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How to apply the four-step model for 150,000 travel zones: The HIPAT model

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ABSTRACT

Current European transport demand models following the classical four-step approach are less suitable for analysing the traffic volumes on inter-regional road infrastructure with relevant demand of regional trips, as they consider only about 10% of the trip demand with passenger cars. Mainly due to runtime problems, these models are limited to operation at the NUTS-3 level. This level comprises around 1500 regions for Europe with an average diameter of about 50 km. However, more than 90% of the trips are shorter than 50 km and are, therefore, not adequately considered in the trip distribution model and the trip matrix. Computing this matrix at a higher spatial resolution, such as the LAU-2 level, is not possible as the runtime of the overall model and the size of the trip matrix increase quadratically with the number of travel zones. In the HIPAT model, this obstacle is overcome by an innovative concept operating at different hierarchical levels. This reduces the complexity of the trip matrix, such that the HIPAT model can be applied at large scale for 150,000 travel zones without any runtime problems. This is demonstrated by a prototype implementation for a case study that handles 33,000 travel zones in two minutes. In addition, the limitations of applying NUTS-3-based travel zones for transport modelling are shown: 94.6% of the trips are shorter than the average diameter of the travel zones (50 km) and are therefore not correctly represented by the model. Smaller travel zones decrease this number and provide a better basis for analysing infrastructure policies and, ultimately, for decision-making.

1. Introduction

European transport policy pursues several targets, such as reducing CO_2 emissions and improving the efficiency of transport systems (EC, 2011b). In order to investigate the effectiveness as well as the socio-economic welfare impacts of potential policy measures, transport demand models are applied. However, the travel zones used in recent transport demand models operating at European scale are often too large, mainly due to complexity and runtime problems, and limited data availability. For instance, the travel zones of the European network-based transport demand model TRANS-TOOLS (see Burgess et al. (2008), Rich et al. (2009), Berglund and Algers (2016)) are defined in accordance with the European NUTS-3 regions.[1] The average diameter of the NUTS-3 regions is about 50 km, and the TRANS-TOOLS model can therefore only assess transport policies which concern inter-regional and long-distance trips. It fails to capture the important issue of road congestion caused by regional commuting trips. This is a limitation with regard to the capability of carrying out capacity bottleneck analyses.

The spatial disaggregation of travel zones provides an enormous potential to improve the accuracy of current European transport demand models, due to the fact that over 90% of the trips carried out with passenger cars are shorter than 50 km (cf. Section 2.1.6). Increasing the number of travel zones from 1500 NUTS-3 to 150,000 LAU-2 regions is not possible for transport demand models following the classical four-step approach due to complexity and runtime problems. The main reason is the complexity of the O/D trip matrix that increases quadratically with the number of travel zones. If the number of travel zones is increased by a factor of 100, the complexity increases by 10,000, which causes runtime issues particularly in the assignment step. Runtime problems already exist at NUTS-3 level. For instance, the runtime of the TRANS-TOOLS v2.1.9 model exceeds two days (cf. Ibañez-Rivas, 2010).

In this paper, this challenge of exploding runtimes is addressed by introducing the HIPAT model, which has been developed by Ihrig (2018). Methodologically, it is based on the PAT and the IPAT model which were developed, validated and applied in the course of two

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[1] The NUTS classification distinguishes four regional levels, NUTS-0 to NUTS-3, and two local levels, LAU-1 and LAU-2. For instance, NUTS-0 refers to European countries, NUTS-3 to cities and districts, and LAU-2 to communes (cf. EC, 2008).

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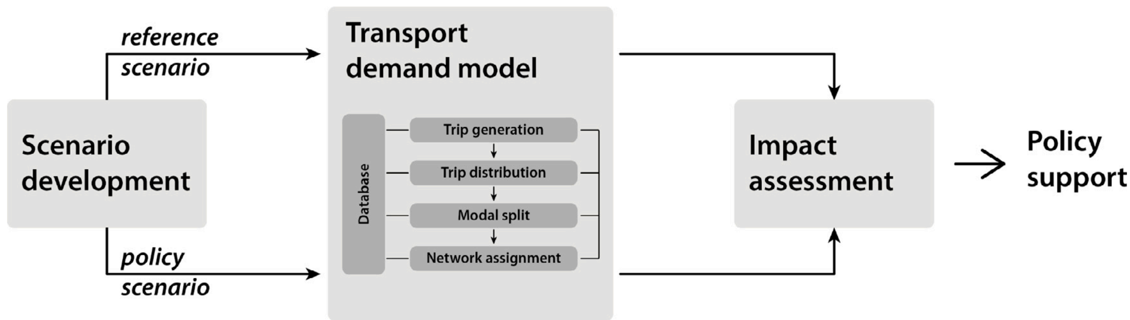

Fig. 1. Transport demand modelling and policy assessment.

European projects – ETISplus (see Newton et al., 2013) and HIGH-TOOL (see Szimba et al. (2016), Szimba et al. (2018)) – for calculating trip demand matrices and for transport policy assessment.[2] In contrast to its predecessors, the HIPAT model follows a hierarchical approach and computes long-distance and regional trips at different levels, e. g. NUTS-0 and LAU-2. This reduces the complexity of the trip matrix and avoids runtime problems. The implementation of the hierarchical approach requires far-reaching adjustments in the formulation of the classical four-step model, in particular the trip distribution model.

The main objectives of this paper are to prove that the HIPAT model can handle 150,000 travel zones without runtime problems, to demonstrate the advantages of smaller travel zones for transport modelling, and to outline the improvements for the analysis of infrastructure policy scenarios. This paper is structured as follows: Section 2 outlines the classical four-step model and the linkage to transport policy assessment, and Section 3 provides an overview of the HIPAT model. Section 4 then demonstrates the application of the HIPAT prototype with 33,000 travel zones for a case study and discusses the results. Finally, conclusions are drawn in Section 5.

2. Transport policy assessment and the four-step model

Transport demand and impact assessment models play a central role in the evaluation and planning of transport policy measures. They support decision-makers in achieving policy goals, such as climate or cohesion objectives. At the European level, mainly four-step models have been used for transport demand modelling. Fig. 1 outlines the general structure of a classical four-step model and its integration into the transport policy assessment process.

The modelling starts with a calibration step of the four-step model to represent the current transport demand of the reference scenario. Then, modelling parameters are identified that can be altered to reflect transport policy measures, such as extension of the high-speed rail network or increase in road charging. After defining a policy scenario, the aforementioned parameters are altered accordingly and the four-step model is run again. The comparison of policy scenarios with the reference scenario yields a prediction on the effectiveness of transport policy measures. The corresponding results serve policymakers as a cornerstone for their decisions on different policy measures.

2.1. The four-step model

The four-step approach is a standard concept in transport modelling. To explain the process of traffic formation, it uses the four consecutively applied sub-models trip generation, trip distribution, modal split, and network assignment (Ortúzar and Willumsen, 2001). The results that are computed in each step feed into the next one. Harmonisation of the four steps is essential for consistent results (see, for example, Schulz, 2012). However, the integration of the four sub-models increases the complexity of the overall model. Thus, most European and national transport models follow a non-integrated approach. For instance, the PAT model executes the four sub-steps independently (cf. Ihrig, 2012), the GENDIS and the IPAT model integrate two steps (cf. Gaudry et al. (1994) or Ihrig (2014)), while TRANS-TOOLS and the HIPAT model integrate three steps (cf. Rich et al. (2009) or Ihrig (2018)).

2.1.1. Trip generation model

The trip generation model is the first sub-model of the four-step approach. It computes the trip demand T for each travel zone i, which is generated by the population. T is frequently computed by a trip production function:

$$T_i = \sum_{a,g} R_i^{ag}\,\mathrm{pop}_i^{ag} \tag{1}$$

where R refers to a region-specific trip rate factor[3] and pop to the population. Both variables are distinguished by age group a and gender g. Besides the generation of trip demand, the trip generation model frequently computes the attraction of each travel zone as well, in order to estimate the number of trip endings D_j in the destination zone j.

2.1.2. Trip distribution model

The trip distribution model computes trip estimates T_{ij} for each pair of travel zones based on information on trip generation T_i in origin i, estimated trip endings D_j in destination j, and generalised cost c_{ij} of travelling from origin i to destination j. Most frequently a gravity-based model is applied, e. g. the accessibility-based gravity trip distribution model satisfying:

$$T_{ij} = T_i \frac{D_j f(c_{ij})}{A_i} \qquad \text{with} \qquad A_i = \sum_{j=1}^{n} D_j f(c_{ij}) \tag{2}$$

where A_i is an accessibility indicator and $f(..)$ a deterrence function. The computed trip estimates T_{ij} are stored in the O/D trip matrix. The trip distribution model is a bottleneck for the application of the four-step model at European scale based on small travel zones, as the number of O/D relations stored in the matrix depends quadratically on the number of travel zones. Between the NUTS-3 and LAU-2 levels, the number of travel zones increases by the factor of 100 and the number of O/D relations by 10,000.

2.1.3. Modal split model

In the modal split step, the trip matrix, which was computed by the trip distribution model in the previous step, is disaggregated into several mode-specific trip matrices as follows:

[2] HIPAT is an acronym for hierarchical, integrated passenger transport demand (model), IPAT for integrated passenger transport demand (model) and PAT for passenger transport demand (model).

[3] Trip rate factors are frequently represented by "annual trips per capita".

$$T_{ijm} = T_{ij} P_{ijm} \tag{3}$$

where P_{ijm} is the modelled market share. In many cases, a logistic regression model is applied for computing the market shares, which is better known as the multinomial logit (MNL) model:

$$P_{ijm} = \frac{e^{-\mu c_{ijm}}}{\sum_{m \in M} e^{-\mu c_{ijm}}} \quad \text{with} \quad c_{ijm} = \sum_k \beta_{km} x_{kijm} \tag{4}$$

where M identifies the set of transport modes (e. g. M = {rail, road, air, coach}), c_{ijm} the travel cost related to the transport mode m and O/D relation (i, j), and $\mu > 0$ is a heterogeneity parameter. c_{ijm} is frequently computed by a linear cost function, where x refers to specific cost indicators k, e. g. travel time and fuel cost, which are weighted by β coefficients. Derivation of the MNL and estimation of the modelling parameters (β_{km}, μ), for instance, is explained by Ben-Akiva and Lerman (1985).

2.1.4. Network assignment model

In the last step, network assignment, the traffic volumes at the level of network links are determined, based on information on the routing of each trip for each transport mode. The optimal routing for each O/D relation can be computed by shortest path algorithms, e. g. the Dijkstra's algorithm (Dijkstra, 1959). Information on the most cost-effective routing is also relevant for deriving the travel impedances for each O/D relation, e. g. travel time and travel distance. These travel impedance indicators are required to compute the generalised cost of travelling which is applied in the trip distribution and the modal split models. For this reason, the network assignment model is typically applied at least once prior to the actual application of the four-step transport model, in order to compute the travel impedances for all O/D relations.

2.1.5. Main outcomes

The main output of the four-step model are: O/D trip matrices by mode of transport, and modelled traffic loads at the level of network links. The trip matrices can be translated into aggregated transport demand indicators at regional and national level, such as trip volumes and derived indicators like passenger-kilometres and CO_2 emissions. However, they only allow a basic evaluation of the modelled policy scenario. For many policy measures, it is also relevant to assess their impact at a geo-spatial resolution. Therefore, a convincing spatial resolution of the results from the fourth step, network assignment, is crucial. This includes capacity bottleneck analyses for both road and rail infrastructure, as well as an assessment of external effects taking into account the distribution of the population in a region (e. g., for the evaluation of health risks due to the emission of pollutants like particulate matter $PM_{2,5}$). The HIPAT model significantly improves this capability.

2.1.6. Limitations

The main strength of the classical four-step transport model is its transferability to different scopes by choosing the size of travel zones and network models accordingly. It can be used for transport demand modelling at urban and European level. As a result, it is widely applied, but also comes with several shortcomings (cf. Mladenović and Trifunović, 2014). Further limitations stem from the macroscopic approach, such as consideration of aggregated travel zones and aggregated demand segments. For some purposes, like the modelling of trip chains and individual travel behaviour at a microscopic level, agent-based simulation models are better suited (see, for example, Algers et al., 2005). However, models like MATSim (Horni et al., 2016), SIMBA-MOBI (Scherr et al., 2020) and mobiTopp (Mallig et al., 2013) require a large number of agents and are therefore limited to smaller study areas. Agent-based models are very popular in urban transport modelling and have also been applied at a national level, but not yet at a larger scale (see, for example, Kagho et al., 2020).

One of the main issues of the classical four-step model is its long runtime. This is one of the reasons why Europe is currently modelled by only 1500 travel zones with an average diameter of 50 km and not by significant more and smaller travel zones. The application of overlarge travel zones and the runtime problems lead to several subsequent drawbacks, as intra-zonal trips and trips between neighbouring travel zones cannot be modelled adequately. In the European countries over 90% of the trip demand with passenger cars is shorter than 50 km. For instance, in Germany 90.8% are shorter than 50 km (infas and DLR, 2010), in Denmark 93.3% (Christiansen, 2011), in the Netherlands 92.0% (MVW, 2010), in the United Kingdom 94.7% (DfT, 2008), and in Spain 98.1% (Pérez Lou et al., 2007).

With travel zones at the NUTS-3 level, the majority of passenger car trips are intra-zonal and are neglected in the network assignment step. It is therefore often difficult to interpret the assigned traffic loads at network level. This issue concerns particularly commuting trips that contribute heavily to capacity overloads on major roads. In consequence, impacts of infrastructure policies on regional trip demand cannot be assessed adequately by a standard European transport demand model. A current way to overcome this shortage is to link different models, each focusing on specific segments, such as long-distance, inter-regional and regional transport. Another approach is, for example, implemented in the European network-based transport demand model VACLAV, in which the trip matrix is modelled at NUTS-3 level and then disaggregated during the network assignment step (see Schoch (2004), Szimba and Kraft (2011)). However, both approaches come with other limitations. From the current perspective, consideration of overlarge travel zones limits the validity of bottleneck analyses, which are often the basis for planning and prioritising investments on the Trans-European Transport Network (TEN-T). It is therefore necessary to disaggregate the travel zones.

2.2. Scenario development

Scenarios usually relate to future years. They can include several transport policy measures as well as changes in the population, settlement and regional structure in relation to the reference scenario. More complex scenarios are often split into several scenarios to model and to assess the impact of the individual effects separately. In the four-step model, different modelling parameters can be relevant for the development of scenarios.

First of all, structural indicators of the travel zones can be altered in the trip generation model, which compute trip volumes originating from or ending in a travel zone. These indicators include population by age and economic group (e. g. number of students and employed/unemployed population), share of the population working from home, number of working places, motorisation and income level of the population. Also the trip rate factors can be altered to take account of changes in the mobility behaviour, e. g. as response to a policy measure. While the trip generation model is very sensitive to changes in regional indicators, the trip distribution and the modal split model are sensitive to changes in cost variables. These cost variables can be used to model impacts on changes in user costs and improvements in the transport system (e. g. shorter travel times and improved railway services). Improvements can lead to longer journeys and a shift in the modal split. The last sub-model, network assignment, operates on the transport network modelling graphs. These graphs can be modified to reflect concrete infrastructure upgrades and road pricing policies, for instance.

2.3. The European TRANS-TOOLS policy assessment model

In order to obtain a network-based passenger transport demand model at EU level for analysing network-based investment strategies and policies, the European Commission funded the development of the TRANS-TOOLS model (Burgess et al., 2008). For several years TRANS-TOOLS was developed further and was used to support European transport policy analysis and impact assessment. For instance, it was used just to compute passenger and freight demand forecasts for EU countries (Hansen, 2009), or to simulate more complex policy scenarios combining different assumptions, e. g. on infrastructure charging, internalisation of external costs, and development of travel costs (Petersen et al., 2009). TRANS-TOOLS data were also used for a study carried out by the EC to measure congestion on the European road network and to derive economic losses due to delays (Christidis and Ibañez-Rivas, 2012). Among other models, TRANS-TOOLS was used for the development of the EU Reference scenario (2010–2050), which "is a benchmark for evaluating new policy measures against developments under current trends and policies" (EC, 2011a).

The follow-up model TRIMODE represents an integrated model that covers the whole of Europe with a multimodal network and zoning system at the level of NUTS-3 and below (Fiorello et al., 2018). The model is supposed to support the assessment of network flows in the TEN-T network and the identification of bottlenecks from a European perspective. However, according to the best knowledge of the authors, neither results of the model at a regional or network level, nor information on model runtime are publicly available yet.

For the simulation and analysis of infrastructure measures from a European perspective that also affect regional commuting trips, both models, TRANS-TOOLS and TRIMODE, are pushed beyond their limits due to the overlarge travel zones. The HIPAT model is based on much smaller zones, and regional trips can be modelled. It therefore provides a better basis for decision-making on policy issues that primarily affect regional transport than existing models.

3. The European HIPAT model

One of the main bottlenecks of European transport models following the classical four-step approach is the computation of the O/D trip matrix by the trip distribution model. As the complexity of the trip matrix increases quadratically with the number of travel zones, recent European transport models are limited to operation at NUTS-3 level, i. e. to about 1500 travel zones. The NUTS-3-based travel zones have an average diameter of about 50 km and are therefore not particularly suited for the modelling of regional trips that are shorter than 50 km. All trips, irrespective of their distance, are modelled at the NUTS-3 level. This is unsatisfactory.

The HIPAT model is described by Ihrig (2018). It relies on ETISplus data (see Szimba et al., 2013) and is a successor of the IPAT model which has been published as part of the European transport policy assessment model HIGH-TOOL.[4] The predecessor model IPAT is calibrated to reflect transport demand forecasts of the European Reference Scenario 2013 (see EC, 2013). The model has been validated successfully by a broader audience as part of HIGH-TOOL. However, while the IPAT model only operates at the more aggregated NUTS-2 level, the HIPAT model has been designed to process 150,000 travel zones to model regional trips adequately by LAU-2-based travel zones with an average diameter of 5 km.[5] It overcomes the quadratic dependency of the trip matrix on the number of travel zones by modelling long-distance trips at a more aggregated and regional trips at a more disaggregated level. Following this hierarchical method, the number of flights between Belgium and Greece can be efficiently modelled at country level by two O/D relations. In contrast, a classical four-step model operating at NUTS-3 level requires about 4500 O/D relations.[6] Besides the hierarchical method, the HIPAT model introduces further improvements, such as the refinement of the gravity trip distribution model and the integration of distribution, mode choice and assignment. It is still under development and has been used so far only for the case study considered below.

Table 1
Performance gains of the HIPAT model.

Level	Cells	Full matrix	HIPAT	Gains
0	1	1	1	0.0%
1	4	16	16	0.0%
2	16	256	256	0.0%
3	64	4,096	1,756	57.1%
4	256	65,536	9,016	86.2%
5	1,024	1,048,576	40,756	96.1%
6	4,096	16,777,216	173,296	99.0%
7	16,384	268,435,456	714,796	99.7%
8	65,536	4,294,967,296	2,903,656	99.9%

3.1. Structure of the hierarchical zoning system

The main innovation of the HIPAT model is a hierarchical zoning system in which the travel zones are defined at different aggregation levels and linked to each other according to a tree-based data structure. The underlying concept can be best demonstrated assuming square travel zones, i. e. grid cells. These grid cells are successively subdivided into smaller zones until the desired resolution is achieved (i. e. the LAU-2 level). Fig. 2 outlines a tree-based data structure which consists of three hierarchical levels as well as the successively divided grid cells.

3.2. Performance gains

The performance gains of the HIPAT model, in comparison to a standard approach computing a full trip matrix at the most detailed level, arise from modelling long-distance and regional trips at different aggregation levels, i. e. from NUTS-0 level to LAU-2. In order to quantify these gains, a hypothetical example is discussed below. In this example, the travel zones are grid cells which are arranged in a tree-based structure according to Fig. 2 (i. e. each travel zone is sequentially sub-divided into four sub-zones). The performance gains are then measured by comparing the complexity of the full matrix (computed at the most detailed level) with the complexity of the hierarchical trip matrix (computed by the HIPAT model at several levels).

Table 1 provides an overview of the hypothetical example. The first two columns show the IDs of the hierarchical levels and the numbers of grid cells (i. e. travel zones) that are generated at a specific level. The third column shows the numbers of O/D relations that are produced if a standard model is applied which computes a full trip matrix. The fourth column lists the numbers of O/D relations that are produced by the HIPAT model. The last column lists the savings potentials of the hierarchical modelling. For example, if we set eight hierarchical levels, i. e. if we subdivide the root travel zone eight times, we generate 65.5 thousand travel zones. Thus, a full trip matrix covering all O/D relations consists of 4.3 thousand million relations, while the hierarchical matrix only consists of 2.9 million relations. The corresponding performance gains provided by the HIPAT model are therefore 99.9%.

These tremendous performance gains are possible as the trip demand between two travel zones is always computed at the highest aggregation level possible. This is the case if the two travel zones are

[4] In the HIGH-TOOL context the IPAT model is called "PAD module" and interacts with several other models that provide forecasts on demographic and economic indicators, for instance.

[5] The NUTS-2013 classification for the EU-28 comprises 118,504 LAU-2 regions (Eurostat, 2015). Further travel zones are required to model other countries, e. g. Switzerland and Norway.

[6] According to the NUTS-2006 system (Eurostat, 2007), Belgium consists of 44 NUTS-3 regions and Greece of 51.

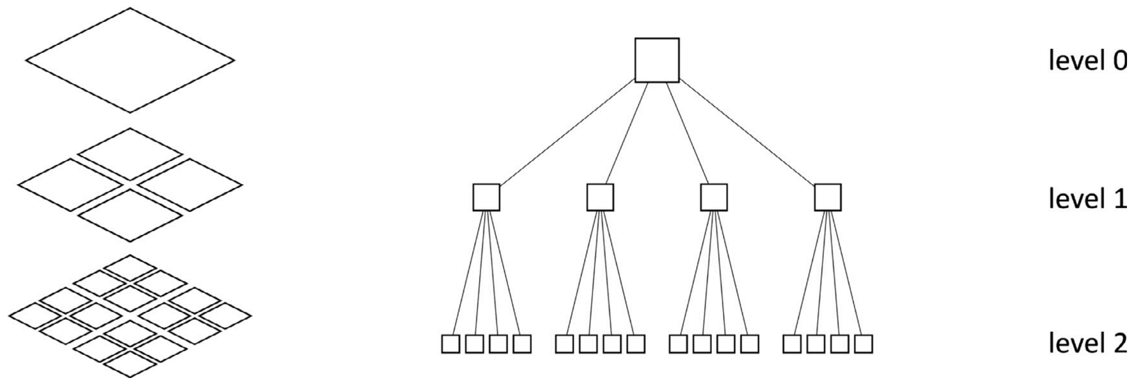

Fig. 2. Structure of the hierarchical zoning system.

not directly adjacent.[7] On the other hand, if the two travel zones of an O/D relation are adjacent, both zones have to be sub-divided into four sub-squares resulting in 16 disaggregated O/D relations. For each of these O/D relations, it is checked again whether the two respective travel zones are adjacent or not (unless we have reached the highest level of disaggregation, i. e. level eight, where the process is halted). Accordingly, some relations can now be modelled at the current level while others have to be further disaggregated.

Taking into account the complexity savings summarised by Table 1, it can be concluded that the hierarchical approach implemented in the HIPAT model overcomes the quadratic dependency of the complexity of the trip matrix on the number of travel zones, and reduces it to a linear dependency. This facilitates consideration of 150,000 travel zones in order to model regional trips adequately at LAU-2 level.

3.3. Generating the input data at LAU-2 level

The HIPAT model requires regional indicators at LAU-2 level, e. g. population, GDP and the number of workplaces. These regional indicators are not always available at LAU-2 level but only at NUTS-3 level. The ETISplus socio-economic data set, for instance, provides regional indicators for all European NUTS-3 regions for the base year 2010 (Schimke et al., 2012). Using the method of downscaling, available indicators can be disaggregated from NUTS-3 to LAU-2 level (see, for example, Gallego, 2007). In the following section, this method is briefly explained.

The basic idea behind downscaling is the disaggregation of available, space-related indicators to smaller regions by proration factors. These proration factors can be derived on the basis of the size of a disaggregated region in relation to the aggregated region, or on the basis of available indicators such as population and land use data for both regions. A common approach is to exploit the Corine land cover (CLC) database (EEA, 2007) that provides the dominant land use type for grid cells at a spatial resolution of 100 m edge length for the whole of Europe. By assigning specific load factors to each land use type, regional indicators can be disaggregated from NUTS-3 level to the grid and then aggregated to LAU-2 level. It can be assumed, for instance, that the population density is higher for grid cells of the type "Continuous urban fabric" than for cells of the type "Industrial or commercial units". Furthermore, it can be assumed that the population density is close to zero for those land use types referring to non-artificial surfaces, like agricultural areas, forests or water bodies.[8]

Table 2
Load factors by land use type — workplaces.
Source: Schoch (2004).

Land use type	Type id (s)	Load factor (s)
Continuous urban fabric	1	150.9
Discontinuous urban fabric	2	10.2
Industrial or commercial units	3	41.9
Road and rail networks and associated land	4	3.7
Port areas and airports	5, 6	61.5
Mine, dump and construction sites	7, 8, 9	1.6
Vegetated and non-artificial areas	10, .., 44	0

According to Gallego (2007), load factors $l(t)$ for each land use type t can be estimated by regression analysis.[9] Having determined $l(t)$, the population P of region R can then be downscaled to the corresponding grid cells c_i ($\cup c_i = R$) as follows:

$$p_{i|R} = P\omega_{i|R} \quad \text{with} \quad \omega_{i|R} = \frac{s_{i|R}\, l_i(t)}{\sum_i s_{i|R}\, l_i(t)} \tag{5}$$

where $p_{i|R}$ identifies the population that is assigned to the part $s_{i|R} \in [0,..1]$ of the grid cell c_i (since some grid cells are not entirely located in one region), and $\omega_{i|R}$ identifies the applied proration factor. In a second step, the disaggregated indicators $p_{i|R}$ can be aggregated from the grid cells to nearly any spatial level, e. g. to the level of LAU-2 regions.

Besides population, other regional indicators can also be disaggregated following Eq. (5). Fig. 3 outlines the procedure of downscaling the indicator "Number of workplaces" from NUTS-3 level to LAU-2 level, based on the CLC database and load factors from Table 2. The left-hand image drafts the boundaries of the aggregated region, providing the indicator number of workplaces. The image in the centre shows the subdivision of the aggregated region into different clusters of equal land use types. Border-crossing clusters are subdivided, i. e. each cluster can be clearly assigned to one disaggregated region. The clusters were computed based on the grid cells (that are not shown). The right-hand image shows the proration factors determined for each disaggregated region that are applied for downscaling the regional indicator.

4. Model application for a case study

This section deals with a prototype implementation of the HIPAT model for a case study with a limited scope, in order to gain experiences of the runtime and the results provided. To demonstrate the advantages of smaller travel zones on the accuracy of the results, the model was applied for three scenarios in which the travel zones were limited to

[7] Each origin can have up to nine adjacent travel zones that are located around the origin (including the origin itself).

[8] In total, the CLC database covers 44 land use types, but only the first nine types are relevant for the current disaggregation, i. e. the load factors for the land use types related to vegetated and non-artificial areas are 0.

[9] For the regression analysis, georeferenced data is required which provides the spatial distribution of the population at a very disaggregated level, e. g. household and census data.

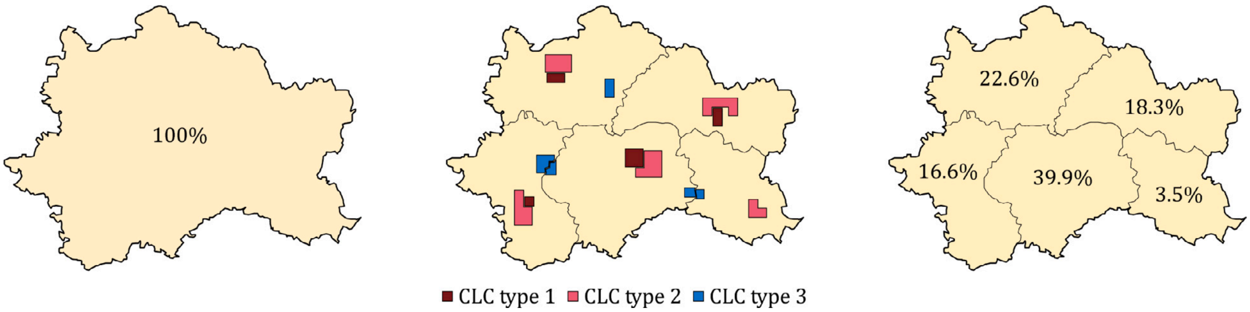

Fig. 3. Downscaling regional indicators based on land cover data and load factors.

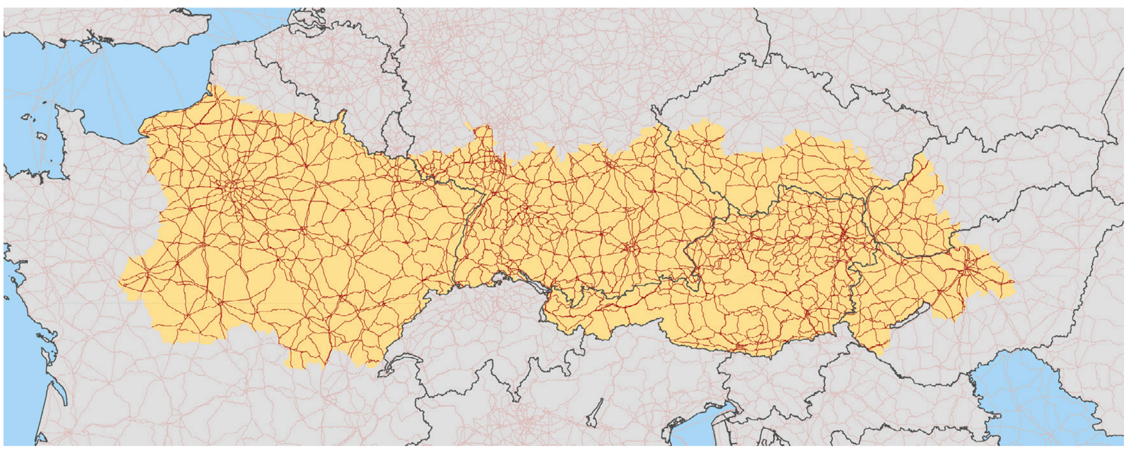

Fig. 4. Geographic scope of the investigated corridor and density of the road network model.

Table 3
Key features of the HIPAT prototype model.

Feature	Description
Methodology	Tailored four-step approach
Scope & zoning	Magistrale corridor; hierarchical zoning system (NUTS-0, ..., LAU-2)
Complexity	33,191 travel zones; 10,914,221 O/D relations
Demand segment	Road commuting trips ranging from 0 below 280 km
Remarks	Pre-calibrated Java model for testing purposes
Model runtime	About 2 min including data exchange with the file system

different aggregation levels. The aggregation levels were also chosen with regard to existing European transport models, and reveal the specific limitations of overlarge travel zones in simulating and testing transport policy scenarios. Particularly infrastructure scenarios benefit from smaller travel zones as provided by the HIPAT model.

4.1. General overview of the prototype

The HIPAT prototype was implemented with a reduced scope of 33,000 travel zones and for one travel demand segment. It follows a tailored four-step approach and has a runtime of about two minutes. The model takes into account road commuting trips, which make a significant contribution to capacity overloads on the TEN-T network. It covers Europe as a whole but focuses on the European "Magistrale" transport corridor between Paris and Budapest.[10] While regions located along this corridor are modelled at the most detailed LAU-2 level, the rest of Europe is modelled at NUTS-2 level, and neighbouring countries at NUTS-0 level. The geographic scope of the prototype, i. e. the Magistrale transport corridor, is outlined by Fig. 4. The key features of the model are summarised in Table 3.

[10] This corridor was chosen due to data availability from a former study (IWW et al., 2001).

4.2. Travel zones

The prototype implementation relies on 33,191 travel zones that are defined at seven different hierarchical levels according to Table 4. The top level encompasses the "root" travel zone referring to the whole geographic scope (Europe and neighbouring countries). The second level refers to the NUTS-0 regions (i. e. the individual countries) and the next levels to the NUTS-1, NUTS-2, NUTS-3, LAU-1 and LAU-2 regions. The travel zones are basically defined in accordance with the NUTS classification. Existing data gaps at LAU-1 level were closed by adding the respective LAU-2 regions. In addition, artificial city districts at LAU-1 and LAU-2 level were added for 39 cities located along the Magistrale.

4.3. Scenario definition

In order to investigate the advantages of modelling European passenger transport at the detailed LAU-2 level with the HIPAT model, rather than at a more aggregated level with a current EU model, three test scenarios are defined. These scenarios differ according to the most detailed aggregation level for the travel zones that are located along the Magistrale. For the first scenario, the respective travel zones are only disaggregated up to the NUTS-2 level. This is in line with the

Table 4
Structure of the zoning system underlying the prototype.

Id	Level	Zones	Diameter	Comment
0	EU	1	3650.7 km	Root travel zone
1	NUTS-0	40	440.2 km	Defined for the whole scope
2	NUTS-1	99	13.8 km	Only defined for Europe
3	NUTS-2	284	127.7 km	Only defined for Europe
4	NUTS-3	229	42.8 km	Only defined for Magistrale
5	LAU-1[a]	5,647	8.5 km	Only defined for Magistrale
6	LAU-2[b]	26,891	4.2 km	Only defined for Magistrale

[a] The figure includes 156 artificial city districts and 3435 LAU-2 regions.
[b] The figure includes 624 artificial city districts.

Table 5
Overview on the test scenarios.

Scenario	Origins[a]	Destinations[b]	Relations	Savings
NUTS-2	36	36 + 248 + 10	3,068	71.0%
NUTS-3	229	229 + 248 + 10	24,273	78.2%
LAU-2	26,891	26,891 + 248 + 10	10,846,130	98.5%

[a] The figure includes only travel zones along the Magistrale.
[b] The figure also includes destinations outside the Magistrale.

zoning system applied in high-level models used for transport policy assessment at a more strategic level, such as HIGH-TOOL. For the second scenario, the NUTS-3 level is also considered. This is consistent with the TRANS-TOOLS model used for analysing transport policy scenarios. For the third scenario, the zoning system of the HIPAT model is used (cf. Table 4), in which the travel zones are disaggregated up to the LAU-2 level. Table 5 outlines the specific properties of the three scenarios. The applied zoning system outside the Magistrale is identical for all scenarios: EU28, Norway, and Switzerland are modelled at NUTS-2 level, neighbouring countries at NUTS-0 level. Accordingly, the number of travel zones and the number of O/D relations are different for the three test scenarios.

The HIPAT model is then applied for each scenario, computing trip estimates for the whole of Europe. However, for the calibration and investigation of each scenario, only trips originating within the travel zones located along the Magistrale are considered. The destinations of these trips can be located anywhere in Europe, including regions outside of the Magistrale (248 NUTS-2 regions and 10 countries). Hence, for the NUTS-2 scenario the trip demand between 36 origins and 294 destinations is considered (cf. Table 5). Given that the respective O/D relations are modelled at different hierarchical levels, the HIPAT approach saves 71.0% of the O/D relations compared to a standard modelling approach computing a complete trip matrix.[11] For the NUTS-3 scenario, the HIPAT prototype saves 78.2% of the O/D relations and for the LAU-2 scenario 98.5%.

4.4. Scenario calibration

The three scenarios are calibrated to meet an average trip length of 19.6 km by adjusting the deterrence function underlying the trip distribution model (cf. Eq. (2)). The functional type of the deterrence function was derived based on observed trip length distributions from travel surveys. Although the average trip length of private road commuting trips is different for the countries located along the Magistrale, this simplification does not limit the analyses carried out based on the produced trip matrices. In the HIPAT model, the so-called "composite deterrence function" is applied, which is built on three classical deterrence functions. The composite function can be calibrated differently for short-distance, regional and long-distance trips.[12] This improves the explanatory power of the deterrence function and, finally, of the trip distribution model. It has to be emphasised that the functions applied in the three scenarios are almost identical. Given this general transferability, it is possible to apply the HIPAT model consistently at different aggregation levels and to compare the computed results for the three scenarios.

Table 6
Share of intra-zonal and inter-zonal trip demand for the three scenarios.

Scenario	T_{ii}	$T_{ij} \le$ 50 km	$T_{ij} >$ 50 km	pkm_{ii}	$\text{pkm}_{ij} \le$ 50 km	$\text{pkm}_{ij} >$ 50 km
NUTS-2	96.6%	0.9%	2.5%	83.1%	2.0%	14.9%
NUTS-3	73.2%	21.4%	5.4%	45.0%	23.6%	31.4%
LAU-2	27.1%	62.5%	10.4%	4.1%	45.8%	50.1%

4.5. Results

This section discusses the model output of the three scenarios and the suitability of the three aggregation levels NUTS-2, NUTS-3 and LAU-2 for the modelling of commuting trips and the assessment of transport infrastructure policies. Taking into account the large diameter of the respective travel zones (cf. Table 4) and the average trip length of 19.6 km (cf. Section 4.4), greater limitations are expected for the NUTS-2 scenario. The first analysis is carried out based on the trip length distributions (TLDs) showing the frequency of trip occurrences by distance bands. The TLDs are then compared to the applied deterrence function which was derived based on an observed trip length distribution. For the second analysis, the trip matrices are assigned to the networks. The modelled loads are then discussed, taking into account expected patterns of traffic flows on the network. The patterns were derived from transport statistics and traffic count data.

4.5.1. Frequency of trip occurrences by distance band

For this analysis, only trips originating along the Magistrale area are considered (cf. Table 5) in order to derive the TLDs based on the computed trip matrices. Table 6 summarises the basic properties of the trip matrices with regard to the share of intra-zonal (T_{ii}) and inter-zonal trips (T_{ij}) as well as the related demands in terms of introduced passenger-kilometres (pkm). In addition, for the inter-zonal trip demand, a distinction is made between trips that are shorter than 50 km and those that are longer. A quick analysis of Table 6 reveals that the NUTS-2 scenario differs significantly from the other two scenarios, given that the majority of the trip demand is intra-zonal in this scenario. This leads to the presumption that NUTS-2-based travel zones are not suited for the modelling of commuting trips.

Fig. 5 compares the applied deterrence functions and the derived distributions of trip lengths in which intra-zonal trips are drafted in grey and inter-zonal trips in red. The y-axis is drawn in different levels for the three graphs due to different peak values for the three TLDs. The x-axis is limited to 50 km and the distribution is not shown for trips longer than 50 km.

At first sight, a large discrepancy between the TLD and the deterrence function can be observed for the NUTS-2 scenario. This can be explained by the large size of the applied NUTS-2 zones, particularly for France, which means that 96.6% of the generated trips are carried out intra-zonally. The travel distance for these trips varies between the distance bands of 6–7 km and 19–20 km, depending on the size of the zones. The high peak value of the TLD for the distance band of 19–20 km can be explained by the large size of the 36 selected NUTS-2 zones located along the Magistrale. Given an average diameter of about

[11] A complete trip matrix consists of 10,584 O/D relations, while the hierarchical trip matrix computed by the HIPAT model only consists of 3068 relations.

[12] More details on the composite deterrence function and the calibration parameters can be found in Ihrig (2018), Sections 4.4.3 and 9.4.1.

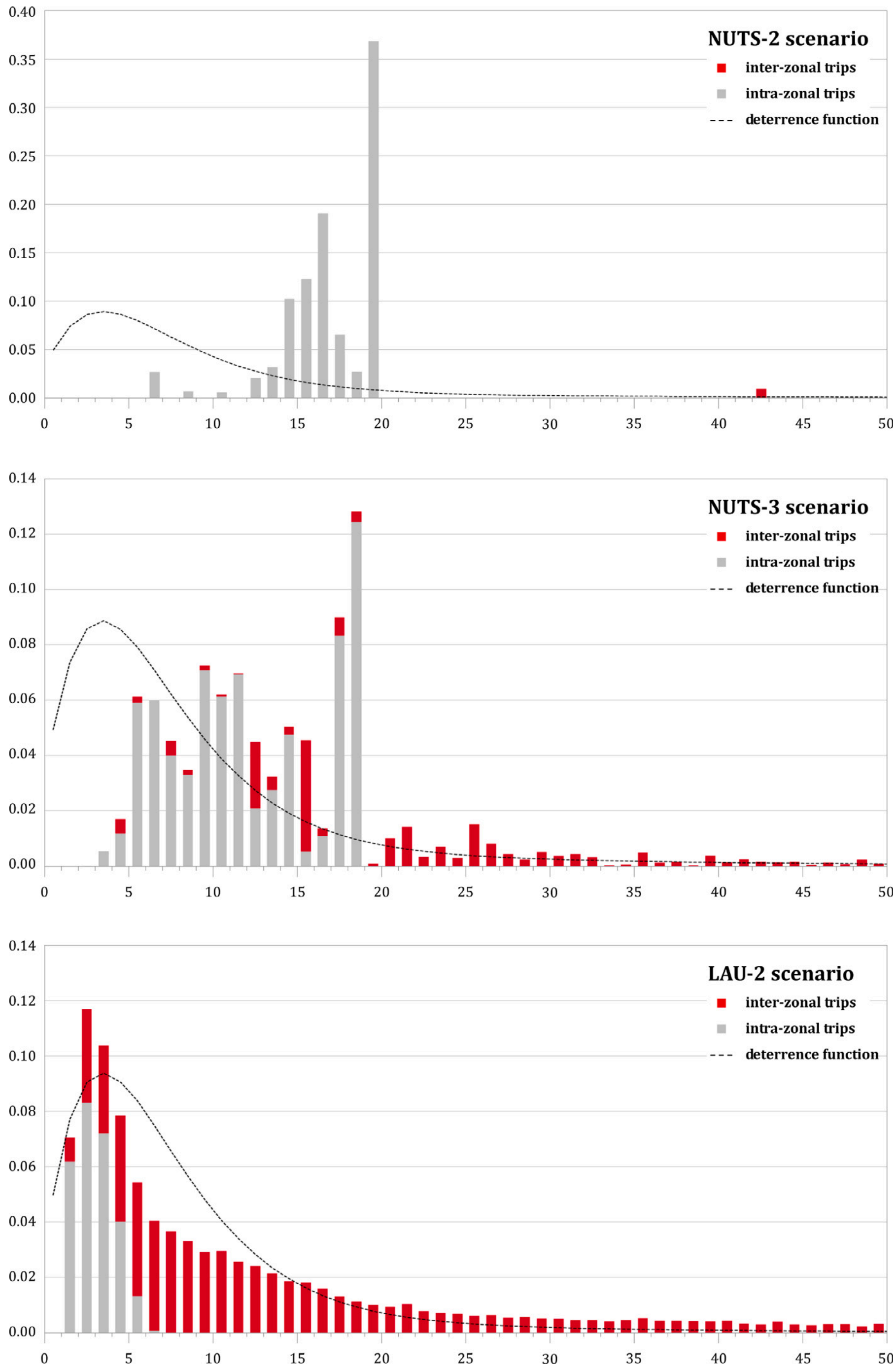

Fig. 5. Distribution of trip lengths for the test scenarios (0–50 km).

120 km for the NUTS-2 zones, intra-zonal trips are longer than 19 km for many of these zones.[13] Besides the small share of inter-zonal trips and the high peak value of the TLD, a further inconvenience is that the first inter-zonal O/D relation only appears in the distance band of 42–43 km or, to be more precise, O/D relations between 20 and 42 km do not exist in the model, given the large size of the NUTS-2 regions. Hence, it has to be concluded that the NUTS-2 scenario does not provide any basis for analysing the distribution of trip lengths based on the computed trip matrix.

For the NUTS-3 scenario, the discrepancy between the TLD and the deterrence function is not as large as for the NUTS-2 scenario due to the smaller size of the NUTS-3 regions, which have an average diameter of about 50 km. In this scenario, 73.2% of the trips are carried out intra-zonally. Given that the TLD only follows a reasonable pattern for inter-zonal trips starting from the distance band of 20–21 km, it has to be concluded that NUTS-3-based travel zones are not suited for analysing the distribution of trip lengths based on the computed trip matrix.

For the LAU-2 scenario, the distortion of the TLD is within an acceptable range. In this scenario, the TLD resembles a continuous distribution and its pattern is very similar to that of the applied deterrence function. In particular, it must be noted that even the distribution

[13] The prototype is calibrated to an average trip length of 19.6 km. Hence, the length of intra-zonal trips is always below 19.6 km.

of trip lengths for intra-zonal trips follows a reasonable pattern. In addition, only 27.1% of the trips are intra-zonal. It can therefore be concluded that LAU-2-based travel zones provide a sound basis for analysing the distribution of trip lengths based on the computed trip matrix, and for modelling the trip distribution.

A comparison of the TLDs produced for the three scenarios shows that the trip matrix computed at LAU-2 level provides the best basis for analysing the distribution of trip lengths. Given that only 4.1% of the generated demand in terms of passenger-kilometres is intra-zonal, almost no limitations are expected for the modelling of traffic loads at link level. For the NUTS-3 scenario, it only makes sense to analyse the distribution of trip lengths for inter-zonal trips starting from the distance band of 20–21 km. Given that the share of passenger-kilometres related to intra-zonal trips amounts to 45.0%, limitations have to be expected for the modelling of traffic loads at link level by NUTS-3-based trip matrices. In contrast, NUTS-2-based trip matrices are not suited for the modelling of traffic loads at link level, given that the majority of the demand is related to intra-zonal trips.

4.5.2. Passenger loads at link level

For this analysis, the whole trip demand originating along the Magistrale corridor was visualised as summarised by the trip matrix. To this end, passenger loads at link level were computed by the network assignment model following an all-or-nothing method. This ensures comparability of the three scenarios. Fig. 6 outlines the computed load values along the Magistrale for the scenarios. Seven categories are distinguished: the highest is shown in bright red, the lowest in light blue, and unloaded links are shown in light grey.

As might be expected from the previous analysis, the NUTS-2 assignment looks rather empty. As 96.6% of the trip demand relates to intra-zonal trips (cf. Table 6), the majority of the trip demand summarised by the trip matrix cannot be assigned to the network links. Nevertheless, the NUTS-2 assignment shows some network links in the highest load category, for instance the network links between Paris located in the NUTS-2 region Île de France (FR10) and Amiens located in the region Picardie (FR22). In this case, the trip distribution model assigns 7.5% of the trip demand generated for the region FR22 to the O/D relation FR22/FR10. This pattern can be explained by the very large number of workplaces provided by the region Île de France, which attracts commuters from the region Picardie. However, for the majority of the network links (72.2%), no passenger loads can be computed. Hence, it has to be concluded that the computed trip matrix at NUTS-2 level is not suited for modelling loads at link level by the network assignment model.

For the NUTS-3 scenario, the derived passenger load values look much better. In this case, the share of inter-zonal trips is only 26.8% and load values can be computed for about two thirds of the network links (61.0%). In addition, the distribution of the load categories follows a reasonable pattern in which the highest categories are computed for those network links located around big cities. For instance, the agglomeration areas of Paris and Munich can easily be recognised. However, apart from the high load values computed for links around big cities, the NUTS-3 assignment still has significant gaps (i. e. unloaded links shown in light grey). The largest gaps can be observed for France due to the comparably large size of the French NUTS-3 regions. It has to be concluded that the NUTS-3 level is not optimal for modelling demand segments like commuting trips with a more regional character.

The best assignment results can be achieved for the LAU-2 scenario, in which load values are computed for 95.5% of the network links. Particularly for France a significant improvement from NUTS-3 to LAU-2 level can be observed. For example, the "star-shaped" pattern indicating high load values around Paris is more apparent. The improved accuracy can be clearly attributed to the smaller size of the LAU-2 regions. 72.9% of the trip demand relates to inter-zonal trips and contributes to the computation of the passenger load values at link level. It can therefore be concluded that the LAU-2 level provides a sound basis for modelling the distribution of trips with a regional character, such as commuting trips.

A comparison of the three assignment results clearly indicates the potential of LAU-2 travel zones for transport modelling at European scale and the assessment of network-related transport policies. Given that the majority of the trips are carried out inter-zonally, the majority of the trip demand is therefore considered for the network assignment. The accuracy of the NUTS-3 assignment seems to be acceptable, but only for countries like Germany that are covered by rather small NUTS-3 zones. In comparison to the LAU-2 map, however, many links in the NUTS-3 scenario are unloaded, e. g. in France and peripheral regions in the northeastern part of the Magistrale that are modelled by comparably large travel zones. The NUTS-2 assignment, in contrast, is almost worthless.

4.6. Findings

This section describes the application of the HIPAT model for a case study considering the European Magistrale transport corridor between Paris and Budapest and road commuting trips. The model was applied for three scenarios, in which the level of detail of the travel zones was limited to the NUTS-2, the NUTS-3 and the LAU-2 level. The outputs of the three scenarios were analysed at network level in order to illustrate the limitations of current EU transport demand models for transport policy assessment and to demonstrate the advantages of smaller travel zones. The results further prove that the HIPAT model can be applied for 33,000 travel zones without any runtime problems, and that the model can be applied consistently at different aggregation levels.

The travel zones in the NUTS-2 scenario were defined in accordance with the zoning system of the HIGH-TOOL model, which was developed for analysing transport policies at a more strategic level. Due to the large size of the zones, the majority of the trips are carried out intra-zonally and the standard network assignment cannot be used for further analyses. This result was expected. The network assignment produced by the NUTS-3 scenario, which corresponds to the level of detail used by the TRANS-TOOLS model, has some significant gaps (i. e. unloaded links). These gaps disappear in the LAU-2 scenario and show the advantages of applying smaller travel zones for transport modelling.

For the assessment of European network-based transport policies with a regional scope, the level of detail of NUTS-3-based transport models is not sufficient. Such policies include the planning of investments in the transport infrastructure that can also be used by regional transport. Given an average diameter of about 50 km of the European NUTS-3 regions, regional trips cannot be modelled at this scale and policy scenarios can only be analysed with regard to inter-regional and long-distance trips. One example is the planning of a second Rhine bridge to close an existing bottleneck due to congestion (cf. Ihrig, 2018, Section 1.2). It is located in the wider scope of the Magistrale transport corridor. The existing bridge connects two neighbouring NUTS-3 regions and is also relevant for commuting trips below 10 km. However, the modelled network distance between the two NUTS-3 regions is about 40 km and the commuting trips cannot be modelled at this scale. It is therefore not possible to evaluate whether the construction of the second bridge solves the problem of congestion or leads to an increasing demand for regional trips. At LAU-2 level, the commuting trips can be modelled. For this reason, European transport policies with a regional impact like certain infrastructure investments should be investigated at the LAU-2 level as provided by the HIPAT model. At this level of detail, the impact on regional and even short-distance trips can be modelled, in addition to the impact on inter-regional and long-distance trips.

5. Conclusions

This paper discusses the HIPAT model, which allows for the first time to apply the four-step transport model at the disaggregated

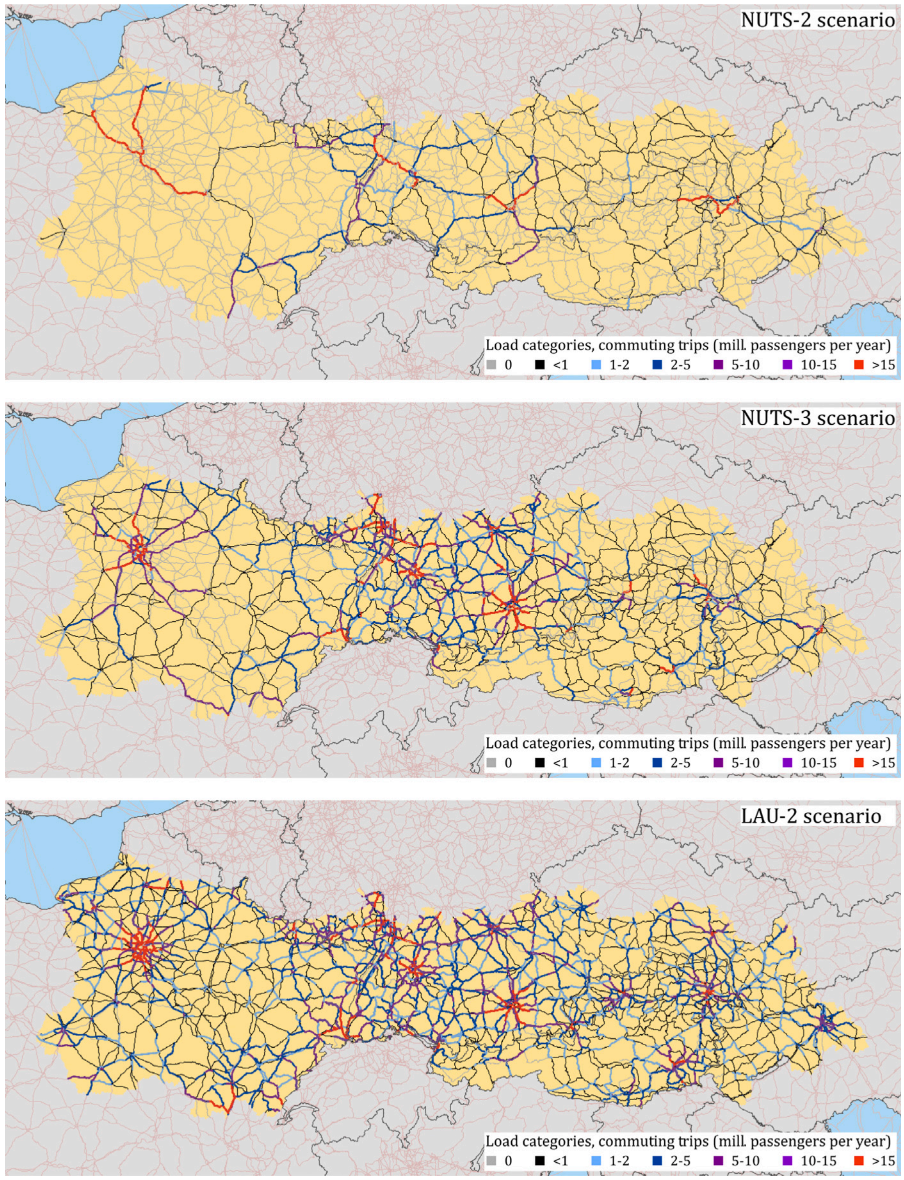

Fig. 6. Road commuting trip flows.

LAU-2 level for 150,000 travel zones. This is a significant improvement for current European transport demand models and may improve the basis for future policy decisions, especially when it comes to the consideration of bottlenecks within the European transport network. As the TRANS-TOOLS model has already runtime problems for 1500 travel zones, its application at the more detailed LAU-2 level is not possible. The main novelty of the HIPAT model is the computation of long-distance and regional trips at different levels, e. g. NUTS-0 and LAU-2. This facilitates a quantum leap between the two models, by a factor of 100 in terms of spatial resolution and an expected reduction in runtime from two days to about one hour. In order to demonstrate the advantages of modelling transport by the LAU-2 regions with an average diameter of 5 km, rather than by NUTS-3 regions with an average diameter of about 50 km, a prototype implementation of the HIPAT model was realised for a case study. It is based on about 33,000 travel zones located along the European Magistrale transport corridor, focuses on road commuting trips and has a runtime of two minutes.

Taking into account the significant progress achieved between the network assignment results produced at NUTS-3 and LAU-2 level, a worthwhile future task will be to complete the implementation of the HIPAT model for the whole of Europe, encompassing 150,000 travel zones, four transport modes and four trip purposes. In comparison to a spatial resolution of 50 km, the resolution of 5 km offers unprecedented opportunities for analysing infrastructure policies from a European perspective. As the HIPAT model covers the whole of Europe, it is possible to analyse several policies simultaneously and to assess their impacts on regional and even short-distance trips, in addition to their impacts on inter-regional and long-distance trips. Finally, European policy makers gain more insights into the effectiveness and the welfare impact of potential policy measures, which improves the basis for decision-making.

CRediT authorship contribution statement

Jan Ihrig: Conceptualization, Writing – original draft, Writing – review & editing. **Patrick Jochem:** Supervision, Writing – review & editing. **Eckhard Szimba:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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