Towards efficient urban road transport using multimodal traffic management

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Abstract

As travel demand and urbanization increase, they cause road congestion. This results in lost productivity, reduced accessibility, and negative effects on the environment. Solutions to reduce congestion in the transport network include urban traffic management. It could for example be regulating signal control, variable speed limit, and ramp metering, or distributing traveler information about travel times and congestion through radio broadcasts, variable message signs, or navigation apps. A multimodal traffic management system utilizes several transportation modes within an integrated system to improve network performance and robustness. Large-scale mobility data from both the public transport network and private vehicles enable a better understanding of multimodal travel patterns. Traffic data can also be used to estimate reliable traffic models that can support evaluation and prioritization of traffic management measures.

The aim of the thesis is to identify synergies and challenges of multimodal traffic management. The aim includes analyzing, developing, and evaluating dynamic route choice models that can support multimodal traffic management decisions, using large-scale passive mobility data. First, recent trends are explored in the transition to more efficient road transport, emphasizing the role of monitoring and modeling traffic. Second, related literature is surveyed to identify the potential synergies and challenges of multimodal traffic management. Requirements of data and models in a decision support system that can help to prioritize between multimodal traffic management measures are also identified. Based on these requirements, route choice in the road network is analyzed using GPS trajectory data. This provides insights into how data-driven route choice models can be a component in multimodal traffic management.

The thesis contributes to the understanding of how a decision support system for multimodal traffic management can be developed, how route choice modeling can be used in such a tool, and how multimodal traffic management is needed in the transition towards more efficient road transport.
Sammanfattning


Sammanfattningsvis bidrar avhandlingen till en förståelse av hur beslutsstöd för multimodal trafikledning kan utvecklas, hur ruttningsmodeller kan användas i ett sådant system, och betydelsen av multimodal trafikledning i skiftet mot ett mer effektivt transportsystem.
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Norrköping, March 2024
Anna Danielsson
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Chapter 1

Introduction

1.1 Background

Throughout history, transportation has always been a necessity. Although, the methods and distances have evolved. At the beginning of the 20th century, the main mode of transportation was by horse and carriage and the average daily travel distance was one kilometer per person (Naturskyddsföreningen, 2021). Nowadays, the average daily travel distance is around 40 km, and the number of alternative modes keeps increasing with new technologies. Alongside the rise in travel demand, urbanization rates have also increased. It is predicted that by 2050, urban areas will be home to 66% of the global population (United Nations, 2018).

With increased travel demand in combination with increased urbanization, the capacity of the road network in many cities is not enough. Operating transport systems near their capacity limit make them vulnerable to incidents. Even small incidents can imply major effects on the system performance and cause congestion. Congestion in the network not only triggers frustration among drivers but also leads to losses in productivity and accessibility, and increased emissions (Grant-Muller and Xu, 2014). Given that traffic significantly contributes to emissions, environmental concerns are of utmost importance in traffic research (Othman et al., 2019). Currently, the transportation sector is responsible for 25% of the CO₂ emissions in Europe (IEA, 2021).

Congestion can be mitigated with urban road traffic management
measures and intelligent transport systems (ITS), including signal control, variable speed limits, and traveler information. With traffic management measures, travelers can be impacted to change their route or their departure time, or even cancel the trip if there is an incident in the network causing congestion. Figure 1.1 shows an example of how car travelers change their route when there is an incident in the network, observed in GPS data from the autumn of 2019. The width of links illustrates the share of the total number of observed vehicles going from the origin to the destination, that uses each link. The share of observed vehicles on each link in the morning rush hours during normal conditions is shown in the left part of the figure. The right part of the figure shows the share of observed vehicles on each link during an incident that occurred during the morning rush hours on October 1st 2019 (marked by a red star). The travelers normally use the highway to go from the origin to the destination, but when the incident occurs many of them change to alternative routes.

![Share of vehicles per link during normal conditions](image1.png) ![Share of vehicles per link during an incident](image2.png)

**Figure 1.1:** Example of how car travelers change their route when there is an incident in the network. The left part shows the share of observed vehicles going from the origin to the destination that use each link during normal conditions and the right part during an incident.

To understand how to manage traffic and prioritize between management measures, we need to understand the mobility patterns. With the recent growth of sensor and mobility data, there are more possi-
bilities to understand these mobility patterns better on a large scale. Probe vehicles, with information about location and speed, enable a wide coverage of accurate and reliable mobility data, since it provides observations of the revealed travel behavior.

These data can be used as input to, and as calibration of, traffic models. A traffic model can estimate and predict the traffic state from data samples, based on a number of fundamental assumptions, e.g. that travelers make rational choices. With a traffic model, the effect of management measures in future scenarios can be predicted. As an example, a route choice model can be used to understand where travelers on a specific location in the network are coming from, and where they are going. Figure 1.2 (a) shows the road vehicles passing by a target inflow link to Stockholm, marked with an orange arrow indicating the direction of the vehicles. The width of the links represents the share of observed vehicles on the link, that also uses the target inflow link. It can be noted that about half of the vehicles coming from the south of Stockholm continue towards and through the city center. This can be valuable insights into providing targeted traveler information. In similar matters, Figure 1.2 (b) shows the share of vehicles passing by a target link that starts their trip in each traffic analysis zone (TAZ). Knowing where travelers on a link are coming from provides insights into which travelers that need information in case of an incident at the target link.

Recently, the idea of shifting travelers to other modes has been raised as a measure of traffic management, i.e., suggesting travelers to use another mode of transport when there is an incident in the road or public transport network. This multimodal traffic management utilizes the full potential of the transport network with several modes. Integrating the management of several modes in one system makes the transport network more robust to incidents and potentially less congested.

1.2 Aim

The aim of the thesis is to identify synergies and challenges of multimodal traffic management. The aim includes analyzing, developing, and evaluating dynamic route choice models to use as a component in multimodal traffic management decision support systems. Large-scale passive mobility data is used to train and test the models. The thesis
(a) Trips of travelers using the target link. The width represents the share of vehicles using each link.

(b) Start and end of trips using the target link aggregated over TAZ. The colour represents the share of vehicles starting/ending in the zone.

Figure 1.2: Example of how route choice analysis can be used in urban road traffic management.
work is motivated by improvements in methods for traffic management
decision support, potentially leading to improved network efficiency.
Stockholm is used as a case study area and the results can be used by
traffic managers and policymakers.

1.3 Methodology

To address the aim of the thesis, the following methodology is used.
First, literature exploring recent trends towards a more efficient trans-
port network is reviewed. The motives to monitor and model mobility
patterns are identified and the connection between an efficient traf-
ic network and mobility analysis is illustrated with an example of
data-driven energy estimation.

Second, a literature survey is conducted to define multimodal
traffic management, as well as to identify synergies and challenges
associated with it. Requirements of data types and traffic models to
support decisions in multimodal traffic management are identified. A
two-step search methodology over three online publication databases
is used to identify relevant literature. First fundamental concepts on
traffic modeling and traffic management are identified and then recent
trends of multimodal traffic management are explored. Search terms
related to the application, method, and data used are combined.

Lastly, based on the identified requirements of models, a discrete
route choice model is estimated and evaluated on large-scale GPS tra-
jectory data from the urban area of Stockholm. The dataset is divided
into a training and a test set. Using the model to predict route choice
can be useful as decision support in proactive traffic management.
The data used show revealed preferences (secondary data) of route
choice and have been collected passively, which means that the data
was not actively provided by the respondents, but collected without
additional intervention (e.g. in contrary to survey data). In the data
set used, no socioeconomic aspects of the respondents are included,
such as age, income, or gender. Thus, choice parameters related to
such information are not explicitly included.

1.4 Outline

The remainder of the thesis is structured as follows. Chapter 2 intro-
duces urban traffic management and presents related work, followed
Chapter 1. Introduction

by a theoretical background of traffic models in Chapter 3. Chapter 4 presents data sources that can be used for multimodal traffic management. In Chapter 5, the contribution of the thesis is described in terms of the research gap intended to fill, research questions, and summaries of the included papers. Chapter 6 concludes the thesis with a discussion of how the included papers are related to each other, as well as future research directions. The three papers that are a part of this thesis are included in the appendix.
Chapter 2

Urban traffic management

Urban traffic management aims to maintain and improve safety and efficiency in the traffic network by guiding travelers in case of disruptions or incidents to reduce congestion. Reducing congestion and improving the efficiency of the transportation network also reduces traffic emissions (Sheikh and Peng, 2022). There are traffic management measures affecting both the supply and the demand of traffic, as illustrated in Figure 2.1. Traffic management includes traffic control measures to regulate the traffic flows, and traveler information influencing travel behavior and decisions. The infrastructure, e.g., the static road network, and incidents in the network constitute the supply. The demand for travel depends on the mobility patterns of travelers, i.e., travelers’ decisions to make a trip, where to go, and what route to use. The resulting capacities of the supply in relation to the flows of vehicles from the demand results in a traffic state. The traffic state is typically described in the flow, density and speed (Treiber and Kesting, 2013), and is a useful input to evaluate traffic management measures.

Examples of traffic control measures are signal control (Li et al., 2020), ramp metering (Papageorgiou et al., 1991) and variable speed limits (Khondaker and Kattan, 2015). Traveler information measures include route guidance and information about the traffic state through radio broadcasts, variable message signs (Peeta et al., 2000), and navigation systems in cars or mobile devices. Traveler information can be classified into pretrip and enroute advice, distinguished between the
point in time the information was given (Papageorgiou et al., 2003). The result of the pretrip information could be a postponement or canceling of the intended trip, route choice changes, while the enroute information mainly results in changes in route choice. Nowadays pretrip information through navigators in cars or mobile devices is commonly used (Levinson, 2003; Meng et al., 2018; Essen et al., 2016).

Recently, the trend within traffic management has been towards a larger focus on data-driven algorithms and ITS. ITS refers to technologies, applications, and systems developed to improve traffic safety, efficiency, accessibility, and user service (Zhang et al., 2011; Qureshi and Abdullah, 2013). Today, the availability of mobility data

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{traffic_management_diagram.png}
\caption{Overview of traffic management}
\end{figure}
from travelers is growing, enabling a data-driven approach in ITS, complementing the traditional model-based system.
Chapter 3
Traffic models

A traffic model describes the movements of travelers making a trip, the interaction between drivers, and how it can lead to new patterns and collective effects (Sheffi, 1985; Ortúzar and Willumsen, 2011; Treiber and Kesting, 2013). There are macroscopic models, that describe the flows on a network level, similar to a stream of water in a river, microscopic models, where the interaction between individual vehicles is modeled, and mesoscopic models, that are hybrids of macroscopic and microscopic models (Treiber and Kesting, 2013). The models estimate the current, and predict the future, state of the traffic network based on data samples and some fundamental assumptions, e.g. that travelers make rational choices such as aiming to minimize their traveltime and cost.

The state of a system is represented by the information needed to determine future outputs, given future inputs (Glad and Ljung, 2000). In traffic flow theory, the state is typically defined by flow, density, and speed of the traffic (Treiber and Kesting, 2013). A traffic state prediction is an important input to traffic management. It can be used to determine optimal routes in navigation systems, plan and optimize the logic of traffic signal control and variable speed limit, and simulate the environmental effects of traffic operations such as fuel consumption and $CO_2$ emission (Treiber and Kesting, 2013).

Predicting the traffic state includes a prediction of Origin-Destination (OD) demand. An OD demand model estimates and predicts the number of travelers that desire to travel from an origin to a destination, often stored in an OD-matrix. The origins and destinations are often aggregated into TAZ that are connected with a
transport system built up by roads and public transport lines.

The interaction between the OD demand and the transportation system is described by a traffic assignment process, generally using behavioral models of mode and route choice (Bliemer et al., 2017). The theory of traffic assignment is based on Wardrop’s principle of user equilibrium, assuming all travelers choose the route minimizing their traveltime (Wardrop, 1952). Thus, in equilibrium, no traveler can improve their traveltime by choosing a different route.

In dynamic traffic assignment (DTA), a time component is added to the process, that is, the OD-flows, as well as the mode and route choice are time dependent (Peeta and Ziliaskopoulos, 2001; Szeto and Wong, 2012). In the dynamic loading process the vehicles are propagated on the network. The arrival time at a link is different from the departure time, thus the model can capture temporal variations of traffic. There is an iteration between the route choice and departure time choice, and a network loading process, leading to a dynamic user equilibrium (Iryo, 2013). In the dynamic context, it is assumed that travelers can predict the traveltimes they will experience during their trip, taking current congestion into account, with the motivation that recurrent travelers tend to know when and where congestion occurs (Iryo, 2013).

Route and mode choice are related to the behavior of individual drivers about to make a trip between a given origin and destination (Sheffi, 1985; Ortúzar and Willumsen, 2011; Prato, 2009). Estimations of mode and route choice are historically often based on discrete choice models with survey data as input. A multinomial logit model (MNL model), where each alternative (different modes of transportation or different routes in this case) is described using attributes weighted against each other in a utility function. It is assumed that a traveler chooses the alternative with the greatest utility. The weights of the attributes are often estimated with maximum likelihood estimation, where the weights that maximize the likelihood of the observed alternative being chosen are found.

Route choice estimation includes two main components, route set generation where the alternatives each traveler is assumed to choose between are defined, and route selection, where the probability of each route being chosen is calculated. In the choice set generation, the considered routes are selected out of the universal set of routes and there are several methods to do so, e.g. $K$-shortest path search with link penalty (Bekhor et al., 2006), labeling (Bekhor et al., 2006), a
breadth first search with link elimination (Montini et al., 2017), a
stochastic link-based sampling approach with successive choices at each
node (Frejinger et al., 2009), or a data driven route identification (Ton
et al., 2018). The attributes describing the utility of the alternatives
could for example be traveltime, route length, road type, number
of intersections, and delay (e.g., Hess et al., 2015; Yao and Bekhor,
2020; Duncan et al., 2021). The MNL model is restricted by the
independence from irrelevant alternatives (IIA) property (Washington
et al., 2009), which does not hold in the context of a route choice
model where the alternative routes typically overlap with each other
to some extent (Frejinger and Bierlaire, 2007). To overcome the IIA
property, a correction attribute that penalizes overlap is added to
the model (e.g., Cascetta et al., 1996; Ben-Akiva and Bierlaire, 1999;
Axhausen and Schüssler, 2009).

In the network loading process, the estimations of demand, mode
choice, and route choice are converted to linkflows in the transport
network (Iryo, 2013; Peeta and Ziliaskopoulos, 2001). The total travel
demand is distributed across the network, taking the capacity of each
road segment into account. Each link in the network is associated with
a link cost, typically expressed as a function of the link volumes. In the
simplest case, any propagation effects are neglected and the network
loading is instantaneous, implying that all assigned vehicles to a route
are present at all links of the route simultaneously (Tsanakas, 2021).
The vehicles can also be propagated in the network. If traveltime is the
only factor affecting the link cost, the cost can be determined using a
volume delay function. As congestion builds up, it can influence future
route and mode choices as travelers seek to optimize their journeys
(Iryo, 2013).

The usefulness of a traffic model depends on its performance to
correctly predict future states of the network (Ortúzar and Willumsen,
2011). There are several ways to evaluate the performance of a model.
With a data-driven approach, it is common to compare training data
with test data. That can show you how general the model is, that is,
if it works generally on other data than it was trained on. Common
metrics to compare between observed and estimated behavior are
$R^2$-value and root mean square error (RMSE). $R^2$-value shows how
much of the variance in the dependent variable that is explained by
the explanatory variables (or attributes) in the model. It is a measure
of how well the model fits the data points (James et al., 2017). RMSE
shows the magnitude of the error term, i.e., how much the estimation
differs from the observation (James et al., 2017).
Chapter 4

Traffic data

In this thesis, large-scale passive data is used to analyze mobility patterns. The word large-scale indicates that the data sets contain a large number of observations. That the data is passive refers to that it has been collected without any active action from the respondents to provide the data. In the thesis, Stockholm is used as a case study area. No data collection is conducted in the thesis. Examples of available data sources in Stockholm that can be combined to analyze multimodal mobility patterns are

- **GPS trajectories**
  GPS trips with trajectories from INRIX covering the area of Stockholm is one main source of data used in this thesis. For a detailed description of the dataset the reader is referred to (Ahlberg et al., 2021). Around 400 000 trips collected during 5 weeks 2019 in and around Stockholm are included. The estimated penetration rate (capture rate) is 1-2%. The data has been collected as way points with a location and a timestamp mainly from GPS-units in vehicles. To preserve the privacy of the drivers, while retaining the trip information, many trips get a new trip id after one hour. The way points have been map-matched to links in the network. The data set contains a user ID, a timestamp and a link among other things. Both consumer vehicles (75%) and fleet vehicles (25%) are included and the average travel length of a trip is 22 minutes for consumer vehicles and 41 minutes for fleet vehicles.
• **Network data**
The open street map road network (OpenStreetMap contributors, 2017) of Stockholm used in this thesis constitutes 86,917 links and 40,640 nodes. The road classes are 1 to 6, with 1 being highways and 6 being small streets. The speed limits vary from 30 to 120 km/h. From the south end to the north end in the network it is about 25 km, while the width of the network (from west to east) it is about 30 km.

• **Public transport ticket data**
Smart cards have been introduced in the public transport system in Stockholm. It has increased the convenience for the passengers and decreased the costs for operators (Breyer, 2021). The data set of smart card data in the Stockholm region is presented in more details in (Gundlegård et al., 2024). The data contains a card ID (that might be rehashed periodically), a timestamp and the stop location of the tap-in, i.e., at the start station of the trip. The data set is collected in Stockholm from 2011 until today and there are around 2 million tap-ins per day. Several modes of public transport are included; metro (45 %), bus (40 %), commuter train (12 %), tram (2 %) and other (1 %) (Gundlegård et al., 2024).

• **Mobile network data**
Mobile network data refers to data collected by cellular network operators, with penetration rates of up to 20-50 %. The location is typically approximated by the cell location (Breyer, 2021). The data contains a user ID, a timestamp and a cell ID. Mobile network data is well suited for mode choice modeling but is possible to use for route choice as well, to some extent. However, the position can only be roughly approximated, thus within-a-city route can be challenging to identify, especially in regions with low cell density.

• **Other**
Other mobility data sources that can be used for estimation and validation of traffic models are link counts and portal data. These have been collected with radar sensors at the congestion charging portals or on the highways around Stockholm. The portal data contains home postal code of vehicles passing the congestion charging portals in the central part of Stockholm.
Chapter 5

Contribution of the thesis

5.1 Research gap

There is a lack of literature on quantitative assessments of multimodal traffic management in general, and of decision support systems for it in particular. There exists no well-recognized definition of multimodal traffic management and the link between transport efficiency and traffic management is not clear. There is also a gap in how quantitative models can support multimodal traffic management decisions. Many studies utilize GPS data for route choice modeling, but the focus on traffic management applications, where the attributes are based on information that is available in real-time, is not well studied.

5.2 Research questions

Based on the research gap, the following research questions are proposed.

1. How does monitoring and modeling of mobility support the transition towards a more efficient road transport network?

2. What are the synergies and challenges of multimodal traffic management?
Chapter 5. Contribution of the thesis

How can route choice models utilizing large-scale passive data be developed to be used as a component in multimodal traffic management?

Research question 1 is answered by a literature survey of efficient road transport and recent mobility trends in Paper I. The second research question is answered in Paper 2, where literature on multimodal traffic management, including models and data to support multimodal traffic management decisions, is surveyed to identify potential synergies and challenges associated with it. Research question 3 is answered in Paper 3 where a route choice model is estimated based on GPS and network data to use as decision support in urban traffic management.

The thesis contributes to an understanding of multimodal traffic management and its connection to an efficient transport network. The main contribution of the thesis also includes understanding of how a route choice model based on GPS and network data can be developed to be used in traffic management decision support.

5.3 Summary of the included papers

The thesis is built up of three papers that were produced within the research project Multimodal traffic management. A summary of the papers is also provided in the final report of the project (Gundlegård et al., 2024).

Paper I: Transition towards more efficient road transports: insights from mobility analytics

Paper I addresses the trade-off between the need for mobility and the negative environmental impacts of transportation, such as the contribution of greenhouse gases and the air pollution. Three major dimensions in the transition towards more efficient road transport are discussed: reduce transport demand, improve transport efficiency, and reduce fuel consumption. The paper answers research question 1 by illustrating how traffic monitoring and modeling can be used in practice for more efficient road transport.

In the transition towards more efficient road transport, a data-driven approach to estimate and predict demand and traffic work is identified as an important step. That can be used as input to monitoring and following up energy use of transportation. The proposed
approach, described in more detail in (Tsanakas, 2021; Tsanakas et al., 2021), is based on large-scale traffic flow data, including GPS trajectories, mobile network data, and stationary vehicle count sensors. Estimates and predictions of demand and route choice are used as input to a vehicle flow propagation process resulting in linkflows over time. Using the framework HBEFA, the linkflows are converted to estimations for energy and estimations. The main benefit of the proposed approach compared to traditional techniques is that less calibration is needed.

The paper also provides a discussion of emerging mobility trends, such as demand management, mode shifts, electrification, biofuels, automated vehicles, mobility as a service, electric road systems, and digital accessibility.

The paper contributes to the understanding of the relationship between transportation and traffic management, and climate impact. Suggestions for addressing challenges range from behavioral aspects to the role of emerging technologies and the need for traffic management measures supported by data-driven analyses, monitoring, and modeling.


**Paper II: Extending urban traffic management to a multimodal perspective: a survey of synergies and challenges**

Paper II answers research question 2 by surveying literature covering urban traffic management. The study aims to identify synergies and challenges of extending road traffic management to a multimodal perspective by integrating public transport in road traffic management. Relevant literature is found by using different categories of search terms, with synonyms, different spellings and related concepts combined using boolean logic, truncation, masking, and proximity operators in several databases. A growing trend in number of publications indicates an increased interest in the subject over the past two decades.
In general, traffic management aims to ensure safe and efficient movement of travelers and goods by guiding and redirecting the traffic. Management measures, ranging from traveler information in variable message signs, radio broadcasts or mobile phone apps, to signal control and ramp metering, are provided in real-time to influence traveler behavior and route selection during incidents. Traditionally, urban traffic management primarily adopts a unimodal approach, focusing on individual transportation modes separately.

Based on the literature overview, multimodal traffic management is defined as ”... the simultaneous management of road traffic and public transport, utilizing the potential of the complete transport system to ease congestion and provide efficient traveler mobility.” (p. 66 in Paper II).

Synergy effects of multimodal traffic management include increased flexibility for traffic managers, increased information availability of travelers and improved mode shifts. Thus, providing a multimodal system with integrated traffic management opens new possibilities for seamless and efficient mobility. However, there are also challenges associated with such a system, including collaboration and data sharing between stakeholders. A multimodal traffic management system also introduces the need for data and traffic models to serve as decision support in evaluating actions related to multimodal management measures. In addition to multimodal traffic assignment, these requirements include providing support for traveler information, and connection points between modes (e.g., parking).

The contribution of the literature survey lies in its examination of multimodal traffic management, covering definitions, synergies, and challenges.

The paper is co-authored by David Gundlegård and Clas Rydergren. The author of this thesis contributed as main author and took the leading role with the conceptualization, development, and writing of the paper. Paper II is currently a working paper. The study has been presented at

- Transportforum, Linköping, January 2024.
Paper III: Analysis of route sets and attributes in route choice estimation for urban traffic management using GPS-data

Paper II identifies requirements on data and models for multimodal traffic management. In Paper III, some of these requirements are met in a route choice estimation process based on vehicle GPS trajectory data, answering research question 3. GPS trajectories from Stockholm during 4 weeks 2019, are used to identify a route choice set and attributes to describe the utility of each alternative. Two approaches of choice set generation are compared and the results show that a data-driven choice set augmented with routes from a shortest path algorithm gives a model with high responsiveness to dynamic traveltimes. It is assumed that a model responsive to traveltimes is well suited in a traffic management context, since the traveltimes are typically affected by incidents in the network. Logit-based discrete choice models are implemented and attributes are selected based on a forward stepwise selection process, where one attribute at the time is added to the model. Evaluation metrics include log-likelihood, Bayesian Information Criterion (BIC), a hit rate, and $R^2$ value for observed and estimated route shares and OD-specific link flow. Results show that the proposed models have a significantly better fit compared to naïve models, with only free flow traveltime as explanatory variable. It is concluded that mean traveltime, road class, and other measures of the simplicity of the route are important to the route choice. The study suggests a promising future for data-driven route choice models, especially with the anticipated increase in available GPS data.

The contribution of Paper III includes a comparison of two route set generation approaches and logit-based discrete choice models for road network route choice. The study provides insights into improving data-driven route choice models for more efficient urban traffic management.

The paper is co-authored by David Gundlegård and Clas Rydergren. The author of this thesis contributed as main author and took the leading role with the development of algorithms, analysis of results, and writing of the paper. Paper III has been presented at and published in the proceedings of the 103rd Transportation Research Board Annual Meeting, in Washington D.C., USA and previous results has been presented at

- the 10th Symposium of the European Association for Research in Transportation (hEART), Leuven, Belgium, June 2022.
Chapter 5. Contribution of the thesis


Chapter 6
Discussion and conclusion

An efficient transportation system is a critical goal for our society, envisioning a future where motorized travel is minimized, and when necessary, facilitated by an efficient transport network. Paper I motivates the need for traffic monitoring and modeling in the transition towards efficient transportation. Recent mobility trends are presented, together with an example of how large-scale mobility data can be used to estimate the energy use of transport.

This transition not only puts new requirements on travel behavior but also on the network, traffic models, and mobility data. Rather than increasing the capacity of the network by constructing new roads which induces new demand, the transport network must be managed given the current infrastructure to limit emissions. Together with increasing urbanization, limiting traffic emissions is a challenge that makes it crucial to utilize the full potential of the transport network. Paper II explores this aspect by focusing on multimodal traffic management. It discusses the integration of public transport in private vehicle traffic management under a unified system. Model and data requirements for such a system, along with its potential benefits and challenges, are identified.

Paper III illustrates how some of the model requirements for traffic management can be met, that is how traffic modeling can be used as decision support in traffic management. More specifically, a data-driven approach to route choice estimation for traffic management is
analyzed. It is concluded that a route choice model is useful in traffic management to identify travelers affected by incidents and congestion, and to identify routes for re-routing during incidents.

While the use of large-scale mobility data has led to insights into travel behavior on a wide geographic scale at a reasonable cost (Ahsani et al., 2019), there are some concerns about using these data. The input data may suffer from quality issues, including biases and inaccuracies, which affect the validity of the models and the predictions. Data bias refers to the potential inaccurate representation of the population in the dataset, which could lead to misleading conclusions if not corrected for (Richterich, 2018; Meppelink et al., 2020). In addition, large-scale mobility data can lead to privacy and ethical issues. Under certain circumstances, it is possible to identify individuals in mobility data, even if personal attributes have been removed since long-term travel-patterns are highly unique (Montjoye et al., 2013). To address privacy concerns related to large-scale mobility data, the data can be aggregated or randomly hashed, noise can be introduced to datasets, or synthetic data sets can be generated (Gursoy et al., 2019). However, this may reduce the effectiveness of the data. Thus, there exists a trade-off between data utility and privacy concerns.

Future research directions include development, analysis, and evaluation of further components for multimodal traffic management. In particular, public transport ticket data and mobile network data will be integrated to add a mode choice component to the decision support system. In addition, incident data will be analyzed to explicitly model mode and route choice during incidents in the network.

The operative aspect of traffic management, that is, evaluating relevant traffic control measures and targeted traveler information, is another important research direction. The analysis of the behavioral effects of management measures is also left as future work.

Improving the ability to use traffic models to support traffic management decisions makes management measures a powerful tool to mitigate congestion in urban areas. While multimodal traffic management does not guarantee an efficient transport network, reducing congestion in a robust and holistic way is essential in the transition towards achieving it.
Bibliography


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Abbreviations

OD  Origin-Destination

ITS  intelligent transport systems

MNL model  multinomial logit model

IIA  independence from irrelevant alternatives

DTA  dynamic traffic assignment

RMSE  root mean square error

TAZ  traffic analysis zone
Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

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