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Traffic assignment and simulation models
State-of-the-Art Background Document

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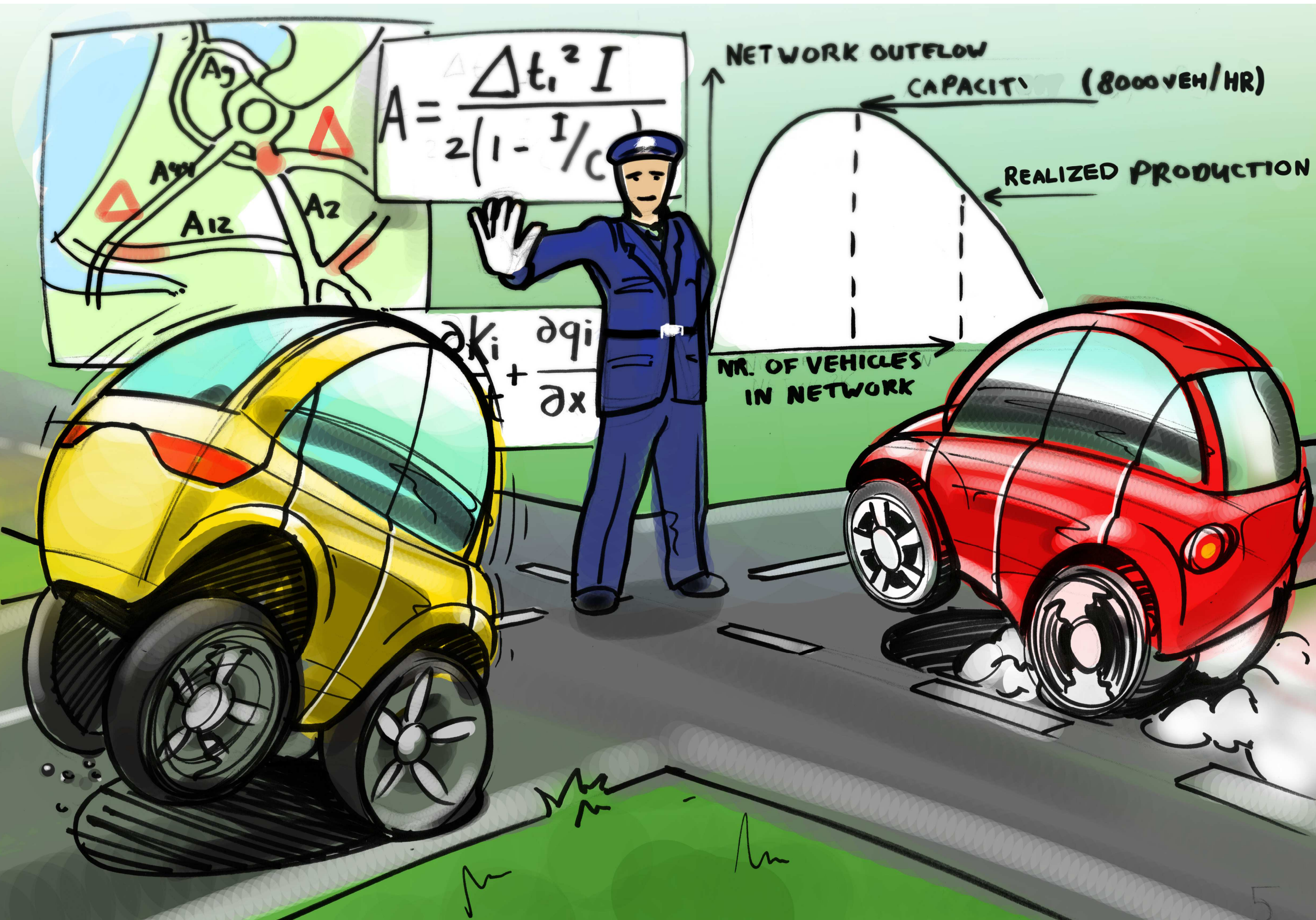
TrafficQuest

CENTRE FOR EXPERTISE ON TRAFFIC MANAGEMENT

TrafficQuest report

Traffic assignment and simulation models

State-of-the-Art Background Document



Colophon

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TrafficQuest
CENTRE FOR EXPERTISE ON TRAFFIC MANAGEMENT

Traffic Assignment and Simulation Models

State-of-the-Art

Background document

20 July 2016

Table of contents

Foreword

TrafficQuest continuously reviews the state of traffic management and the direction of current and future developments. Traffic management is on the verge of many changes. Multiple developments will make traffic management more efficient, pro-active, and applicable on a network level. This requires further research effort. Therefore, a research agenda is presented in the pamphlet “The Future of Traffic Management” (In Dutch: “De toekomst van verkeersmanagement”), which can be found on the TrafficQuest website (www.traffic-quest.nl).

While writing this booklet, TrafficQuest collected a huge amount of background material on a wide range of traffic management aspects. This material is published in a series of reports, all of which have the following structure:

- What is it about?
- What is the State-of-the-Practice in the Netherlands?
- What is the State-of-the-Practice in other countries?
- What is the benefit?
- What is the perspective for the future?

This report focuses on the above questions in relation to traffic simulation and assignment models, with a specific interest in the application of these models for traffic management.

List of definitions

Word	Definition	In Dutch
Calibration	Process of tuning model parameters to allow a model to produce accurate results	Kalibratie
Continuous	Uncountable and non-segmented values; opposite of discrete	Continu
Data-driven	Process based on data	Data-gedreven
Demand, traffic	Travel/traffic demand	Verkeersvraag
Discrete	Countable in a finite amount of segments; opposite of continuous	Discreet
Dynamic	Process involving a time dimension	Dynamisch
Event-based	Method using events to trigger actions	Event gebaseerd
Hybrid	Use of multiple methods	Hybride
Measures, traffic	A physical action to influence traffic	Maatregelen, verkeers-
Modal split	Distribution over vehicle types (modes)	Vervoerwijzekeuze
Mode, multimodal	Vehicle type, multiple vehicle types	Vervoerwijze, (multimodaal)
Off-line	Time independent and not connected to a real-time, operational process	Off-line
On-line	Time dependent and connected to an operational process, often real-time.	On-line
Platform, modelling	A system on which individuals models can operate and in some cases interact	Platform
Prediction	Making a statement about a future state	Voorspelling
Propagation	Movement of traffic through a road or network	Voortbeweging
Real-time	Process that makes use of the latest available data with minimal delay (normally minutes to seconds)	Real-time
Assignment	Distribution of the traffic for the available routes	Toedeling
Route	A set of interconnecting links or roads from an origin to a destination	Route
State-of-the-Art	The latest advancement in developments in a specific domain	Huidige stand van zaken
State-of-the-Practice	The latest advancement in application of developments in a specific domain	Huidige stand van toepassing
Static	Process without a time dimension	Statisch
Trip distribution	Distribution of trips across a network	Ritverdeling

Trip generation	Process which determines the number of trips to be made between an origin and destination	Ritgeneratie
Validation	Process of checking the accuracy of a model, normally preceded by calibration	Validatie

1. Introduction

In traffic management a clear understanding of traffic situations now and in the future is useful for operational and planning purposes. Traffic systems in many countries are characterised by a high-quality network of sensors and data systems, which together supply an assessment of the traffic situation at a particular time. Based on this assessment and the expected effects of specific measures, predictions can be made on how traffic will behave in the near or far future. This enables choices to be made the on the best measures to implement or to put in operation, based on predefined criteria for traffic flow, safety and/or environmental effects. In order to choose the most applicable tool to make these traffic predictions and to make a choice of measures, it is essential to have a good understanding of the available tools and the range of applications.

Traffic prediction models are often applied to determine the effectiveness of infrastructural, design, mobility and traffic management measures. However traffic prediction modelling is a vast domain in which a wide range of models exist. There are many models which each have a specific purpose and approach to modelling traffic. Often the applied approach is deliberately developed with that purpose in mind and therefore only performs well for that purpose. Various trends have seen models developed with a more general purpose, but sometimes at the cost of specific accuracy and flexibility for certain measures and uses. Other trends have focussed on developing high quality and accurate models for specific applications, however with a higher level integration as part of modelling suites.

The goal of this report is to give the reader a feeling of the different types of traffic models and their applications. To understand which options are available for modelling traffic and which applications are relevant, it is necessary to make a distinction between the various different applications. To be able to do this it is also necessary to give a global overview of the type of models that exist. This process is performed in chapter 2. An overview is given of what prediction entails, which is followed by a review of applications for prediction models in traffic management along with an overview of the main types of traffic prediction models.

The current state of practice in model forecasting is given in chapter 3 and gives a description of the current models that are in use in The Netherlands and internationally. In many cases there will be a great deal of overlap, as the traffic model market is generally also universal. Nevertheless there are some local preferences. The specific application areas of different forecasting models is important, as not every model is able to capture and reproduce all traffic characteristics. The benefits and application on different policy levels are therefore described in chapter 4. Furthermore it is apparent from the current state of art that a shift in modelling approaches is ongoing in which modelling packages and suites are considered important to avoid inconsistency between different levels of forecasting. However other developments are also evolving in the core of models which reflect developments in traffic flow, but also in science. These future perspectives are described in chapter 5.

2. Traffic prediction models: what is it about?

A large number of different traffic models exist for the purpose of traffic prediction and many other applications. While at an abstract level these models have much in common, they all predict uncertain futures, at a technical level they may attempt to represent very different phenomena and traffic systems. Before explaining the main types of available models, this chapter first lays the basis of what models are about and how they are constructed. This is followed by a description of the main model types used in traffic modelling.

2.1. Prediction with traffic models

A prediction or forecast makes a statement about future developments mostly based on experience or knowledge of the system they are predicting. This is not different for traffic models. Therefore a prediction within the field of traffic operations consists of the following statements:

- a statement about the system: **what** is being modelled;
- a statement about developments: **how** relevant variables evolve in time;
- in the future : gives the **time horizon** which is considered during a period of time starting from a given time instant;
- based on experience or knowledge: the applied modelling **approach**, based on modelling techniques, derived relationships and/or data.

Modelled system

"A statement about the system…" indicates which system is modelled. That could be a separate transport system, such as rail or public transport, or a highway network, but also a mix of different transport modes and networks.

Modelled aspects

"A statement about developments…" indicates a prediction statement for a system and indicates which aspects develop and are predicted. In traffic modelling, there are a number of different items that may be considered. In respect to predictions in the area of traffic management, the following prediction topics can be distinguished as relevant:

- Aggregated traffic flow indicators, which are a result of individual choices. These indicators are often used to evaluate the performance of a road or a network and often give fundamental quantities of traffic flow, such as average speed, density, average lane usage. In traffic propagation models, it is very common for these quantities to be predicted.
- Aggregated demand figures, which are a result of individual choices related to trip making and mode choice. To predict how traffic flow indicators will develop, it is necessary to know what the traffic demand is. Thus for example, the number of trips between origins and destinations, route distribution, modal share and departure time.
- Behavioural choices of traffic participants on a detailed level. Each individual traveller also has their own preferences in traffic, which is part of a complex system of choices. Predicting such

behaviour can be challenging and can involve choices such as en-route route choice, speed choice, lane choice and headway choice.

- Behavioural choices of people is related to trip making and mode choice. Prior to estimating the effect of traffic itself and even how a participant travels, one can consider pre-trip choices that potential traveller can make. In some cases these choices will not even lead to a trip being performed, while other choices will affect how a trip is performed. Examples are the choice to make a trip or not, transportation mode choice, destination choice, departure time choice, pre-trip route choice.

In order to make predictions on one of these topics a traffic model may commonly be used. The term traffic model is used in a broad sense and covers a broad range of models using different techniques and requiring different input parameters and data. In section 2.2 a number of categories of model types are discussed, which are most commonly used for traffic flow prediction.

Prediction horizon

"..in the future.." gives the horizon for predictions. In general, the application of a traffic model results in a prediction of something. For example, a simulation model of traffic flow can calculate the number of vehicles passing at road section x at time interval t for a specific situation (e.g. a specific day and peak hour period). This results in a prediction of traffic flow characteristics for that specific situation and time period. Mostly, such a calculation is performed using prepared historical data for that specific day and peak hour. This approach is often referred to as 'off-line' because the model can be applied without using real-time data at a defined moment in the past. Offline refers to the lack of necessity to be connected to 'online' real-time data. This off-line approach is sufficient for e.g. studies focusing on policy issues like impact analysis of extra infrastructure, or the impact of a speed restriction and can be used for both short-term (e.g. the effect of a traffic management measure during a peak period of next month) and long-term predictions (e.g. the expected traffic flow on major highways in 2030). Note that a prediction model may be applied to predict the input data for a traffic model in case historical data cannot be used directly (e.g. the expected number of trips in a network in 2030 assuming a specific economic growth scenario).

On the other hand there are models that use real-time collected data as input and may run at certain time intervals or whose start is event triggered. The real-time data will mostly be used in combination with historical data. Although there is usually some delay between the time the data was actually collected and the actual model calculation, these type of models are still referred to as 'on-line', as use is made of live data feeds. This type of on-line models can be applied for operational management goals in urban areas, like the decision making of an optimal traffic signal control strategy, the implementation of a traffic management scenario during an incident situation, or traffic information systems that visualize the traffic conditions in a network in the nearby future. On-line models generally focus on short-term predictions.

Modelling approach

"..based on experience or knowledge.." refers to the source of information. In order to make predictions, a wide range of techniques are available, depending on the topic. Some predictions can

be made using experience or knowledge about the prediction variables as manifested in the past (e.g. at 8:00 AM on an average Tuesday the total queue length in the Netherlands is 150 km, so next Tuesday we can expect the same length round that time). For other prediction variables more sophisticated models are needed.
Roughly, one can distinguish between data-driven approaches (like regression models, pattern recognition) or more explanatory models (simulation using validated driver behaviour parameters, mathematical models using traffic theory). For both approaches sufficient data is required, together with calibration and validation of the prediction model, possibly using an indicator for expressing the reliability of the prediction. The next section describes available traffic model types.

2.2. Types of models

In this section a description is given of the main types of traffic models used in the Netherlands as well as in the rest of the world. The vast majority of traffic model types are country independent barring local road parameters. The first model considered is the demand model, which predicts the number of trips made in a network with a specific mode of transport. Macro-, meso and microscopic traffic models predict traffic states in a network by assigning the trips determined by the demand model. Hybrid models make use of different approaches depending on the traffic situation (e.g. using microsimulation at controlled intersections and macroscopic models at motorway sections). The assignment models can be multi-modal, i.e. covering public transport trips, bicycle trips and car trips, although this is not a common practice due to the data requirements. In this report, the focus is on assignment models for trucks and cars because most traffic management measures focus on motorized road transport. For each model type we now describe the main function.

Demand model
A demand model is used to forecast the number of trips between origins and destinations in a specific area with a specific mode of transport. This may include a departure time choice, although this is not currently common practise. The demand calculation is normally part of the 'classical' four-step urban transportation planning modelling approach (McNally, 2007) that consists of following steps:

- *Trip generation*: determines the frequency of origins or destinations of trips in each zone by trip purpose, as a function of land uses and household demographics, and other socio-economic factors.
- *Trip distribution*: matches origin departures with destination arrivals, often using a gravity model function, equivalent to an entropy maximizing model.
- *Mode choice*: computes the proportion of trips between each origin and destination that use a particular transportation mode. Mode choice can be performed as a separate step or simultaneously with the previous step.

- *Route assignment*: allocates trips between an origin and destination by a particular mode to a route. Often Wardrop's principle of user equilibrium is applied, wherein each driver (or group) chooses the shortest (travel time) path, subject to every other driver doing the same.

Note that the fourth step, the route assignment, can be accomplished by numerous models that can roughly be divided into macro-, meso- and microscopic models. These models have one thing in common: they predict traffic conditions in a road network.

An alternative approach in travel demand models are the 'activity-based-models'. This is a class of models that predict for individuals where and when specific activities (e.g. work, leisure, shopping) are conducted and in this way construct a demand pattern. The advantage of this type of models that it is possible to include demand management measures and even combine them with traffic management. The disadvantage is the amount of input data needed to feed these models and to kalibrate them. Well known examples of this type of model are the American TRANSIMS (TRANSIMS, 2015) and the Dutch ALABATROSS model (Arentze, et al., 2000). More information can be found in a report written by Castiglione, et al. (2015).

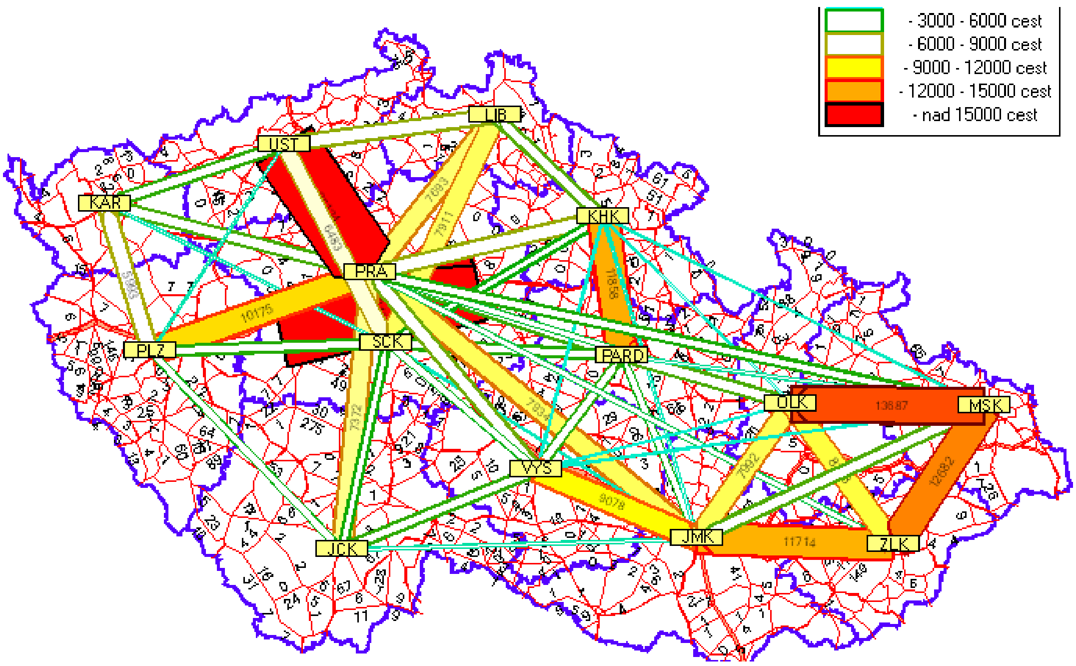

Figure 1: An example of a travel demand model. In this case the car traffic demand on a national scale for the Czech Republic [source: http://www.motran.info/en/graphic-outputs/]

Macroscopic model

A macroscopic model is a mathematical model that formulates the relationship between aggregate traffic flow characteristics of a traffic stream, like density, flow, mean speed, etc. The method of modelling traffic flow at a macroscopic level originated under an assumption that traffic flows are comparable to fluid flows. The first major step in macroscopic modelling of traffic was taken by Lighthill and Whitham in 1955. Richards (1956) complemented the idea with the introduction of ‘shock-waves on the highway’, completing the so-called LWR model, called after their names: Lighthill-Whitham-Richards.

Since individual vehicles are not modelled in a macroscopic model, the resulting predictions of speeds are an average of the traffic flow on a specific road section in a network. Therefore, these models cannot predict the lane choice and speed choice of individual vehicles at a random cross-section in the network and can therefore not be used to evaluate measures focusing on lane, speed and headway choice in great detail. An exception to this are ‘multi-pipe’ representation of traffic flow, in which each lane is modelled as a separate road. However these approaches are limited and have other disadvantages. In many cases predicting an ‘average’ speed for a group of drivers on a specific section of road suffices for the purpose for which a macroscopic model is used. Such purposes focus mainly on network and demand changes for future years without considering major changes to the composition of traffic. Examples are infrastructural changes, traffic management measures and road pricing.

Within macroscopic modelling one can distinguish between:

- *Static macroscopic models*: in these models time dependency is not considered and therefore the impact of spill-back due to congestion is neglected (or solved using a vertical queue).
- *Dynamic macroscopic models*: in these models the impact of spill-back due to congestion is taken into account according to mathematical sound relations based on e.g. the fundamental diagram. These models predict using a time dimension.

Because queues are modelled realistic in dynamic models, the average speeds (travel times) on the road sections are also more realistic. As a consequence, this will affect the route choice when multiple iterations are performed to reach an equilibrium on a network level in space and time. Recent developments show a trend towards a mixture of static macroscopic models with dynamic properties, such as the correct location of bottlenecks and blocking back. An example of such a model is STAQ (Brederode, et al., 2010).

Mesoscopic model

The term ‘mesoscopic model’ is generally used for a range of models that use groups of vehicles as starting point for the traffic flow condition calculations, while individual vehicles are moved over the network applying the calculated speeds of the groups they belong to. Some mesoscopic models use cells (fixed length road sections) to group vehicles. Movement of groups of vehicles is based on macroscopic relations, which consider the amount of vehicles attempting to propagate and the available capacity to accommodate these vehicles.

Since in mesoscopic models individual vehicles are modelled, one can predict individual speeds, lane and car-following headway. However, due to the group-based approach to determine these variables, it is only of limited value, comparable with a macroscopic model. It is better to use the predicted ‘average’ speeds instead of individual speeds. Other variables may be more reliable or realistic, such as the route choice of an individual vehicle-driver-combination using individual preferences, although this will depend on the correctness of the equilibrium approach of the software package used. Most mesoscopic models are dynamic, which means they take care of spill-back in case of congestion.

Microscopic model

A microscopic traffic flow model simulates individual vehicle-driver units, such that the dynamic variables of the models represent microscopic properties like the position and velocity of single vehicles. One can predict individual speeds, lane usage and car-following distances at any time at any place in the network. Compared to the meso- and macroscopic approach it has the highest level of detail but on the other hand also the highest calculation time.
Due to the relatively large computation times, microscopic models are limited to a reduced network size and forecast horizon. As microscopic models consider individual vehicles, they are dynamic by definition. It must be noted that obtaining an equilibrium state is not always a goal in microscopic modelling studies, which means finding a balance in route choice which can be reproduced time and time again. For instances in which reproducible results are required, it may mean making use of multiple simulations runs, of which the results are averaged out.

Data-driven model

Data driven models are purely statistical models that make use of patterns in traffic data to make predictions. It has been shown that there are many recurrent patterns in travel demand, traffic flow and other traffic indicators. By making use of these recurrent patterns, sometimes adjusted using real-time data, situations can be compared, allowing the model to map out a forecast based on past occurrences. In the early years of data driven models, most research employed statistical approaches to predicting traffic at a single point. However, most classical approaches have shown to be ‘weak’ or inadequate under unstable traffic conditions or complex road settings. Consequently, research has focused on more computational intelligence-based approaches such as neural and Bayesian networks, fuzzy and evolutionary techniques. In addition, the available datasets have grown in size, with both structured and unstructured data.

Combined or hybrid model

Besides models that consist purely of one specific modelling type, a new type of model has emerged which makes use of different modelling types. These combined models make use of different traffic models under certain conditions or for a certain part of the network, such as macroscopic simulation for high level representation of traffic operation on motorways and major roads, together with micro-simulation at (controlled) intersections. While some of these are marketed as mesoscopic models, as they represent something between micro- and macroscopic models, they are actually not, but rather a combined or hybrid model. There are several combinations possible between various main characteristics of traffic models. Probably the most common combination is the use of a macroscopic part to model motorway or main traffic flows together with a microscopic model being applied to model intersections or road sections with increased traffic interaction. Other hybrid combinations also exist which make use of mesoscopic modelling, or even combine continuous flow models with discrete models. These last type applies generalised traffic flow characteristics over long homogenous road sections and time and space segmented simulations where more detail is required. The main advantage of approaches with multiple models is that each model is only used when the conditions apply (fit-for purpose). This allows hybrid models to take advantage of the strengths of the model parts and drop many of the disadvantages.

Modelling urban roads

The development of most macro-, meso- and microscopic models originally started by modelling motorway segments and networks or modelling traffic signal control. In the past decades, a shift can be observed towards urban traffic operations. Traffic problems in urban areas have historically not been given much priority over motorway traffic. Nowadays many motorway networks have been optimised, using traffic management, or extended with new infrastructure. However the road transportation system in many urban areas has not reached the same level of optimisation and has now become a focus for policy makers instead of motorways.
In order to realistically model traffic operation in urban areas, adapted driver behaviour models are required, together with models that can deal with traffic lights and priority rules. Most state-of-the practice micro- , mesoscopic and hybrid traffic models do sufficiently include functionalities to model urban traffic, although preparing a large urban network with detailed controlled intersections is a time-consuming task. Macroscopic models are not always equipped with sufficient features to model urban road networks, such as intersection configurations or the stop-start driving behaviour often seen on urban streets.

2.3. Comparison of model characteristics

There are various types of models and each model type has different characteristics and makes use of different behavioural choices to make predictions. On the one hand demand models have a large focus on how people travel, which is seen in choices of destination and modes of travel. On the other hand assignment models tend to focus much more on the manner in which travel is performed, such as through route or speed choice. The different scales of models also influence which choices are possible. Table 1 gives an overview of these choices and for which type of model they are most relevant.

Table 1:

	Trip / destination	Mode of travel	Departure time	Route choice	Speed choice	Lane choice	Headway choice
Demand model	X	X	X	-	-	-	-
Macro-model (static)	-	-	X	X	-	-	-
Macro-model (dynamic)	-	-	X/-	X	X	-	-
Meso-model	-	-	-	X	X	X/-	-
Micro-model	-	-	-	X	X	X	X
Data-driven model	X	X	X	X	-	-	-

Traffic models aim to predict traffic states such as travel times and traffic volumes. Micro-, meso and macro traffic models use mathematical models with a more or less direct relation to behavioural choices. Short-term traffic forecasting based on data driven methods use approaches such as data mining, in which the relation with behavioural choices is less clear. The relevance of which models consider different behavioural characteristics of a model is given in Table 2.

Table 2:

	Modal split	Route proportions	Travel time / average speed	Lane distribution	Volumes
Demand model	X	-	-	-	-
Macro-model (static)	-	X /-	X /-	-	X
Macro-model (dynamic)	-	X /-	X	-	X
Meso -model	-	X /-	X	X/-	X
Micro-model	-	X /-	X	X	X
Data driven model	**-**	-	X/-	X/-	X/-

Calibration

Regardless what type of model is applied for predictions, a model needs well calibrated parameters. Calibration involves the fine-tuning of model parameters. For example, macroscopic model calibration will focus on correct macroscopic traffic flow parameters such as fundamental diagram parameters (e.g. density at capacity, jam density). Macro-, meso- en microscopic models should use correctly estimated traffic demand (number of cars measured at on-street counting sites should be as close as possible as the counts in the traffic assignment), otherwise the origin-destination matrix should be updated or route choice adapted. Microscopic models should include well calibrated driver behaviour parameters (desired headway to predecessor, lane change behavioural parameters, etc.). Data driven models compare historical predictions with realized traffic flow variables and update the model parameters to improve estimates in later iterations.

3. State-of-Practice in the Netherlands and elsewhere

3.1. Introduction

The traffic modelling market is generally an international market in which products and models from different countries and regions are in competition. Many developments at the forefront of traffic modelling techniques are made in the academic arena. In many cases these developments find their way to commercial products when a technique becomes mainstream and common practice, usually a number of years after being introduced. On one hand commercial companies further develop described techniques for practical implementation. These implementations are mainly in large existing product packages that can be expanded with new insights or additional modules. On the other hand academic institutions offer products to the market, either independently or in cooperation with a commercial company. Often this route can lead to a faster implementation in practice of new techniques, though sometimes with a limited functionality. In the Netherlands these same trends can also be observed between universities and commercial companies, of which most also operate on the international market.

This chapter focusses on the current level of development in traffic modelling in the Netherlands as well as worldwide. Significant differences between the two are also highlighted. This is done based on the classification from the previous chapters. Every paragraph describes a type of model and the state of practise of that type of model. For every type a number of examples of state-of-the-art model packages are also mentioned.

3.2. Demand models

Demand models have existed for decades, mostly as part of the ‘classical’ four-step urban transportation planning modelling approach. Modern ‘state-of-the-art’ demand models for passenger transport should include departure time modules, be able to deal with multiple modes of traffic, and take into account the impact of traffic congestion on travel times. Besides passenger transport, modelling traffic demand for freight is a separate discipline with its own issues. Examples of state-of-the art demand models are the Netherlands Regional Models (NRM) and the Dutch National Model (In Dutch: Landelijk Model Systeem, LMS) used by the Dutch government. These models are developed and maintained by Rijkswaterstaat and are used to predict the developments in mobility, for the both the main road network and rail network. Based on these predictions the impacts of policy measures on accessibility and liveability are predicted. The NRM models also play an important role in the planning of large infrastructural projects.

Other packages , such as OmniTRANS , VISUM and AISMUN are able to construct demand models and perform related calculations. In the United States the packages CUBE from Citilabs and EMME from INRO are often used.

A separate class of demand models are the more complex activity-based models. In the Netherlands the ALBATROSS model (A Learning-based Transportation Oriented Simulation System) is developed since 2000 (Arentze, *et al.*, 2000). This model of activity-travel behaviour is derived from theories of choice heuristics that consumers apply when making decisions in complex environments. The model predicts which activities are conducted when, where, for how long, with whom, and the transport mode involved. In addition, various situational, temporal, spatial, spatial-temporal and institutional constraints are incorporated in the model (Arentze and Timmermans, 2004). Although a lot of research has been done related to this model, the developments seem to have ceased. An American example is TRANSIMS (TRansportation ANalysis and SIMulation System). It was developed to meet the State Department of Transport needs for more accurate and more sensitive travel forecasts for transportation planning and emissions analysis. TRANSIMS estimates activities for individuals and households, and plans trips satisfying those activities. This requires an incredible degree of detail on simulated individuals. The model makes use of submodules which are run iteratively during a calibration procedure and includes a population synthesizer, an activity generator, a route planner and a micro simulator. It was converted into an open source development (TRANSIMS, 2015), but since 2011 no new developments or applications have been reported.

Since this state-of-the-art document focuses mainly on predictions related to traffic management measures, an extensive state-of-the art of demand models is not given here.

3.3. Macroscopic models

Traditionally macroscopic models have been applied most frequently due to their relative availability and lower computation times compared to microscopic models. Initially they were applied as static models, meaning that time dynamics were not considered. The market for macroscopic traffic models is a mature one with a large number of established names. Most macroscopic traffic models offer the capability of a static assignment of traffic, such as Cube Voyager, PTV VISUM or OmniTRANS. In the Netherlands OmniTRANS is the leading static macroscopic modelling package, and is often used for municipal and regional traffic analyses. Internationally AIMSUN is probably the best known dynamic macroscopic model. PTV VISUM, Cube Voyager, EMME and TransModeler are also among the leading model packages.

Static macroscopic models have been common practice for many years. While static models are mainstays in the traffic model spectrum, their use is diminishing slowly as other more realistic and capable models, both microscopic and dynamic macroscopic, increase in performance. Dynamic macroscopic models are also increasingly being used as dynamic traffic assignment considers the impacts of congestion more realistically. In the Netherlands, INDY is a dynamic macroscopic model developed by TNO and the KU Leuven which was applied in various studies (Bliemer, *et al.*, 2004). Although INDY is not a recent development, it has only recently been applied on a wider scale commercially, as policymakers have started to realise the potential of dynamics models. Another model that was developed around the same time is MARPLE (Taale, 2008), which has also been applied in various studies involving traffic management. A more recent upcoming dynamic model originating from the Netherlands is OmniTRANS StreamLine.

Most of these models make use of the Link Transmission Model (LTM) in the dynamic network loading (DNL) part. The LTM (Yperman, 2007) has become the leading DNL model in traffic models in the past decade and has replaced many Cell Transmission Model (CTM) type models, although many CTM based model remain in use. However, also other DNL models are used: MARPLE is based on flow – travel time relations and StreamLine incorporates a second order DNL model.

A software package on the forefront of developments is the PTV VISUM TRE. It computes dynamic assignment where path choices and demand loading depend on the travel times obtained through any network simulation model which assumes the resulting node splitting rates. The propagation of traffic flows is based on a new generation of LTM model, the GLTM – General Link Transmission Model. The implementation of the software is completely parallelized in order to maximize performance by fully exploiting the available computing resources.

While developments are still ongoing in macroscopic modelling, a shift in focus has occurred from improving macroscopic models to combining the advantages of combined or hybrid models. This is further discussed in the relevant paragraph in this section.

Example of a macroscopic modelling platform: OmniTRANS

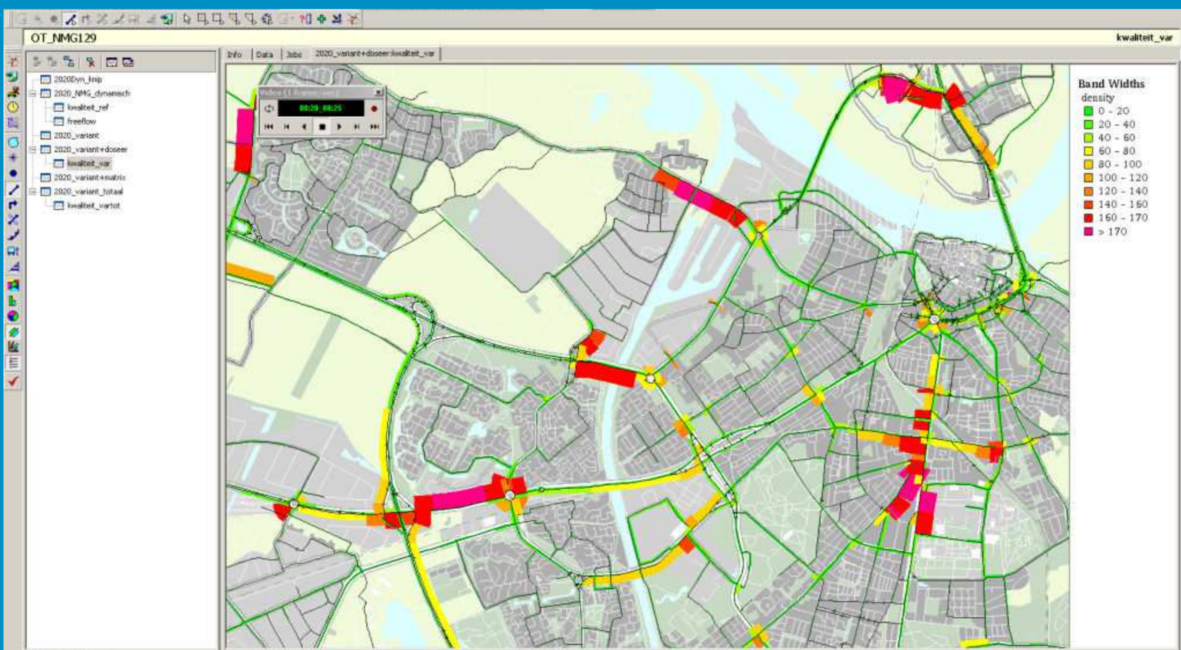

Figure 2: Macroscopic model OmniTrans [source: OmniTrans-International]

OmniTRANS is described as an integrated development platform for multi-modal transport modelling. The OmniTRANS framework is developed to allow easy multi-class and multi-modal traffic modelling, which are among its main strengths in comparison to other macroscopic models. OmniTRANS has a long track record in static modelling. In recent years the ability for dynamic modelling was also introduced with the StreamLine dynamic traffic assignment model. Custom modelling and analysis is possible through open access scripting. Furthermore the software is includes a wide range of functionalities which allow for fast and in-depth analysis of results. OmniTRANS is currently the leading macroscopic modelling platform in The Netherlands

3.4. Mesoscopic models

Mesoscopic models have taken a long time to develop to the level that practical implementation is possible. The main developments of mesoscopic models are found outside of the Netherlands, however their application in the Netherlands is found through contracts with a number of local companies. One of the first widely used mesoscopic traffic models is DYNASMART, originally developed by University of Texas, Austin, as part of a project, funded by the US Department of Transportation, to develop tools for online traffic prediction and offline traffic operations planning. A version for planning purposes, called DYNASMART-P, developed in 2007, is still distributed by the Federal Highway Administration through McTrans (University of Florida). However, it seems that DYNASMART is no longer supported and it is therefore unclear if it can still be defined as a state-of-the-art model for commercial applications anno 2015.

Within the same project as DYNASMART, DynaMIT was developed. DynaMIT (Dynamic Network Assignment for the Management of Information to Travelers) is a state-of-the art simulation and assignment model developed by Massachusetts Institute of Technology (MIT). Also for DynaMIT a real-time and planning version are available (Milkovits, *et al.*, 2010). The package is less commercialized compared to AIMSUN and Paramics, but also for this model the developments seem to have ceased.

Dynameq is a mesoscopic model that is better known in North America than in Europe and is developed by INRO (see Figure 3). Dynameq is described as a true mesoscopic model as it uses microscopic equilibria, while considering macroscopic traffic flow. It can be considered as a state-of-the-art model due to its dynamic routing approach and its microscopic elements together with fast calculations. It is available for all kinds of applications. It has an add-on for the EMME demand modelling tool and that makes it easy to combine both models in the complete range from demand to intersection modelling (INRO, 2015).

Other mesoscopic models do exists but are mainly used for scientific purposes at universities or non-commercial institutes.

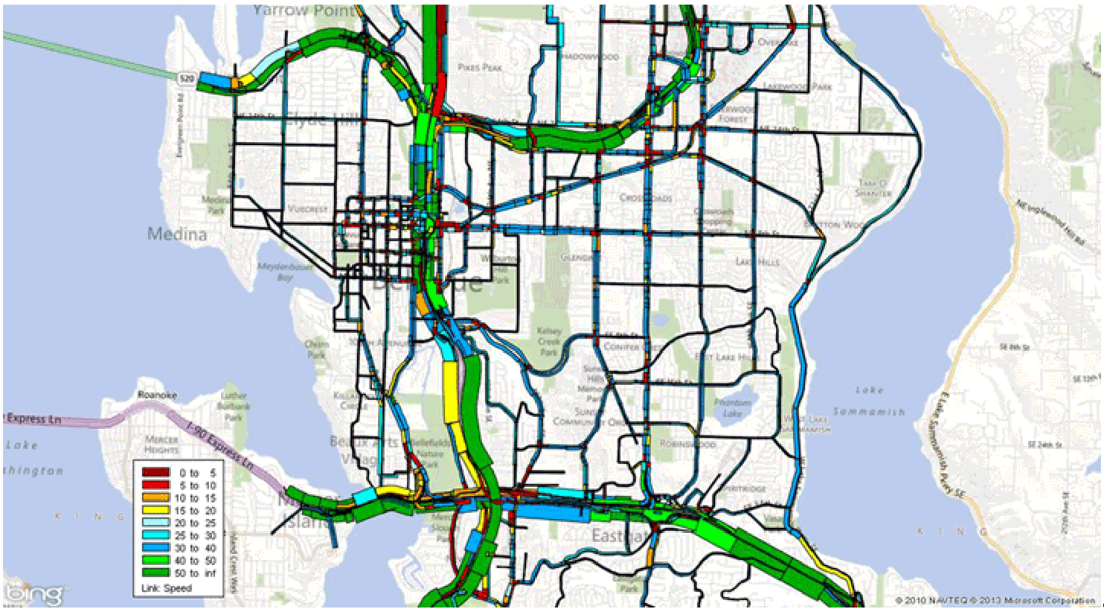

Figure 3: Mescoscopic model Dynameq [source: INRO]

3.5. Microscopic models

Microscopic models traditionally follow a different line of development compared to macroscopic models. As driver behaviour plays a more prominent part in these models, the development has tended also to be undertaken by research groups and companies with a strong focus on behavioural aspects. Internationally one of the best known microscopic model packages today is VISSIM developed by PTV Planung Transport Verkehr AG in Karlsruhe (see detail frame).

Another well regarded and often applied microscopic model is Paramics developed by Quadstone Paramics. The Paramics software was born out of a University of Edinburgh project in the early 1990’s. Paramics is used for the purpose of simulating and analysing existing traffic and transportation problems and includes public transport as well as pedestrians.

Other microscopic packages include AIMSUN, which is a package that can also be used as a decision support system for real-time, simulation-based online traffic forecasting (AIMSUN Online). AIMSUN is developed by TSS-Transport Simulation Systems, a Barcelona based company. It uses a combination of dynamic traffic assignment (DTA) techniques to give a realistic representation of network behaviour. Dynamic user equilibrium techniques and stochastic route choice models are both available in AIMSUN and can be combined with either mesoscopic, microscopic or hybrid modelling.

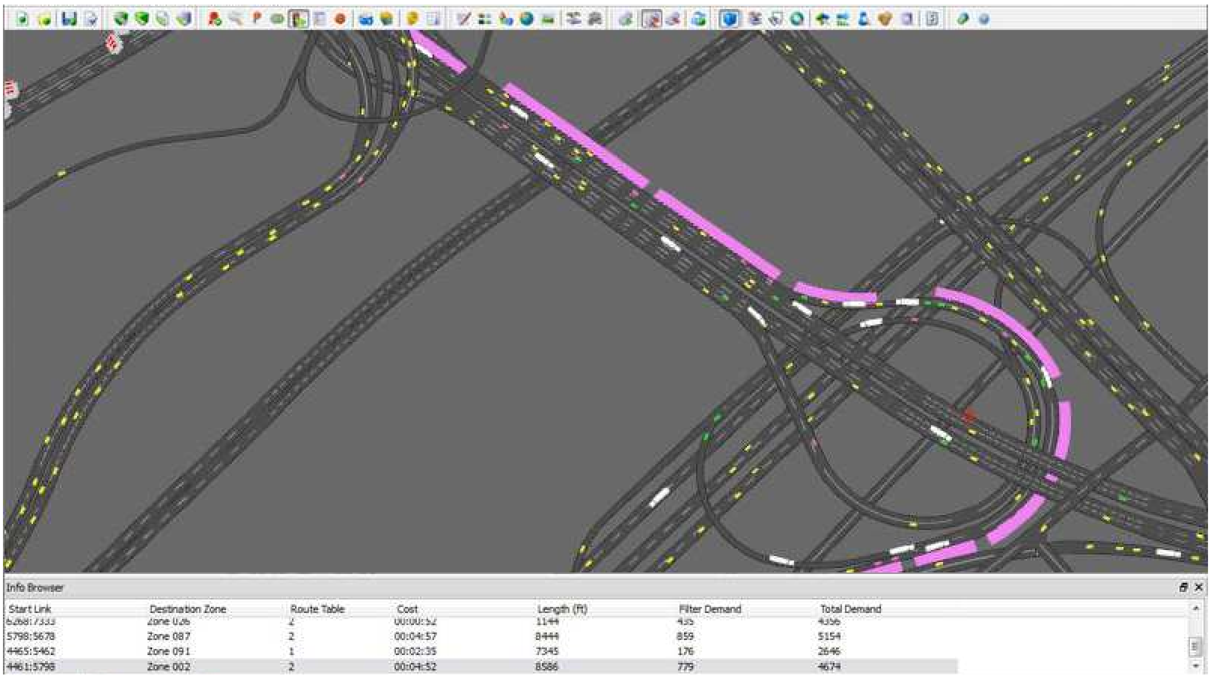

Figure 4: Microscopic model Paramics [source: Quadstone]

TSIS-CORSIM is a microscopic traffic simulation software package for signal systems, highway systems, freeway systems, or combined signal, highway and freeway systems. CORSIM (CORridor SIMulation) consists of an integrated set of two microscopic simulation models that represent the entire traffic environment.

Most of the previously named microscopic models are applied in practice in the Netherlands and hold nearly the entire commercial market. In the past, Rijkswaterstaat developed and used the FLEXSYT model. This was an event-based simulation model, capable of simulating small networks to develop and test signal controllers. Another model from Rijkswaterstaat is FOSIM (Freeway Operations SIMulation). The model was specifically developed to study traffic operations on Dutch motorways. Several road geometry characteristics can be specified, just as a number of local traffic measures (such as, prohibiting overtaking by trucks) and traffic characteristics. The model is mainly used to determine the capacity of road segments.

VISSIM

PTV VISSIM is internationally one of the most used microscopic modelling packages. The model has a strong emphasis on multi-class and multi-modal traffic, but is also often used for single traffic types. A user has the ability to apply road vehicles, goods transport, rail traffic, pedestrians and cyclists. The various simulations models designed for user-specific adjustments of vehicle characteristics and movements. The combination of default settings and flexibility to customize settings allows both consulting and academic users to use it for various applications. Vissim is one of the first commercial packages that also paid significant attention to visualizations alongside the theoretical models, which has also aided its popularity.

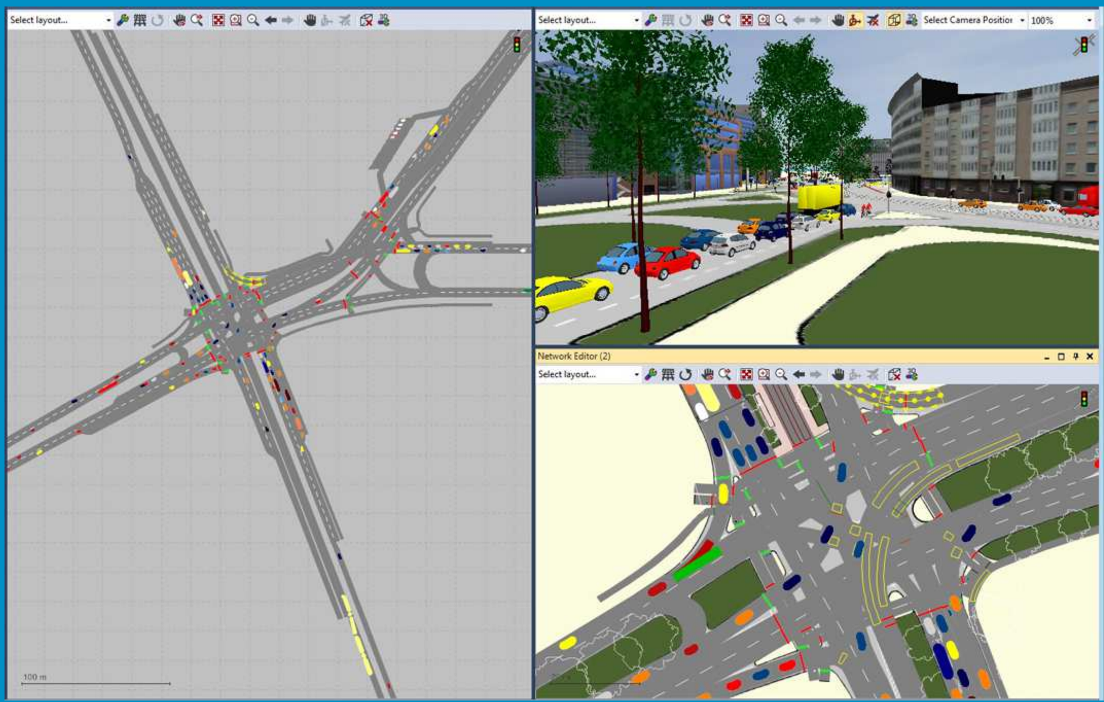

Figure 5: Microscopic model VISSIM [source: PTV]

In addition to the commercially available models, there are models that are mainly used for research purposes. One model developed in the Netherlands is the ITS Modeller, developed by TNO (a commercial version is available, but still has a limited uptake). This model can be used to model ITS measures, including road-side or in-vehicle traffic management measures, cooperative systems and automated driving.

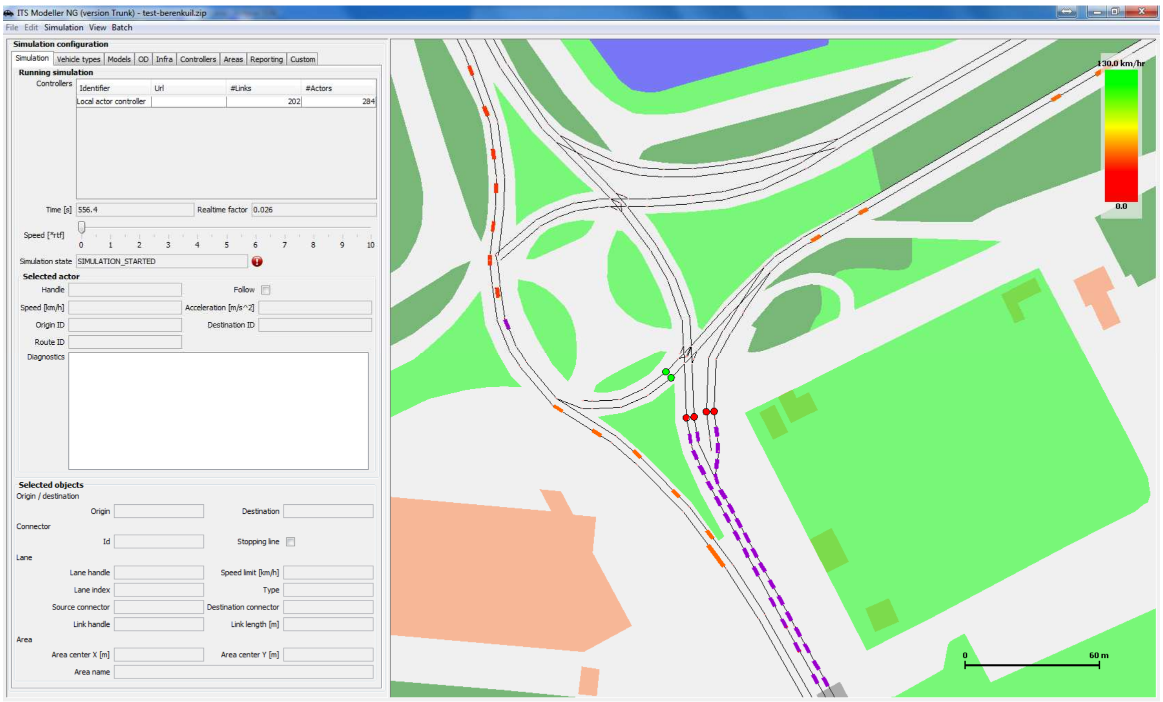

Figure 6: Microscopic model ITS Modeller [source: TNO]

3.6. Combined or hybrid models

Most hybrid models only exist in an experimental state and are not openly marketed. However some are beginning to find their way into commercial modelling packages, for example AIMSUN. Hybrid models are models that make use of more than one type of modelling approach, either combining or integrating these approaches in the model package. Initially research for widely applicable hybrid traffic models focussed on the transition between one type of flow, i.e. macroscopic, into another, such as microscopic. However academic and fundamental research has led to a wider variety of options which include switching between model type and detail, microscopic intersection modelling in macroscopic models, variable time intervals, integrated demand and assignment modelling, and an increased number of model types for which interaction is possible.

There are very few commercial hybrid packages available for traffic simulation. One that has broken through is the AIMSUN hybrid simulator. Within the package AIMSUN 8 (see frame) travel and traffic demand modelling can be fused with mesoscopic, microscopic and hybrid simulation – all within a single software application. It also covers traffic demand modelling within the same interface. It is therefore described as an integrated four-step model, which refers to the total chain of modelling steps: Trip generation, trip distribution, mode choice and route assignment.

AISMUN

Figure 7: Mesoscopic model AIMSUN [source: AIMSUN]

The AIMSUN hybrid simulator, within the AISMUN 8 package, offers simultaneous microscopic and mesoscopic simulation. This allows the user to model large areas using an event-based mesoscopic model while zooming in on all areas that require a finer level of detail with a microscopic simulation model, such intersections or small parts of a network. Event-based refers to the way the model calculates the movement of traffic. Traditionally traffic is moved in consecutive time steps, however it can often be computationally advantageous to only recalculate traffic movement for certain events, such as vehicles reaching a certain point on a network. This approach captures the main advantages of both models and applies them where required, resulting in a higher computational efficiency and shorter calculation times.

3.7. Data-driven models

According to a comprehensive review by Vlaghogianni, *et al*. (2014), most of the data-driven research has concentrated on testing alternative modelling approaches on short-term traffic data, possibly because of data availability and the ease of applying many of the available analytical approaches on a small short-term prediction horizon. Existing literature on short-term data driven empirical models can be categorized based on certain criteria; when looking at the result of such a categorization it becomes clear that most effort has gone into the following subjects:

- Data from motorways/freeways,
- Employing univariate statistical models,
- Forecasting traffic volumes or travel time,
- Using data from single point sources.

The most basic type of data-driven model is a naive model that predicts travel times based on the actual instantaneous travel times. This approach is often applied by route-planner websites and some satellite navigation systems. More advanced approaches combine historic data with the actual traffic situation to make a prediction.

Application of a data driven approach in the Amsterdam Practical Trial

A recent example of the application of an empirical data driven model in The Netherlands is in the Amsterdam Practical Trial (In Dutch: Praktijk Proef Amsterdam, 2014) in which TNO developed a travel time forecast model that uses live data combined with historical traffic data (volumes, speeds, travel times). In the used methodology different prediction methods are evaluated against performance criteria and the best approach is chosen in real-time.

Other examples of similar data driven approaches are Routeradar developed by RTL and TNO, and the Fileradar, originally started as PhD research at Delft University of Technology and now developed by the Fileradar company, both aiming to predict and visualize travel times on main roads in the Netherlands and inform end users. Also Google, Be-Mobile and TomTom combine historic data with the current data coming from loop detectors and floating device data.

Figure 8: Data-driven model Routeradar [source: Routeradar, RTL Nederland]

3.8. Other modelling tools

A special tool which uses both input from strategic models and measured data is the Mobility Scanner (Mobiliteitsscan in Dutch). The Mobility Scanner is a GIS/internet traffic & transportation tool, especially developed to evaluate the impact of infrastructural and socio-economic changes in a town, city or region. With this Internet tool, scenarios can be built in which locations, programs (size) and networks can be independently varied. The Mobility Scanner provides spatial, mobility and environmental indicators in order to evaluate, score and judge scenarios. The tool provides sufficient information to underpin choices on a structural level. The Mobility Scanner uses Big Data as well as data that is generally available in a transportation model, but due to its GIS/internet applicability, the tool is more capable of assessing and evaluating scenarios swiftly and easily without detailed knowledge of transport modelling software or other mobility data-handling tools. The biggest advantage of this tool is that its results are more or less instantly available and that means also that all stakeholders involved in the process have access to input and output of scenarios and can easily analyse and view the results.

4. What are the benefits of modelling?

In this chapter the main application areas for prediction models are presented and described. As each model category holds different characteristics and abilities, the application areas of each model category is also specific. In road and traffic systems a distinction is often made between strategic (tools for planning & design), tactical (traffic management & off-line prediction tools) and operational levels (on-line prediction tools). These are therefore also the levels used to explain the general application areas of each model category as shown in Table 3. An additional application level 'Evaluation' is added. This is done, because sometimes models are used to assess the impacts of implemented traffic management measures if no measurements are available or if external disturbances are too dominant to determine an effect with measurements only. For each application area we also give a few examples.

Table 3:

	Strategic	Tactical	Operational	Evaluation
Demand model	X	X/-	-	-
Macro-model (static)	X	X/-	-	X
Macro-model (dynamic)	X/-	X	X/-	X
Meso-model	X	X	X/-	X
Micro-model	-	X	X/-	X
Data-driven model	X/-	-	X	X

4.1. Strategic level: planning and design

A major application area of traffic models is their use as a strategic planning and design tool for infrastructure. Foreseen changes and expansion of infrastructure often bring significant costs. These costs require extensive substantiation to determine the net benefits of such an investment, which has been performed in part by traffic models.

For long term planning purposes static macroscopic models are commonly applied. Macroscopic models are used as it is normally the overall network performance that is analysed. Microscopic models focus much more on traffic on a smaller scale, which is unnecessary for planning purposes, especially when considering situations many years in advance. Furthermore calculation times of static macroscopic models are much shorter than microscopic models. This has two advantages: firstly the networks that are considered in planning and design are normally large (either in physical size or detail) and secondly multiple scenarios are often desired resulting in a larger number of simulation runs. By using multiple scenarios different uncertain trends in the use of future infrastructure and traffic can be considered. There are multiple examples of static macroscopic models used for such projects throughout the past decades. The most obvious examples in The Netherlands is that of the Dutch Regional Model (Nederlands Regionaal Model - NRM) and the Dutch National Model (Landelijk Model Systeem - LMS). Both these models are extensively calibrated using vast amounts of societal data for the demand and consider multiple modes, including public transport. The models also incorporate a high level of detail and on large networks. It is has been tried to use dynamic assignment models for long term planning, but most of the time this gives problems for the future years, because the demand for the future is based on a static model. To improve that, the dynamic model should be integrated into the whole modelling system, but this hasn’t been tried yet in the Netherlands.

Historically static models have been used in planning. For many urban and municipal network evaluations, this is still the case. For example, OmniTRANS is used by many Dutch municipalities for static modelling of demand on their road transport network. However with increased computational power and new dynamic models, dynamic models are more commonly applied and continue to increase in market share. Dynamic models have a strong ability to consider changes in traffic behaviour during a peak period or day and allow resulting congestion to be modelled in a realistic manner. The use of dynamic models is by far preferred especially when considering network improvements to reduce congestion and consider time demand traffic flow and occurrence of congestion. But to be able to use them, they should be integrated into the whole system of models.

Another upcoming, but not yet widely applied type of model, are stochastic traffic models, sometimes also known as probabilistic models. These models allow uncertainty to be modelled without having to consider scenarios and in doing so reduce calculation time. It is necessary to note that traffic forecast models need an estimate of the (future) traffic demand. This is achieved by applying demand models, among other things, as trip forecasting tool, and thus generating important data input for strategic traffic flow models.

Mesoscopic models are also being applied for planning purposes. However with a higher calculation time, their use remains limited. Advantages of using mesoscopic models is their ability to give a bit more detail on critical locations in a network. This can especially be useful where changes are made to a network at locations where vehicle specific interactions are important. Examples of practical application of mesoscopic models on a strategic level remain limited, mainly as these models are relatively unknown and have still to build a reliable reputation.

An example of a strategic level application is that of travel pricing strategies and road charging decisions. This topic is especially reliant on the use of demand models, and much less on propagation models, except for pricing strategies such as HOT lanes (High Occupancy Toll lanes), where the price to use a certain lane is varied according to the traffic situation. However the use of macroscopic models to predict the effect on traffic flow is also possible. Table 4 gives an overview of the elements affected by policy related measures such as peak hour avoidance or road charging.

Table 4:

Measure	Trip / destination choice	Mode of travel	Departure time choice	Route choice	Speed choice
Peak hour avoidance (rewarding)	X	X	X	X	-
Road charging (variable cost structure)	X	X	X	-	-
Road charging (cordon based)	X	X	-	X/-	-

4.2. Tactical level: traffic management and off-line prediction

Traffic models also play an important role for small scale planning purposes, such as smaller adjustments in infrastructure, the planning of road works and the application of traffic management measures. Contrary to large scale investments, many more smaller projects consider the use of the urban road network. However many tactical projects also involve the application of (dynamic) traffic management on specific places on motorway networks.

On this level all three dynamic model categories (including combinations) are commonly applied. Although static models have been used a lot in the past, current model development is such that there is no longer the need to apply sub-standard static modelling for tactical purposes. As most modelling studies on a tactical level deal with dynamic characteristics in traffic, congestion, and shifts in traffic flow in time, dynamic models must be considered.

The application of a macro-, micro- of mesoscopic model is highly dependent on the goal of the study. Microscopic and mesoscopic models may be applied for relatively small networks, while macroscopic models are especially suited when one is interested in the effects of a wider and larger network. Also, if a high level of consistency is required in the results between scenarios, a macroscopic model may be regarded as a preferred option. The use of microscopic models can result in slightly differing results for identical model runs due to the stochastic effects between individual vehicles and also with the infrastructure. A recent example is the use of dynamic macroscopic model INDY for modelling the effects of planned roadworks in the Amsterdam area (see Figure 9).

In many cases local and lane-specific measures are applied, which may also influence interaction in traffic, such as a result of lane-changing, vehicle speed differences, or effects on certain vehicle groups. For such projects the use of microscopic models will almost always be required, while certain mesoscopic models may also be applicable depending on the exact question. There are many practical examples of the use of a microscopic model for this application with most focussing on urbanised areas. One such example is shown in Figure 10 for the reconstruction of a part of the A10 ring road around Amsterdam. With VISSIM the traffic flows on the connecting infrastructure were analysed (see Figure 10).

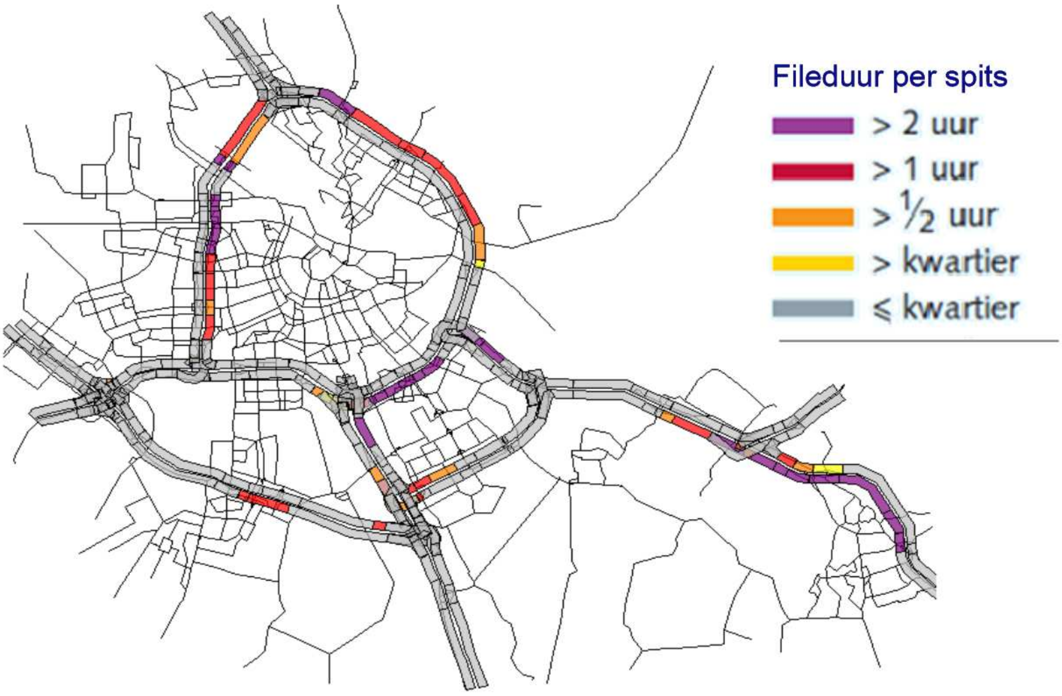

Figure 9: Application of dynamic macroscopic model INDY for the Amsterdam network

Figure 10: Application of VISSIM for the reconstruction of junctions on the ring road of Amsterdam

On a tactical level changes may also occur in demand patterns due to local changes in a network. These however will not be as large as in most strategic level projects. In Table 5 the impact of some examples of infrastructural measures on trip choices are given.

Table 5:

Measure	Trip / destination choice	Mode of travel	Departure time	Route choice	Speed choice
Peak hour lanes	-	X	X	X	X
Small infra measures	-	-	-	-	X
Lane measures (road surface marking)	-	-	-	-	X

4.3. Operational level: on-line prediction

Application of models for operational purposes demands more than for the two previous application areas. Models are generally required to operate at real-time speed or faster, are required to be stable and are mostly connected with real-time databases (live traffic data). Furthermore, operational application also demands that models can adapt to changes in traffic in time, and therefore only dynamic models will be found in this application area.

The condition that a model must be able to run in real-time obviously makes a macroscopic model the main choice for operational and on-line application. Various on-line applications include travel-time predictions and route advices. In most cases a general aggregated output from a model (at the traffic flow level) is sufficient. For example, a travel time prediction for a certain route only needs to consider the general travel time on average, so does not require the consideration of individual vehicles.

Data-driven models are also extremely suited for application as an tactical or operational model. This is especially the case as operational models often require short term forecasts to be made, which is well suited to data-models. Furthermore, data-driven models can generally be designed to give results with short calculation times and are therefore suitable for real-time applications. Many different data approaches exist for forecasting traffic flow and times, such as statistical, Bayesian, and Neural networks, among others (Vlahogianni, *et al*. 2014). A more recent application is found in ensemble methods, which considers a combination of multiple different data approaches. This allows the strengths of different approaches to be captured, while the weakness can be disregarded. A recent example of such an approach has been the practical application for the Amsterdam Practical Trial (APT) by TNO and ARS (Calvert, *et al*. 2015).

In some cases it may be possible, or even desirable, to make use of microscopic models. Projects dealing with individual travel time predictions, or comparison of individual and roadside sensor data, may require specific consideration of individual trips. However it should be noted that these applications are very few compared to those for which macroscopic models are applied.
Besides for their use in travel time prediction and advice, another important operational application is the use of models in traffic control centres. In these centres, the state of a traffic network is monitored. When disturbances occur in a network, traffic controllers have the ability to apply various traffic management measures to alleviate detrimental effects of disturbances. Often these will be predetermined, but sometimes forecasting models can be applied to give a quick estimation

of the effects of applying various measures. These models can give advice on which measures to take and where and how to implement them. This demands that the models must be able to calculate multiple future situations in a very short time for a much longer time horizon of minutes up to a few hours.

Operational Traffic Management

In increasingly more applications model predictive control is used. In the long term, traffic predictions will be at the heart of traffic management. Measures can then be chosen based on predictions of effects that are made with traffic models. However their application is in part dependent on accurate behavioural effects. Traffic models must be supplied with valid behavioural models as behavioural and performance models together make up the building blocks for the modern day road operator and road designer. Table 6 shows traffic management measures and behavioural choices they may affect.

Table 6: Dynamic traffic management related measures and their possible impact

Measure	Trip / destination choice	Mode of travel	Departure time	Route choice	Speed choice	Lane choice	Headway choice
Traffic lights	-	X	X	X	X	-	-
Ramp metering	-	-	-	X/-	X	-	-
Speed measures	-	-	-	-	X	X	-
Pre-trip advise	X	X	X	X	-	-	-
On-trip advise	-	-	-	X	-	X	X

5. What is the perspective for the future?

Not only will developments in traffic modelling and prediction continue to change in the coming years and decades, traffic itself is likely also to undergo changes. Therefore the perspective for the future of traffic prediction models should not just consider the models themselves. In this section we will consider developments in traffic modelling, but also developments in traffic and how these are expected to influence traffic forecasting.

5.1. Changing society

Society continues to change at a fast rate. Both employers as well as employees are opening up to a greater flexibility in working patterns. Non-work related trips also show a steady shift towards a more flexible pattern. Increased digitalization of society and possibilities to communicate and interact through social media will possibly lead to a reduction of trips per capita. It is also hypothesized and found increasingly that trips will shift to more convenient times leading to a change in travel profiles. Even when trips are made, a change in modes is also expected in the future, as has been shown in recent research by the Netherlands Institute for Transport Policy Analysis in the Netherlands (KiM, 2012). Each of these shifts in demand will challenge demand models to adapt to a more complex mix of travel patterns. This is also the case in how the models are calibrated. New insights in the choices made by travellers and how these correspond to the final travel patterns may also be required.

Traffic forecasting modelling methods, especially on an operational level, are also expected to be greatly influenced by societal trends. This is not necessarily on the level of how traffic moves, but rather on the way predictions are made. Traditionally generic predictions are given, which are deemed suitable for the collective traffic flow. A clear example of this is the use of travel time predictions from Dynamic Route Information Panels (DRIPs). As society becomes ever more 'connected', it becomes possible to offer individual travellers personalised travel information and advice. This shows a definite shift from road side information to in-car information. Operational forecasting models will play an increasingly important role in these shifts, as they will be required to consider the trip of both a single traveller as well as the interaction with the collective traffic flows, keeping the balance between the optimal solution for the users and for the network as a whole. This challenge may lay at either the macroscopic or microscopic level, but more probably at a combination thereof and is most definitely dynamic. In the aforementioned Amsterdam Practical Trial (Calvert, *et al*., 2015), this principle is being actively encouraged as a future replacement of collective road-side travel advice..

5.2. Influx of data

In past years the amount of available data on traffic flows, speeds and travel times has exploded exponentially. Initially, the uptake of this data was cumbersome due to a lack of proper data-processing techniques and sufficiently powerful tools. However this quickly changed and the development of fast, powerful, and integral approaches has also come up to speed and continues to develop. This upturn in data and data-processing also opens the door for increased possibilities to apply data-driven models. In previous sections this has already been touched upon. However the growing trend and application of data-driven approaches is far from finished and is expected to continue to grow in the future. While data-driven approaches currently struggle to predict uncertain and disruptive traffic situations, such as incidents, it is predicted that even these difficulties will be increasingly overcome. The application area for such models is mainly focussed on operations. It remains to be seen how extensively they can be applied in strategic and especially tactical areas.

Besides the use of data for data-driven approaches, data can also be used to refine the algorithms of existing models. This is especially the case when it comes to behavioural aspects of traffic models. While macroscopic models apply aggregated variables, microscopic and demand models include a wide range of behavioural algorithms and assumptions. By using historical data, or even real-time travel and movement information, these assumptions and algorithms can be updated and improved. While such advancements are being made, the changes in behavioural patterns may be more substantial than correcting past behavioural patterns, nevertheless these developments are valuable to advance model accuracy. These trends also allow the development of activity-based model to further advance. Activity based models consider activities of individuals and which mobility movements are likely. With increased information on movements and behaviour of individuals, such models can be improved and may offer a strong contribution to the existing model suite. Another main advantage of an uptake in the quantity of data is the ability to further calibrate models. This includes the calibration of parts of models as well as overall model performance. An increase in data allows models to be fined-tuned to a better extent. This also offers challenges in the way models are calibrated and how the data is processed for this purpose.

Vlaghogianni, *et al*. (2014) describe several challenges for researchers due to the recent developments in technology and the widespread use of powerful computers and mathematical models. A short summary of some of these challenges to create state-of-the-art data driven models are given below:

- Developing responsive algorithms and prediction schemes;
- Developing network predictions, synergy with traffic flow theory and models;
- Using data from multiple sources or using novel technologies for collecting and fusing data and estimate travel times;
- Data resolution: determining the optimal degree of aggregation in relation to short-term forecasting;
- Testing the efficiency of new technologies for collecting and fusing data;
- Compare models or combine forecasts.

5.3. Computational power

An increase in computational power of computers is not necessarily a modelling advancement, but does facilitate the application of scale in existing and future forecasting models. Models that previously were considered inapplicable due to long calculation times are now becoming feasible. This is especially the case for dynamic models, which in most cases will be preferred. This will be the case for all model categories. The application of operational models stand to gain the most from greater computational power. It is essential that these models perform their calculations well beyond real-time speeds and ideally as fast as possible. Furthermore it may be expected that operational models can become more complex and therefore more accurate as the processing power increases. The downside of more computational power can be that development is tempted to increase the level of detail in such a way that gain in speed is counterbalanced by simulating more detail. Not to mention the data needed for more detailed models.

An increase in computational possibilities is also expected to assist the growing trend in hybrid and ensemble models. Hybrid models are traffic forecasting models that make use of multiple modelling categories to allow for a greater detail for a limited additional cost. An example of such an approach is a dynamic macroscopic model that allows the user to zoom in on a detailed section of a network and few traffic flow microscopically. While some mesoscopic models are constructed close to this principle, most do not have the ability to switch between detail levels, but remain on a single level of detail. The first of these types of models have already been developed, but have still to be proven consistent and find widespread implementation. An example of such as model is AIMSUN 8.

Ensemble models refer to data-driven models that make use of multiple data based prediction methods. These models were previously described and are already applied in practice. However this has only recently become possible due to increases in computational power. As this continues to develop, such methods are expected to advance further both in terms of forecasting power and complexity.

5.4. Traffic evolution

Not only are forecasting models expected to further develop in coming years, also traffic itself is expected to change. Changes to traffic characteristics and composition must also eventually be considered by forecasting models, even if the changes are slow. The main and obvious evolution in traffic is that of the traffic fleet and its capabilities. Although every vehicle is different, most can be presumed to be of an average type and correspond accordingly. The introduction of automated vehicles is a first and relatively small step in this evolution. These vehicles have different abilities to manually driven vehicles, which will influence the characteristic of traffic flow and should be considered when a sufficiently high penetration is achieved. A greater change to the traffic performance of vehicles lies in connected, cooperative and finally automated vehicles. It may still be some way off before all these types of vehicles are actively present on roads and in sufficient numbers. Nevertheless their introduction will have a large influence on traffic performance and will need to be eventually considered in models. It may even be the case that strategic predictions are already being made for scenarios a few decades in advance in which a considerable percentage of vehicles will make use of some part of this spectrum.

Most models currently only consider a single mode. In this context a mode indicates a type of vehicle, such as a car, truck, HGV, bus, tram, train, etc. Mobility is more than just car movements and therefore an increasing trend shows a movement towards so-called multiclass and multi-modal models which consider multiple modes of transport. It makes sense that if the population have the ability to consider different forms of transport for a trip, that these should be simultaneously considered. Difficulties in multi-modal modelling often stem from a necessity to use different propagation models, a lack of information on the behavioural changes and ability to switch between modes, and the interaction between the modes in the model. However increased urbanisation and mobility in cities demands that all modes be considered as feasible intermodal possibility of travel, especially in urban areas. Examples of current multiclass and multimodal models are strategic models and microscopic models such as AIMSUN, VISSIM and Paramics. Especially for the dynamic macroscopic models there are possibilities to further develop or introduce new multimodal models, which can be applied to a greater extent in the future.

5.5. From singular to modular models and platforms

In traffic modelling there has always been a trade-off between generic models that claim to be suitable for almost every situation and others that are purpose built with a unique purpose for which they are very effective, but much less outside of that scope. In recent years there has been an increased trend away from single stand-alone models towards combined models or model packages. These model packages make use of multiple different purpose specific models that can be linked, sometimes based on a more generic modelling platform. In this document we have highlighted some of these current developments. However this trend is still ongoing and is expected to result in an increased trend of models to specialise and be very accurate for specific purposes, while being able to connect with other models for other purposes. This modular approach also opens the door further for new innovative platforms and also for open source traffic model construction. An example such developments can be found in the traffic simulation platform OTSim (2015) as an open-source traffic simulation platform with the objective to support research and development of multi scale and multi modal traffic models. It provides a software environment that offers free to use knowledge and utilities, and can act as a starting point to create and develop new methods and models. While obviously not all developments will be open source, both academic and commercial model building trends are keyed very towards model platforms and modular models, more so than in the past.

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