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A nation-wide macroscopic freight traffic model

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Abstract

It has long since been recognised that it is insufficient to estimate freight flows as a part of passenger transport models. However, there is still no established standard for dedicated commercial traffic models, like there is in private traffic. A reason can be seen in the complexity of the topic and in the scarcity of representative data. In order to bridge this gap, available data has to be put to its best use. Models which are able to take all the complexity of logistics into account will have to be limited to narrow fields (i.e. a restricted area, one transport mode, one commodity group or such) due to the high expectations towards data quality. Furthermore, a generally applicable model will have to be based on simplified assumptions. This contribution describes a general, scalable, multimodal freight flow model.

The model is developed as a 6-Step-Model for the area of Germany for the spatial level of NUTS 1. It also links with all European countries as aggregated traffic zones (NUTS 0). Global trade is connected through seaports and airports. Within the model 60 business branches are distinguished that are related to the transport of 20 type of goods (NST 2007). The multimodal approach allows a choice of 12 means of transport on road, rail or inland waterways. Furthermore, the model also distinguishes between loaded and empty runs.

The model is intended to calculate freight flows on a large scale. Scenario techniques can be used to forecast the freight flows based on changes in conditions of all sorts, e.g. economic developments, employment structures, spatial development.

This development in modelling extends our knowledge in the use of the existing data, the understanding of them in relation to the description of commercial traffic and is an important step in large scale freight traffic modelling.

Keywords: Macroscopic commercial transport model, goods traffic, Europe

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1. Introduction

1.1. Outline

This article describes a macroscopic freight traffic model developed at the Institute of Transport Research at the German Aerospace Centre (DLR). The understanding of the relevance and the challenges of freight transport modelling leads to the rationale behind the developed model (sections 1.2 and 1.3). The model itself is described in section 0. The article concludes with a description of the current state of realisation of the model, further steps, and the context in which the model will be used.

1.2. Relevance and challenges of freight transport modelling

Freight transport plays a significant role for the environment, the society, and consequently for transport planning. While the capacity limits of many parts of the transport infrastructure (roads, railroads, seaports, airports) have been reached, an end of the steady increase of ton kilometres of transported goods is not to be seen in the near future. Currently the transport infrastructure is used inefficiently in terms of time and space. Budget constraints and an increasing awareness of environmental costs of traffic call for intelligent management of the available infrastructure and resources [1]. Effectively accomplished transport in terms of cost, operational efficiency and economic viability is a key factor for an economy that relies on fast and reliable delivery of goods [2].

The consumer's behaviour is mainly responsible for the demand for freight transport. The available transport infrastructure, however, is funded and decided upon by the public sector, which thus affects freight traffic. Therefore, decision makers from the public sector rely on an understanding of changes in traffic demand in order to ensure good decision making regarding investments and improvements [3].

Examining existing conditions of the transport system, detecting changes as well as forecasting future freight flows and freight transport demand is a task of particular importance. Thus, determining the effect of measures regarding the transport system plays an essential role in this context. In order to come to terms with this problem it is mainly empirical surveys and model-based calculations that help answering the question for future transport demand and the drivers behind it. At first glance, surveys appear to be the best provider of data to describe the existing conditions. Since most data cannot be recorded directly (or just by complex and expensive surveys) and due to the fact that they only make statements about the current situation but not about future conditions, model calculations are indispensable [4].

Instead of trend forecasts, which predict changes in a certain context with certain probability, models consider factors with influence on transport demand and their relationships and interactions. Therefore, the relevance of transport modelling is founded in understanding interactions in the transport system and forecasting future developments in transport demand [5]. By integrating freight traffic models into the transport planning process, decisions on future investments can be derived from a solid basis [1].

The selection of a suitable model for reproducing and calculating freight traffic demand is a challenging task. There are as many different types of models as there are different objectives related to them. Thus, there is no single model addressing all problems and responding to a general range of questions. Most models are focused on and adapted to the specifics of a particular research question. A brief overview of the state of the art in European commercial modelling is given by de Jong/Gunn/Walker [6] and Tavasszy [7]. Further references are provided in these articles. The Freight Model Improvement Program of the U.S. DOT [2] also offers a comprehensive overview of available models in its freight modelling bibliography.

Existing models do not only differ in terms of their scale (international, national, regional, local and urban) but also in relation to the data used and their depth of aggregation, corresponding measurement variables used (vehicle vs. freight flow models) or their scale of analysis (macroscopic, mesoscopic and microscopic).

Taking into account that the spatial coverage differs and, therefore, characteristics related to these spatial units differ as well (e.g. operation of freight transport in urban areas is very different in its characteristics in comparison to its pendant executing long-range transport across regions such as the European Union), the requirements of those models vary. Thus, general model requirements are hardly named because they are usually linked to their individual application [4].

However, there are general requirements and challenges shared by all existing models. These are mainly caused by the characteristics of freight transport and the process of modelling. Freight is a very heterogeneous object of modelling, especially in comparison to passenger transport. Modal choice, for example, is mostly influenced by the specific characteristics of the goods. Additionally, there are several actors (shipper, freight forwarder, carrier and receiver) involved, which may not act in obvious ways because of their complex relationships and their influence on decision-making. In addition, the supply network does not only consist of general nodes and links but also of terminal nodes (hubs, logistic centres etc.) that show specific characteristics. In that manner, freight transport is more an indirect than a direct demand that is derived from industrial and logistic processes and decision making and its complex variables [8].

These characteristics result in specific challenges. Linking freight transport and the economy with consumption patterns is one of them. It is also essential to accomplish the conversion of trade value to trade volume, a challenging task regarding the fact that freight transport is a derived demand from economic activities. Hence, trip generation is a complex matter. Dealing with the sensitivity to cost changes or situational response to cost changes (e.g. truck type, road type, time of day etc.) and the differentiation between goods with different logistics backgrounds are challenges that need to be faced in model development. In this context, forecasting the causes and impacts of choice of vehicle type is also a major obstacle. Emerging considerations and integrations of supply chain management is similarly complex. The link between and combination of different transport models (road, rail, inland waterways) to a multimodal network is considered essential widely. Most difficult is to ensure accuracy of forecasts and the level of detail. Therefore, there is a growing demand on detail (vehicle types, logistics, spatial detail) and on extension of the dimension of freight modelling into the broader transport system, geographically as well as functionally [7]. Linking passenger with goods transport as well as private with commercial transport is an important field of the extension mentioned.

Depending on the scale, the availability of comprehensive and high quality data is a major challenge. If there are available data of the quality mentioned, it is usually for specific areas, which hampers the transferability of models. If there are no comprehensive data available, standardised ones usually limit forecasts and can only provide the basis for a general overview. Therefore, it is necessary to expand and specify the benefit of given data by skilful handling and combination.

One of the most important challenges is found in the accuracy of the statements and their verifiability. As the interactions between impact variables (input) and effects (outputs) are described by model parameters, it is important to calibrate and validate them. The calculated values (model parameters) have to be calibrated by using an adjusted method of calibration and, hence, they are bound to be approximated to the situation of reality. Validation (comparison of calculated and observed values) will allow a review of the accuracy of predication and can help to identify potential and fundamental errors [4].

Existing large scale freight models have been developed during the last decades in the USA (e.g. CMAP, FAME) and Europe (e.g. SAMGODS, ASTRA, SCENES). An assessment of advantages and shortcomings has been conducted, for instance, as part of the European project EXPEDITE [9]. Some of these models already provide valuable information on freight flows now and in the future. Prerequisite for these models is the existence of representative commodity flow surveys, which are conducted only in a minority of countries (e.g. FAME in the USA, SAMGODS in Sweden). The development of tailored freight models in the USA (Los Angeles Freight Forecasting Model, Florida State Freight Model, Texas State Analysis Model, etc.) underlines the individual needs, but also the current lack of standards for freight modelling and standardised data for their calibration [10]. The situation in Europe is determined by the increasing influence of the European Union on standardisation, which fosters data provision from the either economic or traffic point of view, neglecting so far the logistics perspective [11].

1.3. Rationale of the described model

Freight traffic is a crucial part of a thriving economy and, thus, a driver behind the construction of transport networks. It is also a major cause for green-house gas emissions and noise. For decision makers it is important to understand, how the negative impacts can be minimised without compromising unduly the positive sides. It is apparent that this is a challenge on large scale requiring an at least national perspective. While regional models have been successfully developed (e.g. EUNET for the Trans-Pennine Corridor in the north of England, and LASER for the London region and the south east of England), large-scale models pose additional challenges due to the inhomogeneity of the larger area, and the limitation to data available for the whole considered area (here Germany and the surrounding countries).

A national perspective, furthermore, offers the opportunity to use statistics gathered on national scale. Commonly reliable information is available on traffic between states or countries, which can be used for the calibration and validation of models. These statistics are commonly gathered on a regular basis and standardised. They offer a macroscopic view. The more detail is required, the higher the data requirements get and consequently the more limited becomes the scope or the accuracy of the research due to resource limitations [12]. Thus, the rationale behind the model introduced here is to enable a depiction of freight traffic on national scale (for Germany) for all surface transport modes under best utilisation of available national statistics. Statistics on freight in Germany are available for all transport modes from the perspective of vehicle traffic (based on vehicle owner surveys), but not of logistic chains. The model, thus, has to be calibrated with OD matrices (shipped tons) and vehicle related parameters (e.g. vehicle kilometres). The model presented is only a first version to be improved in the future. Therefore the model has the aim of being general and flexible for future extensions. The freight demand is embedded in a framework for (private and commercial) passenger and goods traffic and can be calibrated with publicly available data which is updated on a regular basis (mainly statistics available from the German Federal Statistical Office and from the Statistical Office of the European Union, Eurostat).

2. Description of the model

2.1. Basic structure

The model is a commodity flow model based on an extended four-step process. Freight is generated by 60 distinct business branches on district level for 20 types of commodities, distributed across Germany and assigned to road, rail and inland waterways. The transport modes are further distinguished between vehicle, train and ship types (transport means). Commodity flows are converted to trips by a simple factor model. The generated origin/destination matrices on a yearly basis are combined with the demand from private passenger and service related transport demand. Finally, total demand is assigned to the transport networks using commercial software. The European context is incorporated by taking the surrounding countries as origins and destinations into account. Transit traffic through Germany is added to the national demand.

The model is divided into separate modules with interfaces between them.

1. Freight generation
2. Freight distribution and modal split
3. Conversion into trips (tons to trips, empty trips)
4. Route assignment

The modules are described in more detail in the following sections. An illustration is given in FIGURE 1.

This approach follows existing macroscopic freight flow models (e.g. ASTRA, NEMO, SCENES, BVU/ITP [13]). It is fitted to the special situation of Germany and dispenses with extensive data needs while maintaining a level of detail beyond strategic large scale (European) models (e.g. ASTRA, EXPEDITE). As will be explained in more detail, the freight generation is based on a detailed synthetic data set generated from different statistics. The calibration of freight distribution and modal split uses an evolutionary algorithm which makes the calibration adaptable to various needs. The transport demand is assigned to a detailed road, rail and waterway network together with passenger traffic and commercial service related traffic.

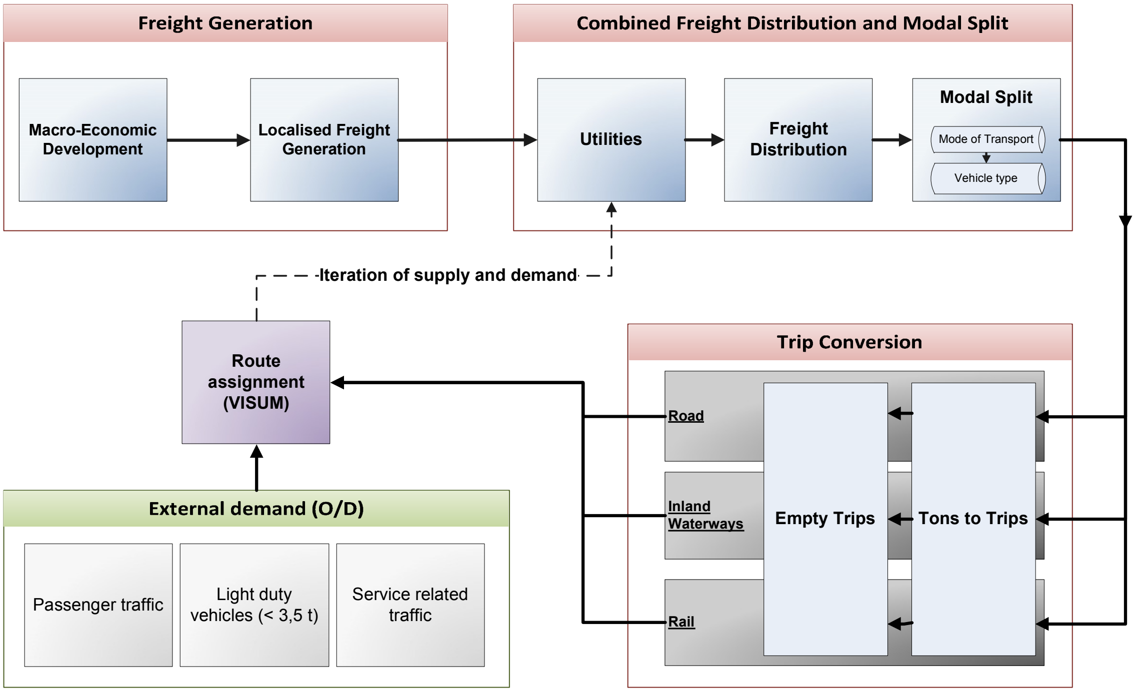

FIGURE 1 Overview of the macroscopic freight modelling approach

2.2. Freight generation

The freight generation module determines the sources and sinks of the transported goods in tons of specific types of commodities. The connections between sources and sinks (origins and destinations) are established in the distribution module.

As in other freight demand models, shipped tons are derived from economic data by using national accounts and gross domestic product (GDP; or more precisely: gross value added, GVA). Shipped tons of goods are determined for the investigated area in total. The GDP is coupled to the transported tons, which is currently suitable for most of the developed countries. Therefore the explanation power of the GDP of different business sectors to the number of transported tons of a commodity is analysed. This regression is used to calculate the derived number of tons for a given GDP in the considered year distinguished by the commodity, input and output of Germany. The operational level is 20 types of commodities (the divisions in the classification NST 2007[†]) and 60 business sectors (classification WZ 2003[‡]). This approach of coupling transported tons to economic development in different business sectors makes good use of the available forecasts of economic growth (e.g. IWH [14]).

To add international trade to the described procedure, which is very important for a consideration of the investigation area in goods traffic modelling, the European neighbour countries are described as single zones (NUTS 0). Together with the seaports and the airports they represent the *singular traffic generators* in the model. Seaports and airports are treated separately following the rationale of making best use of easily available data. On the one hand they represent large traffic generators and would bias the model if simply subsumed in the surrounding zone, on the other hand detailed statistics are commonly available for the received and shipped goods.

In a second step the generated goods are assigned to the traffic zones within the model. This is based on the assumption, that firms are sending and receiving goods. The goods received by private consumers (not by retail) is mostly part of the private passenger traffic. The amount of goods shipped or received by firms is related to the size of the respective branches, defined by the number of employees. Thus the amount of tons can be allocated to the number of employees by every firm in a traffic zone. The advantage of this procedure is – besides the availability of employment statistics with reference to business sectors – the high level of detail for the freight generation. As compared to existing models this brings the freight generation down to the firm level, enabling investigations on a very small scale. Due to the combination of the freight demand model with a synthetic business environment (described by Bochynek et al. [15]) the potential of the model for further improvement is greatly increased. The given model uses input-output-tables to analyse the exchange of commodities between different business sectors and derives commodity flows from business activities. The distinct influence of a branch on the amount of a special kind of commodity and the generated and attracted commodities is thus considered.

In a next step the generation-rate and the attraction-rate within the model is created by dividing the tons trough the number of employees of a branch. These rates were used to calculate the production and attraction of commodities of each traffic zone by multiplying the rates with the number of the employees within a traffic zone.

It is important to stress that the freight generation provides transported tonnage as opposed to produced tonnage. Due to the fact that the model does not use tour patterns, tours are split into single trips. Thus, intermodal tours become a chain of monomodal trips. The cutting points are all locations where economic activities take place (which are captured by statistics). Logistics hubs are among such locations. Thus, logistic chains are indirectly reflected in the freight generation without the need for a separate logistics module as it is used in many other models (e.g. SAMGODS [15]).

While this approach poses a challenge for scenario forecasts, because logistic concepts cannot be directly reflected, it makes the model output robust due to the sound knowledge of economic activities and their development.

2.3. Freight distribution and modal-split

[†] "Nomenclature uniforme des marchandises pour les statistiques de transport 2007" (NST) is a uniform directory of transported commodities used in the European Union.

[‡] "Klassifikation der Wirtschaftszweige 2003" (WZ) is a classification of business branches according to their economic activity by the Federal Statistic Office of Germany, based on the European industry standard classification system NACE Rev. 1.1 and thus the international ISIC Rev. 3.1.

The distribution of commodity flows between the traffic zones is achieved by a synthetic entropy maximising approach. Distribution and modal split are combined following the suggestion and discussion by Wilson [15]. At first, utilities are computed for all O/D pairs differentiated by commodity and transport mode. The utilities are based on transport cost and travel time as deterrence due to their relevance and availability. Further influences, which cannot be determined quantitatively, are covered by a dummy variable. The distribution follows a gravity model while the modal split is computed by a nested logit model for the transport modes road, rail and inland waterways as nests. Similar approaches proved to be suitable for freight demand modelling (cf. NEMO, SAMGODS).

A major challenge of all freight transport models is the calibration and validation. The chosen approach enables a calibration based on regularly available statistics for all commodities. Like most European countries, Germany has no regular commodity flow survey, which would be required for a more detailed distribution and modal split model. By distinguishing 20 commodities and covering all surface transport modes even with only two impedance variables (cost and time), hundreds of single parameter values have to be determined. Some parameters can be well interpreted, like the value of time (relative importance of transport cost and travel time). Others are less illustrative and can only be analysed in comparison to past experience, like the nesting parameter for the modal split. Commonly the complex problem of calibration is simplified based on expert knowledge by setting some parameters a priori and focusing the attention on the parameters which can be interpreted and have major impact on the model outcome. The calibration then often follows a ceteris paribus approach by adjusting only one parameter at a time-step. This calibration procedure results in the given context in a tedious and time consuming task.

A different approach was developed to accelerate the calibration process and to facilitate best use of available data for calibration. The interpretation of parameters and a setting of assumed limits for each parameter by the modeller cannot and should not be avoided to ensure the plausibility of the model. The determination of suitable parameter values, however, can be eased by evolutionary algorithms. While such algorithms in their basic form do not know about the meaning of parameters, they offer the opportunity to test a much larger range of values and value combinations than it would be possible by a manual ceteris paribus approach.

Evolutionary algorithms (in the given case a Particle Swarm Optimiser, PSO, was chosen, but other evolutionary algorithms could be utilised, too) rely on the definition of a fitness for the individuals of their population. For the freight traffic model, the fitness was defined as the difference between the modal freight O/D matrix (in tons per year for the different commodities and transport modes) and a calibration matrix of the same dimensions. This fitness can be easily adjusted to the specific model purposes. In the given case, absolute tons as the basis for ton kilometres and vehicle kilometres have been fitted separately for the different commodities.

The calibration OD matrix is computed from national and European statistics. The commodity flows for Germany are collected and published by different state agencies on NUTS 1 level (16 states) and differentiated according to NST 2007[§] and transport mode (road, rail, inland waterways). This data was combined to result in a matrix of the same dimensions as the aggregated output freight matrix. The aggregation of the output freight matrix given for NUTS 3 (county level in Germany) to NUTS 1 (state level) and to three transport modes (instead of 12 vehicle types) is necessary due to the granularity of the available statistics. If more detailed data would be available, the procedure could easily be adapted to this data.

The described approach enables the calibration of the distribution and modal split module of the freight traffic model irrespective of the conversion to trips, which is achieved in a subsequent step (cf. 2.4). The evolutionary algorithm provides parameter sets which lead to a good fit of the output freight matrix with the calibration matrix for the base year. A plausible parameter set is used in a disaggregated run of the freight distribution and modal split module (NUTS 3 and all vehicle types). The output (modal freight O/D matrix) is passed on to the subsequent modules.

[§] Until 2008, for road traffic the older classification NST/R was used and had to be transformed.

2.4. Conversion of commodity flows to trips

In the trip conversion module the number of trips between all traffic zones is derived from the commodity flows. More than ten different means of transport are considered within the modes road, rail and inland navigation, with a defined maximum vehicle payload and an average utilisation, complemented by the traffic demand from private and service related traffic (TABLE 1). The utilisation was derived from statistics in case of road and inland navigation (KBA [16], DESTATIS [17]). Data for the rail system was provided by Deutsche Bahn, the major German railway company. That approach does not consider logistic optimisation but it is valid for the modelling of single trips between the traffic zones as opposed to trip chains.

TABLE 1 Means of transport used in the assignment

Means of Transport	*Mode*	*Demand category*
car	road	private traffic
car	road	service related traffic
light duty vehicle	road	service related traffic
light duty vehicle	road	freight traffic
heavy duty vehicle (GVM 3.5-7 t)	road	freight traffic
heavy duty vehicle (GVM 7-12 t)	road	freight traffic
heavy duty vehicle (GVM >12 t)	road	freight traffic
semi-trailer truck (GVM ≤ 44 t)	road	freight traffic
self propelled vessel (GVM ≤ 1350 t)	inland waterways	freight traffic
towboat (GVM ≤ 6000 t)	inland waterways	freight traffic
tanker (GVM ≤ 1718 t)	inland waterways	freight traffic
block train (GVM 1185 t)	rail	freight traffic
single wagon train (GVM 930 t)	rail	freight traffic
intermodal freight transport train	rail	freight traffic

Empty runs are an unavoidable part of commercial traffic because they are the consequence of some of the loaded trips. Liedtke [18] derived different tour patterns of truck operation where the empty runs are included. Since such an approach requires detailed calibration data which is difficult to obtain for a large scale model, the described model simply multiplies the trips of the transpose of the loaded trip matrices with an empty run factor. This way of adding empty runs is simple but open to further upgrade like calculation of empty runs depending on covered distances or commodities transported.

2.5. Traffic assignment

The loaded and empty runs are assigned to routes within the infrastructure. In consequence of this route assignment the deterrence matrices (time and cost) are updated and passed back to the distribution and modal split module. The European infrastructure for road, rail and inland navigation was updated and implemented in the commercial macroscopic traffic assignment software VISUM. To obtain realistic route choices and deterrence matrices it is necessary to add the demand of the private and commercial passenger transport to the demand of goods transport. They are computed by separate models developed at DLR [19], [20]. Overall, 14 means of transport, 12 of which are related to goods traffic, are used in the traffic assignment.

The infrastructure model includes links in Germany and the neighbouring European countries. While Germany is described in detail for the modes road, rail and inland navigation, a level based on the Trans-European Transport Network (TEN-T) was chosen for the other European countries. This step is dedicated to the computational velocity and also for the fact, that these links are relevant for the international exchange of goods. The attributes of the link which are important to cover route choice processes (capacity, velocity, electrification or not, allowed for rail services for goods, number of locks on channels, etc.) and also attributes to calculate the deterrence between OD-relations (special volume-delay-function, cost per kilometre and mean of transport) are complementing the infrastructure model. Containing more than 472.000 nodes and 1.1 Mio links the constructed network model is one of the most extensive and detailed ones across Europe.

3. Conclusions and outlook

This article presents the concept for a pragmatic robust and modular nationwide macroscopic freight traffic model. The aim of the model is to make it suitable for calibration with generally available data for Germany and the surrounding countries. It follows existing macroscopic approaches in its structure (freight generation from economic data, freight distribution and modal split as gravity model and nested logit, factors for load and empty trips). Standardised data are used which are available for many years in the past and most likely also in the future for all surface transport modes and commodities according to NST. The model splits trip chains into single trips and thus does not depend on detailed data on tours or logistic chains (e.g. commodity flow surveys), data which are not generally available. By avoiding a high degree of sophistication, furthermore, the model steps are easy to understand by practitioners, the model can be calibrated for the whole of Germany on state level and provides output for 20 commodities and, all surface transport modes.

The freight generation uses employment statistics on firm level, enabling more detailed scenarios and balancing the lack of a logistics module to some extent. The exchange of 20 kind of goods between 60 business branches is covered in the model. Furthermore, the calibration is supported by an evolutionary algorithm which greatly facilitates the adaption to different calibration objectives and accelerates the calibration significantly. The route assignment is reflecting the full traffic volume by considering goods transportation, private and business oriented traffic. The network used is one of the most extensive and detailed ones in Europe.

The structure of the model can be understood as a general process for freight modelling. Due to its modular structure, which ensures a robustness and transparency, the model can easily be extended or combined with other models. The usage of national statistics ensures the applicability of the model even in the future. It is embedded in the European context based on European data provided by Eurostat, the statistical office of the European Union.

The model is currently realised as a software tool and calibrated for the year 2008. The calibration is achieved for each module separately. The model will subsequently be tested for its suitability to reflect scenarios incorporating transport related measures and the economic development of the coming two decades.

A combination of the freight model with demand models for private and commercial passenger traffic in the assignment step is essential. Consistent input data has been used for all these models. In addition to support the understanding and quantification of commercial transport, the output of the integrated models, which provides a complete picture of all kinds of surface traffic, will be used by environmental models to analyse the impact of traffic on regional and global emissions and the climate. In the future, this nationwide model will serve as a framework for demand analysis on smaller scale both in terms of space, time and sector (commodity/economy).

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