EXECUTIVE SUMMARY

The INTERCONNECT module (IC Module) on modal choice and assignment has been programmed to investigate how interconnection facilities and services influence the costs of transport, and therefore, how the upgrading of interconnections in Europe may impact on the European transport system.

State-of-the-practice forecast models are based on a conventional modular structure with trip generation, distribution, modal split and network assignment, having two major draw-backs:

- The separation between mode choice and traffic assignment means that intermodal chains can be hardly included and analysed in these kinds of model.
- Interconnections between local and regional networks are neglected.

The IC Module is intended to overcome the weaknesses of state-of-the-practice forecast models at continental level in relation to the integration of interconnections into their modal choice and assignment procedures.

The IC Module is fed with trip matrices originated by TRANS-TOOLS, and works as stand-alone software to perform multi-modal network assignments. A meta-model approach is later adopted to process the large data outputs of the IC Module and produce sets of indicators. This deliverable *D5.3 Modelling module for interconnectivity* focuses on the implementation of the IC Module. For execution and analysis of outputs of the INTERCONNECT Meta-model, see report deliverable *D5.2 Meta-models for the analysis of interconnectivity* in this same project, produced in parallel to this report.

The first objective of this report is to narrate the process of construction of a single multi-modal network where modal-split and traffic assignment can be performed all at once with the IC Module. This process has adopted the so-called *supernetwork approach*. In this approach, the different modal sub-networks (uni-modal networks) are completely integrated, and the combined modes and the interactions among the vehicular modes on the roads might be explicitly taken into account. The multi-modal graph has been constructed using the road, rail and air graphs from TRANS-TOOLS, identifying intermodal terminals and establishing connectors between networks at these points.

The IC Module later assigns TRANS-TOOLS matrices, rearranged to be assigned all together onto the multi-modal graph. Resulting traffic on the networks - travel behaviour - depends on the topology of the integrated multi-modal graph and the impedance of its different elements. Interconnections are an additional element equivalent to other transport links, having a direct impact in the route choice processes. The variation of multi-modal parameters at connectors and transport terminals allow for analysis of the influence of interconnections in the behaviour of travellers.

TRANS-TOOLS model is calibrated so that its results sufficiently fit Eurostat statistics (transport pocketbook). That means that internal parameters in TRANS-TOOLS are set so that results from its modelling process sufficiently fit reality. The internal parameters of the IC Module – mainly travel costs and interconnectivity costs - have also been adjusted in a process of validation. Instead of using Eurostat statistics, TRANS-TOOLS outputs have been used to do so.

The most relevant ways for further work in the future after the task initiated by INTERCONNECT can be, among others, the following: testing a stochastic user equilibrium algorithm to allocate trips among reasonable multi-modal chains between ODs; implement a service scheme for the rail mode as in the case of air services or ferry services; simulate airports using different interconnected nodes for each terminal; refining the process of automatic connector creation; introducing user behaviour not only by trip purpose but also by age population segment.

1 INTRODUCTION

1.1 APPROACH

The INTERCONNECT module (IC Module) on modal choice and assignment has been programmed to investigate how interconnection facilities and services influence the costs of transport, and therefore, how the upgrading of interconnections in Europe may impact on the European transport system. The IC Module is intended to overcome the weaknesses of state-of-the-practice forecast models at continental level in relation to the integration of interconnections into their modal choice and assignment procedures. As a module, it is fed with trip matrices originated by TRANS-TOOLS. The IC Module works as stand-alone software.

The importance of interconnections between local and regional networks has increasing importance as European transport networks become more integrated. However, the time and cost needed to change from one mode to another and from long-distance to short-distance services is not integrated in large-scale models.

State-of-the-practice forecast models are based on a conventional modular structure with trip generation, distribution, modal split and network assignment, having two major draw-backs:

- The separation between mode choice and traffic assignment means that intermodal chains can be hardly included and analysed in these kinds of model.
- Interconnections between local and regional networks are neglected.

At the same time, a meta-model approach is proposed to process the large data outputs of the IC Module and produce sets of indicators, and to target potential impacts of interconnection upgrading in the European transport system without requiring intensive time- and resource-consuming processes. The meta-model is a tool to be used in parallel to the IC Module and TRANS-TOOLS to evaluate interconnectivity. The development of the meta-model is also useful to investigate how state-of-the-art models can be improved, or how to develop a new generation of transport models able to work at continental level and internalise detailed interconnectivity aspects at the same time.

This deliverable *D5.3 Modelling module for interconnectivity* focuses on the implementation of the IC Module. For execution and analysis of outputs of the INTERCONNECT Meta-model, see report deliverable *D5.2 Meta-models for the analysis of interconnectivity* in this same project, produced in parallel to this report.

1.2 OVERVIEW OF INTERCONNECT TASK T5.2

Task T5.2 *Test with EU Model* is reported in two separate deliverables:

- D5.2 *Meta-models for the analysis of interconnectivity*, and
- D5.3 *Modelling module for interconnectivity.*

The first deliverable D5.2 mostly deals with the INTERCONNECT meta-model, while the present deliverable D5.3 mostly deals with the IC Module. Although reported separately, both activities have taken place simultaneously.

The scheme below provides a glimpse into the inner logics of the modelling process in INTERCONNECT Task 5.2. The flows of the work are as follows:

- TRANS-TOOLS is used as a reference and a base for inputs onto the IC Module;
- The IC Module,
    - takes the road, rail and air uni-modal graphs of TRANS-TOOLS to build the INTERCONNECT multi-modal graph,
    - takes the modal OD matrices of TRANS-TOOLS segmented by trip purpose and transport mode, and rearranges them for assignment onto the multi-modal graph (still segmented by trip purpose), and

- uses TRANS-TOOLS outputs as a reference to validate its own outputs through adjustment of interconnection and multi-modal internal parameters in an iterative process.

➢ The meta-model

- reads output data from the IC Module, processes it and produces a bounded set of indicators on modal split, interconnectivity and transport cost, and
- does sensitivity analysis of modal split variations, global transport volume variations and CO2 emission variations in the European transport system.

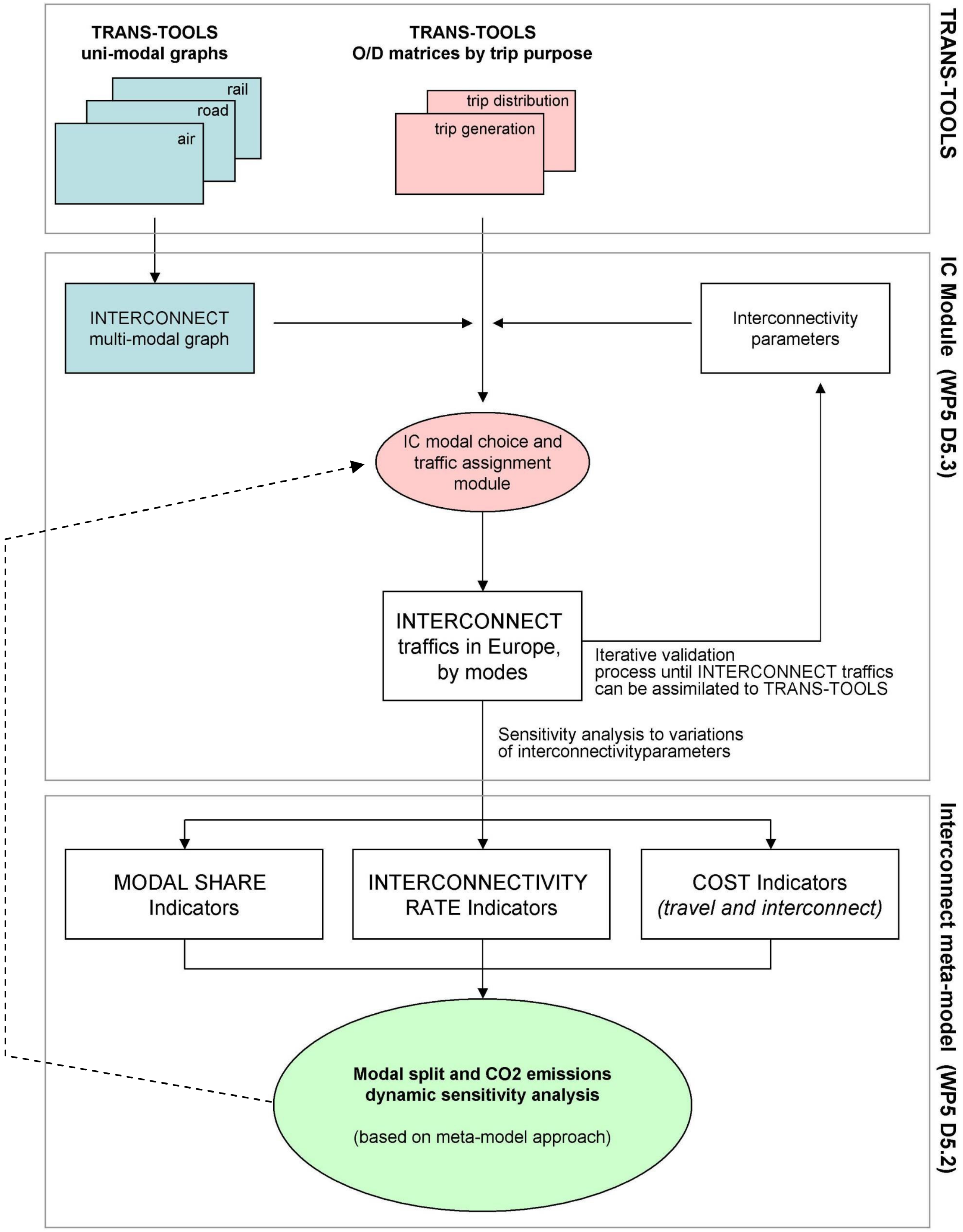


Figure 1-1 WP5 Task 5.2 overview

1.3 OBJECTIVES

The objectives of the task 5.2, object of this deliverable, are: first the construction of a multi-modal network graph; and secondly the implementation of the IC Module, an integrated modal split and traffic assignment tool to study interconnections able to assign traffic onto the multi-modal graph.

Developing an interconnected multi-modal graph of the European transport system

The first objective is to build a single multi-modal network where modal-split and traffic assignment can be performed all at once with the IC Module.

The approach here corresponds to the supernetwork approach (see chapter 2.2, page 14). In this approach, the different modal sub-networks (uni-modal networks) are completely integrated, and the combined modes and the interactions among the vehicular modes on the roads might be explicitly taken into account.

Using the transport graphs from TRANS-TOOLS, the different transport networks are integrated by first locating all intermodal terminals in the EU and then establishing connectors between networks in these points.

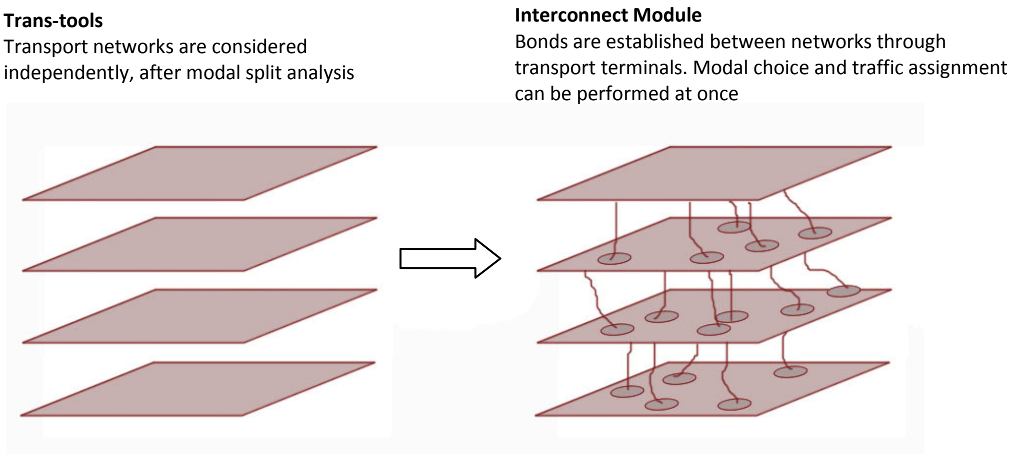


Figure 1-2 Construction process of the multi-modal graph

Currently used graphs in TRANS_TOOLS and other large-scale European models do not have transport terminals such as rail stations but assume that the nearest NUTS3 capital acts as a terminal, except in the case of airports, because of the complexity of calculation, which grows exponentially with the number of nodes and links in the network. In INTERCONNECT, segments linking rail stations to airports represent access to airports by train, and segments linking rail stations to cities represent access to the city centre from the train station. These links contain information on travel length, travel speed, and other penalties to be imposed such as transit walking time or check-in time requirements.

Also, the location of NUTS3 centroids has been refined, moving them from geometric centres to precise geographic locations of NUTS3 capitals, in which the majority of users are. By doing so, connectors linking the different transport networks to NUTS3 centroids become more realistic and are able to better simulate the final step of a long-distance trip, in terms of length and speed.

Implementing an integrated tool for interconnection analysis

The IC Module is intended to bridge the problem of integrating interconnections in the modelling of transport systems. The IC Module integrates modal choice and traffic assignment in one single module.

Traditional transportation modelling approaches are generally based on the segmentation between different transport modes and are not able to correctly model mode combinations within a trip. Modal split in TRANS-TOOLS is determined a priori based on transport generalised costs after the generation and distribution steps. Uni-modal traffic is assigned separately in the 4th step in different uni-modal graphs making impossible to study interconnections, which are not considered in this approach.

The IC Module assigns TRANS-TOOLS matrices, rearranged to be assigned all together at once, onto a multi-modal graph. Resulting traffic on the networks - travel behaviour - depends on the topology of the integrated multi-modal graph and the impedance of its different elements. Interconnections are just an additional element in this approach, equivalent to other transport links. Therefore, in this approach, interconnections have a direct impact in the route choice processes, allowing for analysis of their influence in the behaviour of travellers. The IC Module returns modal split at the end of the simulation as a result of the multi-modal assignment, as opposite to the classical 4 step approach.

In the IC Module, trips can be assigned totally or partially according to trip purpose (business, private, holiday, commuter). Trips are assigned in the multi-modal graph according to an all-or-nothing routine linked to a shortest-path algorithm. Congestion is not considered in the IC Module as the INTERCONNECT project deals only with long-distance traffic and it is assumed that for this kind of traffic, users have the capacity to properly plan their trips in advance to avoid congestion events on the network (e.g. travelling at night or at off-peak hours). Furthermore, in long-distance trips, only relatively short percentages of total travel take place over congested networks on peak hours.

1.4 PROBLEMS WITH INTERCONNECTIVITY

From the travellers' perspective, the main problems with interconnections are delays, inconvenience, and costs associated with the local leg of the trip which seem out of proportion to the relatively short distances involved[1]. This delay, inconvenience and cost may be incurred at the point of interchange (e.g. within an airport) or en route between that interchange and the origin or destination of the trip.

The basic problems of interconnection are associated with:

- Non-provision or inadequate standard of the infrastructure for local links;
- Poor design, maintenance or operation of modal interchange points;
- Inefficient procedures for interchange;
- Inadequate provision of local transport services (e.g. no fast public transport from an airport to city centre);
- Local transport services exist but do not serve the needs of connecting long-distance travellers (e.g. timetables are uncoordinated, nearest bus stop requires a long walk);
- Inadequate provision of information; or
- Unavailability of integrated tickets (covering the local as well as the long distance parts of the journey).

At a deeper level, the problems may be a consequence of financial, organisational, regulatory or commercial factors which act as barriers to the effective integration of different transport services. Consulted stakeholders opined that problems having the most serious consequences for long distance travellers in Europe were related to poor links and interchange points, and lack of information.

Work in Task 5.2, reported in this deliverable D5.3 and its twin D5.2, constitute an attempt to abstract these problems onto a modelling framework, and an investigation on how the overcoming of these problems can improve the European transport system by lowering global transport costs, favouring the use of most sustainable transport modes and reducing GHG emissions.

[1] INTERCONNECT work package WP3 identified the fundamental problems of interconnectivity between transport networks, especially between long distance and short distance transport networks, prior to proposing a full toolkit of solutions to overcome these problems. The most relevant aspects for this deliverable are reiterated in this section.

1.5 PROBLEMS WITH MULTI-MODAL MODELLING

Traditional transportation modelling approaches are generally based on the segmentation between private and public transport modes and are not able to model correctly mode combinations within a trip[2]. Nevertheless, in recent years growing attention was given to the modelling of multi-modal trips. Interest in multi-modal modelling tools has increased, but mostly at regional scale (La Spezia model, ATMax Barcelona, Orestads Traffic Model). There is some experience of such an approach at a European scale but this is mostly specialised on certain sorts of interconnections. The VIA model, for example, covers rail, road and air mode, but since the focus of the model is on air passenger transport, no interchange points between car and rail are considered.

Current practice in transport modelling centres around the four-step procedure, in which each of the stages: generation (production and attraction), distribution, modal split, and traffic assignment, are modelled subsequently. Specifically:

- The trip generation step provides the amount of travel produced by or attracted to different zones;
- The trip distribution provides the amount of movement between each zone pair;
- The modal-split step (or mode choice) indicates the transport mode used for the trip between zone pairs; and
- The traffic assignment step computes the exact routes or services within the network used for inter-zonal movements.

As an example, the TRANS-TOOLS model, the DGMOVE main reference model for transport analysis in the EU, is a four-step model that treats passenger transport by assigning uni-modal matrices to uni-modal networks. That is, starting from OD matrices at NUTS3 level for each of the several transport modes, TRANS-TOOLS assigns these to each one of the different transport networks. TRANS-TOOLS is therefore not able to model passengers' multi-modal routes and does not model expressly interchanges. Only the air mode interacts to some extent with land transport modes in the sense that air network connectors take into account the travel costs to access airports by road or by train modes.

The IC Module developed in INTERCONNECT Task 5.2, and described in D5.3, is intended to provide a tool to bridge some of these problems. Using the several transport networks from TRANS-TOOLS and the corresponding OD matrices, the IC Module links these different transport networks by locating the major intermodal terminals in the EU and establishing connectors between networks in these points, obtaining as a result a multi-modal network for the EU. From this point, OD matrices can be assigned to this multi-modal graph to better simulate the behaviour of travellers in Europe, and the role of interconnections.

[2] INTERCONNECT work package WP2 (Milestone M2.4, "Availability and utility of analytical techniques") reviewed state-of-the-art modelling tools and the fundamental problems found when modelling interconnectivity between transport networks. A full description of these problems can be found in depth in the Milestone report M2.4 which is not in the public domain, and also in chapter 2 of deliverable D5.3, but the most relevant aspects for this deliverable are reiterated in this section.

2 GOING BEYOND THE STATE-OF-THE-ART

2.1 BACKGROUND REFERENCE: THE TRANS-TOOLS MODEL

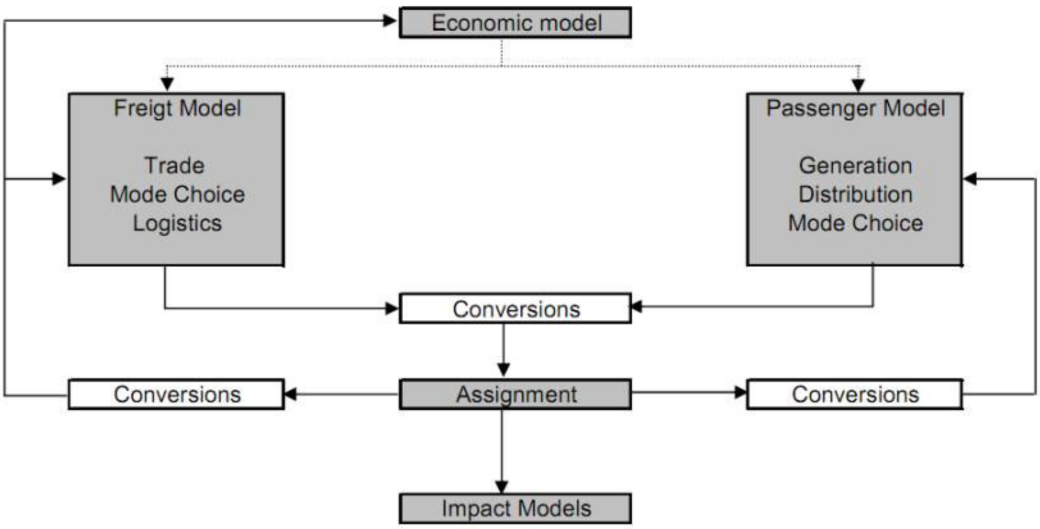
TRANS-TOOLS is the reference tool for transport policy assessment at EU level[3].

TRANS-TOOLS was first developed in 2005, aiming to become a European transport network model covering passenger and freight, as well as an approach to intermodal transport based on separate networks, overcoming the shortcomings of previously existing European transport network models. The objective of TRANS-TOOLS was to build on the experience of existing transport models and implement a number of improvements that would become the basis of the development of an integrated policy support tool for transport at EU level. The TRANS-TOOLS model is also able to offer answers on policy questions indirectly affecting transport costs and transport times, calibrated for a short-term period.

In 2007 a revision of the model was carried out resulting in TRANS-TOOLS v2, where a new approach to the freight model was developed as well as some changes regarding the passenger model were introduced.

TRANS-TOOLS is a network-based transport model of Europe starting from the ideas consolidated in previous modelling experiences: the ASTRA and VACLAV transport models are used as basis for the development of the passenger demand model, freight modelling is based on the NEAC model for trade and mode choice and SLAM for logistics. All model components are integrated into ArcGIS.

TRANS-TOOLS remains close to a traditional four-step model, including freight and passenger modelling. TRANS-TOOLS is mainly integrated by three sub-models which correspond to a freight demand model, a passenger demand model and a network assignment model. In addition to these, it also includes an economic model based on CGEurope and an impact model. The model framework allows feedbacks between the sub-models to achieve equilibrium between supply and demand.



Source: TNO Inro, 2006

Figure 2-1 General structure of TRANS-TOOLS

In TRANS-TOOLS the passenger model covers the first three steps of the classic four-step-approach, which is trip generation, trip distribution and modal split. The assignment itself is being handled by the TRANS-TOOLS assignment model. Feedback mechanisms are prepared to transfer average

[3] TRANS-TOOLS has been developed in collaborative projects funded by the European Commission Joint Research Centre's Institute for Prospective Technological Studies (IPTS) and DG TREN (now DGMove). Full documentation of the model can be found at http://energy.jrc.ec.europa.eu/transtools/index.html. The following are extracts of TRANS-TOOLS specifications.

generalised times to the trip distribution logit function. The trip distribution process depends on results of the modal split stage.

Trip generation is the first stage of the classical four-step transport modelling approach, performed at NUTS3 level. It considers three socio-economic variables: demographic structure, employment respective unemployment and car-ownership. The exogenous passenger trip rates implemented - adapted from SCENES project - reflect the various specific patterns of trip making behaviour of all modelled population segments. They are disaggregated into country, functional zone, age classes, employment status, car-ownership status and three trip purposes: business, private and tourism. The following equation illustrates the generation of trips per NUTS3 zone, population segment and trip purpose in ASTRA. Trip rates are represented by *TR*, population segments by *POP*:

$$T_{i,AS,Emp,CO,TP} = POP_{i,AS,Emp,CO} * TR_{i,AS,Emp,CO,TP}$$

At the second stage, trips are distributed among destinations, being the vector containing generated trips transferred into an OD matrix. A classical logit function is applied to distribute trips among destinations. The implemented logit function considers in its utility function averaged generalised times as major driver of destination choice behaviour. Generalised times will be calculated after the modal split stage for all modes. Via a feedback mechanism averaged generalised times over all available passenger modes are transferred from the modal split to the previous trip distribution stage. In the trip distribution the provided averaged generalised times *AGT* define the input into the utility function. The described logit function distributes generated trips among the destinations. As it is based on System Dynamics methodology, the output of the trip generation and distribution stage is dynamically computed for all years between the starting and the final time.

$$GT_{i,j,m,TP} = \left(\frac{TTC_{i,j,m,TP}}{VOT_{i,TP}}\right) + TTT_{i,j,m,TP}$$

where: TTC = total travel costs per trip

TTT = total travel time per trip

VOT = value of time

$$T_{i,j,TP} = T_{i,TP} * \left(\frac{\exp^{((-\lambda_{i,j,TP} * AGT_{i,j,TP}) + SD_{i,j,TP})}}{\sum_j \exp^{((-\lambda_{i,j,TP} * AGT_{i,j,TP}) + SD_{i,j,TP})}} \right)$$

In the third step, the mode for the travel is chosen. Hence impedance data from the TRANS-TOOLS assignment model as well as OD matrices per trip purpose are applied. Travel costs, travel time and information about the trip itself like frequencies and number of transfers are used to split the trips between the modes. The mode-choice is performed in just one step. For each origin-destination pair the modal split model calculates the probability of selecting a modal alternative out of a set of available modes. The modal choice set comprises rail, road and air modes. A non-linear logit function is used in order to calculate the choice probability. The explanatory variables represent the transport service level between two zones e.g. in the dimensions travel costs and travel time.

$$P(m|(i,j)) = \frac{\exp(U_m)}{\sum_{m' \in C((i,j))} \exp(U_{m'})}$$

where $U_m = \beta_{m0} + \sum_k \beta_{mk} X_{mk}^{(\lambda_{mk})}$

with $X_{mk}^{(\lambda_{mk})} = \begin{cases} \dfrac{X_{mk}^{(\lambda_{mk})} - 1}{\lambda_{mk}} & \lambda_{mk} \neq 0 \\ \ln X_{mk}^{(\lambda_{mk})} & \lambda_{mk} = 0 \end{cases}$

Output of TRANS-TOOLS passenger demand model, which serve as input to the assignment model, are uni-modal passenger OD matrices at NUTS3 level in number of passengers per mode (rail, road, air), that in the case of road are converted to number of vehicles so that they can be assigned onto the network. The level of service matrices with generalised costs per OD relation and per mode represent the output from TRANS-TOOLS passenger assignment model to the economic model.

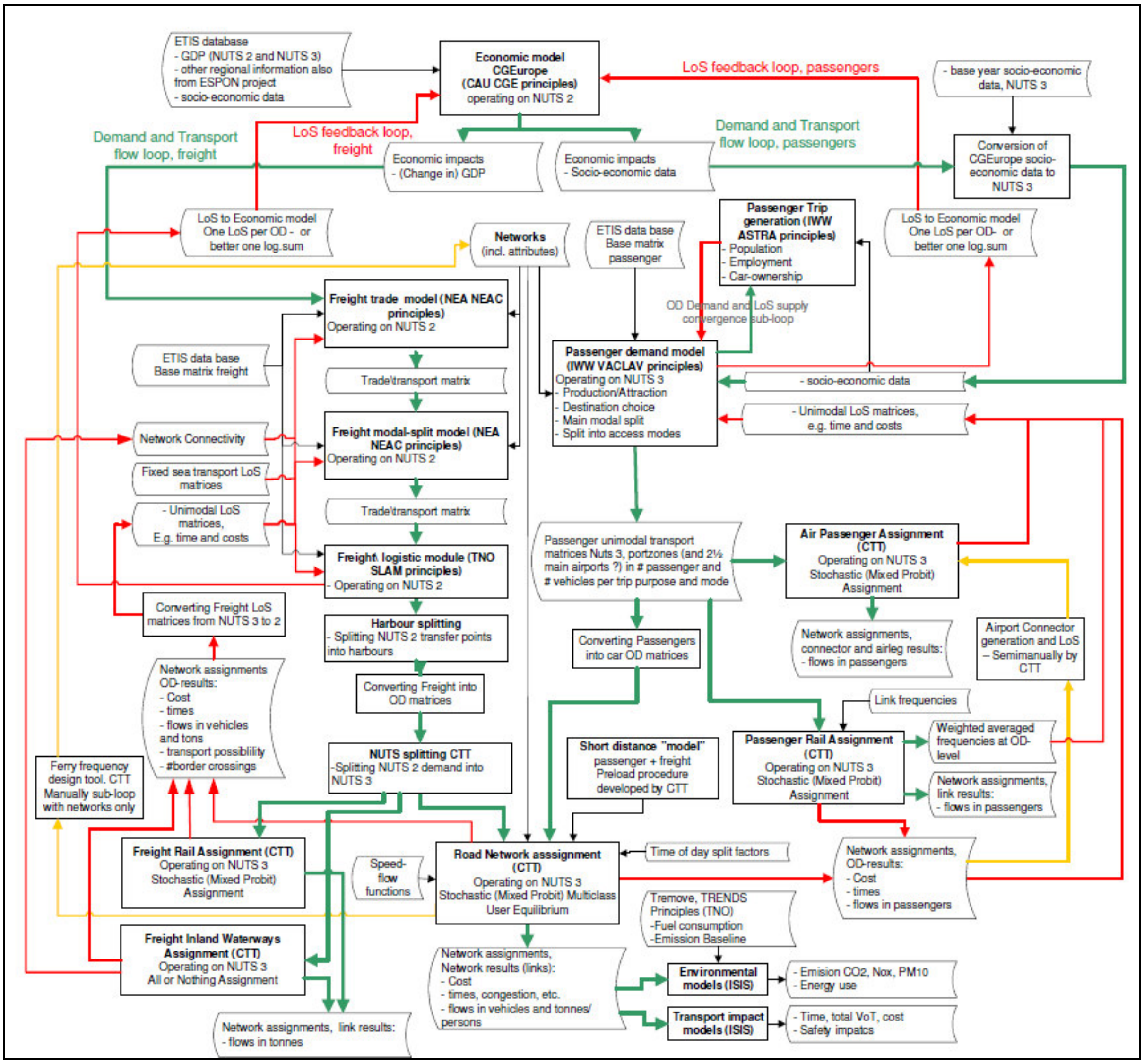
In the fourth step, network assignment is performed. The network assignment module generates level-of-service data (LOS) as feedback input to passenger, freight, and logistic models, forming a loop structure.

Working TRANS-TOOLS in a uni-modal basis, regarding the traffic assignment procedure, four different assignment models are developed within the model to work on the different transport networks. Passenger assignment specifically deals with the following networks (as inland waterways are reserved to freight only):

- Road;
- Rail;
- Air.

Passengers by rail and air are assigned based on an average day, since congestion is not considered and information on service data differentiated by time and day is not available. LOS in the road assignment is calculated by time period. TRANS-TOOLS applies a stochastic assignment procedure founded on probit-based models.

The economic model CGEurope determines the effects of each policy scenario in monetary terms. Policy evaluation measures, in particular real GDP impacts and equivalent variation, by region, year and scenario are other outputs of the TRANS-TOOLS economic model. The Impacts model is used to calculate energy consumption, emissions, external costs and safety based on output from the assignment model.



Source: TNO Inro, 2006

Figure 2-2 TRANS-TOOLS flow diagram

The most direct indicators of policy effects in TRANS-TOOLS consist of variables like:

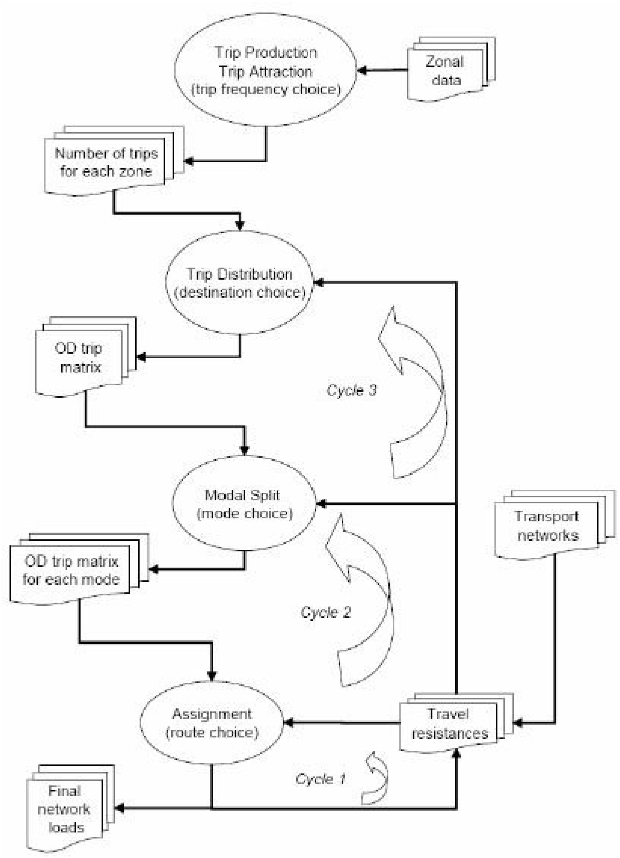
- *Transport performance* (i.e. passenger-km, tonne-km, vehicle-km); (at EU, national, NUTS2 level and for passengers also NUTS3, on annual basis or more detailed[4]);
- *Modal split* (share of demand using road modes, rail, air, etc.) both with reference to passengers and tonnes and to passenger-km and tonne-km, thus also *average distance* of transport can be assessed;
- *Load on corridors* (passengers and freight vehicles) and, therefore, levels of congestion on road infrastructure (TEN-T and main national links), and also, annual averages, and if available, daily peaks;
- *Fuel consumption;*
- *Emission levels* for $CO_{2;}$
- Change of *Gross Domestic Product* of regions.

2.2 MULTI-MODAL MODELLING OPTIONS

As already mentioned in section 1.5, current practice in transport modelling centres around the four-steps procedure, in which each of the stages: generation (production and attraction), distribution, modal split, and traffic assignment, are modelled subsequently.

The complete model consists of a concatenation of these sub-models. The exogenous input data of each sub-model are shown in the right part of Figure 2-3, whereas the endogenous demand prediction data produced by each sub-model are shown in the left part. Travel resistances or disutilities consisting of travel times, costs and distances play an important role in nearly all travel choices. These resistances depend on the level of usage of the network elements: the higher the network is loaded, the higher the travel resistances are. Since the level of usage is only known at the end of the calculation cycle (after the network assignment step) an iterative calculation procedure is required in order to achieve consistent final results. Mostly travel resistances resulting from the assignment are assumed to influence the route choice (feedback loop 1), the mode choice (feedback loop 2) and the destination choice (feedback loop 3) steps. Ideally, these iterative processes should be performed several times for each distinct analysis case in order to achieve a satisfactory consistency between the demand prediction results at the various stages.

[4] TRANS-TOOLS produces output on traffic at link level. Links are identified in relation to the country where they belong and since TRANS-TOOLS update version 2, to the NUTS3 they belong. Aggregation at higher levels (e.g. EU level, NUTS2 or nation level) is straightforward.



(Source: M.S. Fiorenzo-Catalano)

Figure 2-3 Classical four-step model scheme

In most application cases, the assignment cycle is restricted to the car network, implying that travel resistances in the other networks (e.g. public transport networks) are fully determined by the input assumptions of these networks and are independent of the flows in these networks. There are however some interdependencies between the predicted demand levels in the various modes: predicted low levels in the car network determine the resistances in the car network which in turn influence, via the mode choice mechanism, the flow levels in the other modal networks. In this demand modelling approach the various modal networks are completely separated such that only uni-modal trips can be predicted while multi-modal trips are neglected.

Modelling multi-modal trips centres on the issue of how to model (and represent) travellers' route and mode choice decisions. According to Fernandez et al. (1994) there are three ways of doing this:

- All relevant combined-mode alternatives are seen as distinct (and artificial) modes (here called the extended classical approach);
- All transfer nodes are modelled as a mode alternative (extended classical approach with explicit modelling of transfer nodes and stops);
- All choice decisions emerge from route choice in an integrated multi-modal network (here called the supernetwork approach).

Each approach can be categorised according to the degree of consideration of the interdependencies of travel modes at various levels:

- The modal transport networks (e.g. public transport and car networks) are treated separately or are integrated;
- The modal split is performed before the assignment (mode and route choice are modelled separately);

- The combination of modes, such as car and train, within a trip, are explicitly accounted for;
- The interactions between vehicular modes within the same infrastructure, such as e.g. bus and car on the roads, is explicitly accounted for.

These types of approaches, together with the uni-modal classical approach, are summarised in the table below and briefly described afterwards.

Table 2-1 Classification of multi-modal transport modelling approaches
(Source: M.S. Fiorenzo-Catalano)

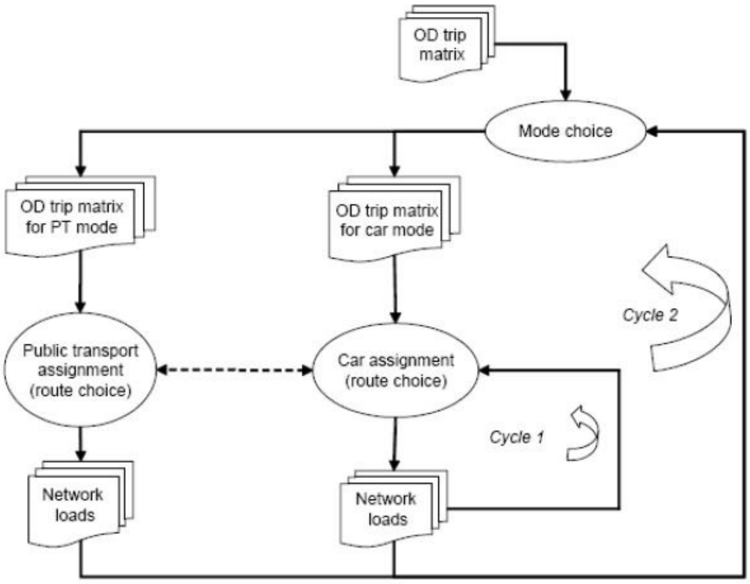
Features	Separate uni-modal (Classic)	Joint uni-modal (Classic)	Multi-modal (Extended classic)	Intermodal fixed	Intermodal free (supernetwork)
Modal networks	Separated	Separated	Separated	Coupled	Integrated
Mode choice modelling	Independent	Joint	Joint	Joint	Absent
Mode/Route choice	Sequential before assignment	Sequential before assignment	Sequential before assignment	Sequential	Simultaneous
Combined modes	No	No	Fixed	Fixed	Free
Mixed modal flows?	No	No	No	Yes	Possible
Equilibrium?	Only in car network	In car network, dependent on PT shares	In car network, dependent on PT shares	Simultaneous	Simultaneous
Main reference	Ortuzar and Willumsen (1994)	Cascetta (2001)	Fernandez et al. (1994)	Florian et al. (2000) De Cea et al. (2003)	Sheffi (1985) Fiorenzo-Catalano (2007)

The separate uni-modal approach is the classical approach of the last four decades exhibiting complete separation of the modal networks; only pure uni-modal trips are considered which are modelled independently; there is no feedback from the public transport networks to the mode choice.

In the more recent so-called joint uni-modal approach, there is a slight interdependency between the modes (private and public modes) via the joint consideration of flow-dependent modal resistances in the mode choice mechanism; however, only pure uni-modal trips are considered.

Both these classical approaches typically use a mode choice model at origin/destination level, splitting the OD-trip matrix into mode-specific OD-matrices, followed by a network assignment procedure in which often a user-equilibrium is sought. Trips are always uni-modal, meaning that they can only have a single main mode (such as car or train or plain) and are modelled independently; access or egress modes are not explicitly distinguished. The advantages of the classical approach are familiarity and simplicity; the disadvantage of course is a limited ability to investigate the entire spectrum of available modes.

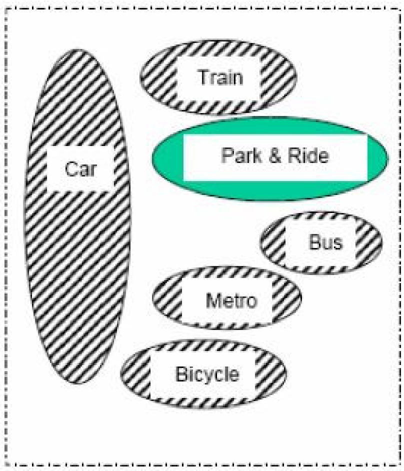
Figure 2-4 shows a simplified scheme of the joint uni-modal approach in which the mode and route choices are modelled separately and sequentially; the assignment and the modal networks are completely uni-modal. This approach is not able to model the choice of combined mode options such as car and train within a trip, nor the choice of transfer nodes such as Park & Ride facilities. In those classical approaches the feedback in the assignment (cycle 1) is almost always performed, whereas the feedback into the mode choice (cycle 2) can be an option. The dashed line from the car to the public transport assignment box represents the modal flows dependencies.



(Source: M.S. Fiorenzo-Catalano)

Figure 2-4 The joint multi-modal approach

The extended classic approach introduces new artificial separate modes by pre-specifying fixed modal combinations (combined-mode trip alternatives) being combinations of the given main modes (see Figure 2-5 in which as an example the Park&Ride option is specified as a new separate modal alternative additional to the standard main modes). Although the added combined mode trip alternatives consist of two or more main modes, they are considered as an additional main mode, without specifying access or egress sub-modes.



(Source: M.S. Fiorenzo-Catalano)

Figure 2-5 The extended classic approach

By introducing an additional artificial mode for each modal combination to be studied, the problem can be recast (from a purely formal point of view at least) as a formulation that standard transportation modelling toolkits can handle. This means that the mode choice model now is applied to a wider set of modal options, and the OD trip matrix now is split up into several mode-specific OD-matrices including matrices for the new artificial modes. In all the other aspects, the modelling follows exactly the same lines as the classical joint uni-modal approach.

The advantages of extending the classical approach to handle multi-modal trips in this way are obvious: practitioners can continue to leverage their standard toolkits, datasets, and skills. The disadvantages emerge upon consideration of the implementation consequences. The mode choice alternatives now include artificial modes that represent multi-modal options. For example, an intermodal transfer can be modelled quite artificially by introducing a new mode consisting of two travel modes and a transfer at a predefined transfer node in the network. It will be obvious that such an approach might be suitable when only one or two transfer nodes are considered, but that in the case of multiple multi-modal combinations and multiple transfer nodes the number of alternatives will explode. In addition, this has to be done for all relevant OD-pairs in the area.

A further extension of this approach is the so-called intermodal-fixed approach that, apart from specification of fixed artificial combined modes, adopts a high level of interdependency among the modes in trying to achieve a simultaneous equilibrium among all involved modes. In this case the route choice process it is able to model the appropriate transfer point that minimises the generalised travel cost between a certain OD pair.

The final category adopts the supernetwork approach defined such that OD-routes in this network may represent arbitrary ('free') uni-modal and multi-modal trips (no fixed modal combinations) where the route choice and network assignment automatically includes modal choices. In this approach the modal sub-networks are completely integrated, and the combined modes and the interactions among the vehicular modes on the roads might be explicitly taken into account.

Such a network has the interesting property that mode choice now is part of route choice, thus providing a natural unification of the two. In addition, this multi-modal route choice naturally includes the choice of transfer locations, boarding/alighting stops, and possibly the choice of train type (intercity, express, local). So the multidimensional travel choice situation travellers are faced with in reality is transformed into a one-dimensional choice situation of alternative routes in the supernetwork. Therefore with the supernetwork approach there is no need to pre-specify the available multi-modal options. These should emerge in a natural way by search in the supernetwork for attractive trip opportunities from origin to destination. Another peculiarity of the supernetwork approach is that the rigid separation between mode choice and route choice disappears including the question of their right sequence.

It should be noted that, even if the definition of supernetwork dates back to 1985, the supernetwork approach can be considered an innovative approach. This approach is also being currently developed in the TRANSFER model within research projects at Delft University. It is still not available at “commercial” level and only applications restricted to simple cases are known. The IC Module has also taken this approach.

2.3 BASIC CHALLENGES OF MULTI-MODAL TRANSPORT MODELLING

2.3.1 How Multi-Modality Should Be Modelled

There are no official definitions of the terms used for describing the transport of goods and passengers using more than one transport mode; in current literature the words “multi-modality” and “intermodality” are used often to define a “characteristic of a transport system that allows at least two different modes to be used in an integrated manner in a door-to-door transport chain”.

Usually, a trip may be defined as being “multi-modal” or “inter-modal” where it uses at least two different modes from origin to destination. Both multi-modality and inter-modality have to consider the existence of connections that allow transfers between different transport modes. Modelling interconnectivity means modelling transport systems whose networks allow multi-modal trips. In this case special attention should be devoted to modelling transfers between different transport modes.

Within a multi-modal trip in principle three different trip parts can be distinguished: the main part, the access part, and the egress part:

- The main trip part is that part performed over the largest distance with the highest possible speed compared to the access and egress trip parts. Typical main trip modes are car, train, plane, sometimes also bus instead of train. The main trip part is in-between two end nodes that connect the access and egress trip parts to the trip origin and trip destination respectively.

- The access trip part connects the trip's origin to the start node of the main trip part (often a transfer point) and consists of one or more legs.
- The egress trip part is the part of a multi-modal trip connecting the end node of the main trip part (often a transfer point) to the trip's destination and consisting of one or more legs.

Quality of interconnections' representation

When modelling transport systems, a proper quality of the network representation should facilitate the travel demand analysis since the travel costs predominantly are determined by the network, and should allow for a proper route choice modelling. Transfers' representation plays an important role in multi-modal trips' modelling, since these transfer links are used to model costs and/or restrictions of choosing or transferring between the alternatives. Transfers are fundamental for the route and the mode choice processes: their existence allows the modelling of multi-modal routes and their disutility is taken into account when computing total travel costs used in the mode choice.

Ideally, a proper transfer representation should describe the main activities performed at interchanges, such as the access and egress phases, the waiting time, the boarding and alighting phases, etc. Each activity should be described by a link with its specific characteristics, e.g. in a road-rail interchange, the access link should be characterised by the average time required to find a free parking space, by the parking fare, and by the walking time needed to reach the station from the park lot. The increasing level of detail at interconnections brings, however, substantial increases in computation times. The larger the scale of the model is (i.e. European-wide model), the further need for simplification of parameters at interconnections.

Quality of travel behaviour representation

Another important feature in passenger transport modelling, and especially in multi-modal trips modelling, is the proper representation of the traveller choice process performed in the mode choice step. This can be obtained only if detailed information about traveller characteristics is given. The choice of the used transport mode can be influenced by the age of user classes or by their personal income, or by the trip purpose. Given the importance of transfers, in modelling multi-modal trips also the route choice can be highly influenced by population characteristics: elderly people may prefer uni-modal trips just to avoid the discomfort of transferring between modes; businessmen may not even consider the possibility to choose public transport at an airport interchange.

Realistic multi-modal travel chains

In order to model multi-modal trips, it is fundamental to have an assignment algorithm that is able to compute realistic multi-modal routes that do not comprise a high number of transfers and an improbable combination between transport modes. In this respect, in most of the adopted modelling approaches, a list of all possible mode combinations is a priori defined in order to avoid the creation of improbable multi-modal routes when the disutilities between alternatives are very small.

Resource consumption of the modelling process

Another important issue related to modelling transport systems is the capability of the model to be executed by current computational instruments. In fact, even though the development of the computational power of common personal computers has led to an improved capability of executing transport models, limitations about the size of the model (e.g. number of zones, links and nodes handled by the model) still remain. An increase in the complexity of the model can lead in the best case to long run-times and, in the worst case, to the impossibility of computation. Multi-modal passenger travel modelling needs to deal with a wide range of mode combinations, among various vehicular modes for access and egress - e.g. car, metro, commuter train - and main modes of travel – e.g. train or airplane. This results in a huge number of multi-modal alternatives.

In order to have a tool that is able to process such complex combinations of travel modes and interchanges it is necessary to limit the complexity of the model. This limitation in general leads to a compromise between the geographical scope of the model and the level of detail of the modelling framework (e.g. demand segmentation, networks representation, transfers modelling etc.): the wider the coverage of the model, the lower the level of detail. It should be noted that the network representation could have a deep impact on computational issues: a complex network will require a complex research of the possible routes and substantial computational power.

Calibration

The main purpose of a model is to depict reality. Model development normally starts with observations or the collection of data regarding the behaviour of the system in reality. The aim is to describe the process in a mathematical model, which can ultimately be used to simulate system performance. However, the mathematical model will be based on a theory on how the system works. Once the hypotheses that support the theory are proved right, the model is calibrated by means of available empirical data. This means that the model parameters are estimated so that they correctly reflect the observed data. Subsequently, the model should be validated to check if the outcomes correctly predict the system performance in all other situations. The quality and amount of available data, therefore, directly determines the performance of the model.

2.3.2 How the IC Module Responds to these Challenges

In relation to the level of detail of interconnections

The IC module has established a compromise between modelling detail at interconnections and reasonable time consuming modelling procedures. In a European-wide model, it is not possible to extend the detail of the network to embrace local and county road networks, even city roads, or metropolitan public transport systems like metro lines or commuter trains. Computation times would become unmanageable, and analysis would be heavily compromised. Simplifications can be made without substantially altering the general behaviour of the simulation procedure. The IC Module is based on a NUTS3 scale, meaning that all socioeconomic and mobility parameters are aggregated for NUTS3 units.

Access and egress travel from origins or destinations to transport networks are represented in the IC graph with connectors with standard unit travel costs and travel time parameters specifically conceived to condense all information relative to average access/egress transport phase, that is representing an abstraction of costs and times required by users to access or leave destinations from long-distance transport networks by means of all different local transport networks available, e.g. metro, commuter trains, car, taxi.

Secondly, to better represent the magnitude of the access/egress phase of the trip, origin and destination centroids have been moved from geometric NUTS3 centres to geographic location of NUTS3 capitals, which is where most trips originate or are bound for. In doing so, travelled distance by most users when accessing or leaving long-distance transport networks is closer to reality, and the assumed error is lowered considerably.

In relation to the level of detail of traveller behaviour

The IC Module does not perform the generation and distribution processes of a conventional four-step traffic model. Instead, the IC Module uses OD matrices from TRANS-TOOLS. These matrices are disaggregated in relation to trip purposes, that is in terms of business trips, private trips, commuters and holiday or leisure trips.

Each of the four TRANS-TOOLS OD matrices is assigned separately onto the multi-modal graph of the IC Module. For each of the assignments, several parameters are varied in terms of the trip purpose being dealt with in order to be able to model different behaviours of different kinds of users. Variations are mostly done by means of different sets of travel time values for the different kinds of users, e.g. business travellers tend to use faster means of transport, because as they have a higher value of travel time, they save more when reducing travel times than when using cheaper means of transport.

The IC Module also takes into consideration geographical differences in terms of costs of travelling in the network: links in higher income countries are more expensive than those in lower income countries; it also does so in terms of users' travel budget: residents in higher income countries are assigned higher travel budgets through modification of their travel time values, and are therefore more likely to use more expensive modes. The range of these variations can be controlled with dispersion parameters integrated in the IC Module.

Differences in travel behaviour resulting from different target users niches like elderly or youths have not been considered in the IC Module due to lack of input data availability, but could be stated as a possible way of improvement towards the future.

In relation to realistic multi-modal travel chains

The assignment algorithm is built in such a way that establishes penalties to interconnections between networks, representing waiting and transfer times. These penalties are introduced by means of cost functions and speeds at connectors between different transport networks, and between transport networks and centroids representing cities.

The concept of services was also introduced in the IC Module to overcome problems were penalties need to be established in interconnections intra-mode (e.g. scales at intermediate airports). In order to properly model air travel, each link was assumed to represent a single flight. The representation of flights in a service basis allows introducing waiting times and transferring times at airports, in relations which would otherwise be continuous. A similar strategy was established for ferry services.

For rail services, due to the difficulty of establishing train services in the different lines, as a difference to the air network or in ferries where each flight can be assimilated to one link alone, a differentiation was made between long-distance networks – identified with TEN-T networks - and short distance networks – all others. It was not possible to introduce penalties when changing from a short-distance to a long-distance network, but it was possible to count these changes of network as interconnections intra-network, taken into consideration by the Interconnectivity Rate indicator (see deliverable D5.2 *Meta-models for the analysis of interconnectivity*).

In relation to the calibration of the IC Module

The IC Module has been validated with respect to TRANS-TOOLS results by modes at EU level.

The TRANS-TOOLS model is calibrated so that its results sufficiently fit Eurostat statistics. That means that internal parameters in TRANS-TOOLS are set so that results from its modelling process sufficiently fit reality.

The internal parameters of the IC Module, mainly travel costs and interconnectivity costs, have also been adjusted in a process of validation. Instead of using Eurostat statistics, TRANS-TOOLS outputs have been used, because the module is built on this model: as a starting point, it takes already elaborated matrices by TRANS-TOOLS, so it is logical to check consistency with the TRANS-TOOLS results.

More specifically, it has been sought that the amount of travelled kilometres in Europe over each of the different transport networks obtained with simulations in the IC Module be equivalent to those obtained with TRANS-TOOLS, despite the fact that the first traffic is assigned altogether onto a multi-modal graph, while the later is individually assigned on the corresponding uni-modal graphs.

This validation has been complemented with comparisons at NUTS0 level (Member State level), attempting to get as equilibrated results as possible.

To refine this process, the next developments of the module should go in two directions:

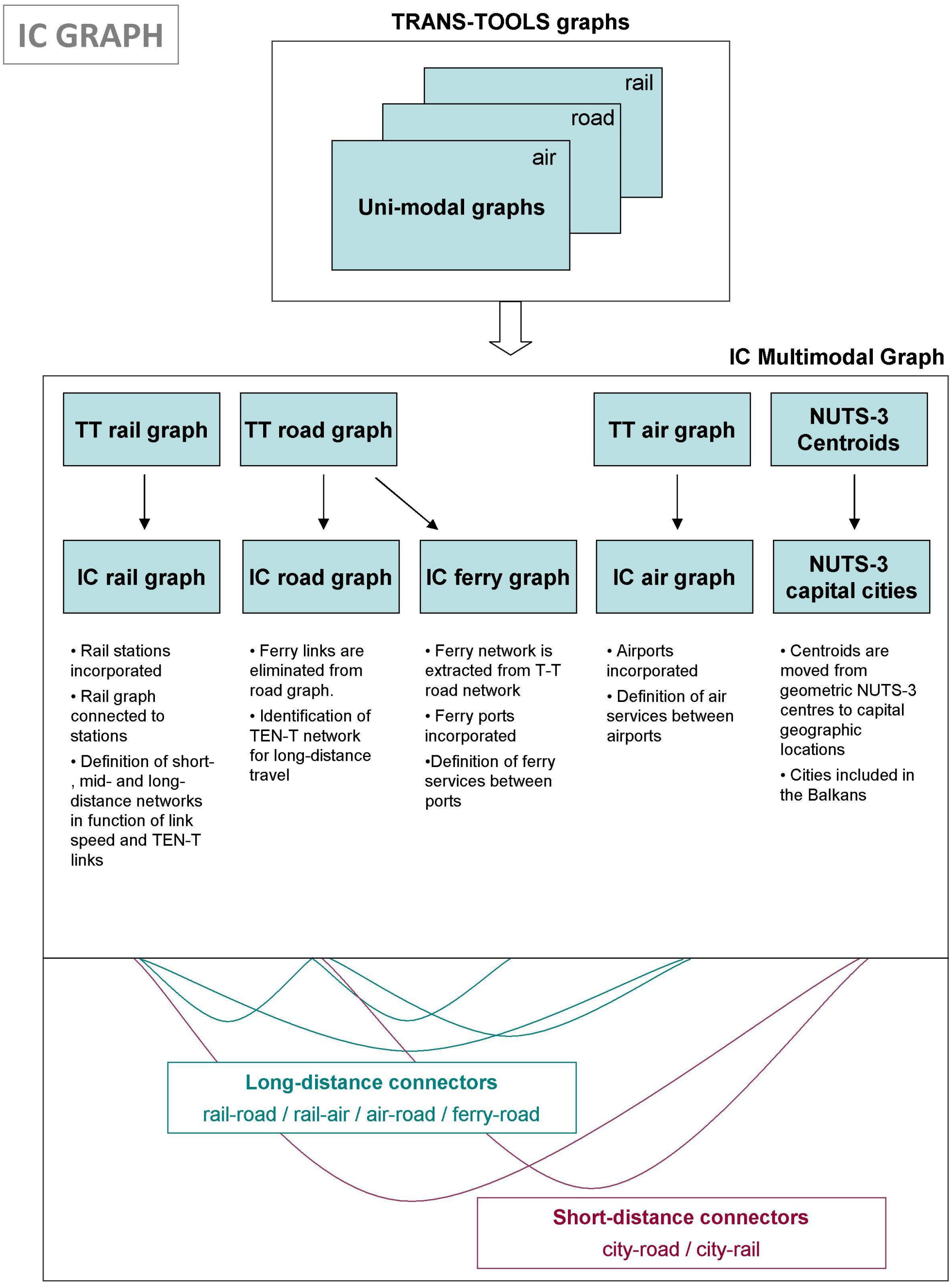
- Including explicit rail services in the network;
- Testing a stochastic user equilibrium algorithm to allocate trips among reasonable multi-modal chains between ODs.

3 DEVELOPMENT OF A MULTI-MODAL GRAPH TO ANALYSE INTERCONNECTIONS

3.1 OVERVIEW

The IC Module graph is built using the TRANS-TOOLS uni-modal graphs, three separate networks for road, rail, and air. Within INTERCONNECT, these graphs are joined with connectors at transport terminals to constitute the multi-modal graph. Connectors in the graph represent interconnections.

Figure 3-1 provides the framework of operation used by INTERCONNECT to build the multi-modal graph. Each of the processes will be developed in depth in the following chapters.



(*) Airport-city connectors are not considered. Instead, airports are connected to rail and road networks, and these are connected to cities.

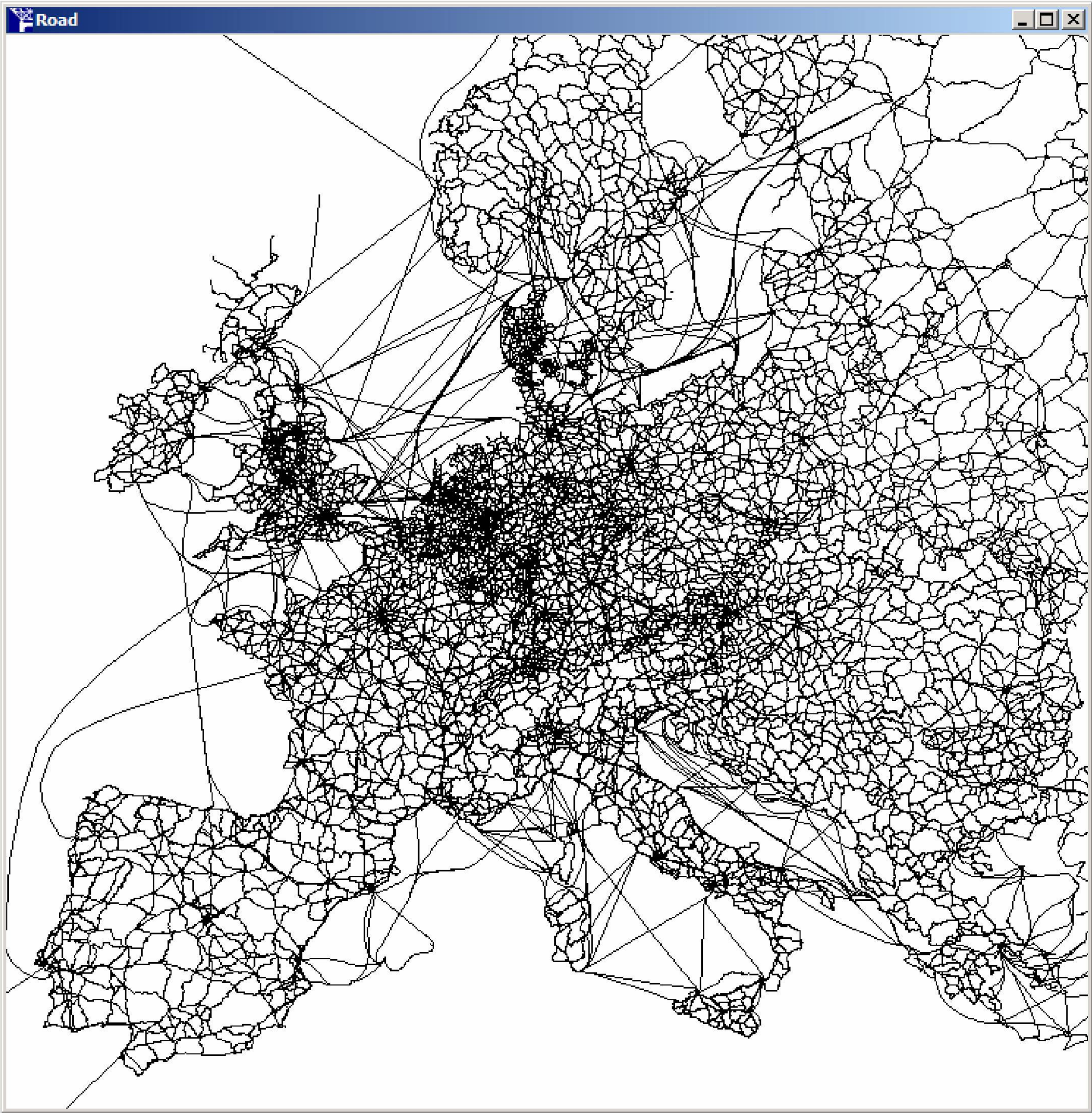
Figure 3-1 INTERCONNECT strategy to construct the multi-modal graph

3.2 STARTING POINT: THE TRANS-TOOLS GRAPHS

The starting points to building the IC multi-modal graph are the TRANS-TOOLS transport graphs.

All graphs were updated in 2008 in the framework of the DG-TREN study TEN-CONNECT. The base year for that update was 2005. The updates were especially important for the air network, since the sector of low-cost carriers had heavily developed between 2000 – the year of the previous graph version - and 2005. For road and rail, updates mostly consisted of extensions of the networks onto neighbouring countries, e.g. to Turkey and Russia, and upgrading of national networks.

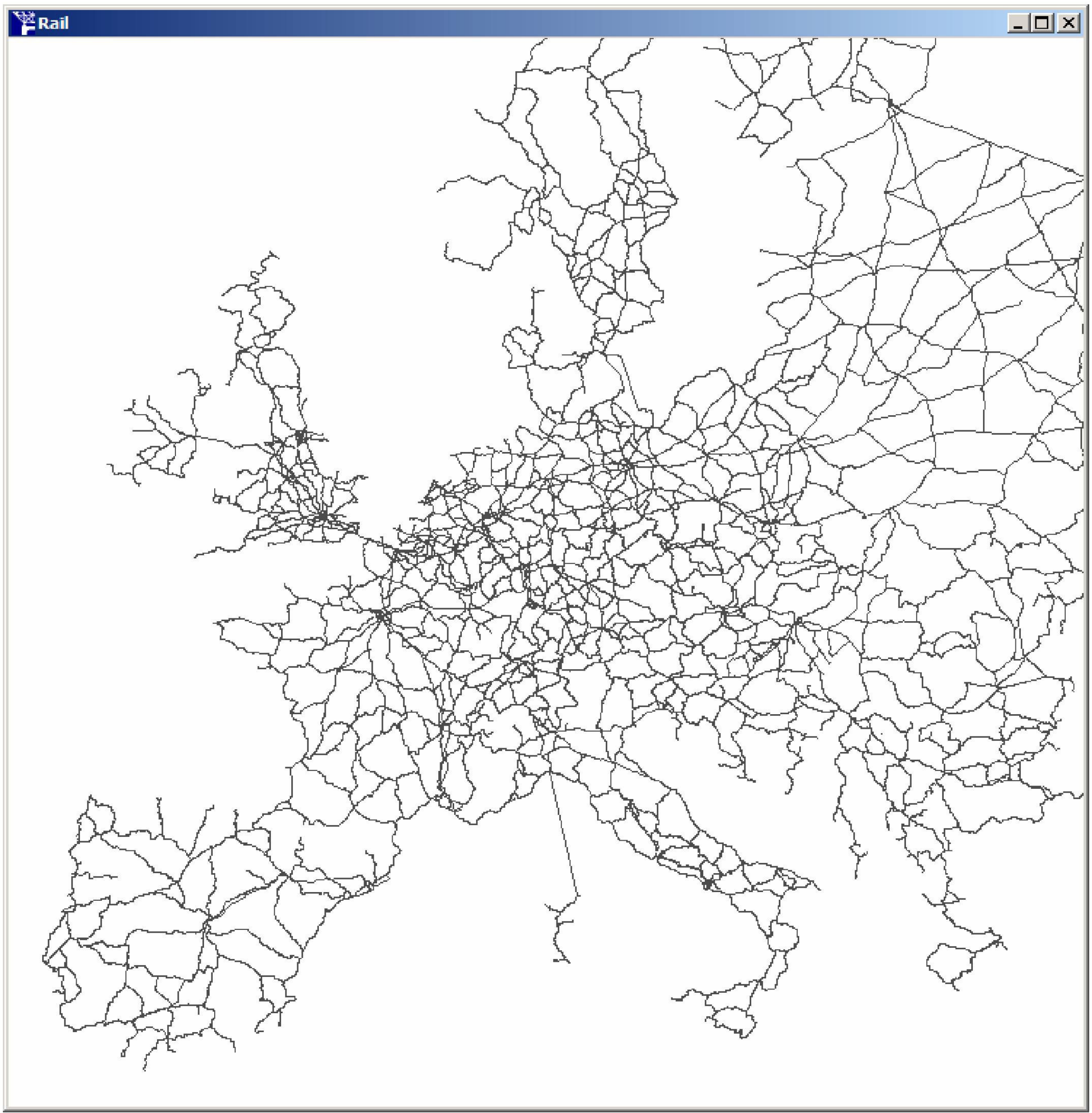
- The road graph includes almost 37,000 links, mostly TEN-T links, major national road networks for each of the EU-27 countries and some regional high capacity road links.



(Source: TEN-CONNECT, 2008)

Figure 3-2 TRANS-TOOLS road uni-modal graph

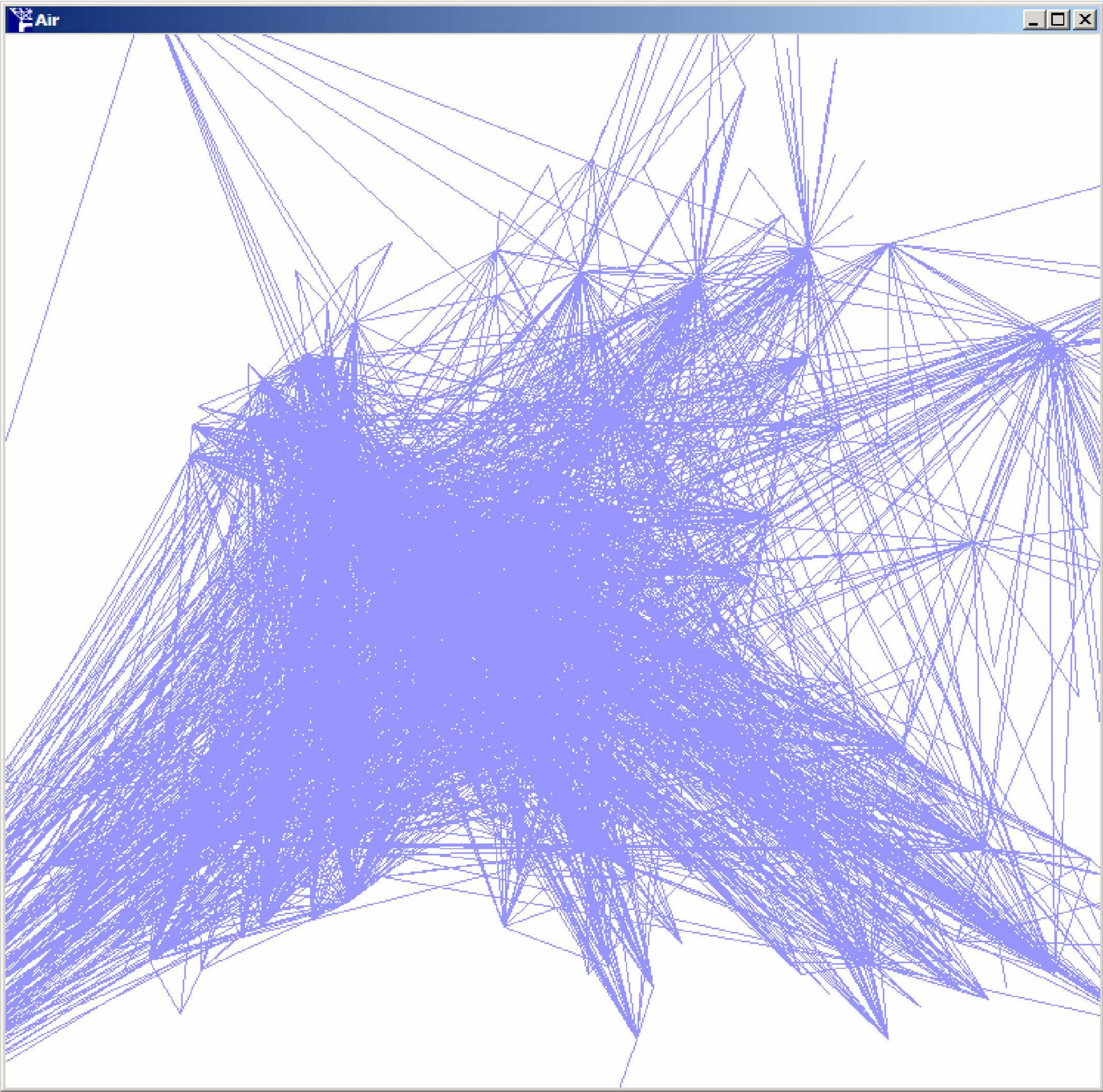
- The rail graph includes around 5,500 links, mostly TEN-T links and major national rail networks. The graph does not include rail stations.



(Source: TEN-CONNECT, 2008)

Figure 3-3 TRANS-TOOLS rail uni-modal graph

- The air network contains links between airports where air services were available in 2005. The links have travel time and travel cost information, and the number of available daily services.



(Source: TEN-CONNECT, 2008)

Figure 3-4 TRANS-TOOLS air uni-modal graph

TRANS-TOOLS socioeconomic data and OD matrices are provided at NUTS3 level; centroids are located at geometric centres of NUTS3 perimeters.

TRANS-TOOLS has an Inland Water Ways network graph for freight but not a proper ferry network graph. Ferries are considered in the road and rail networks as links with reduced travel speeds and time and waiting times.

3.3 INCORPORATING TRANSPORT TERMINALS TO INTERCONNECT TRANSPORT NETWORKS

3.3.1 Overview

Within TRANS-TOOLS transport terminals are not represented per-se. Each network has a particular arrangement for transport terminals:

- For the air network, each one of the nodes between two links represents an airport.
- For the rail network, no rail stations are considered.

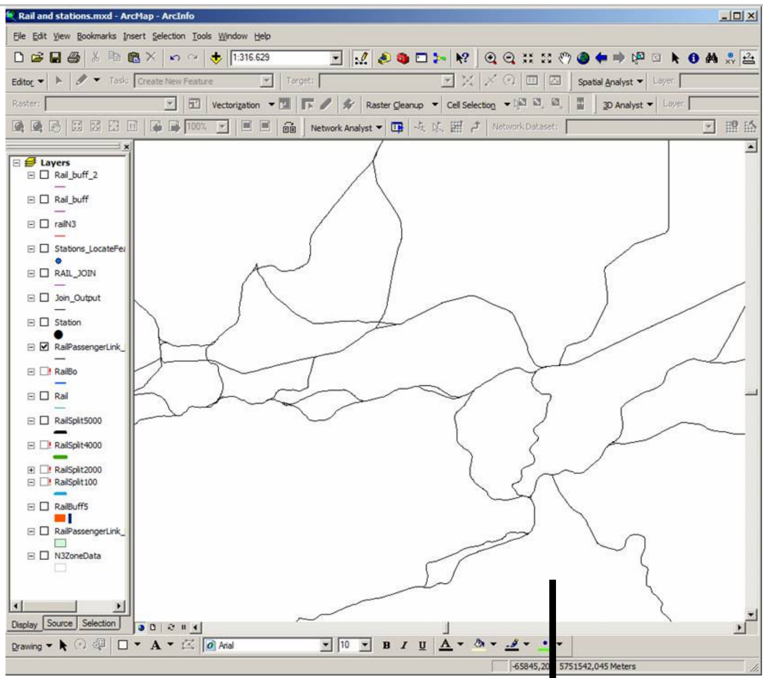
- For the ferries, no terminals are considered, although they can obviously be tracked in those areas where the road and rail networks run into the sea.

3.3.2 Rail Stations

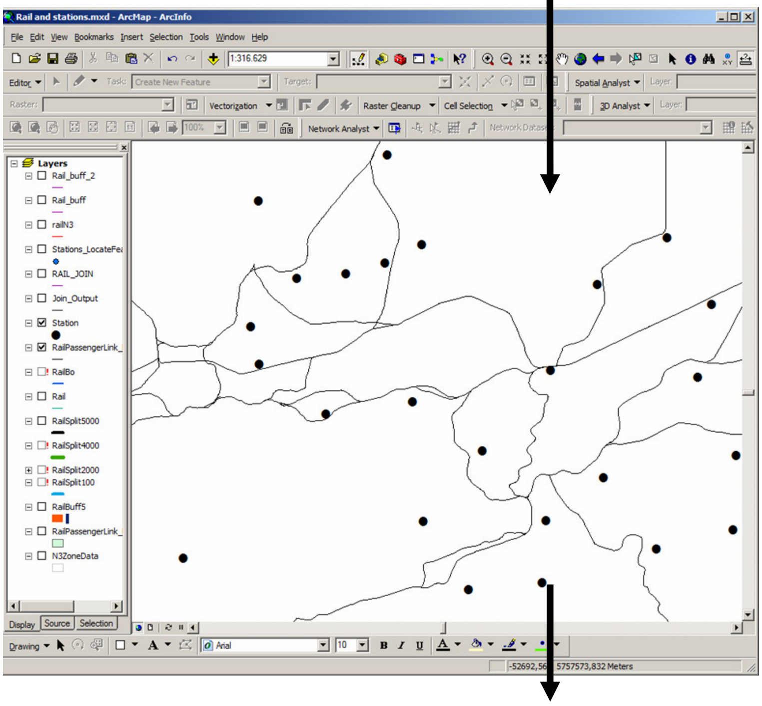
The TRANS-TOOLS rail graph does not have a layer of rail stations incorporated. A proper connection of the rail network to other transport networks required the import of a detailed rail stations layer with all relevant European stations in it, and the establishment of connections to road, air or ferry networks from rail station nodes.

To incorporate rail stations in the rail graph, they were first imported from the IGIS graph. The IGIS tool was produced by MCRIT for the European Investment Bank between 2004 and 2007 to keep track of all infrastructure projects financed by the Bank in Europe, including analysis of territorial impact. Only stations located over the TRANS-TOOLS rail graph were considered, while all others, like stations on local networks, were ignored.

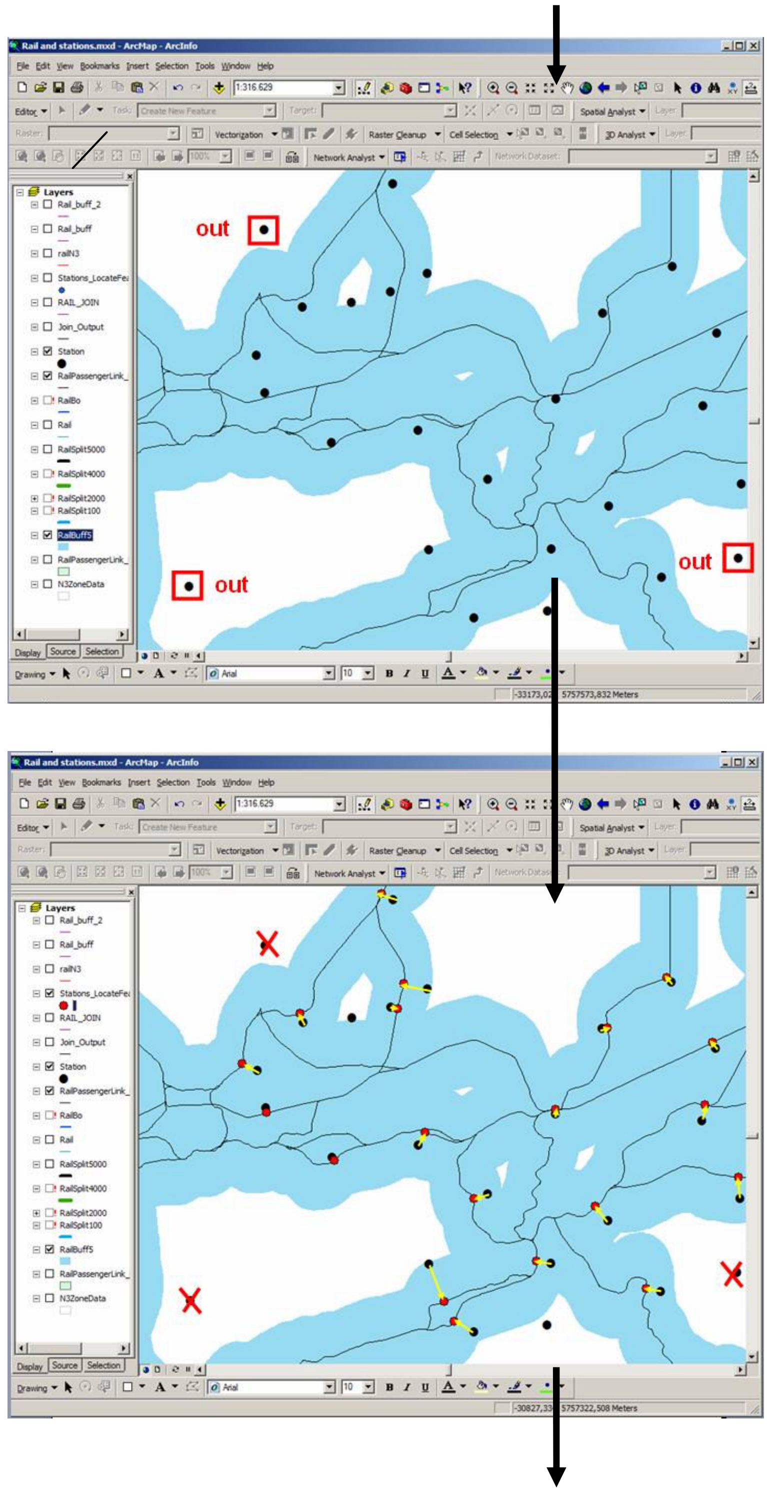
Figure 3-5 shows a step-by-step scheme of incorporating rail stations in the multi-modal graph.



Trans-tools rail graph without rail stations



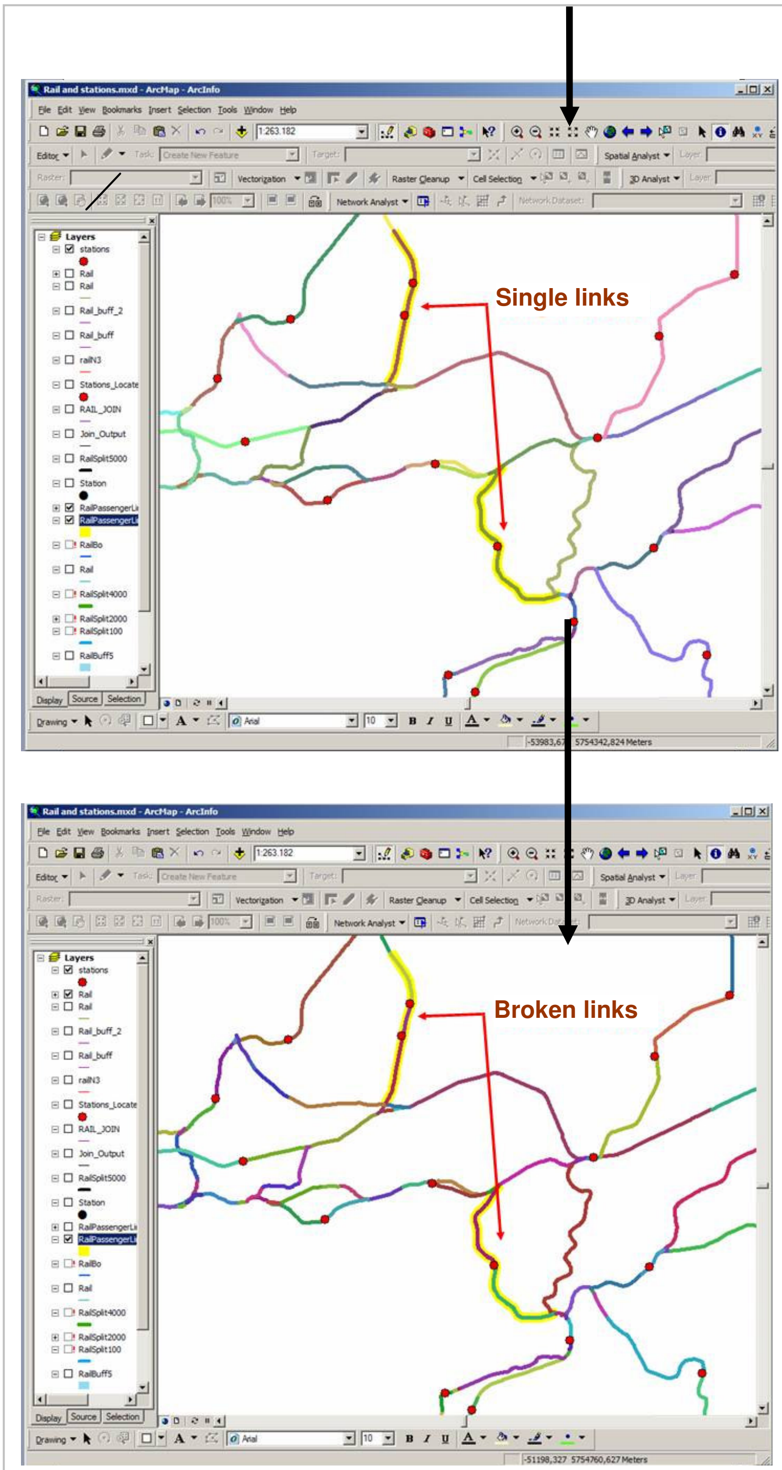
IGIS database stations are added onto the rail graph



Rail stations located far from Trans-tools networks are omitted

Other rail stations are drawn over the rail line in an automated process

.



Even if stations are now over the rail lines, they are not connected to these. Links are continuous and still ignore stations.

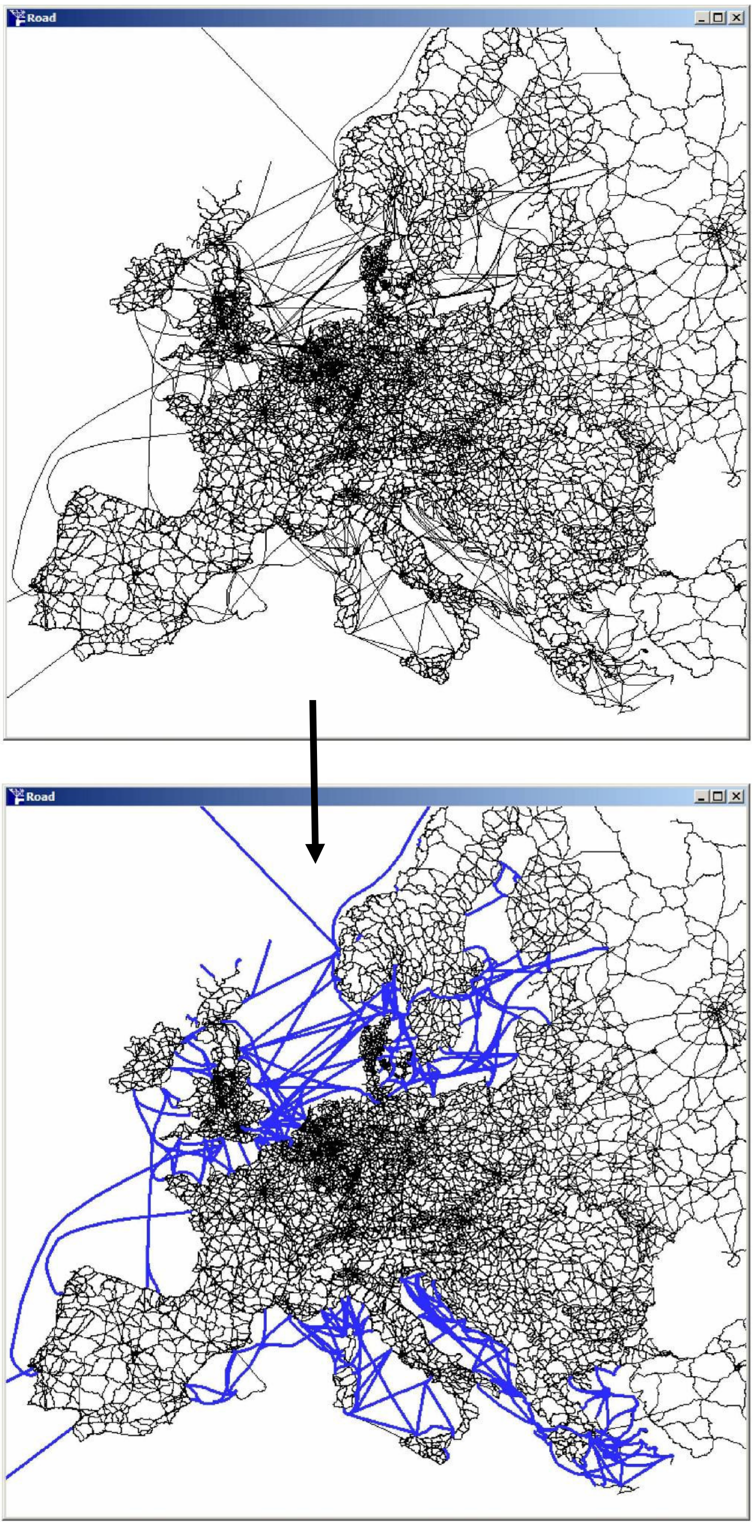
Links are broken in order to make them begin or end always at a rail station. In doing so, stations and the rail network become connected and are ready to be interconnected to other networks

Figure 3-5 Equipping rail networks with rail stations, step by step

The stations were thereafter connected to the rail graph. Stations were automatically re-located to fall onto the rail network links, and links were broken accordingly to establish different legs. From the new stations, connectors would link the rail network to the road network, and to airports or ferry ports where necessary.

3.3.3 Ferry Terminals

Ferry terminals are not properly considered in TRANS-TOOLS graphs, but can be tracked whenever road or rail networks run into the sea. Ferries are in fact represented in TRANS-TOOLS integrated in the road and rail network, as specific links incorporating additional travel times to represent waiting times at ports and lower commercial speeds.



Trans-tools graph integrates ferry links within the road and rail graphs.

Ferry terminals are detected in those points where road and rail segments run into the sea. Ferry links are separated in the IC Module and treated specifically.

Figure 3-6 Identification and incorporation of ferry links from TRANS-TOOLS road and rail networks

3.3.4 Airports

The TRANS-TOOLS air graph is built on the set of links representing airplane services. That is a graph with links linking airport pairs were flights were available in 2005. Air OD matrices for Europe are assigned onto this graph. The IC graph incorporates all these airports as nodes of the IC multi-modal graph and connects them to the road and rail networks with connectors representing interconnections.

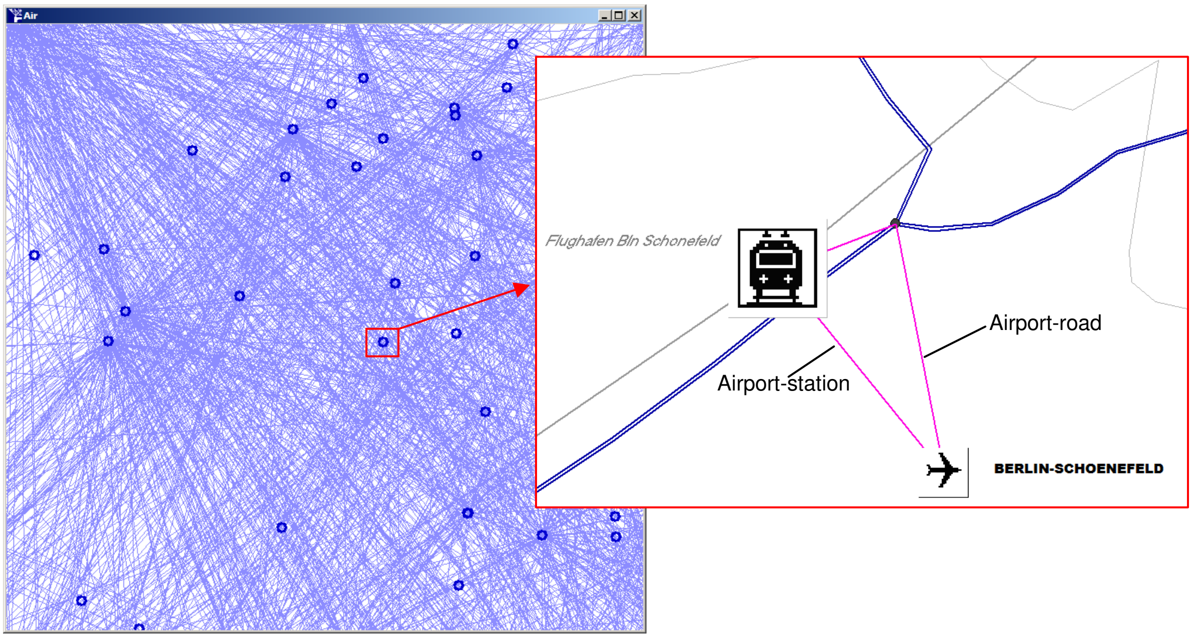


Figure 3-7 Incorporating airports into the multi-modal graph

All airports in the TRANS-TOOLS graph are represented as nodes. There has been an attempt to increase the resolution of the modelling process in airports by creating nodes for each of the airport terminals, allowing with that the analysis of internal interconnections at airports. Airports in Europe with more than one terminal and significant transit times between them were located, new nodes were created in the geographic position of the terminals, and connectors were established between them. However, due to the lack of information regarding to flight arrival/departure split among terminals, this task was finally abandoned, but could represent a way for further improvement of the graph.

City	IATA	Airport	Terminal	Lat	Long
Madrid	MAD	Madrid Barajas	T4S	40º29'30,42"N	3º35'28,39"W
Madrid	MAD	Madrid Barajas	T4	40º29'38,70"N	3º34'05,09"W
Madrid	MAD	Madrid Barajas	T1T2T3	40º28'19,20"N	3º34'14,15"W
Barcelona	BCN	Barcelona el Prat	T1	41º17'21,13"N	2º4'32,96"E
Barcelona	BCN	Barcelona el Prat	T2	41º18'08,73"N	2º4'41,08"E
London	LHR	London Heathrow	T1T2T3	51º28'20,00"N	0º27'26,07"W
London	LHR	London Heathrow	T4	51º27'37,50"N	0º27'51,94"W
London	LHR	London Heathrow	T5	51º28'16,56"N	0º29'17,82"W
Paris	CDG	Paris Charles de Gaulle	T1	49º00'50,34"N	2º32'30,56"E
Paris	CDG	Paris Charles de Gaulle	T2	49º00'15,81"N	2º34'36,56"E
Paris	CDG	Paris Charles de Gaulle	T3	49º00'34,98"N	2º33'51,89"E
Frankfurt	FRA	Frankfurt am Main	T1	50º03'02,13"N	8º34'19,02"E
Frankfurt	FRA	Frankfurt am Main	T2	50º03'04,99"N	8º35'14,49"E
London	LGW	London Gatwick	T1	51º09'39,45"N	0º10'37,87"W
London	LGW	London Gatwick	T2	51º09'44,68"N	0º09'44,68"W
Paris	ORY	Paris Orly	T1	48º43'41,88"N	2º21'35,20"E
Paris	ORY	Paris Orly	T2	48º43'41,47"N	2º22'07,94"E
Manchester	MAN	Manchester	T1	53º21'41,63"N	2º16'28,29"W
Manchester	MAN	Manchester	T2	53º22'03,29"N	2º16'44,85"W
Manchester	MAN	Manchester	T3	53º21'38,95"N	2º16'11,00"W
Antalya	AYT	Antalya	T1	36º54'54,60"N	30º48'08,18"E
Antalya	AYT	Antalya	T2	36º53'54,90"N	30º48'04,97"E
Stockholm	ARN	Arlanda	T2	59º39'05,44"N	17º55'48,72"E
Stockholm	ARN	Arlanda	T5	59º38'39,56"N	17º55'42,67"E
Lisbon	LIS	Lisbon Portela	T1	38º46'12,27"N	9º07'42,27"W
Lisbon	LIS	Lisbon Portela	T2	38º45'49,20"N	9º08'12,67"W
Nice	NCE	Nice Cote D'Azure	T1	43º39'53,47"N	7º12'48,24"E
Nice	NCE	Nice Cote D'Azure	T2	43º39'34,13"N	7º12'22,70"E
Budapest	BUD	Budapest Ferihegy	T1	47º26'22,90"N	19º13'27,00"E
Budapest	BUD	Budapest Ferihegy	T2	47º26'00,69"N	19º15'43,82"E

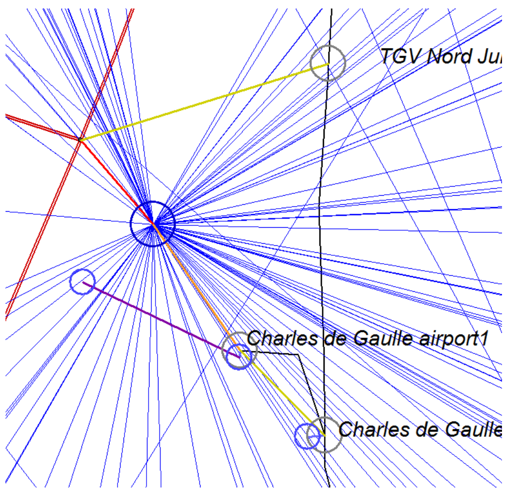


Figure 3-8 Modelling airports as interconnected terminal nodes