIMSUN [90], [91], [92]	Mesoscopic and hybrid modes available; Simplification of GIPPS-car following model, which produces a triangular density-flow diagram.	- The front vehicles are classified as free-flow speed or with an constant speed. - A large area can be modelled. - The following vehicles speed is adjusted. The maximum speed is the allowed speed. - Advantage: More detailed than the macro model; Efficiency where no detailed information is needed; Large area can be modelled
Mezzo [93], [94]	Discrete event traffic simulation	- Traffic is simulated at the level of individual cars - Aggregated behaviour on links - Hybrid combined with Mitsim available
MATSIM [95], [96]	Agent based modelling	- Vehicle joins link after elapsed time under free flow - If the number of vehicles in queue has reached the maximum, the queue extends backwards
POLARIS [97], [96]	Agent based dynamic activity planning and travel scheduling	- Impacted by different time dependent travel times in the traffic network - Infrastructure is as well included (e.g., ramps, traffic lights)

The mesoscopic simulation mode in SUMO is based on a queuing model and was originally developed by Eissfeldt [98]. Starting a mesoscopic simulation at least two input files (e.g., route file and vehicles) as well as the network file are needed. The mesoscopic traffic simulation is enabled by setting the mesoscopic option (*meso-sim*), which means that all default values of possible mesoscopic settings are activated. An overview of the most relevant settings, their default values and their functionality is provided in table 4.2, gathered from literature (written by Eissfeldt) and the SUMO-User documentation [99], [59].

Table 4.2.: Overview of available mesoscopic settings in SUMO [59]

Setting	Default value	Functionality
Meso-sim	false	Runs mesoscopic simulation
Meso-edgelength	98	Length of traffic queues in mesoscopic simulation
Meso-jam-threshold	-1	Minimum percentage for a segment to be considered jammed; A negative argument: thresholds are computed based on edge speed and tauff
Meso-multi-queue	true	Multiple queues are enabled at the end of edges
Meso-junction-control	false	Junctions are modelled as in the simplified microsim model
Meso-tls-penalty	0	Sets a time penalty for driving over traffic light-controlled junctions based on green split instead of the actual phase
Meso-overtaking	false	Lateral movement is not modelled explicitly. Vehicles may overtake each other if the option –meso-overtaking is enabled. This is a randomized process depending on vehicle speeds and density.
Meso-recheck	0	Time interval for rechecking insertion into the next segment after failure
Meso-tauff	1.13	Minimum headway when travelling from free segment to free segment
Meso-taufj	1.13	Minimum headway when travelling from free segment to jammed segment
Meso-taujf	1.73	Minimum headway when travelling from jammed segment to free segment
Meso-taujj	1.4	If a jam appears, the vehicles travel backwards through the jam. Between the vehicles is the headway (i.e., space). In a completely occupied segment the actual headway is computed with vehicle number * taujj

Due to the permanent development in SUMO, additional information regarding the calculations can be found in the SUMO-User-Forum as well as in the ChangeLogs for program versions [100] and should be checked in advance.

Mesoscopic mode
In the following it is explained how the simulation mode works.
Each node of the network is divided into pieces each 98 m long by default, but can have any length if required by the geometry of the net (short edges). Each piece is organized as a queue. A

vehicle can enter a queue only if there is enough space left, i.e., if the sum of the vehicle lengths, which can have any length, already in the queue leaves enough room for this vehicle to enter. Upon entering, it gets assigned an earliest departure time which is simply $t_{\mathrm{In}} + q_{\mathrm{Length}}/v_{\mathrm{Car}}$. This makes sure that a vehicle obeys its maximum speed, which is a feature of the car, though, if there is a speed limit on this edge, vehicles do obey it. If this earliest leaving time has been reached, the vehicle is allowed to leave only, if the vehicle that has left before is at least τ_{ff} seconds ahead, and, of course, if the following link again has enough space to accommodate this vehicle. $1/\tau_{ff}$ is the maximum capacity of the link.
If the leaving time has been reached and the upcoming link does not have enough space, the vehicle can not leave. In this case, the vehicle has to wait and due to the jam additional time will be added to the travel time. If the following segment is jammed depends on the occupancy (e.g., is there enough space for another vehicle with a certain length) or on the allowed vehicle speed, with which the vehicles can drive at a maximum. The simulation program allows to define if a segment is jammed either on the percentage of occupancy or speed limit.
If the vehicle is in a currently jammed link and the upcoming link is free or the current link is free and the upcoming is jammed, the vehicle must keep at least τ_{jf} or τ_{fj} seconds distance to the followed one.
If the current and upcoming segment is jammed, the distance to the front vehicle is defined with at least τ_{jj}.

Parameter values
In the following possible parameter values for the mesoscopic mode are described.
The length of each node can be set or the default value will be used (98 m - within default vehicle length ∼13 vehicles per queue). To define the length of the queue the 25-quantile, 75-quantile, median and average edge length for urban areas and suburban/rural areas in Upper Austria are calculated. Due to the recommendation of Eissfeldt the test is contributed with values over 50 m (i.e., minimum ∼7 vehicles per queue, within default vehicle length).
As described before, there are different ways to compute when a link is defined as jammed. This is set in the functionality *meso-jam-threshold*. To investigate the influence of the parameter *jam-threshold* the following values will be specified:

- *jam-threshold* “-1”: This value is recommended for urban areas and is set as the default value. This value is sensitive to the *meso-tauff* setting.
- *jam-threshold* “1”: A segment will never be considered as jammed.
- *jam-threshold* “-0.33”: Setting values between 0 and -1, the jam will be computed as jammed by the speed-limit multiplied with this negative value. A segment is considered as jammed when the current speed is below 33 % of the speed limit, which is specified due to ITS-requirements (compare 2).
- *jam-threshold* “0.80”: Setting values between 0 and 1, the jam will be computed as jammed if the current occupancy is higher than the maximum occupancy multiplied with the set value. Using 0.80, a segment will be considered as jammed when 80 % of the occupancy is reached.

In a network with different traffic categories, values for τ need to be defined.

$$Q = kV \tag{4.1}$$

[101]

$$Q = \frac{1}{\tau + \frac{L}{v}} \tag{4.2}$$

$$k = \frac{1}{\frac{v}{\tau} + L} \tag{4.3}$$

$\frac{v}{\tau} + L$ is the space a moving vehicle needs, where τ is the net headway (e.g., vehicle front bumper to leader back-bumper). If the speed is set to zero, the capacity is as well zero (compare equation 4.1). If the length of the queue is set to zero, the capacity is $1/\tau$ (compare equation 4.2). Therefore, the capacity is independent of the vehicle speed, which means that in the SUMO-model the gross headway is defined by $1/Q$ [98]. The queue-model ignores the additional term that stems from the vehicle length, i.e., gross headway = net headway. In contrast to reality, and SUMO-micro, the gross headway and net headway are related by $\tau_{\text{gross}} = \tau_{\text{net}} +$ L/v.
If the capacity is calculated, equation 4.3 is inserted in equation 4.1. In this case, the capacity is depending on the vehicle speed.
Summarising, the following behaviours can be computed and each value can be adjusted independently:

- *meso-tauff* : Minimum headway travelling from free segment to free segment; time headway between front-bumper to rear-bumper
- *meso-taufj*: Minimum headway when the first segment is stated as free, the following segment as jammed
- *meso-taujf*: Minimum headway when the first segment is stated as jammed, the following segment as free
- *meso-taujj*: Minimum headway when both segments are stated as jammed. This headway computes the spaces to travel backwards because of the jam. If it is occupied completely, the headway will be calculated by the number of vehicles times the meso-taujj.

Eissfeldt proposes four different ways to combine and set the τ-values:

1. only *meso-tauff*
2. *meso-tauff*=*meso-taufj* , *meso-taujj*= *meso-taujf*
3. *meso-tauff*=*meso-taufj*, *meso-taujj*, *meso-taujf*
4. *meso-tauff*, *meso-taufj*, *meso-taujj*,*meso-taujf*

These proposed combinations will be used in section 4.3 to find well-fitting parameters. In the following section the methodology for the parameter analysis is introduced.

4.2. Methodology for parameter analysis

In this section the methodology for the parameter analysis is presented. Combining the relationship between traffic variables (e.g., speed, flow and density) with a “One-at-a-time-analysis Sensitivity Analysis (OAT)” the influence of the mesoscopic settings as well as different parameter values can be investigated. In the first paragraph fundamental diagrams are explained, following the OAT and the combined parameter analysis is presented in the second passage.

Fundamental diagram
During the 1930s Bruce Greenshields discovered a linear relationship between speed and density, which has been modified over the last years [101]. The fundamental diagram curves, which tend to a left side distribution, have changed due to validation with measurements. However, Greenshields fundamental diagrams are still valid and basically comparable to the adjusted ones. The relationship between the maximum flow and capacity, which provides information about the jammed traffic state on a lane as the relation ship to the density is provided [102].

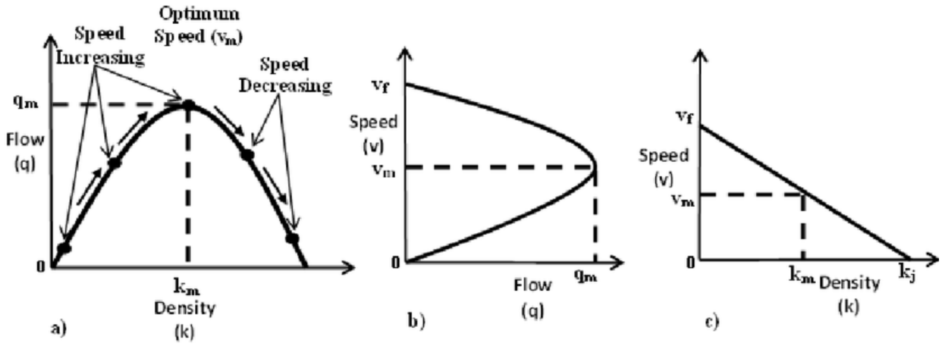

Figure 4.1.: An example Fundamental Diagram using Greenshield's model [103]

For microscopic models usually the behaviour of each vehicle is in the main point of interest. To find a well working configuration in the present work macroscopic variables are used for the comparison between different mesoscopic outputs and microscopic output. Because each parameter influences the variables differently the impact of each are analysed and presented in the results section 4.3.

Parameter analysis with One-at-a-time (OAT)
One possibility to understand how different parameters and their values influence the simulation is to perform a sensitivity analysis, which is a common use in operation research for testing (prediction) models and the influence of each parameter. It is as well applied on traffic simulations [104], [105], [106]. For example, Ciuffo et al. [107] carried out a sensitivity analysis for the mesoscopic simulation model of Aimsum. Therefore, two different methods are available: one is the "One factor at A time (OAT) Sensitivity Analysis", where all parameters are fixed and just one at a time is changed. Though, one main disadvantage can appear using this method: the influence of other settings and the mutual impact can not be detected. To be able to analyse these effects another method, called a "global" sensitivity analysis, can be applied. Different combinations of parameters are applied on the simulation and the influence of parameters can be discovered with a Monte Carlo framework or an Analysis of Variance (ANOVA) [106], [105], [104], [108].

In this thesis, first an OAT is contributed for each possible parameter value. This means that a parameter is set and the values are changed one at a time. First, it is tested if changing the parameter settings has influenced the output data or not. If one of the variables is not identical to the previous version, an ANOVA is contributed to identify if a setting or value has a significant influence on the model output. If the parameter indicates a significant change in one or more traffic variables (e.g., critical density, maximum flow and maximum speed), the fundamental diagram is analysed and compared to the output of a microscopic model. After

the impact is identified, combined settings are tested, comparing each model output to each other and to the microscopic mode.
In the following analysis the settings are changed step by step. First, the mesoscopic simulation needs to be enabled on a simple microscopic model. Within this step all default values are automatically set. Following, further mesoscopic settings are investigated.
The values are adjusted in a new configuration file for each possible setting. On the test network several virtual counting stations are placed, as well as the output for each edge is returned in a one minute interval. SUMO returns the *density (k)* in veh/km and the *traffic volume* is calculated additionally via $V3.6k$ (compare [59]). The *critical density* is defined as the density when the maximum traffic volume is reached.
In the following section the analysis is applied onto the test network.

4.3. Results

In this section firstly the test network is explained, secondly the results of the analysis are provided. The configuration settings, applied in this chapter, are depicted in the appendix C.
The network of Upper-Austria consists of around 200.000 edges, 90.000 nodes and a total network length of 260.000 km. To perform the parameter analysis a much smaller test network (see figure 4.2) and a corresponding route file is created. The number of vehicles is increased until the capacity is reached, to be able to generate fundamental diagrams. A routing file is created, which is the basis for all upcoming models. The advantage of using this test network is that the re-calibration is much faster then applied on the Upper Austria model. The results indicate which parameters might have a positive influence on a large model and the number of re-calibrations can be reduced to a smaller amount of possible configuration settings. To create a representative test model the following requirements are considered for the test network, depicted in figure 4.2:

- The V85-traffic categories are used for the maximum allowed speed in the test network (compare chapter 3)
- The length of the edges variate taking into account the proportions of the edge length in urban and rural areas (e.g., in urban areas edges have smaller lengths, in rural areas longer ones).
- Traffic-lights and roundabouts are implemented

All edges are two way lanes, except for one edge (e.g., drawn thinner). The inserted direction in the figure points out the driving direction of the measured vehicles in the upcoming analysis.

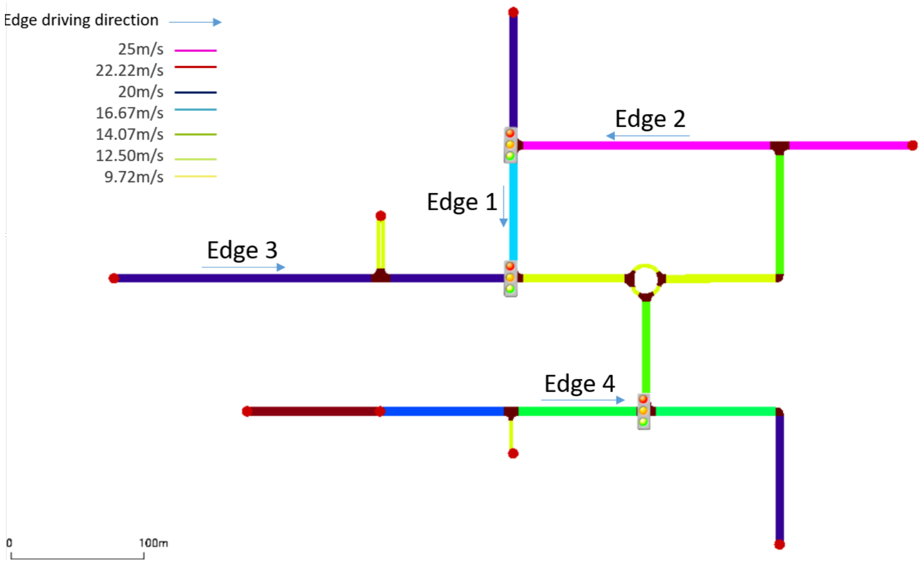

Figure 4.2.: Test network for parameter analysis

Mesoscopic basic settings

To use the mesoscopic simulation it needs to be enabled (compare section 4.1), which computes the output using all default values of the mesoscopic settings (see table 4.2). All other settings are identical with the Upper-Austria model (e.g., speed-deviation, vehicle characteristics). Before running both settings, mesoscopic and microscopic, one routing file is created, i.e., both models are based on the same routing file. The simulated traffic data is collected for each edge using the SUMO-output function.

The results (see 4.3) indicate that if the mesoscopic model is enabled, the traffic flow increases, in contrast to the critical and the maximum density, which decreases. In conclusion, by enabling the mesoscopic functionality, more vehicles can pass, but the capacity is reached faster than in the microscopic version. Running the simulation with mesoscopic settings, the maximum speed is returned higher than the allowed speed.

Table 4.3.: Output of the model once with mesoscopic enabled (meso-enabled) and once with microscopic (micro) settings for selected edges

Edge	**Settings**	**Allowed V[m/s]**	**Max. V[m/s]**	**Max. K[veh/km]**	**Max. Q[veh/h]**	**Crit. K[veh/km]**
1	micro	16.67	15.86	140.19	1253.95	62.2
1	meso-enabled	16.67	21.42	120.33	1830.95	41.62
2	micro	25	24.43	140.09	1191.36	62.43
2	meso-enabled	25	29.05	52.16	1384.21	17.25
3	micro	20	18.09	139.27	1077.98	37.09
3	meso-enabled	20	19.31	107.78	1652.08	39.94
4	micro	12.50	12.12	53.56	897.28	27.48
4	meso-enabled	12.50	12.17	45.85	1292.12	42.78

Enabling the setting *meso-overtaking* does not have an effect on the output of the model, which enables that vehicles are able to overtake each other. The missing effect can be due to missing vehicle types and/or due to missing two-road-lanes, where no lateral movement is possible.
In the current implemented model of ITS-UA the "meso-multi-queue", "meso-overtaking", "meso-junction-control", as well as "junction-control.limited", are enabled in the configuration file, for other possible settings the default values are computed. Applying these configuration settings on the test model is named as *meso-1* in the following analysis. It is, additionally to the microscopic model, used to compare if the adjusted settings have a significant influence on the model.
In table 4.4 the results of the comparison between the microscopic model and the *meso-1* configuration is listed. *Meso-1* shows that the critical density (example edge 2 k= 21.68 [veh/km]) is lower than the density of the microscopic model (example edge 2 k= 62.43 [veh/h]) (i.e., the congested state is reached earlier than with the microscopic model). The traffic flow of the microscopic model is around ~35 % less than the mesoscopic model, except for edge 2, which is longer than the other streets. The traffic flow through the roundabout varies up to 78 %.

Table 4.4.: Comparison between the results of the output of mesoscopic and microscopic settings

Edge	Settings	Allowed V[m/s]	Max. V[m/s]	Max. K[veh/km]	Max. Q[veh/h]	Crit. K[veh/km]
1	micro	16.67	15.86	140.19	1253.95	62.2
1	meso-1	16.67	21.42	128.50	1420.54	30.33
2	micro	25	24.43	140.09	1191.36	62.43
2	meso-1	25	29.05	129.31	1109.84	21.68
3	micro	20	18.09	139.27	1077.98	37.09
3	meso-1	20	19.31	122.77	1542.20	95.23
4	micro	12.50	12.12	53.56	897.28	27.48
4	meso-1	12.50	12.75	41.74	1287.37	40.09

In figure 4.3 the fundamental diagrams of the microscopic model, mesoscopic enabled model and the mesoscopic settings of the ITS-UA simulation ("meso-1") are depicted for edge 2. The output data of the *meso-1* returns that there is a need for adjustment of mesoscopic parameters. The parameters need to be optimised, because the traffic flow should be lower, the maximum speed is to high and the critical density needs to be adjusted.

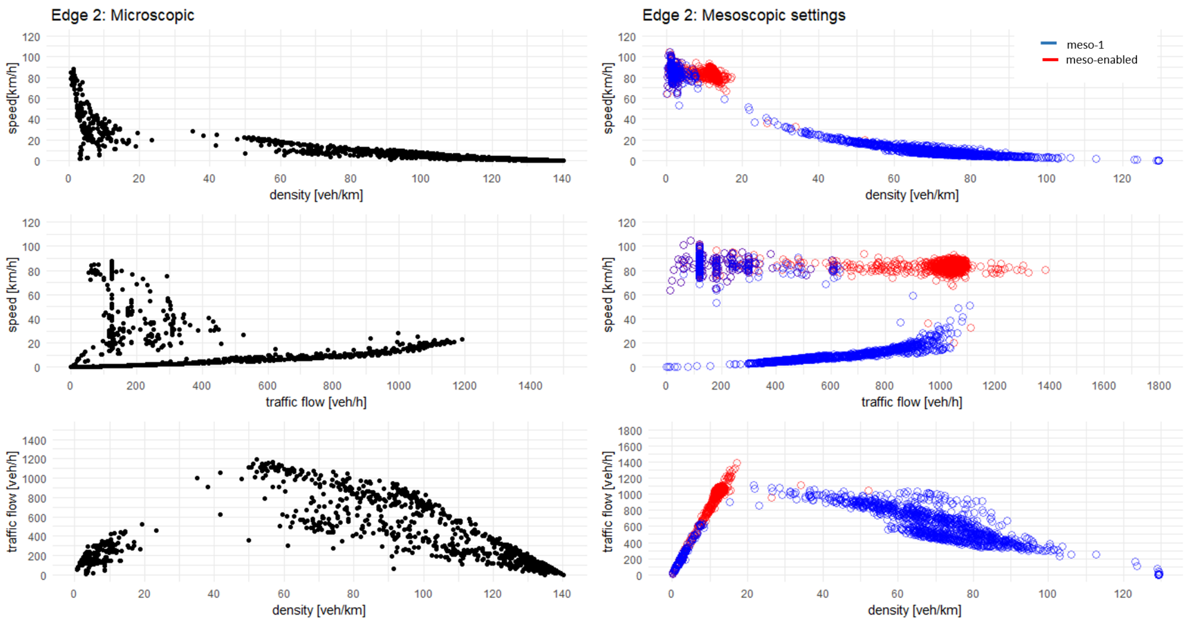

Figure 4.3.: Fundamental diagrams before (meso-enabled) and after calibration (meso-1) of edge two (microscopic remains unchanged)

Further mesoscopic settings

edge-length

For each edge-length the testing simulation is re-calibrated. The output variables are tested if their value changes compared to the mesoscopic-basic settings (i.e., 98 m).

The results of the ANOVA show that the values 58 m, 68 m and 195 m and 362 m generate

a significantly different output compared to the microscopic model. Significantly different to the *model-1* are models with *edge-lengths* 58 m and 68 m. Table 4.5 provides an overview of the maximum speed, maximum density and traffic flow for selected edges received by the re-calibrated models with 58 m and 68 m, the *meso-1* and microscopic version. Comparing results of the adjusted mesoscopic models with the *meso-1* the maximum speed does not change with the adjustment and the maximum traffic flow differs up to 5%. The maximum density deviates up to 20 [veh/h] from each other, the exception is the roundabout. The critical density differs more between the set values, for example on edge 2 the model with *edge-length* "58 m" shows a critical density around 71.01 [veh/km], the one with "68 m" crit-k= 31.97 [veh/km] and with "98 m" crit-k= 21.68 [veh/km]. This indicates that the shorter *edge-length* is, the higher the critical density is.
The results show, that compared to the microscopic model the traffic flow and the crit-k is more similar using a shorter edge-length than the default value and the maximum density is lower than the microscopic version.
Because the results do not differ much from each other, both values (58 m and 68 m) will be used for the upcoming parameter analysis in combination with further parameters. The fundamental diagram before and after re-calibration (edge-length=58m) is depicted in the appendix D.

Table 4.5.: Overview of output values for different *edge-length*

Edge	**Configuration *edge-length***	**Allowed V[m/s]**	**Max. V[m/s]**	**Max. K[veh/km]**	**Max. Q[veh/h]**
1	micro	16.6	15.86	140.19	1253.95
1	58.00	16.6	21.42	120.78	1395.91
1	68.00	16.6	21.42	96.46	1388.15
1	meso-1	16.6	21.42	128.50	1420.54
2	micro	25	24.43	140.09	1191.36
2	58.00	25	29.05	129.31	1175.93
2	68.00	25	29.05	120.07	1183.15
2	meso-1	25	29.05	129.31	1109.84
3	micro	14.73	18.09	139.27	1077.98
3	58.00	14.73	19.32	102.09	1613.18
3	68.00	14.73	19.31	114.18	1518.59
3	meso-1	14.73	19.31	122.77	1542.20
4	micro	9.72	12.12	53.56	897.28
4	58.00	9.72	12.75	43.62	1283.72
4	68.00	9.72	12.75	42.65	1337.33
4	meso-1	9.72	12.75	41.74	1287.37

Additional: Effect of edge-length
Eissfeldt noted that the *edge-length* will create same length segments over the complete network, e.g., the idea is to cut the edges into segments of the same length [98]. The cutting either starts on one point of the network and develops segments all over this network or they start cutting

with the beginning of each new link. In the second case, there would be a part of the link missing and this influences the entire network (compare cellular models [109]). For testing this phenomena, virtual vehicle detection loops are added onto one edge. In one model the link has a total length of 185.6 m. In the second model it is divided into two edges, each with a length of 92.8 m. In a third model a crossing is added in the middle. The length of each link is around 86 m. To test the influence of the *edge-length* settings the position of the detection loops never change.
The results detect that there is a change in the output. Though, it creates very small differences for example in the traffic flow, but it can have a higher impact on large traffic simulations if edges from the network are left out.
jam-threshold
The test is carried out in two parts, firstly the proposed values in section 4.1 are tested, secondly they are combined with the *edge-length* of 58 m and 68 m.
The ANOVA and Tukey's HSD test indicates a significant influence of all *jam-threshold* values compared to the *meso-1*-model. In contrast to the microscopic model, no significant difference between the speed output and the values "-0.33" and "0.80" is indicated. Setting the jam off has a significant influence on the speed as well as "-1". The Tukey's HSD test indicates no significant influence of the value "0.8" on density, but all other variables are significantly different. To adjust the model output in a way that it is similar to the microscopic output, *jam-threshold* without a significant difference compared to the microscopic model can have a positive impact.
The fundamental diagrams indicate that the value "1" (no traffic jam) has a large gap between the traffic state free-flow and congested. In the congested state the density and traffic flow points of different vehicles are agglomerated. The maximum traffic flow is much higher than in the *meso-1* model and microscopic model.
The values "-0.33" and "0.8" create similar fundamental diagrams, except for the critical density. It is greater with *jam-threshold*="0.8" (edge 2: crit. k=54.73 [veh/km]) than for "-0.33" (edge 2: crit. k=39.3 [veh/km]). The values of speed, density and traffic flow do spread more compared to the output of "-0.33".
The *meso-1* output returns a greater critical density than for "-0.33" and "0.8", though the maximum speed is still greater than the set allowed speed within all tested values.
In table 4.6 the maximum speed, maximum density and maximum traffic flow for selected edges is listed for 58 m and 98 m (default) *edge-length* and the proposed *jam-threshold* values. Only the jam-combination with 58 m is listed in the table, because the output the output is more similar to the microscopic settings than combining with 68 m. The *meso-1* includes the default *jam-threshold* value "-1".
The results indicate that, *edge-length* and jam-threshold influence the maximum traffic flow and density, but not the maximum speed. The maximum traffic flow is simulated greater than the microscopic model. As an example, for edge 2 a good combination computing the *edge-length* "58" and *jam-threshold* value "-1". Output traffic variables of a link from the roundabout shows that the values are two times the amount of the microscopic model. The combination of *edge-length* "58" and "-1" return values similar maximum traffic volume compared to the microscopic model, the other variables point out that an additional adjustment is necessary. The fundamental diagram before and after re-calibration (edge-length=58m, jam-threshold -0.33) is depicted in the appendix D.

τ-values - in combination with *edge-length* and *jam-threshold*

Table 4.6.: Overview of output values for different *edge-length* and *jam-threshold*

Edge	***jam-threshold***	***edge-length***	**Max. V[m/s]**	**Max. K[veh/km]**	**Max. Q[veh/h]**
2	micro	micro	24.43	140.09	1191.36
2	0.8	58	29.05	129.31	1536.70
2	-0.33	58	29.05	129.31	1604.71
2	-1	58	29.05	129.31	1175.93
2	0.8	98	29.05	129.31	1428.45
2	-0.33	98	29.05	119.18	1385.09
2	meso-1	98	29.05	129.31	1109.84
3	micro	micro	18.09	139.27	1077.98
3	0.8	58	19.31	111.6	1900.32
3	-0.33	58	19.31	111.61	1832.03
3	-1	58	19.31	102.09	1613.18
3	0.8	98	19.32	122.77	1680.67
3	-0.33	98	19.32	122.76	1729.58
3	meso-1	98	19.32	122.77	1542.20
4	micro	micro	12.75	53.56	897.28
4	0.8	58	12.75	48.99	1384.46
4	-0.33	58	12.75	41.26	1229.24
4	-1	58	12.75	43.62	1283.72
4	0.8	98	12.75	41.38	1249.14
4	-0.33	98	12.75	48.62	1395.41
4	meso-1	98	12.12	41.74	1287.37

This section is split into two parts: Firstly the effect of the four possible combinations of τ-values, described in section 4.1, are compared. Following, plausible τ-values are calculated and tested.
The combinations are tested with the default *edge-length* (98 m) and default *jam-threshold* “-1”. Table 4.7 provides an overview about the different output for edge 2. Using the configuration with *meso-tauff* only (Combination 1) returns exactly the same results as the *model-1.* Regarding motorway traffic Eissfeldt suggests the second combination [98], which is currently not set as the default value. Combination 1 and combination 2 return similar traffic variable values, as well as combination 3 and combination 4. Again, the different output files return a higher maximum speed than the speed limit. Table 4.7 indicates that the output values are not influenced strongly by the different combinations using the default values. Combination 2 and combination 4 could provide the best influence, in detail combination 2 brings the system to react congested earlier, though the max. density is much less when simulated with combination 4. Considering the requirements of Eissfeldt, the combination 2 will be set with adjusted values.

Adjusting the headway-times can be challenging, because the values can have a great influence on the traffic behaviour. The higher the τ-values the more time between two vehicles is computed and vice versa the lower τ values the more traffic can pass. On edges with lower allowed speed the results indicate that within a higher *meso-tauff* the critical k rises (i.e., the jam is later).

Table 4.7.: Output for different jam-combinations for edge 2

	Micro	**“basic”-meso**	**C-1**	**C-2**	**C-3**	**C-4**
max. traffic flow [veh/h]	1191.36	1109.8	1109.8	1132.1	1206.64	1188
max. k [veh/km]	140.09	129.31	129.31	129.31	107.51	107.50
critical k [veh/km]	62.43	21.68	21.68	25.84	34.59	33.64
max. speed [m/s]	29.05	29.05	29.05	29.05	29.05	29.05

For edges with higher allowed speed values (rural character) the critical density is higher until *meso-tauff* =1.3, raising it, the critical k drops. The maximum traffic value tends to get lower with a higher *meso-tauff*.
Comparing this behaviour with the default values and the microscopic model indicates that the *meso-tauff* needs to be adjusted higher. If the *meso-taujf* is between 2.5 and 3 the amount of traffic is decreasing, the critical density is much lower (i.e., jam is earlier) and the maximum density is increasing compared to the microscopic output. Configuring the test model with *meso-tauff* and *meso-taujf* set to the minimum of 1, *meso-taufj*=1.5 and *meso-taujj*=1.8 the returned traffic flow is nearly 50 % grater then the microscopic output, the critical k is increasing and the maximum density is significantly dropping. This points out the effect, that decreasing the *meso-tauff* and *meso-taujf* is increasing the maximum traffic flow and the jam appears later.The results are are listed in the appendix E.
In the next step only *meso-tauff* and *meso-taufj* are changed by adding one millisecond with each test, the other τ-parameters are set to the default values. The results indicate that the maximum traffic volume, maximum and critical density is in general decreasing when the value is increased, though the relationship between critical density and maximum traffic flow differs from each other. Differing the *meso-taujj* and *meso-taujf* in two millisecond intervals, the other τ-parameters set to the default value, return for 90 km/h that the maximum traffic volume and critical density is decreasing. On edges with a lower maximum speed, e.g., edges that represent urban areas, the influence is not that significant. Adjusting only the *meso-taujf* returns as well a lower maximum traffic volume and the critical density is influenced, but differs a lot to each model version. The combination of both analyses return a *meso-tauff* and *meso-taufj* with 1.2 or 1.3 as well fitting and a *meso-taujf* with less then 2.3 seconds. One combination with good fitting results for edge 2 is setting 1.8 or 2 seconds for *meso-taujj*.
Within this analysis the results indicate an overestimation of the amount of vehicles compared to the microscopic model. Adjusting the parameters can counteract this overestimation.

Additional speed-deviation
As pointed out above, one problem within the speed is, that it is simulated much greater than the allowed vehicle speed. In the test network the problem is identified and the validation of the ITS-Upper Austria model returns that in 23 % the maximum simulated speed values of an edge of a complete day are 10 km/h higher than the permitted speed. In 54 % of the cases, the maximum simulated speed is 5 km/h higher and in 66,03 % the values are 3 km/h higher than the permitted speed. The speed deviation is set to 0 to prohibit this effect [110], due to traffic information service values which are much greater than the permitted speed are not wanted.

4.4. Summary and Conclusion

This chapter described how different parameter settings influence the output of the mesoscopic simulation model. To find well fitting combinations for a large network the settings are tested by “One-at-a-time” as well as in combination with each other. The mesoscopic simulation of SUMO is based on a queuing model. First, the available parameters and their impact on the simulation are explained. Various values are suggested for adjusting the model. In the next section the methodology for parameter analysis is introduced. To be able to investigate the influence of different settings with less effort a testing network is created. The effect of adjusted parameters is provided in section 4.3. First, the already implemented settings are discussed and then more advanced settings are changed. The results indicate that the queuing model tends to overestimate the amount of vehicles for small speeds (i.e., with tau=2 and v=5 m/s and edge length 5m the mesoscopic model returns 1800 veh/h, while the microscopic capacity is 1200 veh/h). The analysis indicates that “58 m” and “-0.33” is a well fitting combination. The tau-values have to be tuned as well. The results indicate that lower τ values for free-free return a better fitness in rural areas. Tau-values for jam-free should not be grater than 2.5 seconds. The results indicate well fitting a *meso-tauff* and *meso-taufj* with 1.2 to 1.3 seconds, a *meso-taujj* 1.8 or 2 seconds and a *meso-taujf* with 2 till 2.3 seconds. The ITS-Upper Austria model is adjusted with these results and validated in chapter 6.

5. Data selection for validation and calibration processes

5.1. Requirements on data sets and data sources

First variables, which should be calibrated or validated with respect to the purpose of the model, need to be defined. To validate traffic models with fundamental diagrams (compare chapter 4) the variables traffic flow, speed and density are needed. If the level of congestion is the main point of interest, these factors are used [111]. Maheshwary et al. [112] provide an overview of various literature for calibration stages and techniques for calibration of microscopic simulation models. Ozbay et al. [113] as well provide a summary of literature regarding performance outputs and data used in calibration for various types of roads. For validation observed loop detector data or trajectory data are used.
Miliam et al. [114] recommends not only to use traffic volume, travel time, travel speed and density, but as well the average and maximum vehicle queue length. In their study, the parameters are validated against output data from CORSIM. The authors provide additional information regarding output variables, to ensure the harmonisation between observed data and simulated data.
Investigating the model fitness during the development of the mesoscopic model of SUMO Eissfeldt et al. [99] compare simulated and observed speeds and traffic flows.
Benekohal et al. [115] provide an overview of validation steps regarding a car following simulation model. The validation process differs between microscopic level and macroscopic level, because for various levels, different relationships are important (i.e., simulating individual behaviour). Therefore, one or more variables are needed from the output files as well as from historical data. Buisson et al. [116] distinguish between multi valued collective variables (e.g., travel time, speed), multi valued individual variables (e.g., trajectory) and single-valued variables (e.g., queue length) for validation of microscopic simulation models. Data for comparison is gained by loop detectors as well as by floating cars or cameras.
Usually before contributing a validation or calibration process historical measured data is needed, though, sometimes validation is carried out without any data (compare chapter 6) [64]. Assuming that a model is calibrated or validated with historical data Wunderlich et al. [117] proposes to check the quality of traffic data and to verify historical data prior to collecting or searching for data. Further, the most recent traffic network data should be applied and traffic data for various traffic situations and a large number of geographical scopes should be considered. This indicates that it is necessary to respect different boundary conditions when collecting data.
For different purposes various data sets can be useful (compare chapter 6). The findings of the project *Multitude* indicates that traffic planers are often confronted with the problem of lack of data. Further it is indicated that, if data is available, the data set is usually split into two

parts: one for the validation and one for the calibration process. With this method the model is only improved by half of the data, the other half is used for evaluation. Sometimes the data will be merged after the final validation, knowing the model fitness, for a last re-calibration. To split the data two possibilities are available: randomly or by geography. Because in some areas more precise traffic data is available this data will be used for model calibration and the other for validation [106]. Observed measures of performance (e.g., flows, speeds, densities) should be chosen with respect to the application context [64].
Summarising, the most used variables for validation or calibration are:

- travel time
- flow
- speed
- crash potential index
- stopped delay
- acceleration and deceleration
- capacity
- queue length

Data sources for model validation and calibration processes
To understand traffic behaviour and to provide high quality traffic information data regarding travel times, speed profiles and traffic volume are collected. Therefore, various sensor types can be implemented, which are distinguished between point-based-data and segment based data. Point based data are permanent detection loops, short term counting or data gathered by traffic video data. Segment based data are Floating Car Data (FCD), Bluetooth-Data, Floating Phone Data (FPD) or test drivings. The technical background and how data sources can be used for real-time information is explained in chapter 2. In the current subsection the focus lies on using data for calibration and/or validation. Various authors, like Ozbay et al. [113] discuss the role of big data in the use of calibration. A short literature overview is provided focusing on different variables as well as on the advantages and disadvantages.
Traffic video data: Lu et al. [118] use video data for calibration of parameters in a microscopic model. During two hours data are collected at a crossing and the data is used to analyse the saturation status of it. It is possible to calculate the headway between two vehicles therefore with this data.
Floating Car Data: The data is used in various literature, where it is shown that the data can not only be used to validate simulation output or to calibrate the model itself. Ciuffo et al. [107] analyse the use of trajectory data for investigating the Gipps' car-following model, which is for example implemented in AMISUM. The authors compare the speed-acceleration relationship of the Gipps' car following model with the observed trajectory data. Treiber et al. [109] as well discuss the calibration of car following models with trajectory data. In their study the Intelligent Driver Model and the Velocity Difference Model is analysed during afternoon peak on a one-lane road. The measurements were taken from three drivers every 250 s, 400 s and 300 s. The data sets include acceleration and deceleration movements. The validation results show that errors between observed data and the model are around 11% to 29%.
Floating Phone Data: Ozbay et al. [113] point out that the use of FPD for calibration can have various issues at the current state of techniques. One problem can accrue due to the resolution and lack of geographic level of detail. It is possible to join trip information like questionnaires with floating phone data to receive the right O/D-matrices.
Commercial data: Ozbay et al. [113] provide an overview of web-based services that offer traffic

information for developers, for example HERE offers data sets of a few countries for research free of charge [6]. These can be used for calibration or validation, depending on the availability.
Example for further data sources - Electronic tool collection data: Ozbay et al. [113] discusses the use of electronic tool collection data of expressways or tollways. An overview of available tool collection data in the USA is provided. The sensor delivers information about the individual vehicle entry time and exit time. Additionally, information about the used lane, vehicle type and number of axles is provided.
In order to decide which data source or which sources should be used for validation and/or calibration processes, if they are available, table 5.1 provides an about different data sources for model validation and calibration. Notably, each traffic variable is distinguished between an interpreted (I), calculated (C) or measured (M) value. In addition, table 5.2 summarises the advantages and disadvantages for each detector regarding calibration and validation.

Table 5.1.: Overview of collected or generated variables with different data sources (compare [2])

	Traffic variable			
	Speed	**Traffic volume**	**LoS**	**Travel time**
Loop detection	M	M	C	C
Short term countings	N/A	M	N/A	N/A
Webcam data	C ∗	C	I or C∗	C*
Floating car data	M	N/A	C	C
Bluetooth data	C∗	N/A	C∗	M∗
Floating phone data	M/C	N/A	M/C	M/C
Test drivings	M	N/A	I or C	M

M... measured variable
C... calculated variable
I... interpreted variable
*... at least 2 sensors are needed
N/A... information not available

Table 5.2.: Overview of different data sources regarding advantages and disadvantages for validation and calibration of traffic models (compare [2])

	Advantages	**Disadvantages**
Loop detection	detection of all vehicles, high quality	only available on certain points in a network
Short term countings	at interesting points additional information can be gathered	individual countings can have a high error rate
		effort to gain the data only at specific areas available
Webcam data	start/end of traffic state can be detected	quality depends on algorithms
Floating car data	wide coverage	depending on number of vehicles available
Bluetooth data	more measurements on a certain route	depending on number of vehicles available
Floating phone data	wide coverage	quality depending on map-matching
Test drivings	precise data for a certain route	high effort in gaining data

5.2. Procedural model for data selection

In the previous sections various requirements on data sets as well as advantages and disadvantages are pointed out. To be able to decide which data source should be gained or used, a procedural model is developed (see figure 5.1). Before selecting the data source, variables, which should be calibrated or validated with respect to the purpose of the model, need to be defined and the data standards should be considered (e.g., the definition of each variable needs to be defined or looked up). For example, if a reference speed is used, the type needs to be defined (e.g., allowed vehicle speed, the V85 or V50). Further, the output variables and how they are calculated need to be defined or looked up. In table 5.1 it is depicted that some variables can be calculated by another variable.

Defining network area: Following, the area which should be validated or calibrated should be defined. Several data sets have an advantage of covering large areas, though sometimes only specific parts of a road network is relevant. Therefore, point-based-data can have a greater quality. Additionally, it can help to re-calibrate or validate selected roads to increase the model fitness or to understand errors.

Analysing a large area, segment based data is needed. Focusing on areas, where the model should return a good performance to suit the model purpose, data should be gathered for these sections. For example, if returning information for streets with a high capacity is the purpose of the model, traffic information of surroundings can be helpful, but is not the data which will be prioritised to receive. Additionally, if an existing model is re-calibrated the area might be reduced to parts where the model defers to reality(compare [20]).

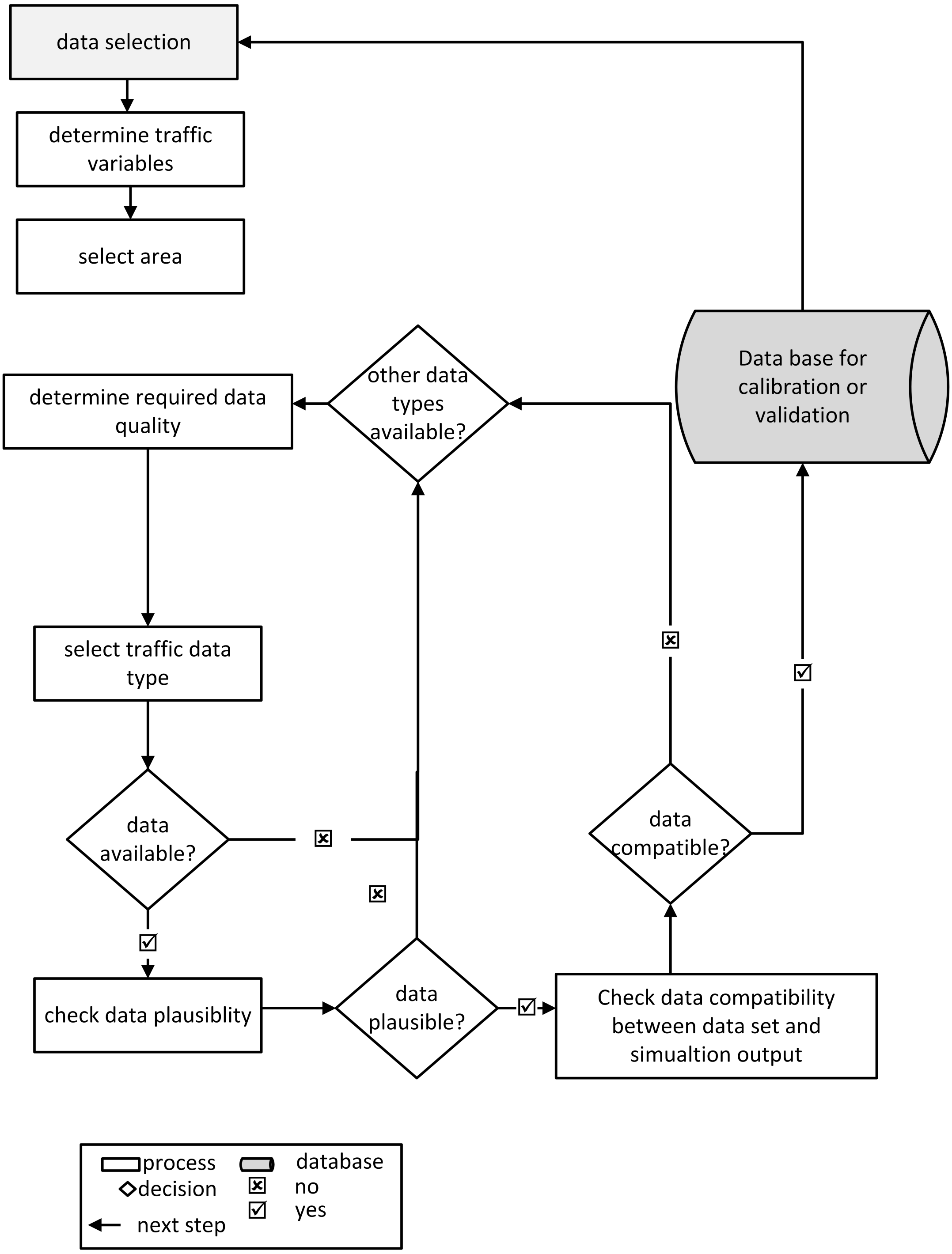

Figure 5.1.: Overview of procedural model for data selection (compare [20])

Determine data quality: In the next steps requirements on the data quality are determined, which is ensured within the plausibility check. As described in chapter 2 and section 5.1 data sources, which cover a large area, usually depend on different algorithms. This indicates that the data quality and area selection is interdependent and should be handled that way. In case

data can be received, a plausibility check of the data should be carried out. The data should be up to date and matched on the same network. If this is not possible, map-matching needs to be carried out either on the simulation output or on the historical data (compare 5.4). If it is not possible to receive the preferred data source, another source can be checked for availability. It should be kept in mind, that it can be a benefit if data is available for parts of the selected area (e.g., if loop data is available at some segments).
In case that limited data is available, ensuring the data quality can be a challenging task. Test rides or short term counting can be one possibility to compare the data, though they are time-consuming. Another possibility is the use of web cam data, which are often available live on web pages of road authorities (e.g., in Austria ASFINAG, or Government of Upper Austria). The data can be helpful to understand, if traffic behaviour is similar to the web cam pictures (e.g., in morning peaks). In addition, it is as well possible to compare the simulation output with loop detection sensors, which has a high quality because (nearly) all vehicles can be measured. In the event of using commercial data, providers (compare chapter 2) sometimes prepare a quality index for live data. The quality index provides the ratio between live data and historical data which is included in the given data [12].
It is important to remember the limitations of each data set regarding data quality when using it for model adjustment or evaluation. The model fitness is depending on the quality of the data set used (compare [20]).
Challenge of data harmonisation: In the final step it is checked if the traffic variables of historical data sets and simulation output do have the same definition. One will notice that if the data is provided by a company, it might be difficult to understand how the data is aggregated and calculated. In the event that the data is not comparable, new data needs to be gathered (compare [20])
Lack of data availability: As mentioned in the beginning of this chapter, the lack of data availability is an important issue. In a first step requirements regarding quality or the area can help to find more data sources. If there is data available, but with many data gaps, various statistical approaches can be used to fill these up(compare [20]). It is important to realise, that if the calibration or validation is carried out with statistically calculated data, the simulation will only be as realistic as the data itself (e.g., it might differ from the real world).

5.3. Requirements for large model validation with ITS use case - approach in this thesis

For validation of large models with ITS use case the requirements are discussed with the procedural model (compare figure 5.1). The applied model on the ITS use case is depicted in the appendix F. In the first step the traffic variables are determined under consideration of the purpose of the model. As noted in chapter 2, in ITS data sets the following attributes are transmitted:

- speed
- travel time
- Level of Service (LoS)

The attributes travel time and LoS can be calculated by speed, this means that the speed-values are needed in high quality. As can be seen in table 5.1, data from FCD and permanent counting

stations can be used. In addition, speed data can be calculated, if available, by Bluetooth sensors or web cam data. Further, travel time can be gathered directly by Bluetooth sensors or calculated using other data sets and the length of each edge. The LoS can be calculated by using speed data and can be interpreted using web cam data.
In the next step the area is discussed, which requires a large data set for the validation or calibration of large scale traffic models. For real-time-traffic information it is important that areas, for which live data is provided, do have a high quality. To understand the model fitness and to re-calibrate, the focus can be set on the roads which are needed for the real-time-traffic information service. Generating speed-over-time data with FCD needs a minimum amount of measurements to generate a representative data base, compared to FPD, which might struggle with precise position data and depends on algorithms or other external factors, like the mobile phone itself (compare chapter 2). In addition, it is important to check the referenced network of simulation and data sets (compare section 5.2). If the network is adjusted regularly, there is a need to compare network changes (e.g., the GIP-AT network changes every two months). If the ID of a street has changed, like missing or new IDs, it means that there is a change in the network, which can either be an update of the map due to previous errors or due to a change in reality. In order to handle two network versions a map-matching algorithm is needed. In case that a new road has been build calculated data sets or the allowed vehicle speed can be used. Because the network changes constantly, for this thesis the simulation is re-calibrated based on the same network every time. The historical data is as well based on one network for validation. The simulation output is converted to the network of the historical data after every re-calibration.
In chapter 2 is noted that for ITS Upper Austria traffic data gained by permanent counting stations, FCD and Bluetooth data is available. Bluetooth sensors were implemented parallel to this thesis, due to the ongoing development of these algorithms the data is not used for the upcoming validation. In speed-over-time data sets speed data, gained by permanent counting stations and FCD, are returned in 15 minute intervals. It is possible to set two requirements for speed-over-time data sets: the time period and the minimum amount of measurements for one interval (=15 minutes). In this thesis for validation a data set of one year is used, excluding weeks with bank holiday, and the minimum amount of measurements is set to 5. In the following step the data plausibility is checked, in order to ensure the data set has the required quality it should be compared with additional data sets. Flitsch et al. compare the different sensor data [20], which are presented with additional information in the following:

Comparison floating car data and permanent counting stations: Analysing FCD and permanent counting stations different speed values are detected. It is expected that the results of FCD and permanent counting stations are not exactly the same. Due to the variation of FCD speeds over a segment, the aggregated speed over the complete edge varies. Another reason is the inconsistent data transmission, which is dependent on FCD fleets and types. This means, that different fleet types return a different driving behaviour as well as they vary in the amount of transmitted data. In contrast to the amount of measurements with the permanent counting stations, which is very high in this example. The driving behaviour is taken into consideration within the plausibility algorithm (i.e., bus lanes and waiting times of bus stations are removed), though it still influences the returned speed values (i.e., trucks drive slower in rural areas and highways than individual drivers). In this example, the number of measurements of the FCD during rush hours is one tenth of the measurements of the permanent counting stations. Due to the amount of data, the calculated speed returns a higher reliability for the counting stations than for the floating car data.

Comparison floating car data, Blutooth data and test rides: Before Bluetooth sensors were implemented in Upper Austria three different companies have agreed to a test setting and their data was collected from the Bluetooth sensors on the B127 in Linz. The positions of the sensors (BT1 and BT2) are depicted in figure 5.2 and a travel time is calculated between these. As described in chapter 2 to each vehicle, recognised by the Bluetooth-Sensor, an ID is assigned. If the vehicle is recognised by both Bluetooth-Sensors (e.g., same ID), the travel time is calculated based on these time stamps.
Depending on the providers the technology of the sensors itself and the algorithms to calculate the travel time can variate. As an illustration, the algorithm can either return the time stamp when the vehicle is first recognised ("first in"), when the vehicle is very near to the sensor or the vehicle has left the sensor area ("first out"). Notably, the algorithm can as well depend on the filter methods, which can for example include the filter of possible alternative routes.
As depicted in figure 5.2 the links from FCD and the test ride is overlapping with the Bluetooth-route.

Figure 5.2.: Position of the Bluetooth-Sensors and depicted FCD-route in Upper Austria Linz B127

In figure 5.3 an own algorithm is applied on the different Bluetooth sensor data (sensor companies 1-3), because the algorithms of the providers are not always transparent. Therefore, the raw-data is used and an own filter-algorithm applied to be able to compare the sensors itself. The results show that finding the right settings for the algorithms can have a high influence on the output of the Blueooth data.
In order to ensure the quality of FCD and Bluetooth data the output was compared with test rides at the same time as the data was gathered. The test rides were carried out between each Bluetooth sensor (e.g., the route depicted in figure 5.3). This step helped to understand how the Bluetooth data and floating car data differs and it can be identified that the FCD are mostly a bit slower than the Bluetooth data. In the morning peak two findings can be received: the time of the morning peak differs between each Bluetooth provider and the FCD travel time is less than the travel time indicated by the Bluetooth data. One of the reasons for this can be the different aggregation times of Bluetooth data and floating car data, which can be corrected during data historisation and is not depicted in this figure or the inhomogeneity in the transmitted amount of data of each sensor type.

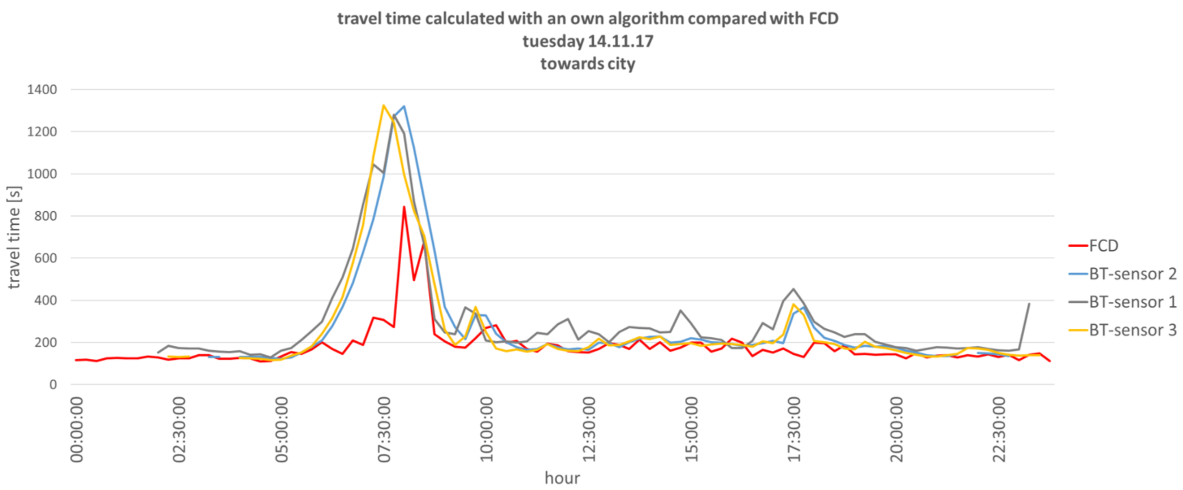

Figure 5.3.: Comparison of floating car data and Bluetooth data applying an own algorithm [20]

Data compatibility:
The data compatibility can be ensured very easily for the present approach. As the model is simulated with SUMO, which is an open source program, a wide documentation about the output and input variables is available. Additionally, a benefit is to be able to calculate further variables with speed data.

5.4. Summary

In this chapter a procedural model for data selection regarding validation and calibration is presented based on literature to avoid complications with data sets in advance. The procedural model is designed to set conditions for data sets and regarding the purpose of the model in the first place. For instance, which variables are supposed to be realistic and which areas of the network are particularly important. Further, in the first section various data sets are presented and an overview of different possibilities of gaining data is presented.
To carry out the validation process in chapter 6 the procedural model returned the following: The traffic variable, which should be realistically simulated, is speed and in addition, the Level of Service should not differ much from reality. For the purpose of the model of this thesis high quality data for edges with FRC 1-4 is gathered. To be able to receive the highest quality, aggregated data consisting of loop detection data and floating car data can be used as a data basis. Bluetooth data will not be used in a first step because the required quality cannot be ensured during this thesis. If necessary it would be possible to gather further data sets, like web cam data, test rides or Google data.
The plausibility of the data and compatibility with the simulation output is ensured.

6. Validation of large models

6.1. State of the art

As specified within the project *Multitude*, validation defines if a model is a good representation of a real system, this means

> *"If a model is valid, then the decision made with the model should be similar to those that would be made by physically experimenting with the system (if this were possible)" [106]*

Therefore, the Measurement of Performance (MoP) needs to be defined in a first step. Daamen et al. [43] state that it is important to define the MoP depending on the used simulation tool and the model objective. Based on the available data and traffic variable the MoP can be specified. One should keep in mind that for model validation measurement data and simulation output is required.
Traffic planners are repeatedly confronted with the problem of lack of data. If data is available the data set is usually split into two parts: one for the validation and one for the calibration process. With this method the model is only improved by half of the data, the other half is used for the evaluation. Sometimes the data will be merged for a last re-calibration (i.e., no validation is carried out after this re-calibration). To split the data two possibilities are available: randomly or by geography. Because in some areas more precise traffic data is available this data will be used for model calibration and the other for validation [106]. For validation different data sets can accrue as useful, depending on the propose of the model. Observed measures of performance (e.g., flows, speeds, densities) should be chosen with respect to the application context [64] (compare chapter 5).
In general, model validation can be divided into component testing, functional validation as well as qualitative and quantitative validation. Component testing involves controlling if the dynamics of a model perform realistically, which is usually carried out by programmers. In the functional validation the relationship between speed distribution and local reality is investigated. Within qualitative validation the expectations of the modeller are tested, even when the results are subjective, they are very important to ensure the realistic behaviour of a model, in contrast to quantitative validation, which compares output data with observed data [119]. Ozbay et al. [113] provide an overview of different literature regarding traffic simulation, their performance outputs and the data used in calibration. Benekohal et al. [115] point out that validation is contributed at two different levels: microscopic level and macroscopic level. In the microscopic level speed change patterns and trajectories are used when in the macroscopic level average speed, density and volume is checked. In the macroscopic level not only the flow variables are validated but also the flow relationships. For performance tests regression or ANOVA is carried out. Daamen et al. [43] define two validation processes, a single or multi valued MoP. The single MoP detects the global behaviour of the scenario with a single value. In contrast to the multi

valued MoP, which calculates the Level of Fitness (LoF) after every interval. In this case the modeller needs to be careful regarding noise, created by the calibration, which can be included in the output.

Within the project *Multitude* a two phase validation process is proposed. In the first phase disaggregated data is used for model estimation, which means that at first, individual behaviour is analysed. This step requires a lot of time and is used to develop model parameters. If the level of tolerance for model fitness is maintained, the model is validated with aggregated data, e.g., measured data. In this step, the simulation output is compared to the model output measuring the model fitness with different data sets [106].

Rao et al. [120] propose a multi-stage validation concept for traffic simulation. It is divided into conceptual validation and operational validation. The statistical validation is contributed using two-dimensional t-tests. Therefore, two means are calculated and two-sample Kolmogrov-Smirnov tests are carried out, where the distribution between two different parameters is compared.

Toledo et al. [121] have calibrated an urban-freeway network for Stockholm with MITSIMLab and validated this model. In their study, traffic flows are compared with RMSNE and MNE in 15 minute-intervals during the morning peak. For the validation of travel times standard deviation is used. Further, queue length was compared to aerial photos, for which the authors stated that there was no significant results because of too few references.

Jenelius et al. [111] use the relationship between traffic variables from real-world to validate a macroscopic model for urban areas. The data for the macroscopic fundamental diagram is gained by sensors and floating car data and only the morning peak and evening peak is used.

Before starting a validation, there is a need to define the level of tolerance of a model. Ortúzar et al. [122] note that either the calibration standards by others have to be followed or own standards need to be set. For each purpose a level of tolerance should be defined. This will help to understand not only when a model is adjusted, but also if it can be used for other studies.

Various studies using different measures of model fitness for validation can be found in literature. Fabritiis et al. [123] trained a model with FCD and used Mean Absolute Percentage Error (MAPE) and RMSE to receive the level of fitness. The validation was carried out for 15-minute intervals and 30-minute intervals. Punzo et al. [124] compare the output of different microscopic traffic flow models using real-time-traffic data. A trajectory translation model, safety distance model, continuous response model and stimulus-response model are calibrated. The validation is contributed with different performance measures, like RMSE, Rooted Mean Squared Percentage Error (RMSPE) and Theil's inequality coefficient (Theil's-U) to test the error rate (see section 6.2). Milam et al. [114] set different validation criteria for different parameters. For comparison of measured and simulated volume 95 % to 105 % of observed value are tolerated, in contrast to average travel time and travel speed, which are measured by the standard deviation and should not differ more than 1. Simulated highway density should be in the range of 90 % to 110 % of the observed value and the average and maximum queue length around 80 % to 120 % of the measured values.

Flitsch et al. [20] discussed the advantage and disadvantage of different sensors for validation and calibration of microscopic models. A procedural model is suggested to help to decide which data sets are qualified for calibration and validation in consideration of data quality and area of validation and calibration.

Author	Designed process	Validation of	MoP
Benekohal et.al. [115]	2 different validation levels (micro and macro level)	Micro: speed change patterns and trajectories; Macro: flow variables, flow relationships	ANOVA
Rao et al. [120]	multi-stage validation concept: conceptual and operational validation	distribution of 2 parameters; 2 means compared	two-dimentional t-test; two-sample Kolmogrov-Smirnov test
Toledo et al. [121]	disaggregated and aggregated validation	traffic flows 15 min interval; travel times; queue length	RMSNE, MNE, SD; queue length with aerial photos and vehicle measurements
Jenelious et al. [111]	relationship between traffic variables from real world	density, flow and speed	macroscopic fundamental diagram relationship
Fabritiis et.al. [123]	Floating Car Data Validation	15 and 30 minute intervals	MAPE, RMSE
Punzo et.al. [124]	validation of various microscopic models with real-time traffic data	headway, speed, spacing	RMSE, RMPSPE, Theil's inequality coefficient

Table 6.1.: Summary of selected literature for validation

6.2. Validation process for large models

In order to discover differences between real and simulated data as well as to be able to define precise suggestions for improvements, the validation process is divided into several steps. The approach presented in figure 6.1 combines different processes and methods from literature (compare section 6.1). The aim is to reconstruct the effects of new settings and changes depending on the traffic behaviour over a large model. Another goal is to repeat the validation as often as necessary with as little human resources as necessary.
Under consideration of the availability of observed data, the validation process is started based on generated output data after each new re-calibration. In case that data is available a quantitative validation is carried out, but if no historical data is available, this step is omitted. As a result, one obtains the level of model fitness based on the calculated MoP, which can be returned for different geographic aspects. If large deviations are identified between simulated values and observed values or if no historical data is available, a qualitative validation is carried out, which requires a lot of human power. Due to this, only areas with a wide variation compared to historical data should be investigated. The procedure behind quantitative processes depends on the available traffic variables in the simulation output, the observed data availability and on the model objective. In this thesis the model objective is defined as follows (compare chapter 1): *"A realistic mesoscopic model to fill data gaps in ITS-information systems"*

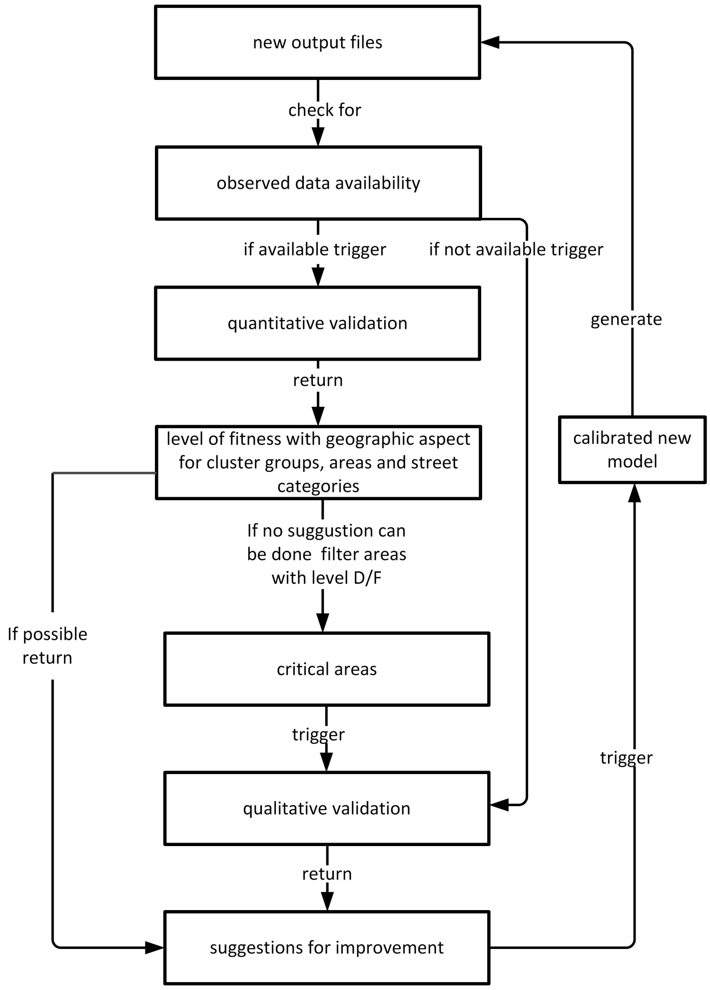

Figure 6.1.: Overview of validation process

Quantitative validation

In figure 6.2 the concept for quantitative validation is depicted. If the ITS system provides route information, travel times can be calculated automatically by using length and speed for a route, therefore the model needs to be optimised regarding *speed data*. If available, the traffic volume can be as well validated, though the error rate is not representative due to the small amount of positions. To identify areas where the model quality is lower, the statistical analysis (MoP) is performed in several steps. The complete network is validated in a first step, based on which a first insight can be gained on the overall quality of the network. The upcoming validation is based on the different traffic categories (compare chapter 3). Within this manageable number of categories it is possible to identify errors based on similar speed-profiles. This has the advantage, that the deviation does not depend on the mixed speed profiles and it is possible to identify problems.

To demonstrate the advantages using traffic categories, the results are compared to select road categories (e.g., FRC, urban, direction).

The validation is carried out for 15 minute intervals between 6 am and 8 pm.

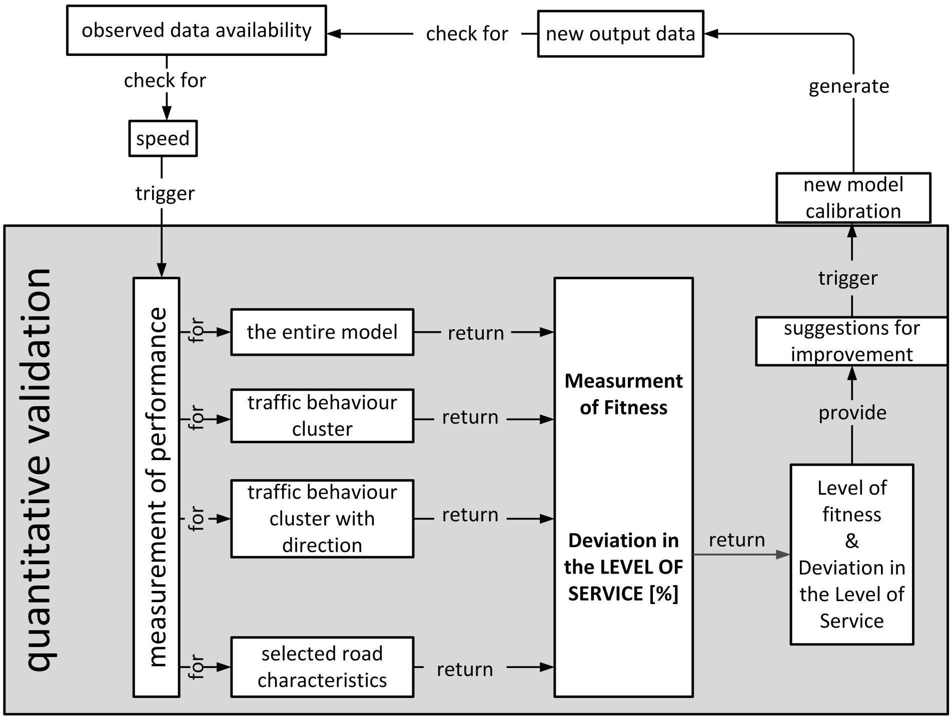

Figure 6.2.: Quantitative validation for large models

Additionally, the LoS is validated, which returns the information of the traffic condition on a road. Regarding the calculation of the LoS, various approaches are available, for instance the HCM defines the LoS by using the capacity of a road [76] and the providers INRIX and HERE are calculating the LoS based on speed information [12], [6]. In EVIS.AT the LoS is as well based on the free-flow speed. The LoS is calculated for the observed data and for the simulation based on speed data in 15 minute intervals. As a result, areas which return a large distribution between simulation and reality can be identified and it is possible to determine if a road is jammed earlier or later than in reality as well as to indicate if the jam is dissolved faster or later than in reality.

Measurement of model fitness

To be able to compare the performance for each evaluated area or street category methods for the measurement of performance need to be defined in advance. Keeping in mind, that validation is a repeating process, different statistical methods should be defined in advance to be able to compare more different calibrated models. Depending on different models some methods might return more informative results than others, due to this they should always be considered in a package. Investigating only one parameter can be misleading on the actual model fitness [106].

Based on literature review the following methods are used for validation:

Mean Absolute Percentage Error (MAPE): To measure the fitness of models in percentage different statistical methods are available. First it is possible to calculate the percent error, which is used for aggregation of network-wide or a single pair of observed and simulated measures. In addition, the mean squared error is often used, which measures the average of squared errors and indicates uncorrelated errors. Calculating the model fitness with Mean Error or Mean

Percent Error an existence of systematic bias is indicated. A lack of this formula is that positive and negative forecast errors can offset each other, in contrast to the Mean Absolute Error or MAPE, which is a common use for returning statistical values. A disadvantage appears when measurements are near zero, in that case the formula can not calculate the error and returns “infinity” and it is not sensitive to large errors. In the following the MAPE is used to understand the forecast accuracy (formula 6.1):

$$MAPE = \frac{100\%}{n} \sum_{i=1}^{n} |\frac{O_i - S_i}{S_i}| \tag{6.1}$$

O : observed value
S : simulated value
n : length of data points
i : time

Rooted Mean Squared Percentage Error (RMSPE): To compare model output and measured values the Root Mean Square Error (RMSE) is recommended in literature (see formula 6.2) [106] . This performance parameter weights high errors higher and makes the response function less smooth around the minimum. In combination with the MAPE, this method can indicate if the outlier rate is very high or low.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{n} (O_i - S_i)^2} \tag{6.2}$$

O : observed value
S : simulated value
n : length of data points
i : time

For validation the Rooted Mean Squared Percentage Error (RMSPE) is used, which provides the error rate in percent. In contrast to the RMSE, the RMSPE is better comparable to the other MoPs.

Forecast bias: Forecasts can generally have a tendency to return higher or lower values than the actual data, this can be calculated with the *Forecast bias* as well-known as *Percentage Bias* (see formula 6.3). A negative value indicates an under-estimation bias, a positive value an over-estimation [125].

$$PBIAS = \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i} \tag{6.3}$$

O : observed value
S : simulated value
n : length of data points
i : time

Theil's inequality coefficient (Theil's-U): Theil's-U returns how well a model, which returns a time series output, fits to the observed data. A bias of zero indicates a perfect fit, 1 would indicate the worst fit[106], [126].

$$U = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{n} S_i^2} + \sqrt{\frac{1}{n}\sum_{i=1}^{n} O_i^2}} \tag{6.4}$$

O : observed value
S : simulated value
n : length of data points
i : time

As pointed out, investigating the MoP is necessary to find weak points in a model. The Theil's-U coefficient returns an overall value about the model fitness, with this a first statement about the overall model quality is provided. When the validation is carried out after a re-calibration of the model, the Theil's-U indicates if the overall model fitness is better or worse than before. The combination the RMSPE and the MAPE indicates if there is a high rate of outliers. The percentage bias helps to discover if a model is over-fitting or under-fitting, e.g., if the simulated traffic volume and observed traffic volume are compared this would indicate that there are either too many or too few vehicles passing the loop detectors. For speed values this indicates that either the vehicles drive too fast or too slow.

Level of fitness
In order to be able to make a statement about the model quality, it must be specified in advance how the results of MoP are interpreted. As already noted in the State-of-the-Art the level of fitness can not generally be defined for all proposes of models or compared variables. In table 6.2 an approach for defining the Level of Fitness for large traffic models, with traffic information propose, is presented. Within each validation for every MoP the Level of Fitness is determined. As already mentioned, the results of RMSPE and MAPE should be checked in combination. In a large network outliers will not be avoidable, therefore the RMSPE has larger values in each level than the MAPE. In the next step the results of all different quality indicators are combined by taking the mean between the Level of Fitness. In the end it is possible to return one model-fitness level for the complete model and for each validation step.

Defining the LoF various requirements are considered. Different guidelines, like the Guidelines for dimensioning road traffic facilities (HBS) or the Highway Capacity Manual (HCM) provide

LoF	Theil's-U	RMSPE	MAPE	+/- Percentage Bias
A	<0,15	<0,25	<0,15	<0,10
B	0,16-0,30	0,26-0,35	0,16-0,3	0,10-0,20
C	0,31-0,45	0,36-0,55	0,31-0,40	0,21-0,30
D	0,46-0,60	0,56-0,75	0,41-0,50	0,31-0,40
E	0,61-0,80	0,76-0,85	0,51-0,65	0,41-0,50
F	>0,81	>0,85	>0,65	>0,51

Table 6.2.: Selected fitness indicator levels for link velocity in respect of logical combinations between each MoP

methods to calculate the LoS regarding road capacity. The HBS defines the LoS for two-lane carriageway using the relation between speed and density. Each LoS is defined in different steps until the maximum density is reached (LoS F-failure). The first steps are in 15% units from the maximum density (A, B, C) [76]. LoS classifications are as well based on the speed, for example in the project EVIS.AT the LoS is defined in 3 steps (red, yellow, green) using the speed.
The percentage bias does not influence the LoF as much as the other values. As mentioned above, the bias can be balanced out (e.g., if it is 0). In this case the simulation does not tend to an overestimation or underestimation. Due to these phenomena, the bias is not weighted the same as the other factors, though it delivers an important information about the model behaviour.

Before starting carrying out the validation process it should be defined which Level of Fitness for the simulation is wanted. To fill up data gaps for real-time-traffic data some things need to be considered:

- the model should return a realistic traffic behaviour, but for real-time-traffic information the speed output is more important than the right amount of vehicles
- the model is needed in areas where few real-time data is available, e.g., a well-done model performance is important in these areas
- ITS services have a high relevance regarding commuter traffic information, e.g., it is necessary to return a well calibrated model in inbound and outbound directions of cities

For the complete model the Level of Fitness, which should be reached is at least B. The goal is to reach for speed values on inbound and outbound directions a Level of Fitness of A, at least B as well for cluster-classes with a low amount of real-time-traffic data.

6.3. Results

To receive a higher model quality various factors can influence the model output, for example routing algorithm, O-D-matrix, the network as well as the parameter settings. In the following the impact of changed mesoscopic settings, using the results of chapter 4, on the model of Upper Austria are analysed by applying the developed validation process.
Therefore, speed data sets are provided, based on the time period between January 2018 and November 2019, using only weeks which were free of holidays and of bank holiday, and a minimum of at least 5 measurements per time interval for each link is set. The algorithm behind

the data generation considers data provided by FCD and permanent counting stations and will only use data older than one year, if there is not enough data available.
The LoS is calculated based on the free-flow speed and the historical/simulated speed-value for each link in a 15 minute interval and is classified based on the harmonisation of EVIS.AT (e.g., jammed up to 33 %, free over 55 % and unstable between 33 % and 55 %).
It needs to be noted, that due to the calibration process only 6 am till 5 pm is validated.

The validation is carried out on three model versions, which are compared with each other, to show that the use of the traffic categories facilitates the validation. Therefore, the results are additionally compared to the validation results based on selected road categories. Model-1 (M-1) represents the primary model of Upper Austria, without any further adjustments, in contrast to model-2 (M-2) and model-3 (M-3), which are re-calibrated model versions. In model-2 the parameters *edge-length* (58 m) and *jam-threshold* (-0.33) are set and some values are changed. The values which are adjusted is the time value to eliminate vehicles to avoid dead locks and the teleport-time for vehicles, which can not continue their route, as well as the speed deviation. Model-3 is based on the parameters of model-2 and additionally the τ-values are adjusted. The headway is set to 1.2 seconds for free-free and free-jam, 2 seconds for jam-free and 1.8 seconds for jam-jam, details about the parameter settings are explained in chapter 4. The configuration settings of the SUMO-files are depicted in appendix G.

6.3.1. Validation of speed

Model fitness of the entire model
Starting with the validation of the entire model (see table 6.3), an overview of the impact of different settings is provided. The MAPE variates around 7 % between the different models, the RMSPE indicates a high rate of outliers in each version, though the best-fitting version is model-2, which is as well indicated by the Theil's-U. All three models have in common that there is an over-estimation in the model simulation (e.g., the vehicles drive too fast).

Table 6.3.: Measurement of Performance over the complete network for adjusted models

Model	RMSPE[%]	MAPE[%]	Percentage Bias[%]	Theil's-U	LoF
M-1	38.84	25.82	13.70	0.29	C
M-2	34.12	21.81	16.30	0.22	B
M-3	41.27	28.90	20.70	0.28	C

Model fitness of traffic categories without direction
An over-estimation of the speed-value is indicated in all categories. Model-1 returns a LoF of "D" for two groups, which have urban characteristics, but differ in detail and returns a better model fitness for rural groups with higher free-flow values (compare with table 3.9 in chapter 3). Within the adjustments model-2 returns a worse model fitness in traffic category 4 than model-1, which has urban characteristics and a low free-flow speed. Further, the fitness deteriorates in category 6, which has as well urban characteristics, but increases in all other categories. Comparing model-3 to the other models indicates, that the adjustments do not influence the model fitness as significant as within model-2.

Table 6.4.: Measurement of Performance for traffic categories without direction over the complete network

Model	Traffic category	RMSPE [%]	MAPE [%]	Percent Bias[%]	Theil's-U	LoF
M-1	1	31.75	20.97	13.2	0.26	B+
M-2	1	27.49	17.80	13.9	0.20	B+
M-3	1	30.97	22.13	18.3	0.23	B
M-1	2	31.05	20.12	13.9	0.25	B
M-2	2	27.96	17.50	13.6	0.20	B+
M-3	2	31.56	21.95	18.4	0.23	B
M-1	3	35.89	23.76	13.2	0.29	B
M-2	3	30.54	19.84	15.6	0.22	B
M-3	3	34.53	24.57	19.7	0.26	B
M-1	4	75.16	60.59	17.4	0.59	D
M-2	4	80.58	58.43	46.2	0.58	E
M-3	4	75.81	60.12	31.2	0.57	D
M-1	5	58.43	43.43	16	0.47	D
M-2	5	53.35	37.02	29.6	0.39	C
M-3	5	58.08	43.26	26.2	0.44	D/C
M-1	6	47.50	35.76	13.4	0.42	C
M-2	6	41.44	28.43	22.8	0.31	C
M-3	6	47.42	34.74	22.4	0.37	C
M-1	7	38.54	26.18	14.3	0.32	C
M-2	7	33.34	22.01	17.6	0.24	B
M-3	7	37.40	26.78	21.2	0.28	B

A-B/B+ LoF
B LoF
C-D LoF
E LoF
E-F LoF
F LoF

Model fitness of traffic categories with direction

When the model fitness is returned for traffic categories with direction a large difference between the results of each version can be identified. Model-2 returns, in comparision to model-1, one level better MoPs for five traffic categories. Between one and two levels it returns a better fitness for six traffic categories and two levels better for three categories. Only two categories return the same LoF. In model-1 and model-2 the simulation has failed for traffic category 14 (LoF =F), which is characterised with a free-flow speed around 30 km/h and is located mainly in rural areas. In contrast to model-1, model-2 only has a LoF of D/E in level 4, which is characterised as well with a free-flow speed around 30 km/h, but, in contrast to category 14, is mainly located in urban areas. That version returns for all other categories a minimum fitness of C, in seven categories the model fitness has increased to A or A/B. These include traffic category 10 and 13, with a model fitness of A, which have a free-flow speed over 70 km/h up to 100 and are located in various areas.

Comparing the results of model-3 to the other versions, the numbers indicate that the model fitness is in many areas similar to model-2 (e.g., the LoF is in 12 categories the same or does only differ less than one level), though in general the errors tend to be higher. If the validation is carried out for the complete model, the model fitness seems as it would be nearly identical within model-1. The values indicate that the model fitness does increase within model-3.

Table 6.5.: Measurement of Performance for traffic categories 1-9 with direction over the complete network

Model	**Traffic category**	**RMSPE [%]**	**MAPE [%]**	**Percent Bias [%]**	**Theil's-U**	**LoF**
M-1	1	43.60	26.03	-2.7	0.40	C
M-2	1	26.33	13.76	9.9	0.16	A/B
M-3	1	34.26	21.50	12.7	0.27	B
M-1	2	62.42	49.52	-11.9	0.59	D
M-2	2	38.78	28.47	23.5	0.31	B/C
M-3	2	51.82	40.65	10	0.45	C
M-1	3	50.35	35.82	-3.6	0.47	C/D
M-2	3	28.74	19.57	16.2	0.23	B
M-3	3	39.98	29.52	14.6	0.35	C
M-1	4	76.74	66.78	-25.2	0.73	E
M-2	4	72.50	52.15	45.2	0.60	D/E
M-3	4	73.25	61.12	4.7	0.66	D/E
M-1	5	70.77	58.80	-12.3	0.66	E
M-2	5	49.62	37.02	32.2	0.43	C
M-3	5	62.59	50.91	11.3	0.57	D
M-1	6	37.45	25.15	8.8	0.33	C
M-2	6	27.05	18.08	14.3	0.21	B
M-3	6	33.67	24.66	17.9	0.28	B
M-1	7	43.80	29.54	2.7	0.40	C
M-2	7	27.63	18.32	14.6	0.21	B
M-3	7	35.15	25.05	16.7	0.29	B
M-1	8	47.01	32.69	1.8	0.43	C
M-2	8	29.77	20.19	16.6	0.23	B
M-3	8	37.33	27.30	18	0.31	B
M-1	9	58.97	45.39	-13.6	0.57	D
M-2	9	32.05	23.07	18.7	0.26	B
M-3	9	46.88	35.81	9.5	0.42	C

A-B/B+ LoF
B LoF
C-D LoF
E LoF
E-F LoF
F LoF

Table 6.6.: Measurement of Performance for traffic categories 10-17 with direction over the complete network

Model	**Traffic category**	**RMSPE [%]**	**MAPE [%]**	**Percent Bias [%]**	**Theil's-U**	**LoF**
M-1	10	45.10	29.59	-5.1	0.43	C
M-2	10	19.51	13.76	11.1	0.18	A-
M-3	10	32.18	23.23	12.4	0.31	B
M-1	11	35.67	23.70	8.8	0.31	B-
M-2	11	25.61	17.10	13.4	0.19	A/B
M-3	11	31.13	22.66	17.6	0.25	B
M-1	12	34.09	21.27	8.9	0.29	B
M-2	12	25.38	15.24	11.8	0.18	A/B
M-3	12	32.30	22.34	15.8	0.26	B
M-1	13	32.33	19.90	6.7	0.28	B
M-2	13	22.37	13.60	10	0.16	A
M-3	13	29.40	20.68	14.9	0.24	B
M-1	14	86.39	79.82	-10.4	0.79	E/F
M-2	14	116.47	90.48	77.7	0.95	F
M-3	14	86.49	77.11	15.3	0.75	E/F
M-1	15	44.07	27.99	-7.5	0.42	C
M-2	15	27.55	14.98	11.6	0.17	A/B
M-3	15	29.42	22.12	16.5	0.24	B
M-1	16	35.54	20.90	10	0.18	A/B
M-2	16	26.56	13.96	11.8	0.16 A/B	
M-3	16	28.84	21.81	17.7	0.20	B
M-1	17	23.93	16.97	14	0.18	A/B
M-2	17	24.11	17.07	14.7	0.19	A/B
M-3	17	27.75	20.82	18.8	0.22	B

A-B/B+ LoF
B LoF
C-D LoF
E LoF
E-F LoF
F LoF

The results above indicate an aggregated model fitness between 6 am and 5 pm over each edge in every traffic category. To understand how the result varies over the day the MoPs are additionally calculated for each hour between 6 am and 5 pm. In figure 6.3 the distribution of the RMSPE for M1, M2 and M3 is depicted for three selected traffic categories. Traffic category "C1" has rural characteristics, with at least 100 km/h. "C3" is characterised as urban characteristics within 50-70 km/h and "C4" is characterised as urban characteristics within 30-50km/h. The figure indicates outliers in "C4", though they have the biggest difference in M2. In "C1" the results vary the most between M1 and the other models.
Investigating the distribution of the MAPE indicates more outliers. This phenomena can be explained due to the fact that the RMSPE considers outliers. The Theil's-U returns, that the

simulated data has the most constant model fitness of M2. In M2 the results do not differ much over time for C1 and C3 (compare appendix I).

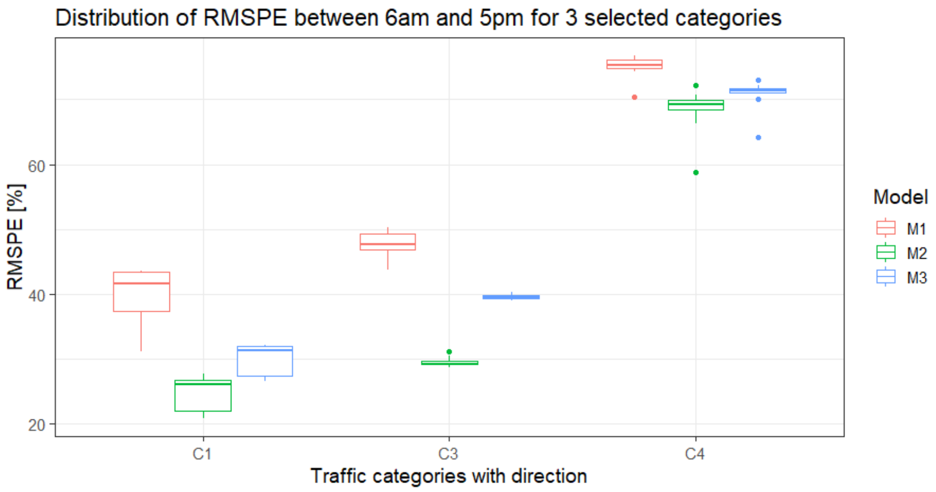

Figure 6.3.: Distribution of RMSPE calculated for each model version between 6am and 5pm for 3 selected categories

Comparing the results to selected road categories

In this paragraph the LoF is returned for selected road categories, to show that the use of the traffic categories is beneficial regarding the validation process.

Investigating only urban and not-urban areas (e.g., everything which are outside of urban areas) (see table 6.7), shows that the results of each MoP for model-1 do not differ significantly in each area. The positive impact of model-2 can be identified in urban areas (RMSPE reduced up to 15 % and MAPE up to 10 %), in contrast to the non urban areas, where the difference is not as significant compared to model-1. The analysis indicates that model fitness in model 3 has decreased significantly in non urban areas.

Table 6.7.: Measurement of Performance for adjusted models regarding urban and non urban areas

Model	**Urban**	**RMSPE [%]**	**MAPE[%]**	**Percent Bias [%]**	**Theil's-U**	**LoF**
M-1	urban	38.68	25.84	12.1	0.29	C
M-2	urban	24.76	15.41	8.3	0.18	A/B
M-3	urban	39.90	28.43	19.7	0.27	C
M-1	not_urban	39.27	26.92	17.1	0.27	C
M-2	not_urban	39.09	24.02	17.6	0.24	B/C
M-3	not_urban	45.02	30.27	22.7	0.28	C

Validating model-1 regarding inbound and outbound direction indicates a high error rate in inbound direction, though the results are better fitting for outbound directed lanes. In contrast to model-2, which indicates a significant better model fitness for both directions. Model-3

returns a better fitness on inbound areas than model-1, but the impact of the adjusted values is not significant in the outbound direction.
A comparison of the urban and non urban areas show that the values of the RMSPE are 10-20% higher if the analysis is carried out on the direction (see table 6.8).

Table 6.8.: Measurement of Performance regarding lane direction for adjusted models

Model	**Direction**	**RMSPE [%]**	**MAPE[%]**	**Percent Bias [%]**	**Theil's-U**	**LoF**
M-1	inbound	55.72	40.20	-6.8	0.48	D
M-2	inbound	35.90	22.74	16.3	0.23	B
M-3	inbound	49.16	35.61	12.9	0.37	C
M-1	outbound	44.32	30.37	7.7	0.33	C
M-2	outbound	35.40	22.42	16.4	0.23	B
M-3	outbound	44.60	32.48	17.5	0.32	C

The validation based on FRC does not indicate significant differences between model-1 and model-3. The analysis returns a better model fitness in FRC-4 for model-1 then model-3. The results for each MoP are listed in the appendix H.

Table 6.9.: Measurement of Performance regarding FRC for adjusted models

FRC	**LoF Model-1**	**LoF Model-2**	**LoF Model-3**
1	C	B+	C
2	B	B+	B
3	B	B+	B
4	B-	B-	C

6.3.2. Validation of Level of Service

Table 6.10 shows the results for the comparison between the LoS of the simulation and historical data. As can be seen, the correct simulated traffic state "free" increases with each model version, in contrast to the consistent output of the traffic state "jam", which is less than before. The difference between the traffic state "free" and "unstable" has increased, though the difference between "jam" and "free" is less. This indicates, that wrongly simulated traffic jams are solved or improved.

Table 6.10.: Validation of Level of Service regarding the complete network

Consistent or differing LOS?	**LOS simulation**	**observed**	**% of edges M-1**	**M-2**	**M-3**
consistent	free	free	90.54	95.03	96.00
consistent	jam	jam	0.07	0.01	0.00
consistent	unstable	unstable	0.05	0.06	0.03
differing	free	jam	0.32	0.42	0.48
differing	free	unstable	3.66	4.32	3.37
differing	jam	free	4.75	0.06	0.05
differing	jam	unstable	0.48	0.01	0.00
differing	unstable	free	0.10	0.06	0.06
differing	unstable	jam	0.03	0.03	0.01

Returning the results for the traffic categories without direction returns a higher amount of consistent LoS in 6 of 7 categories in model-2, in contrast to model-1. The results of model-3 compared to model-2 are similar. The analysis shows, that splitting up the results on the categories returns more information about the differing edges. For instance, it indicates that in category 5 the LoS differs much more between free (simulated) and unstable (observed) as well as between jammed (simulated) and free (observed) then in the other categories.

Table 6.11.: Validation of Level of Service M-1 separated into the cluster classes over the complete day

Model	differing LOS?	LOS s	LOS o	% of edges C1	C2	C3	C4	C5	C6	C7
M-1	c	f	f	96.16	96.61	94.18	60.66	79.05	85.32	92.76
M-2	c	f	f	98.47	94.66	96.94	72.81	87.89	93.57	96.77
M-3	c	f	f	96.17	96.61	94.20	60.95	79.17	85.43	92.81
M-1	c	j	j	~0	~0	~0	3.06	0.18	0.01	0.00
M-2	c	j	j	~0	~0	~0	0.01	~0	~0	0.00
M-3	c	j	j	~0	~0	~0	2.99	0.18	0.01	0.00
M-1	c	u	u	~0	0.05	0.01	0.13	0.02	0.01	0.02
M-2	c	u	u	0.06	0.23	~0	0.15	0.07	0.03	0.02
M-3	c	u	u	0.01	0.05	~0	0.14	0.02	0.01	0.01
M-1	d	f	j	0.16	0.18	0.22	1.17	0.54	0.33	0.24
M-2	d	f	j	0.23	0.30	0.31	4.00	0.81	0.40	0.27
M-3	d	f	j	0.16	0.18	0.22	1.19	0.54	0.34	0.24
M-1	d	f	u	1.39	1.54	1.76	16.84	8.40	4.92	2.58
M-2	d	f	u	1.13	4.65	2.69	22.39	10.93	5.79	2.83
M-3	d	f	u	1.40	1.55	1.79	16.72	8.42	4.92	2.59
M-1	d	j	f	2.24	1.53	3.71	11.53	9.24	8.56	4.26
M-2	d	j	f	0.04	~0	0.02	0.26	0.10	0.12	0.05
M-3	d	j	f	2.21	1.50	3.66	11.48	9.14	8.45	4.20
M-1	d	j	u	~0	~0	0.05	6.31	2.38	0.74	0.08
M-2	d	j	u	~0	0.05	~0	0.15	0.04	0.01	0.00
M-3	d	j	u	~0	~0	0.05	6.24	2.34	0.73	0.07
M-1	d	u	f	0.05	0.06	0.08	0.19	0.18	0.11	0.05
M-2	d	u	f	0.07	0.11	0.04	0.11	0.14	0.08	0.04
M-3	d	u	f	0.05	0.06	0.08	0.18	0.19	0.11	0.05
M-1	d	u	j	~0	0.04	~0	0.10	0.00	~0	0.01
M-2	d	u	j	0.01	~0	~0	0.11	0.01	~0	0.01
M-3	d	u	j	~0	0.04	~0	0.10	0.01	~0	0.01

c...consistent
d...differing
f...free
u...unstable
j...jam
s...simulated
o...observed

6.4. Summary and conclusion

In this chapter a validation procedural model is designed to investigate the impact of changes in a model. Different from other procedural models, the focus relies on the efficient identification

of points of weakness in a large model. Therefore, the traffic categories, which are calculated in chapter 3, are used and the LoF, within a logical combination of the MoPs, is returned for each. Coupled with the knowledge behind each category, e.g., the similarities between traffic behaviour and road characteristics, the influence of adjustments on a simulation model can be identified. Moreover, it is possible to adjust different settings based on the knowledge behind each parameter and the areas which need to be adjusted. The validation is carried out for speed and LoS, due to the propose of the model. Comparing the results of the traffic categories to selected road categories shows that using the categories has a positive influence on the validation results.
The results for the Upper Austria model indicate that adjusting *edge-length* and *thereshold* has a positive impact on the model performance. As well changing the speed deviation of the vehicles to zero (e.g., they can not drive faster than the maximum speed) has a positive impact. It is possible to identify areas where the model is near reality as well as areas where the difference is quite large.
Using the τ-values the impact is not as positive as expected, but better than the primary model. In this case it needs to be identified where the model has changed between version 2 to version 3 to adjust the parameters. The re-calibration is limited to these parameter settings, though further work can consist of further adjustments (e.g., routing, origin-destination matrix). To sum up, the validation procedural model helps to identify the impact of changes efficiently.

7. Conclusion

7.1. Summary

The aim of this thesis was to design **an approach for the efficient development and validation of mesoscopic simulation models for large road traffic networks**. The main part of this research was applied on an existing traffic simulation, which is used for real-time-traffic information. To generalise results a test-network additionally designed.
The focus of this thesis relied on two research questions:

1. How can mesoscopic traffic models for road transport networks be adjusted efficiently?
2. How can mesoscopic traffic models for large road networks be validated efficiently?

To provide a basis for this research an overview about the generation of real-time-traffic data in Europe is provided(compare sub-research question 1.1 *"What are relevant traffic variables and data sources for ITS proposes?"*). Commercial companies and national initiatives are presented and advantages and disadvantages of different sensor types are pointed out. Following the approach in Upper Austria is presented. To fill the data gaps in Upper Austria a simulation model is used. It is identified that there is a need to develop efficient procedures to generate a valid traffic model .
To fill data gaps (compare sub-research question 1.2 "How can data gaps of speed-over-time-profiles be filled?") and, moreover, to handle the validation of the large network (research question 2), similarities between traffic behaviour were analysed. The statistical analysis showed, that there is a need to identify significant road and spatial characteristics in a first step. Moreover, within the applied cluster analysis on the speed-over-time-data set it was pointed out, that the available road characteristics are not enough to return valid clusters. The results pointed out, that the direction of the road is needed to take traffic peaks in account. To fulfil this need a procedure to calculate the "inbound" and "outbound" direction for suburban and urban areas is designed. The new attribute is added and clusters are calculated for these areas. The results show that it is possible to structure the network in 7 different traffic behaviour clusters. In urban and suburban areas 6 clusters are generated for inbound and outbound direction.
To find well fitting parameters a one-at-a-time sensitivity analysis was carried out on a test network (compare sub-research question 1.4 *"What impact do different parameter settings have on the simulation model?"*). The test network is designed based on the results of the cluster analysis regarding *V85* speed. This aims to investigate the changes on a small, representative network (e.g., not to use the large model). Each re-calibration is contributed with a new setting or new parameter value. The change is compared to the previous settings as well as to a basic microscopic model. Thus, it is possible to limit the possibilities of the settings and to set only those with the most positive influence on the Upper Austria simulation. This helps to re-calibrate the model time efficient and to reduce the amount of validation rounds. Furthermore,

the study shows that the one-at-a-time analysis is an efficient way to investigate the mesoscopic parameter settings. The combination of the ANOVA and TUKEY HSD analysis with the fundamental digram provides an efficient procedure to investigate the influence. The results showed that setting the edge-length and the jam-threshold has a major impact on the model performance. The τ-values have as well a large impact, however it is challenging to find the right setting, because it is only possible to set one value for each τ. Another key point is that the τ-values depend on the road capacity, which makes it difficult on large networks.
Before the validation procedure was designed, it was explored which data sources are suitable for validation/calibration of large traffic models (compare sub-research question 1.5/2.2). Advantages and disadvantages of different sensor data for validation and calibration are provided. The findings point out, that for the mesoscopic model, which is used for real-time-traffic information, speed values should be validated. To choose the data sets for validation it is pointed out that highest data quality is returned by the permanent counting stations. In addition the largest coverage is returned by the floating car data. With this in mind, both data sets are used in combination, aggregated over a large period for validation.
Considering the state of the art of validation procedures a procedural model was designed for large traffic models. The model is divided in two parts, first the quantitative validation and second the qualitative validation. To be able to identify points of weakness in a large model as well as the impact of general adjustments (e.g., changing parameters, algorithms) the calculated clusters regarding similarities in traffic behaviour are used. A comparison between applying the validation on clusters or on selected road characteristics returns that the influence and areas of less model fitness can be identified. To calculate the model fitness four Measurement of Performance (MoP) are selected based on literature. In a logical combination these four Measurement of Performance (MoP) can make a clear statement. To define the Level of Fitness (LoF) relationships between the free flow speed, actual speeds (e.g., Level of Service (LoS)) as well as the occupancy are considered. Within this definition it is possible to return a LoF for each cluster and for the complete network. With the results over the complete model, a first impression of the model fitness is provided. It is not possible to find weak points within this overview, which is possible with the clusters. The clusters have the benefit that roads with similar traffic behaviour return similar speed values. Calculating an average of each Measurement of Performance (MoP) shows the variation under consideration of possible speed values (for example a MAPE of 10% has a different effect on 100km/h than on 30 km/h). The comparison of two or more validations show if the model is improved by the new adjustments or not.
The findings suggest areas in which a deeper validation has to be carried out. If needed, a qualitative validation (e.g., searching for errors manually) can be performed. Notably, human effort is much more time-consuming than with the quantitative procedure. The quantitative validation model has the advantage that it is possible to implement the procedure into a script. After each re-calibration the validation can be redone with the same structure and returns the LoF for each cluster, as well as for the complete network.

7.2. Limitations of the thesis

It should be in mind that the thesis has a number of limitations:
This thesis has concentrated on re-calibrating large mesoscopic traffic models by adjusting

parameter settings as well as the validation of these models. This means, that topics, which influence the model, like routing algorithms or the origin destination matrix, are not in the focus of this thesis.
The calculated clusters are limited to the available and additionally calculated road characteristics. Identifying further road characteristics could improve the output of the clusters. This means, that the similarities depend on the road characteristics and a new, significant road characteristic can improve the values. It is possible to re-use the same clusters in other networks if the same road characteristics are available and the same social behaviour is present. This means, the findings should not imply that the clusters are valid on every network/for every area. The clusters as well depend on the social behaviour of people, which is different in various areas of Europe as well over the world.
The analysis of the impact of the mesoscopic traffic behaviour is compared to a basic microscopic model. This means, that the improvement of the microscopic model could improve the output. However, the OAT is only a tool to limit the possible settings. The goal is to adjust a large traffic model with less effort.
As far as possible, within the literature review all sensor types were considered for calibration and validation. The analysis of the suitability for validation/calibration was limited to available data sensors. For example, floating phone data are not analysed because it was not available.
The designed validation procedure focuses on identifying changes after adjustments in the model. The results are limited to the clusters. Though, it would be possible to return the LoF for each link, this would turn into a lot of effort. The procedure suggests investigating areas, which do not fit well to reality, additionally with a qualitative or quantitative analysis.
The proposed model is limited to the quantitative simulation models and does focuses on the quantitative validation procedure.
To re-calibrate an existing traffic simulation model not only the adjustment of parameter settings is important. Further research needs to investigate route algorithms or adjustments on the origin-destination matrix as well. The validation can be carried out with the proposed validation procedural model, if the changes influence the complete model.

7.3. Future work

One of the limitations of this thesis is the re-calibration of the model with only mesoscopic parameters. Adjusting the demand model as well as the routing algorithm is not a focus of this thesis, though to develop a well fitting model these need to be adjusted as well.
For this, there are various methods available, like within SUMO there is the possibility to adjust a simulation model with a function called "the calibrator", which was added to SUMO about 2-3 years ago. "The calibrator" enables to adjust speed and/or the amount of vehicles on one point of an edge in a defined interval to a fixed value. Therefore, a loop is set on a certain possition of an edge and vehicle informations about the passing vehicles are added, as well as their speed and the amount. This means, that in theory the routing will be adjusted depending on the set calibrators as well as the speed and amount of passing cars in the set interval. The possibility of using this functionality for large networks is currently under investigation. In a first step only new speed data and vehicle data will be used, gained by vehicle detection loops. The validation can be carried out again with the proposed validation procedural model of this thesis.

Further a routing algorithm is implemented for the existing model. This routing algorithm might as well need some adjustments - for example to take into account defined "via" streets. As a third important part that needs to be adjusted is the network. Currently it was possible to identify some network related issues, for example a bug in the city center of Linz which has influenced the free-flow speed. However, adjusting the network itself is limited to the information provided by the GIP.AT.
A very important part of future work is the on-line live re-calibration. As described in the introduction chapter it is possible to re-calibrate the simulation online every 5 minutes within currently gained traffic data, which is currently only implemented for detection loops. To be able to use all available data sets (e.g., Bluetooth-data, FCD) further research is necessary. In addition, a feedback loop to receive the model fitness of the on-line re-calibrated model will be implemented, to validate the traffic model.
Further research could as well provide concepts how areas, which do not fit well to reality, can be validated with as less human effort as possible. In this thesis a procedure to investigate the model fitness under respect of traffic behaviour is presented.
Future research could add new road-characteristics to be able to identify similar traffic behaviour more easily. It is recommended to work with the road characteristics instead of edge-IDs for clustering: the clusters can be matched on new networks. The clusters can additionally be used to fill data gaps, which can be another usefully focus.

Glossary

ANOVA Analysis of Variance. 2, 25, 26, 34, 35, 51, 57, 60, 61, 77

C-ITS connected intelligent transport systems. 6

DLR German Aerospace Center. 21, 22

EU European Union. 10, 12, 23, 28
EVIS.AT Realtime Traffic Information Austria. 6, 11, 12, 14, 18, 19, 23, 29, 81, 84, 85

FCD Floating Car Data. viii, 1, 7, 8, 13–21, 26, 27, 37, 67, 72–74, 85
FOW Form of Way. 28, 33, 34, 45, 46
FPD Floating Phone Data. 7, 8, 14–17, 27, 67, 72
FRC Functional Road Class. x–xii, 18, 28, 33, 34, 39, 46, 48, 75, 81, 90, 128–131

GIP-AT Graph Integration Platform Austria. 1, 11, 12, 18, 21, 28–30, 44, 45, 51
GNSS Global Navigation Satellite System. 7, 8, 11–14, 17, 20, 21

HBS Guidelines for dimensioning road traffic facilities. 84
HCM Highway Capacity Manual. 84

ITS intelligent transport systems. 1–4, 6, 7, 10, 11, 16, 18, 22–24
ITS-UA ITS-Upper Austria. vi, 18, 19, 21, 22, 29, 59

JSON JavaScript Object Notation. 7–9

KPI Key Performance Indicator. 10

LoF Level of Fitness. 76, 77, 84, 86–90, 93, 95, 96
LoS Level of Service. 68, 76, 81, 84, 85, 91, 93, 95

MAPE Mean Absolute Percentage Error. 77, 82, 84, 86–90, 128, 129
MC Management Console. 18, 22
MoP Measurement of Performance. 2, 76–80, 83, 84, 87, 89, 93, 95

NUTS Nomenclature of territorial units for statistics. 28, 29

OAT One-at-a-time-analysis Sensitivity Analysis. 2, 55, 57

RMSE Root Mean Square Error. 82
RMSPE Rooted Mean Squared Percentage Error. 78, 82–84, 86–90, 128, 129

SUMO Simulation of Urban Mobility. 14, 18, 21, 22, 52, 75, 96

TEN-T trans-European transport network. 10

Theil's-U Theil's inequality coefficient. 78, 83, 84, 86–90, 128, 129
TMC Traffic Message Channel. 8, 9, 15
TPEG Transport Protocol Experts Group. 7–9, 15, 16
Tukey's HSD test Tukey's honestly significant difference test. 25, 26, 34, 35, 51, 61, 62

UML Unified Modeling Language. 15

V50 median driving speed on a link. 34, 35, 37, 69
V85 speed that is complied by 85% of the drivers and by 15% exceeded. viii–x, 26, 27, 29, 34, 35, 37–41, 50, 51, 58, 69, 111
VAO traffic information Austria. 11, 12, 18, 19

WMS Web Map Service. 19

XFCD Extended Floating Car Data. 8, 14
XML Extensible Markup Language. 7–9, 15, 16

Bibliography

Books, Thesis, Report, Journal and Conference Proceeding References

[2] Flitsch, Christina, Kastner, Karl-Heinz, and Neubauer, Matthias. “Verkehrsinformation: Vom Sensor zur Prognose”. In: *Jahrbuch der Logistikforschung, Schriftenreihe Logistikforschung, Band 2*. Linz: Trauner Verlag, 2019.

[20] Flitsch, Christina et al. “Calibrating Traffic Simulation Models in SUMO Based upon Diverse Historical Real-Time Traffic Data – Lessons Learned in ITS Upper Austria”. In: EPiC Series in Engineering. Berlin: EasyChair, 2018, pp. 25–26. DOI: 10.29007/rnq9.

[26] Sandrock, Michael and Riegelhuth, Gerd, eds. *Verkehrsmanagementzentralen in Kommunen. Eine vergleichende Darstellung*. ger. Aufl. 2014. Sandrock, Michael (Hrsg.) Riegelhuth, Gerd (Hrsg.) Wiesbaden: Springer Vieweg, 2014. 197 pp. ISBN: 3658043903.

[35] Chandra, F. Y. et al. “Improving the accuracy of real-time traffic data gathered by the Floating Car Data method”. In: *2014 2nd International Conference on Information and Communication Technology (ICoICT)*. 2014, pp. 391–396.

[39] Cohen, Simon and Christoforou, Zoi. “Travel Time Estimation Between Loop Detectors and Fcd: A Compatibility Study on the Lille Network, France”. In: *Transportation Research Procedia* 10 (2015). PII: S2352146515002616, pp. 245–255. ISSN: 23521465. DOI: 10.1016/j.trpro.2015.09.074.

[40] Mak, W. K. et al. “Online Travel Time Estimation in Urban Areas Using the Occupancy of Long Loop Detectors”. In: *IFAC Proceedings Volumes* 42.15 (2009), pp. 383–390. ISSN: 1474-6670. DOI: 10.3182/20090902-3-US-2007.0099. URL: http://www.sciencedirect.com/science/article/pii/S1474667016318237.

[41] Gurczik, Gabi. “Verkehrsdatenerfassung mit Bluetooth-Detektion. Möglichkeiten und Grenzen”. Fakultät Verkehrswissenschaften „Friedrich List“ and Institut für Verkehrstelematik. masterthesis. Dresden: Technische Universität Dresden, 2011. 199 pp.

[42] Namaki Araghi, Bahar et al. “Accuracy of Travel Time Estimation Using Bluetooth Technology: Case Study Limfjord Tunnel Aalborg”. In: *International Journal of Intelligent Transportation Systems Research* 13.3 (2015). PII: 94, pp. 166–191. ISSN: 1348-8503. DOI: 10.1007/s13177-014-0094-z.

[43] Daamen, W., Buisson, C., and Hoogendoorn, S. P. *Traffic Simulation and Data: Validation Methods and Applications*. Florida: Taylor & Francis, 2014. ISBN: 9781482228700. URL: https://books.google.at/books?id=iI5qBAAAQBAJ.

[44] Kastner, Karl-Heinz and Pau, Petru. “Experiences with SUMO in a Real-Life Traffic Monitoring System”. In: *Proceedings of the SUMO2015 - Intermodal Simulation for Intermodal Transport*. Ed. by Deutsches Zentrum für Luft- und Raumfahrt e.V. Berlin, 2015.

[45] Schlaich, Johannes. “Nutzungsmöglichkeiten von Floating Phone Data”. In: *9. Fachkolloquium Straße und Verkehr 2005*. Ed. by Lehrstuhl für Verkehrsplanung und Verkehrsleittechnik Universität Stuttgart. Stuttgart, 2005.

[48] Wang, Huan et al. “A traffic data collection and analysis method based on wireless sensor network”. In: *EURASIP Journal on Wireless Communications and Networking* 2020.1 (2020). PII: 1628, p. 150. DOI: 10.1186/s13638-019-1628-5.

[49] Giust, Fabio, Cominardi, Luca, and Bernados, Carlos J. “Distributed Mobility Management for Future 5G Networks: Overview and Analysis of Existing Approaches”. In: *IEEE Communications Magazine* 0163-6804 (2015).

[50] Breitenberger, Susanne et al. “Traffic information potential and necessary penetration rates”. In: *tec* (2004).

[60] Kastner, Karl-Heinz et al. “Real-Time Traffic Conditions with SUMO for ITS Austria West”. In: *Proceedings of the 1st SUMO User Conference 2013*. Ed. by Deutsches Zentrum für Luft- und Raumfahrt e.V. Berlin, 2013.

[61] Xu, Chengcheng and Wu, Shuyue. “Evaluating the Effects of Household Characteristics on Household Daily Traffic Emissions Based on Household Travel Survey Data”. In: *MPDI Sustainability* 11.6 (2019). PII: su11061684. DOI: 10.3390/su11061684. URL: www.mdpi.com/journal/sustainability.

[62] Alonso, Francisco et al. “Conceptualization of aggressive driving behaviors through a Perception of aggressive driving scale (PAD)”. In: *Transportation Research Part F: Traffic Psychology and Behaviour* 60 (2019). PII: S1369847818302961, pp. 415–426. ISSN: 13698478. DOI: 10.1016/j.trf.2018.10.032. URL: www.elsevier.com/locate/trf.

[63] Peng, Yichuan et al. “Examining the effect of adverse weather on road transportation using weather and traffic sensors”. eng. In: *PloS one* 13.10 (2018). Journal Article Research Support, Non-U.S. Gov’t The authors have declared that no competing interests exist., e0205409. DOI: 10.1371/journal.pone.0205409. eprint: 30325948. URL: https://doi.org/10.1371/journal.pone.0205409.

[64] Antoniou, Constantinos et al. “Towards distibution-based calibration for traffic simulation”. In: *IEEE 17th International Conference on Intelligent Transportation Systems (ITSC), 2014*, pp. 786–791. URL: http://ieeexplore.ieee.org/servlet/opac?punumber=6948869.

[65] Shafiei, Sajjad et al., eds. *Deployment and Calibration of a Large-Scale Mesoscopic Dynamic Traffic Assignment Model of Melbourne, Australia*. 96th Annual Meeting of Transportation Research Board, (Washington, D.C). Washington, D.C, 2016. 18 pp.

[66] Kessler, Lisa et al. “Comparing Speed Data from Stationary Detectors Against Floating-Car Data”. In: *IFAC PapersOnLine*. Vol. 51-9. 2018, pp. 299–304. DOI: 10.1016/j.ifacol.2018.07.049.

[67] Rahman M, M et al. “Traffic Pattern Analysis from GPS Data: A Case Study of Dhaka City”. In: *2018 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT)*, pp. 1–6. URL: http://ieeexplore.ieee.org/servlet/opac?punumber=8469206.

[68] Hertkorn, Georg. "Mikroskopische Modellierung von zeitabhängiger Verkehrsnachfrage und von Verkehrsflußmustern". PhD-Thesis. Cologne: University of Cologne, 2004. 164 pp.

[69] Jeon, Seungwoo and Hong, Bonghee. "Monte Carlo simulation-based traffic speed forecasting using historical big data". In: *Future Generation Computer Systems*. Vol. 65. 2016, pp. 182–195. DOI: 10.1016/j.future.2015.11.022.

[70] Russo, Francesca, Biancardo, Salvatore Antonio, and Busiello, Mariarosaria. "Operating speed as a key factor in studying the driver behaviour in a rural context". In: *Transport* 31.2 (2016), pp. 260–270. DOI: 10.3846/16484142.2016.1193054. eprint: https://doi.org/10.3846/16484142.2016.1193054. URL: https://doi.org/10.3846/16484142.2016.1193054.

[76] Schnabel, Werner and Lohse, Dieter. *Grundlagen der Straßenverkehrstechnik und der Verkehrsplanung Band 1: Straßenverkehrstechnik*. Beuth Verlag GmbH Berlin-Wien-Zürich, 2011.

[77] Land Oberösterreich. *Leben in Oberösterreich: Ergebnisse der Registerzählung 2011 in Oberösterreich*. 2011.

[78] Chopde, Nitin R. and Nichat, Mangesh. "Landmark based shortest path detection by using A* Algorithm and Haversine Formula". In: *International Journal of Innovative Research in Computer and Communication Engineer* 1.2 (2013). 04.

[79] Flitsch, Christina and Neubauer, Matthias. "Explorative Analyse zur Füllung von Lücken in Geschwindigkeitsdaten". In: *Preprint HEUREKA 21*. HEUREKA 21 (Stuttgart, Apr. 13, 2021). Ed. by FGSV. Stuttgart: FGSV, 2020.

[81] Backhaus, Klaus et al. *Multivariate Analysemethoden: Eine anwendungsorientierte Einführung*. 13. Auflage. Berlin; Heidelberg: Springer-Verlag, 2010. ISBN: 978-3642164903.

[82] Fahrmeier, Ludwig, Hamerle, Alfred, and Tutz, Gerhard. *Multivariate statistische Verfahren*. 2. Auflage. Berlin, New York: Walter De Gruyter Verlag, 1996.

[83] Forschungsgesellschaft für Straßen- und Verkehrswesen. *Arbeitspapier Data Mining im Verkehrsmanagement und in der Verkehrsplanung: Anwendungen und Verfahren*. Köln: FGSV Verlag GmbH, 2019. ISBN: 978-3-86446-246-7.

[84] Alboukadel. "Types of Clustering Methods: Overview and Quick Start R Code". In: *Datanovia* (Apr. 11, 2018). URL: https://www.datanovia.com/en/blog/types-of-clustering-methods-overview-and-quick-start-r-code/ (visited on 12/03/2020).

[85] Hansen, Pierre and Jaumard, Brigitte. "Cluster Analysis and Mathematical Programming". In: *Mathematical Programming B* 79 (Oct. 1997), pp. 191–215. DOI: 10.1007/BF02614317.

[86] Vazirgiannis, Michalis. "Clustering Validity". en. In: *Encyclopedia of Database Systems*. Springer, Boston, MA, 2009, pp. 388–393. DOI: 10.1007/978-0-387-39940-9_616. URL: https://link.springer.com/referenceworkentry/10.1007%2F978-0-387-39940-9_616.

[87] Charrad, Malika et al. "NbClust: An R Package for Determining the Relevant Number of Clusters in a Data Set". In: *Journal of Statistical Software* 61.6 (2014).

[88] Glenn W. Milligan and Martha C. Cooper. "An examination of procedures for determining the number of clusters in a data set". In: *Psychometrika* 50.2 (1985), pp. 159–179. ISSN: 1860-0980. DOI: 10.1007/BF02294245. URL: https://link.springer.com/article/10.1007%2FBF02294245.

[89] Rousseeuw, Peter. "Silhouettes: a graphical aid to the interpretation and validation of cluster analysis". In: *Journal of Computional and Applied Mathematics* 20 (1987), pp. 53–65.

[90] Barceló, Jaime and Casas, Jordi. "Dynamic Network Simulation with AIMSUN". In: *Simulation Approaches in Transportation Analysis*. Ed. by Ryuichi Kitamura and Maso Kuwahara. Vol. 31. Operations Research/Computer Science Interfaces Series. New York: Springer-Verlag, 2005, pp. 57–98. ISBN: 0-387-24108-6. DOI: 10.1007/0-387-24109-4_3.

[93] Burghout, Wilco, Koutsopoulos, Haris, and Andréasson, Ingmar. "Hybrid Mesoscopic-Microscopic Traffic Simulation". In: *Transportation Research Record: Journal of the Transportation Research Board* 1934 (2005), pp. 218–255. ISSN: 0361-1981. DOI: 10.3141/1934-23.

[96] Souza, Felipe de, Verbas, Omer, and Auld, Joshua. "Mesoscopic Traffic Flow Model for Agent-Based Simulation". In: *Procedia Computer Science* 151 (2019). PII: S1877050919305824, pp. 858–863. ISSN: 1877-0509. DOI: 10.1016/j.procs.2019.04.118.

[98] Eissfeldt, Nils. "Vehicle-based modelling of traffic. Theory and application to environmental impact modelling". Mathematisch-Naturwissenschaftlichen Fakultaet. PhD-Thesis. Cologne: University of Cologne, 2004. 199 pp.

[101] Turner, D. S. et al. *75 Years of the Fundamental Diagram for Traffic Flow Theory: Greenshields Symposium : July 8-10, 2008, Woods Hole, Massachusetts*. Transportation research circular. Transportation Research Board, 2011. URL: https://books.google.at/books?id=x8s4ngAACAAJ.

[102] Knoop, Victor L. *Introduction to Traffic Flow Theory. An introduction with exercises*. 2nd ed. Delft: Delft University of Technology, 2018. 202 pp. ISBN: 978-94-6366-062-4.

[103] Zaidi, Kamran et al. "Data-centric Rogue Node Detection in VANETs". In: *IEEE 13th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom), 2014*. 2014 IEEE 13th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom) (Beijing, China, Sept. 24, 2014). Annual IEEE Computer Conference et al. IEEE, 2014, pp. 398–405. ISBN: 978-1-4799-6513-7. DOI: 10.1109/TrustCom.2014.51.

[104] Duruisseau, Charlotte and Leclercq, Ludovic. "A Global Sensitivity Analysis of Dynamic Loading and Route Selection Parameters on Network Performances". In: *Journal of Advanced Transportation* 2018.1 (2018). PII: 8414069, pp. 1–24. ISSN: 0197-6729. DOI: 10.1155/2018/8414069.

[105] Domschke, Wolfgang and Drexl, Andreas. *Einführung in Operations Research*. 7th ed. Berlin and Heidelberg: Springer-Verlag, 2007. ISBN: 978-3-540-70948-0.

[106] Antoniou, Constantinos et al. *Traffic Simulation: Case for guidelines*. COST-European Cooperation in Sciens and Technology, 2014.

[107] Ciuffo, Biagio et al. "Theory to practice: global sensitivity analysis of the Aimsun meso model". In: *www.tecmagazine.com* (Mar. 1, 2014).

[108] Hiller, Frederick S. and Lieberman, Gerald J. *Introduction to Operations Research. International Edition.* 10th ed. 2015. ISBN: 978-1-259-25318-8.

[109] Treiber, Martin and Kesting, Arne. *Verkehrsdynamik und -simulation. Daten, Modelle und Anwendungen der Verkehrsflussdynamik.* Berlin Heidelberg: Springer-Verlag, 2010. 367 pp.

[111] Jenelius, Erik, Kristoffersson, Ida, and Fransson, Magnus. "Validation of Traffic Simulation Models Based on the Macroscopic Fundamental Diagram". In: *Transportation Research Procedia* 27 (2017), pp. 561–568. ISSN: 23521465. DOI: 10.1016/j.trpro.2017.12.073.

[112] Maheshwary, Palak et al. "A methodology for calibration of traffic micro-simulator for urban heterogeneous traffic operations". In: *Journal of Traffic and Transportation Engineering (English Edition)* (2019). PII: S2095756418300035. ISSN: 20957564. DOI: 10.1016/j.jtte.2018.06.007.

[113] Ozbay, Kaan et al. "Big Data and the Calibration and Validation of Traffic Simulation Models". In: *Transportation Research Circular: Traffic and Transportatio Simulation* E-C195 (2014).

[114] Milam, Ronald T. "Recommended Guidelines for the Calibration and Validation of Traffic Simulation Models". In: *8th TRB Conference on the Application of Transportation Planning Methods* (2001).

[115] Benekohal, Rahim F. "Procedure for Validation of Microscopic Traffic Flow Simulation Models". In: *Transportation Research Record 1320*, pp. 190–202.

[116] Christine Buisson et al. "Calibration and validation principles". In: *Traffic Simulation and Data: Validation Methods and Applications.*

[117] *Scoping and Conducting Data-Driven 21st Century Transportation System Analyses. FHWA-HOP-16-072.* Technical Report. 2017, p. 136.

[118] Lu, Zhengyang et al. "A video-based approach to calibrating car-following parameters in VISSIM for urban traffic". In: *International Journal of Transportation Science and Technology* 5.1 (2016). PII: S2046043016000022, pp. 1–9. ISSN: 20460430. DOI: 10.1016/j.ijtst.2016.06.001.

[119] Still, G. Keith. "Crowd Dynamics". PhD thesis. University of Warwick, 2002-08-01. URL: http://www.gkstill.com/Support/Links/Documents/2000_still.pdf.

[120] Rao, Lei, Owen, Larry, and Goldsman, David. "Development And Application Of A Validation Framework For Traffic Simulation Models". In: *1998 Winter Simulation Conference Proceedings* (1998).

[121] Toledo, Tom et al. "Calibration and Validation of Microscopic Traffic Simulation Tools". In: *Transportation Research Record.* Vol. 1831. 2003, pp. 65–75.

[122] Ortúzar, Juan de Dios and Willumsen, Luis G. *Modelling Transport.* Fourth edition. Chichester West Sussex United Kingdom: John Wiley & Sons, 2011. xix, 586 pages. ISBN: 0470760397.

[123] Fabritiis, Corrado de, Ragona, Roberto, and Valenti, Gaetano. "Traffic Estimation And Prediction Based On Real Time Floating Car Data". In: *2008 11th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, pp. 197–203. DOI: 10.1109/ITSC.2008.4732534.

[124] Punzo, Vincenzo and Simonelli, Fulvio. "Analysis and Comparison of Microscopic Traffic Flow Models with Real Traffic Microscopic Data". In: *Transportation Research Record: Journal of the Transportation Reasearch Board.* Vol. 1934, pp. 53–63. DOI: 10.3141/1934-06.

[125] Yapo, P. O., Gupta, H. V., and Sorooshian, S. "Automatic calibration of conceptual rainfall-runoff models: Sensitivity to calibration data". In: *Journal of Hydrology* 181.1-4 (1996), pp. 23–48. DOI: 10.1016/0022-1694(95)02918-4. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0030162090&doi=10.1016%2f0022-1694%2895%2902918-4&partnerID=40&md5=9f1883a726f8f46763d3ff1e3f92b638.

Additional References

[1] Deutsches Zentrum für Luft- und Raumfahrt e.V. *SUMO User Documentation.* 2019. URL: http://sumo.dlr.de/wiki/SUMO_User_Documentation (visited on 02/14/2018).

[3] European Commission. *The provision of EU-wide real-time traffic information services.* 2014. URL: https://ec.europa.eu/transport/sites/transport/files/themes/its/news/doc/2014-12-18-rtti/swd%282014%29356.pdf (visited on 03/17/2020).

[4] European Commission. *Mobility and Transport: Action Plan and Directive.* 2019. URL: https://ec.europa.eu/transport/sites/transport/files/legislation/swd20190368-its-ex-post-evaluation.pdf (visited on 03/17/2020).

[5] American Digital Cartography, Inc. *HERE Traffic.* 2020. URL: https://www.adci.com/here/here-traffic/ (visited on 02/17/2020).

[6] HERE. *HERE Traffic.* 2020. URL: https://www.here.com/products/traffic-solutions (visited on 02/17/2020).

[7] NAVmart. *HERE Traffic Data.* 2020. URL: https://www.navmart.com/here-traffic/ (visited on 03/16/2020).

[8] American Digital Cartography, Inc. *TomTom.* 2020. URL: https://www.adci.com/tomtom/ (visited on 02/17/2020).

[9] TomTom International BV. *TomTom Real-Time Traffic.* 2020. URL: https://www.tomtom.com/products/real-time-traffic/ (visited on 02/17/2020).

[10] TomTom International BV. *Protobuf.* 2016. URL: https://developer.tomtom.com/intermediate-traffic-service/intermediate-traffic-service/tomtom-traffic-flow-intermediate-service-protobuf (visited on 03/18/2020).

[11] INRIX. *INRIX.* URL: https://inrix.com/ (visited on 02/17/2020).

[12] INRIX Inc. *INRIX Documentation: Getting Started.* 2018. URL: http://docs.inrix.com/ (visited on 03/17/2020).

[13] Be-Mobile. *Be-Mobile: a revolution in traffic.* 2020. URL: https://be-mobile.com (visited on 03/17/2020).

[14] Comm/dg/unit. *ITS national reports - Mobility and Transport - European Commission.* 2020. URL: https://ec.europa.eu/transport/themes/its/road/action_plan/its_national_reports_en (visited on 03/20/2020).

[15] Dave Barth. *The bright side of sitting in traffic: Crowdsourcing road congestion data.* 2009. URL: https://googleblog.blogspot.com/2009/08/bright-side-of-sitting-in-traffic.html (visited on 02/17/2020).

[16] Champion, Ryan. *Does Google Maps Work In China? Your 2019 Guide.* Nov. 2, 2019. URL: https://eggplantdigital.cn/does-google-maps-work-in-china-your-2019-guide/ (visited on 02/26/2021).

[17] Service Objects Blog. *Why GPS Coordinates Look Wrong on Maps of China -.* 2019. URL: https://www.serviceobjects.com/blog/why-gps-coordinates-look-wrong-on-maps-of-china/ (visited on 02/26/2021).

[18] Google Developers. *Directions API:Get Started.* 3/9/2020. URL: https://developers.google.com/maps/documentation/directions/start?hl=de (visited on 03/17/2020).

[19] Google Developers. *Developer Guide: Distance Matrix API.* 2/19/2020. URL: https://developers.google.com/maps/documentation/distance-matrix/intro?hl=de (visited on 03/17/2020).

[21] European Commission. *Smart mobility company Be-Mobile leverages PCP to accelerate growth track.* 2020. URL: https://ec.europa.eu/digital-single-market/en/news/smart-mobility-company-be-mobile-leverages-pcp-accelerate-growth-track (visited on 03/17/2020).

[22] Crocodile. *the crocodile corridor.* 2020. URL: https://crocodile.its-platform.eu/?_ga=2.44284962.70015007.1584452287-756967288.1584452287 (visited on 03/17/2020).

[23] SEE-ITS. *South East Europe-Intelligent Transport Systems.* 2020. URL: http://www.seeits.eu/Default.aspx (visited on 03/16/2020).

[24] AustriaTech. *Mobilitydata Austria.* 2020. URL: https://mobilitydata.gv.at/ (visited on 03/23/2020).

[25] Med TIS. *Med TIS.* 2020. URL: https://medtis.its-platform.eu/activities (visited on 03/17/2020).

[27] MDM. *MDM Platform.* 3/20/2020. URL: https://service.mdm-portal.de/mdm-portal-application/ (visited on 03/20/2020).

[28] Department for Transport UK. *Intelligent Transport Systems in the UK.* 2017. URL: https://ec.europa.eu/transport/sites/transport/files/2018_uk_its_progress_report_2017.pdf (visited on 03/20/2020).

[29] Shepard, Scott. *Traffic management sensor innovations: the Dutch experience.* 2018. URL: https://www.intelligenttransport.com/transport-articles/67329/traffic-management-sensor-innovation/ (visited on 03/16/2020).

[30] Bundesministerium für Digitalisierung und Wirtschaftsstandorte. *Bundesrecht konsolidiert: Gesamte Rechtsvorschrift für IVS-Gesetz, Fassung vom 23.03.2020.* 2020. URL: https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20008275 (visited on 03/23/2020).

[31] Österreichische Länder bzw. Ämter der Landesregierung, Stadt Wien und, ed. *basemap.at - fact sheet.* 2017. URL: www.basemap.at (visited on 03/20/2020).

[32] Vienna city administration and Austrian province governments. *basemap.at – Austrian OGD basemap*. 2016. URL: https://basemap.at/downloads/basemapat-fact-sheet.pdf (visited on 03/20/2020).

[33] ÖVDAT - Österreichisches Institut für Verkehrsdateninfrastruktur. *GIP-AT*. 2018. URL: http://gip.gv.at (visited on 12/17/2018).

[34] Bundesministerium für Verkehr and Innovation und Technologie. *Verkehrstelematikbericht 2019. Statusbericht zur Umsetzung, Forschung und Entwicklung von IVS-Anwendungen auf nationaler und internationaler Ebene gemäß IVS-Gesetz*. 2019. URL: bmvit.gv.at (visited on 03/18/2020).

[36] World Road Association. *Roadway Sensors*. 3/16/2020. URL: https://rno-its.piarc.org/en/its-basics-its-technologies-data-and-information/roadway-sensors (visited on 03/16/2020).

[37] ave Verkehrs- und Informationstechnik. URL: https://www.ave-web.de/download/brochureMAVE-tun.pdf (visited on 12/01/2020).

[38] ave Verkehrs- und Informationstechnik GmbH. URL: https://www.ave-web.de/download/maveurb_d.pdf (visited on 12/01/2020).

[46] Intertraffic. *How to use 'floating car data' from smart devices?* 2020. URL: https://www.intertraffic.com/news/articles/managing-traffic-with-smartphone-data/ (visited on 03/19/2020).

[47] Ericsson GmbH. *5G-Connected Mobility*. 2021. URL: http://www.5g-connectedmobility.com/ (visited on 03/08/2021).

[51] PTV Planung Transport Verkehr AG. *PTV Optima*. 2020. URL: https://www.ptvgroup.com/en/solutions/products/ptv-optima/areas-of-application/traffic-microsimulation/ (visited on 03/19/2020).

[52] Aimsun SLU. *Aimsun Live for real-time traffic management*. 1/24/2020. URL: https://www.aimsun.com/aimsun-live/ (visited on 03/19/2020).

[53] DATEX II. *DATEX II*. 3/18/2020. URL: https://www.datex2.eu/ (visited on 03/18/2020).

[54] Traveller Information Services Association. *The Traffic Message Channel (TMC)*. 2020. URL: http://tisa.org/technologies/tmc/ (visited on 03/16/2020).

[55] TISA. *Transport Protocol Experts Group (TPEG)*. 3/18/2020. URL: https://tisa.org/technologies/tpeg/ (visited on 03/18/2020).

[56] TPEG Project Office EBU. *TPEG- What is it all about?* 2003. URL: https://www.tpeg.org/ (visited on 03/18/2020).

[57] Europe, ERTICO-ITS. *TN-ITS*. 2020. URL: https://tn-its.eu/ (visited on 03/18/2020).

[58] DORIS. *Straßenverkehrszählungen: Detailinformationen*. 2019. URL: https://www.doris.at/themen/verkehr/vkz_details.aspx (visited on 05/15/2019).

[59] Deutsches Zentrum für Luft- und Raumfahrt e.V. *SUMO User Documentation*. URL: http://sumo.dlr.de/wiki/SUMO_User_Documentation (visited on 02/14/2018).

[71] Austria-Forum. *AustriaWiki im Austria-Forum. Amtlicher Gemeindeschlüssel*. 2020. URL: https://austria-forum.org/af/AustriaWiki/Amtlicher_Gemeindeschl%C3%BCssel (visited on 03/05/2020).

[72] GIP.at. *Intermodales Verkehrssystem Österreich (GIP.at)*. Version 2020-02. 2020. URL: http://gip.gv.at/assets/downloads/2002_dokumentation_gipat_ogd.pdf (visited on 03/16/2020).

[73] Statistik Austria. *Statistik Austria: Stadt-Land Klassifikationen*. 2018. URL: http://www.statistik.gv.at/web_de/klassifikationen/regionale_gliederungen/stadt_land/index.html (visited on 08/22/2018).

[74] Österreichische Raumordnungskonferenz. *ÖROK Atlas Raumbeobachtung -Stadtregionale Verpflechtungen*. 2016. URL: http://project2.geo.univie.ac.at/oerok/files/summaries/78.pdf (visited on 08/22/2018).

[75] Statistik Austria. *Urban-Rural-Typologie*. Ed. by Sibylle Saul. 2016. URL: www.statistik.at (visited on 08/22/2018).

[80] Seif, George. *The 5 Clustering Algorithms Data Scientists Need to Know*. May 2, 2018. URL: https://towardsdatascience.com/the-5-clustering-algorithms-data-scientists-need-to-know-a36d136ef68 (visited on 12/03/2020).

[91] Aimsun. *Hybrid simulation in Aimsun Next traffic modeling software*. 2018. URL: https://www.aimsun.com/tech_notes/hybrid-simulation/ (visited on 03/23/2021).

[92] Olstam, Johan Janson and Tapani, Andreas. *Comparison of Car-following models*. Linköping Sweden: Swedish National Road and Transport Research Institute, 2004.

[94] KTH. *Mezzo - Mesoscopic Traffic Simulator*. 2021. URL: https://www.kth.se/sci/2.836/om-skolan/centra/ctr/research/mezzo-mesoscopic-traffic-simulator-1.726113 (visited on 03/23/2021).

[95] MATSim.org. *About MATSim*. 2021. URL: https://matsim.org/about-matsim (visited on 03/23/2021).

[97] *POLARIS Home*. 2021. URL: https://vms.es.anl.gov/POLARIS/Index (visited on 03/23/2021).

[99] Eissfeldt, Nils, Gräfe, and Wagner, Peter. *Simulating Traffic with Queueing Models*. 2003.

[100] German Aerospace Center. *SUMO-ChangeLog*. 2019. URL: https://sumo.dlr.de/docs/ChangeLog.html (visited on 12/16/2019).

[110] Erdmann, Jakob. *Re: [sumo-user] SUMO Meso Max Speed higher than set allowed speed*. 2020. URL: https://www.eclipse.org/lists/sumo-user/msg06030.html (visited on 08/12/2020).

[126] Vose Software. *Vose Software. Thiel inequality coefficient*. 2020. URL: https://www.vosesoftware.com/riskwiki/Thielinequalitycoefficient.php (visited on 06/04/2020).

Appendix

Appendix A.

Supplemental information regarding the applied cluster analysis method

```
> library(factoextra)
> library(NbClust)
> nbC20<-NbClust(V85C[,c(-1)], diss=NULL, distance = "euclidean", min.nc=5, max.nc=2C
+              method = "ward.D2", index = "all")
```

*** : The Hubert index is a graphical method of determining the number of clusters. In the plot of Hubert index, we seek a significant knee that corresponds to a significant increase of the value of the measure i.e the significant peak in Hubert index second differences plot.

*** : The D index is a graphical method of determining the number of clusters. In the plot of D index, we seek a significant knee (the significant peak in Dindex second differences plot) that corresponds to a significant increase of the value of the measure.

*** * Among all indices: * 6 proposed 5 as the best number of clusters * 3 proposed 6 as the best number of clusters * 7 proposed 7 as the best number of clusters * 4 proposed 9 as the best number of clusters * 1 proposed 11 as the best number of clusters * 1 proposed 17 as the best number of clusters * 2 proposed 18 as the best number of clusters

***** Conclusion *****

* According to the majority rule, the best number of clusters is 7

****

Figure A.1.: R-Code cluster analysis if V85-data as described in chapter 3

Table A.1.: Numbers of clusters proposed by various validation indexes for the clusters of V85

	Number_clusters	Value_Index
KL	9.00	11.58
CH	7.00	712.46
Hartigan	7.00	70.76
CCC	5.00	35.56
Scott	7.00	487.52
Marriot	7.00	381217939898258.00
TrCovW	7.00	919494786.99
TraceW	7.00	10131.14
Friedman	11.00	36.64
Rubin	9.00	-3.46
Cindex	17.00	0.16
DB	6.00	0.95
Silhouette	5.00	0.33
Duda	9.00	0.61
PseudoT2	9.00	84.12
Beale	6.00	1.08
Ratkowsky	5.00	0.38
Ball	6.00	9238.20
PtBiserial	5.00	0.51
Frey	5.00	1.66
McClain	5.00	1.33
Dunn	18.00	0.04
Hubert	0.00	0.00
SDindex	7.00	0.19
Dindex	0.00	0.00
SDbw	18.00	0.11

Appendix B.

Supplemental validation of the cluster analysis results

Table B.1.: First 6 street categories of 636 for speed-over-time-curves with median speed in [km/h] for the first 2 intervals

Definition	6:00-6:15 am median speed [km/h]	6:15-6:30 am median speed [km/h]
RA-B-FRC12-FOW2-P-SmallCurves-IHP1-ILP1	62	58
RA-B-FRC12-FOW2-P-Straight-IHP0-ILP0	67	88
RA-B-FRC12-FOW2-P-Winding-IHP0-ILP2	35	45
RA-B-FRC12-FOW2-P-Winding-IHP1-ILP0	37	39
RA-B-FRC12-FOW2-RBL-curvey-IHP0-ILP0	60	57
RA-B-FRC12-FOW2-RBL-curvey-IHP1-ILP0	61	56

Table B.2.: Amount of edges with an assigned V85-traffic category in percent with incoming higher priority lanes

Traffic category	IHP0	IHP1	$\geq$ IHP2
1	4	94	2
2	1	97	2
3	3	89	7
4	25	58	17
5	9	78	14
6	2	96	2
7	15	67	18

Table B.3.: Amount of edges with an assigned V85-traffic category in percent with incoming lower priority lanes

Traffic category	ILP0	ILP1	≥ ILP2
1	78	21	1
2	98	2	0
3	89	10	1
4	53	47	2
5	81	13	6
6	95	5	1
7	71	26	4

Table B.4.: Amount of edges with an assigned V85-traffic category in percent with curves

Traffic category	Curvey	Straight	Winding
1	1	75	24
2	1	87	12
3	27	34	39
4	23	59	17
5	10	84	6
6	5	89	6
7	17	37	46

Table B.5.: Amount of edges for each traffic category regarding speed-over-time-curves without direction in percent with incoming higher priority lanes

Traffic category	IHP0	IHP1	≥ IHP2
1	1	97	1
2	1	99	0
3	3	96	1
4	7	81	11
5	9	80	11
6	6	92	2
7	1	98	1

Table B.6.: Amount of edges for each traffic category regarding speed-over-time-curves without direction in percent with incoming lower priority lanes

Traffic category	ILP0	ILP1	ILP2
1	97	3	0
2	96	4	0
3	94	6	1
4	71	26	3
5	76	17	7
6	81	17	2
7	91	9	1

Table B.7.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with curve characteristics

Traffic category	Curvey	Slightly curves	Small curves	Straight	Winding
1	1	0	0	74	25
2	1	0	0	83	16
3	2	0	0	71	26
4	8	3	1	58	29
5	7	10	0	59	25
6	2	2	1	66	29
7	1	1	0	66	32

Table B.8.: Amount of edges with an assigned traffic category regarding speed-over-time-curves for inbound directions

Amount	[%]
18446	100

Table B.9.: Amount of edges with an assigned traffic category regarding speed-over-time-curves for outbound directions

Amount	[%]
19165	100

Table B.10.: Amount of edges for each assigned traffic category regarding speed-over-time-curves for outbound directions

Traffic category	amount	[%]
1	1894	10
2	652	3
3	5029	26
4	5716	30
5	3612	19
6	2262	12

Table B.11.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with different form of way characteristic for outbound directions

Traffic category	2	3	4/10
1	3	97	0
2	15	82	3
3	11	87	2
4	14	86	0
5	9	91	0
6	2	98	0

Table B.12.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with incoming higher priority lanes for outbound directions

Traffic category	IHP0	IHP1	IHP2
1	1	98	0
2	18	74	7
3	10	81	10
4	11	89	1
5	9	91	0
6	2	98	0

Table B.13.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with incoming lower priority lanes for outbound directions

Traffic category	ILP0	ILP1	ILP2
1	93	7	0
2	43	51	6
3	51	40	8
4	59	39	2
5	85	13	2
6	95	5	0

Table B.14.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with curve characteristics for outbound directions

Traffic category	Curvey	Slight Curves	Small Curves	Straight	Winding
1	1	0	0	96	3
2	8	0	0	85	7
3	4	1	0	83	12
4	1	0	0	73	25
5	3	0	0	76	21
6	0	0	0	74	26

Table B.15.: Amount of edges for each assigned traffic category regarding speed-over-time-curves for inbound directions

Traffic category	Amount	in_percent
1	433	2
2	4920	27
3	2671	14
4	4232	23
5	1624	9
6	2978	16
7	1588	9

Table B.16.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with different form of way characteristic for inbound directions

Traffic category	2	3	4	10
1	1	99	0	0
2	6	93	1	0
3	6	94	0	0
4	8	92	0	0
5	12	88	0	0
6	2	98	0	0
7	23	74	3	0

Table B.17.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with incoming higher priority lanes for inbound directions

Traffic category	IHP0	IHP1	IHP2
1	1	98	1
2	6	93	1
3	6	93	1
4	4	96	0
5	10	90	0
6	1	98	1
7	14	64	23

Table B.18.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with incoming lower priority lanes for inbound directions

Traffic category	ILP0	ILP1	ILP2
1	90	10	0
2	51	36	13
3	36	61	3
4	88	9	2
5	82	17	1
6	95	5	0
7	48	47	5

Table B.19.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with curve characteristics for inbound directions

Traffic category	Curvey	Slightly Curves	Small Curves	Straight	Winding
1	0	0	0	99	1
2	2	2	0	86	11
3	1	0	0	73	26
4	1	0	0	76	23
5	1	0	0	82	17
6	1	0	0	84	15
7	2	2	2	92	3

Table B.20.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with different FRC for inbound directions

Traffic category	1	2	3	4
1	15	32	0	54
2	5	9	7	80
3	24	21	9	46
4	6	7	21	66
5	22	23	28	27
6	8	11	26	55
7	5	9	0	86

Table B.21.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with different FRC for outbound directions

Traffic category	1	2	3	4
1	15	42	4	39
2	5	4	1	90
3	7	13	4	76
4	11	12	13	64
5	14	19	21	45
6	6	10	22	62

Table B.22.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with different freeflow speed for inbound directions

Traffic category	30	40	50	60	70	80	90	≥100
1	0	0	0	0	0	0	2	98
2	0	11	88	1	0	0	0	0
3	0	0	21	79	0	0	0	0
4	0	0	0	55	45	0	0	0
5	0	0	0	1	68	30	0	0
6	0	0	0	0	0	74	24	1
7	21	58	21	0	0	0	0	0

Table B.23.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with different free-flow speed for outbound directions

Traffic category	30	40	50	60	70	80	90	≥100
1	0	0	0	0	0	20	65	15
2	67	9	24	0	0	0	0	0
3	1	21	78	1	0	0	0	0
4	0	0	24	76	0	0	0	0
5	0	0	0	10	83	8	0	0
6	0	0	0	0	8	92	0	0

Table B.24.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with priority at end for inbound directions

Traffic category	priority	right-before-left	traffic-light
1	10	90	0
2	39	46	14
3	62	35	3
4	10	87	3
5	18	81	1
6	5	95	0
7	38	19	43

Table B.25.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with priority at end for outbound directions

Traffic category	priority	right-before-left	traffic-light
1	9	91	0
2	36	21	43
3	49	41	10
4	39	55	5
5	13	84	3
6	5	95	0

Table B.26.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with street category for inbound directions

Traffic category	**B**	**G**	**L**
1	46	0	54
2	12	60	28
3	45	12	43
4	14	2	84
5	46	0	54
6	19	0	81
7	12	83	4

Table B.27.: Amount of edges for each traffic category regarding speed-over-time-curves in percent with street category for outbound directions

Traffic category	**B**	**G**	**L**
1	56	0	44
2	10	83	7
3	21	59	19
4	23	18	59
5	34	0	65
6	12	1	87

Appendix C.

Configuration mesoscopic settings for the test-simulation

Configuration Meso-basic-model:

```
<configuration>
<input>
<net-file value="Test_network.net.xml"/>
         <route-files value="routes_testnetwork.rou.xml"/>
<mesosim value="true" />
<meso-multi-queue value="true" />
<meso-junction-control value="true" />
<meso-junction-control.limited value="true" />
<meso-overtaking value="true" />
<ignore-junction-blocker value="30" />
<route-steps value="1000"/>
<no-internal-links value="true"/>
<sloppy-insert value="true"/>
<time-to-teleport value="1500"/>
<begin value="0"/>
<end value="86400" />
<additional-files value="path\additional_output.add.xml"/>
</input>
</configuration>
```

Configuration with edge-length, jam-threshold and speed-deviation:

```
<meso-multi-queue value="true" />
<meso-junction-control value="true" />
<meso-junction-control.limited value="true" />
<meso-overtaking value="true" />
<meso-edgelength value="58"/>
<meso-jam-threshold value="-0.33"/>
<default.speeddev value="0"/>
</configuration>
```

Configuration Meso-Minimum-tau:

```
<meso-multi-queue value="true" />
<meso-junction-control value="true" />
<meso-junction-control.limited value="true" />
<meso-overtaking value="true" />
<meso-edgelength value="58"/>
<meso-jam-threshold value="-0.33"/>
<default.speeddev value="0"/>
<meso-tauff value="1.0"/>
<meso-taufj value="1.0"/>
<meso-taujj value="1.5"/>
<meso-taujf value="1.8"/>
</configuration>
```

Configuration Meso-tauff=taufj 1.13, Meso-taujj=1.5 and Meso-taujf=2.5:

```
<meso-multi-queue value="true" />
<meso-junction-control value="true" />
<meso-junction-control.limited value="true" />
<meso-overtaking value="true" />
<meso-edgelength value="58"/>
<meso-jam-threshold value="-0.33"/>
<default.speeddev value="0"/>
<meso-tauff value="1.13"/>
<meso-taufj value="1.13"/>
<meso-taujj value="1.5"/>
<meso-taujf value="2.5"/>
</configuration>
```

Appendix D.

Additional fundamental diagrams before and after calibration

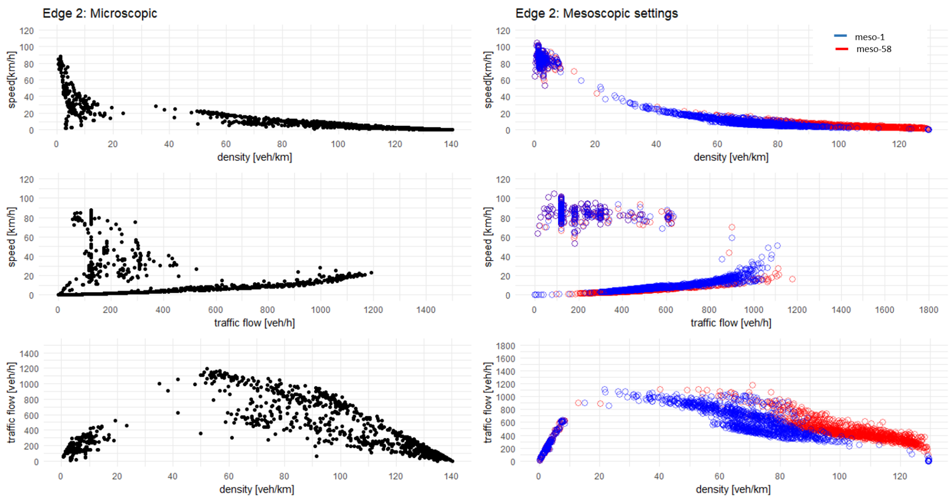

Figure D.1.: Fundamental diagrams before (meso-enabled) and after calibration (mesoscopic with edgelength=58m) of edge 2 (microscopic remains unchanged)

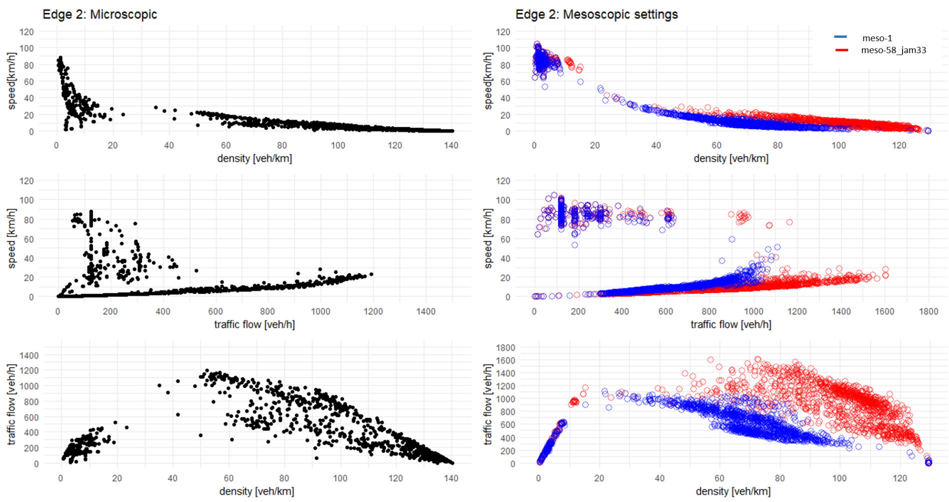

Figure D.2.: Fundamental diagrams before (meso-enabled) and after calibration (mesoscopic with edgelength=58m and jam-threshold=-0.33) of edge 2 (microscopic remains unchanged)

Appendix E.

Output values of the test-simulation enabling various selected tau-values

Table E.1.: Overview of output values for the test-simulation with three different meso-taujf measured on edge 2 with unchanged edgelength and jam-thereshold (58m, ”-0.33”)

Edge 2			**58m & ”-0.33”**		
	Micro	**”Basic” meso**	**2.5 m/s**	**3 m/s**	**3.6 m/s**
Max. traffic flow [veh/h]	1191.36	1109.8	1226.50	1014.92	895.46
Max. K [veh/km]	140.09	129.31	129.31	121.17	116.62
Crit. K [veh/km]	62.43	21.68	68.55	70.13	11.06
Max. speed [m/s]	24.43	29.05	29.07	29.07	29.07

Table E.2.: Comparison of meso-tau minimum settings to microscopic and mesoscopic-basic settings

Edge	**Settings**	**Allowed V [m/s]**	**Max. V [m/s]**	**Max. k [veh/km]**	**Max. Q [veh/h]**	**Crit.K [veh/km]**
1	micro	16.67	15.86	140.19	1253.95	62.2
1	meso	16.67	21.42	128.50	1420.54	30.33
1	min-τ	16.67	15.790	130.60	1971.678	80.78
2	micro	25	24.43	140.09	1191.36	62.43
2	meso	25	29.05	129.31	1109.84	21.68
2	min-τ	25	23.02	128.89	1779.816	70.83
3	micro	20	18.09	139.27	1077.98	37.09
3	meso	20	19.31	122.77	1542.20	95.23
3	min-τ	20	14.730	112.38	2080.93	111.6
4	micro	12.50	12.12	53.56	897.28	27.48
4	meso	12.50	12.75	41.74	1287.37	40.09
4	min-τ	12.50	9.44	45.34	1446.165	45.34

Appendix F.

The applied procedural model for data selection

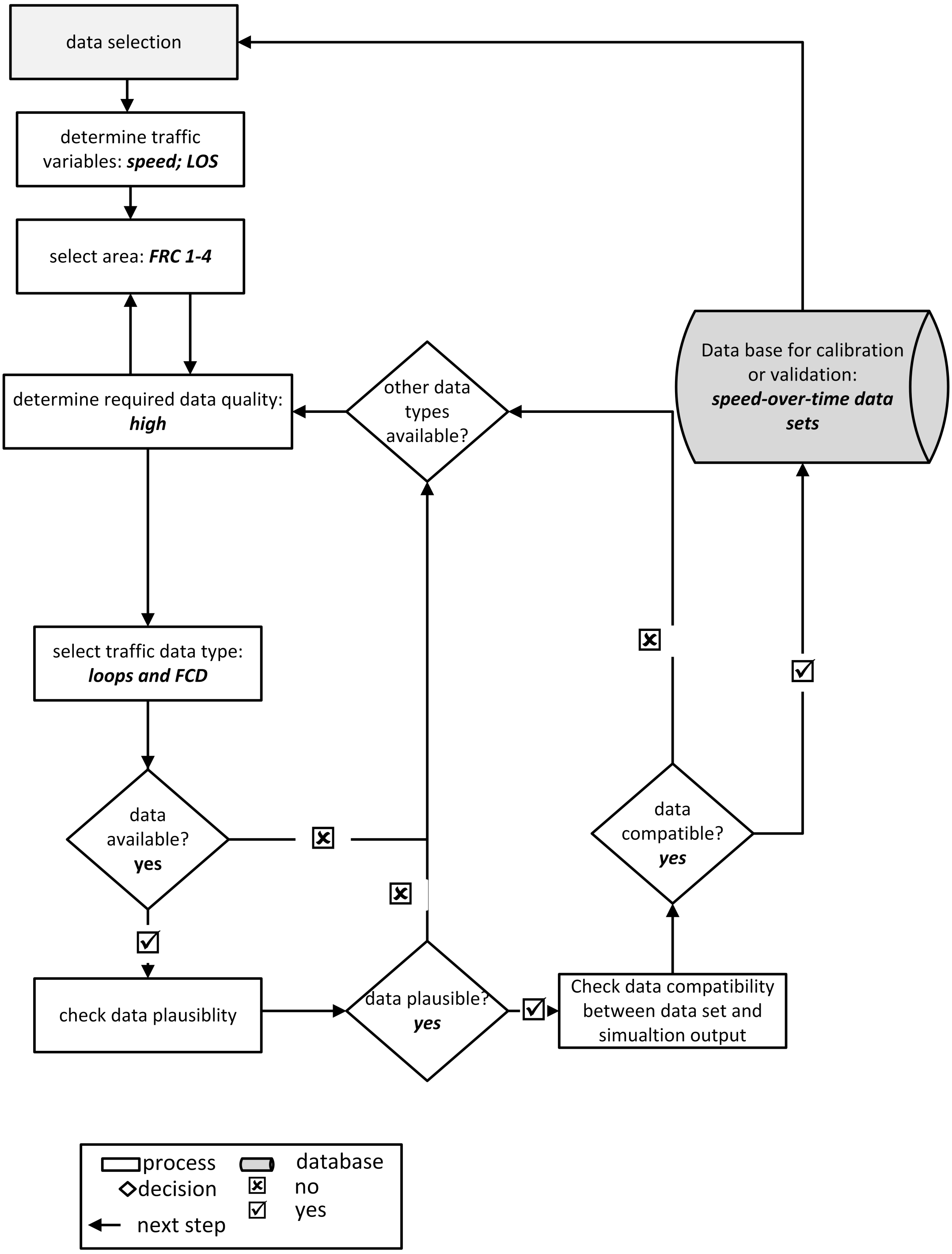

Figure F.1.: The applied procedural model for data selection on the ITS use case for the upcoming validation in chapter 6

Appendix G.

Configuration settings model 1, model 2, model 3

Configuration M-1 (primary model):

```
<mesosim value="true" />
<meso-multi-queue value="true" />
<meso-junction-control value="true" />
<meso-junction-control.limited value="true" />
<meso-overtaking value="true" />
<ignore-junction-blocker value="30" />
<route-steps value="1000"/>
<no-internal-links value="true"/>
<sloppy-insert value="true"/>
<time-to-teleport value="150"/>
<begin value="0"/>
<end value="57601" />
```

Configuration M-2 (re-calibrated model):

```
<meso-multi-queue value="true" />
<meso-junction-control value="true" />
<meso-junction-control.limited value="true" />
<meso-overtaking value="true" />
<\textbf{meso-edgelength value="58"}/>
<\textbf{meso-jam-threshold value="-0.33"}/>
<\textbf{ignore-junction-blocker value="7"}/>
<route-steps value="1000"/>
<no-internal-links value="true"/>
<sloppy-insert value="true"/>
<\textbf{time-to-teleport value="75"}/>
```

Configuration M-3 (re-calibrated model):

```
<meso-multi-queue value="true" />
<meso-junction-control value="true" />
<meso-junction-control.limited value="true" />
<meso-overtaking value="true" />
```

```
<\textbf{meso-edgelength value="58"}/>
<\textbf{meso-jam-threshold value="-0.33"}/>
<\textbf{ignore-junction-blocker value="7"}/>
<\textbf{meso-tauff value="1.2"}/>
<\textbf{meso-taufj value="1.2"}/>
<\textbf{meso-taujj value="1.8"}/>
<\textbf{meso-taujf value="2"}/>
<route-steps value="1000"/>
<no-internal-links value="true"/>
<sloppy-insert value="true"/>
<\textbf{time-to-teleport value="75"}/>
```

Appendix H.

Validation results regarding FRC for each model version

Table H.1.: MoP results for M-1 regarding FRC

FRC	RMSPE [%]	MAPE%	Percent Bias [%]	Theil's-U
1	47.67	31.75	-4.8	0.39
2	22.14	20.26	7	0.27
3	29.89	21.64	15.6	0.24
4	44.75	30.05	17.4	0.31

Table H.2.: MoP results for M-2 regarding FRC

FRC	RMSPE [%]	MAPE%	Percent Bias [%]	Theil's-U
1	27.17	17.75	12.6	0.19
2	21.11	14.71	11.4	0.16
3	26.82	19.20	15.7	0.20
4	41.58	26.51	19.3	0.26

Table H.3.: MoP results for M-3 regarding FRC

FRC	RMSPE [%]	MAPE[%]	Percent Bias [%]	Theil's-U
1	26.03	16.99	12.3	0.18
2	21.07	14.70	11.4	0.16
3	26.83	19.18	15.6	0.20
4	41.69	26.54	19.3	0.26

Appendix I.

Distribution of the MoPs regarding day time

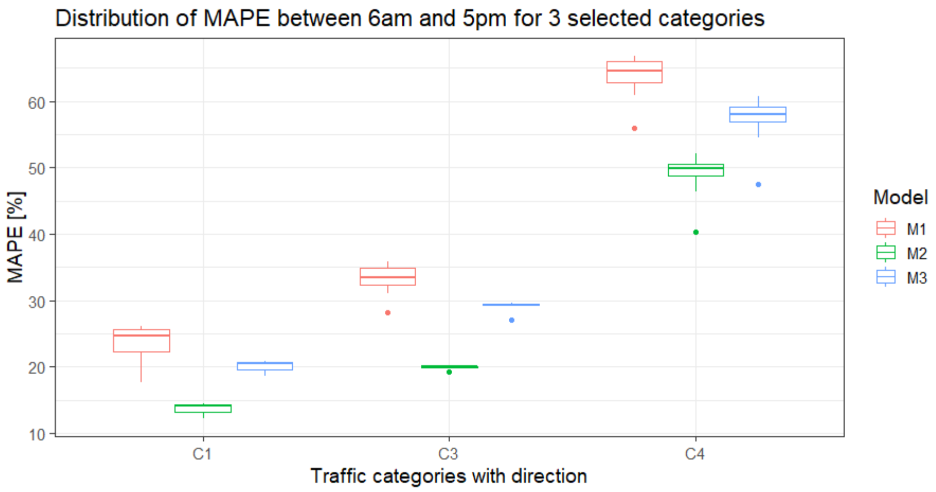

Figure I.1.: Distribution of MAPE calculated for each model version between 6am and 5pm for 3 selected categories

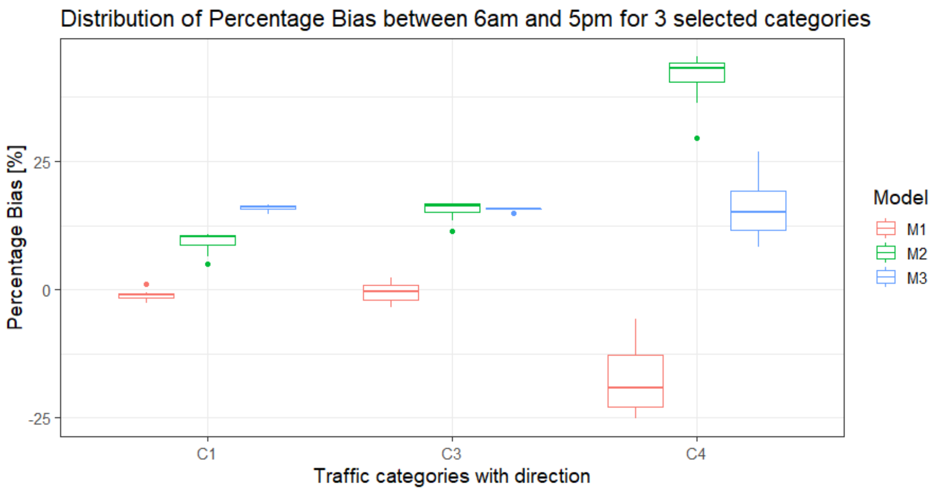

Figure I.2.: Distribution of Percentage Bias calculated for each model version between 6am and 5pm for 3 selected categories

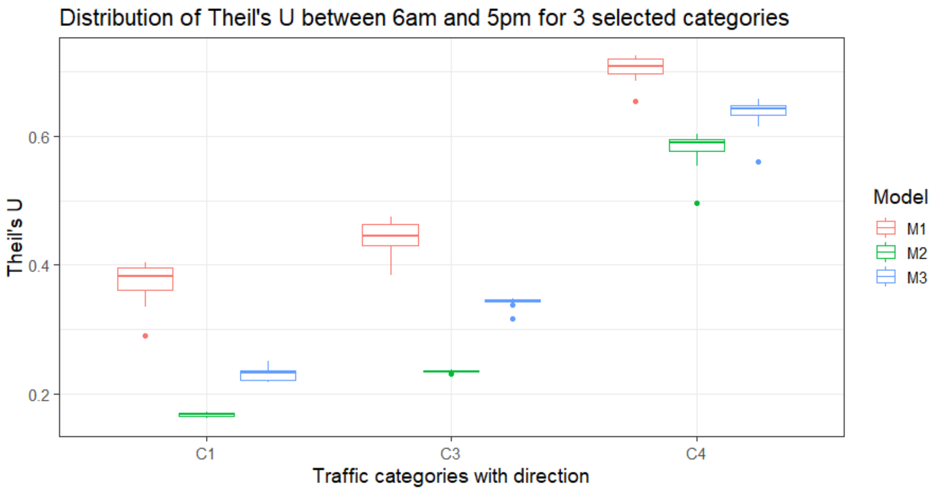

Figure I.3.: Distribution of Theil's-U calculated for each model version between 6am and 5pm for 3 selected categories