A LIAISON BETWEEN A SYSTEM DYNAMICS MODEL AND A NETWORK-BASED TRANSPORT MODEL – ADVANTAGES FOR HOLISTIC PROJECT ASSESSMENT AND CHALLENGES

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ABSTRACT

The broad and multi-dimensional impacts of transport policy strategies can, among other options, be assessed by a System Dynamics model or by the application of a network based transport model. Each assessment option has specific advantages and disadvantages. Coupling these models, in order to be able to make use of the intrinsic features of each model type however, raises certain methodological and technical challenges, since for example data structures and forecast horizon (dynamic forecasts by a System Dynamics model versus static forecasts by a network-based transport model) are strongly different among these model types. The current paper is devoted to the matter of how these two types of models can be linked with each other, by drafting data interchanges and the main challenges.

Keywords: impact assessment, transport model, transport policies, System Dynamics model, model linkage

1 INTRODUCTION

The broad and multi-dimensional impacts of transport policy strategies can, among other options, be assessed by a System Dynamics model or by the application of a network based transport model. Each assessment option has specific advantages and disadvantages.

A System Dynamics approach allows for deriving long-term trends of multi-dimensional, interrelated variables such as Gross Domestic Product, employment and population by age cohorts. Its characteristics enable the simulation of the origins of transport demand in terms of socio-economic drivers. One of its major benefits is the ability to draw long-term evolution paths of examined variables, and, thus, facilitate the comprehension of the way these impact variables are correlated with each other. The main aim of the application of a System Dynamics model is not necessarily to generate forecasts for a certain point of time in the future, but rather to draft the evolution path of an impact variable towards the final forecast horizon, by simulating the performance of the impact variables for intermediate time slices. However, System Dynamics models are usually applied to demonstrate feedback processes in simplified real world systems. Therefore common System Dynamics software packages are not prepared for calculations of large matrices, which are essential for tackling the geographical dimension of transport demand. Hence, transport demand is not covered at the level of transport links of a physical transport network in System Dynamics models, but rather at a 'functional' level, i.e. at the level of virtual flows on virtual link types that connect virtual regions.

On the contrary, a network based transport model allows for the computation of transport demand at the level of existing or planned network links and, thus, enables a detailed geographical depiction of transport demand (e.g. transport flows, congestion) and related impacts (e.g. emission of greenhouse gases or air pollutants). Forecasts are computed for a certain point of time in the future, without any simulations for intermediate years. However, a sole network-based transport model is not capable of covering impact variables of domains outside the transport sector.

The TEN-T Expert Group 1 noted in their proposal on TEN-T network planning *"[...] a single model, which can deliver all inputs needed for a comprehensive assessment [...] does not exist."* and *"[...] specific features of different assessment methods could generate valuable inputs for the final policy analysis [...]"* (TEN-T EXPERT GROUP 1 2010)

Thus, due to the specific features of each of these two model types, a combined and integrated usage of both models may complement these models for a holistic assessment of long-term transport policy strategies: while the network-based transport model is capable of predicting transport demand at the level of network links, and, thus, within a detailed geographical reference, the System Dynamics model can be used for simulating the evolution paths of impact variables beyond the transport domain. Coupling these models, in order to be able to make use of the intrinsic features of each model type however, raises certain methodological and technical challenges, since for example data structures and forecast horizon (dynamic forecasts by a System Dynamics model versus static forecasts by a network-based transport model) are strongly different among these model types. Therefore, the current paper is devoted to the matter of how these two types of models can be linked with each other, by drafting data interchanges and the main challenges.

The paper is structured as follows: After a brief overview over the main peculiarities of System Dynamics models and network based transport model, a rough overview of some representatives of these model types is given in section 2. In section 3, the System Dynamics model ASTRA and the network-based transport model VACLAV is introduced. The main challenges occurring when linking both models are explained in section 4. Section 5 gives an overview on two options of scope of linkages between the models, and on the technical interfaces between ASTRA and VACLAV. The paper concludes with section 6, the conclusions.

2 MAIN PECULIARITIES OF SYSTEM DYNAMICS MODELS AND NETWORK BASED TRANSPORT MODELS

2.1 System Dynamics models

The System Dynamics Society defines System Dynamics as *“a methodology for studying and managing complex feedback systems, such as one finds in business and other social systems”* (SDS 2008). System Dynamics as a methodology has been developed and applied in the 1960ies by FORRESTER (1962). The mathematical background is rather simple, as each System Dynamics model consists of maximum five types of variables: level variables (levels) and flow variables (rates) are the main elements building the feedback loops. Additionally parameters (constants), exogenous and auxiliary variables are completing the list of elements. STERMAN (2000) provides a comprehensive description of the System Dynamics methodology.

As transport can be considered as a derived demand from dynamics in socio-economic systems System Dynamics (SD) is a suitable modelling methodology for transport systems. SD allows the development of integrated modelling approaches like in the ASTRA model. This enables the dynamic simulation of feedback mechanisms between economy, society and transport in all directions. The major difference between static modelling approaches like Spatial Computed General Equilibrium (SCGE) and SD models is of course the steady state that is a prerequisite in SCGE models. Steady states are more an exception in real world systems than a common state such that the SD philosophy of allowing steady state but not demanding it at every point of time matches better to the complexity of real world systems. An example of a SCGE model is CGEurope described by CAU (2008). Additionally, SD allows the analysis of system states for complete time paths as opposed to static modelling methods which provide their results for a selected time in the future. While SCGE models induce dynamics from exogenous pathways of growth, dynamics in SD models arise from the interaction and feedbacks between the systems and within them. The calibration of behavioural parameters over long time series compared to calibration of one single point of time can be considered as a further benefit of System Dynamics compared to SCGE models. Furthermore, System Dynamics allows the application of expert judgements that enables better approximations of real-world systems. Especially this last issue led in the past to doubts about the validity of SD models. SD modellers have to be aware about the ability to produce any possible final result by alternating parameters. Therefore, methods of econometrics are required to ensure the validity of System Dynamics models, which is carried out for each of the ASTRA modules.

The advantage of these characteristics becomes obvious by having a closer look at an example. Freight transport is a result of industrial production of goods. Those goods can be distributed within a country or to other countries such that national production values as well as exports to other countries are drivers of freight transport volumes. On the one hand growing freight transport volumes have a direct impact back on the economy, as the transport service and duty vehicle production sectors benefit from this growth. As a result the final demand in these sectors increases which impacts again foreign trade and in the end again transport. On the other hand, increasing freight transport activities induce congestion which impacts the average freight transport times and also costs. This causal chain then feeds back into foreign trade, as the impact of transport costs and times on foreign trade is approved.

Hence, a modelling technique which enables the simulation of economic, society and transport systems within one integrated model provides a value-added in modelling transport demand. Having this in mind, the readers could raise the following question: Why are, under these circumstances, not all transport models based on this methodology? The answer is the high complexity of transport systems and the classical four stage transport modelling approach. The final stage of this approach foresees the assignment of transport demand per mode between origin and destination zones to the existing transport networks. The required level of detail cannot be simulated in SD models with existing System Dynamics software packages like Vensim© or MATLAB. Therefore, System Dynamics models have strong constraints which prevent from simulating detailed congestion effects on networks. The only imaginable solution to overcome these constraints is to link SD and static network models incorporating all benefits of both techniques.

2.2 Network-based transport models

In contrast to System Dynamics models, which tackle transport demand on a synthetic basis, for instance in terms of transport performance between functional zones, network-based transport models capture transport flows at the level of links of a network. The core of each network-based transport models are mode-specific network models, in which the transportation networks are modelled as directed graph, i.e. a sequence of links that are connected by nodes. The data for each link of a network model should include “at the very minimum” (ORTÚZAR AND WILLUMSEN 2001):

- Length,
- Travel speeds,
- Capacity.

“More elaborate models” (dto.) require –depending of the model’s scope of application – additional attributes, such as type of road/ rail infrastructure, road with, number of lanes/ tracks or type of junctions.

Most of the recent examples of long-distance travel demand studies and long-distance models in Europe and the United States synthesized by ZHANG AND HU (2009) as well as by SOUTHWORTH AND HU (2009) are network-based transport models. In normal practice, network-based transport demand models embrace the stage of assignment, in which the expected demand is allocated to the network models' individual links. In comparison to other model types, network-based transport models have following main advantages:

- Consideration of congestion and bottlenecks;
- More detailed assessment of environmental impacts, such as noise, CO_2, NO_X or particulates;
- Possibility to perform analyses on interdependence among network links or among transport infrastructure projects (SZIMBA 2008).

Furthermore, assignment results of a network based transport model can be used for computing 'level-of-concern' indicators (see e.g. SZIMBA ET AL. 2004), which measure the dimension of impacts that transport movements have on inhabitants living in their proximity, or on natural sensitive areas concerned by negative impacts of transport.

Many of the network-based transport models follow the principles of a 4-stage transport demand model. However, a network-based transport model does not necessarily presume the application of a 4-stage model, as the steps of traffic generation, distribution and mode choice may well differ from the modelling approaches of a 4-stage algorithm.

There is a wide range of different network-based transport demand models available in Europe, most of them at the national, regional or urban level. On behalf of the European Commission, three types of network based transport models have already been applied:

- the STREAMS model and the subsequently developed SCENES model,
- the VACLAV model,
- and the TRANS-TOOLS model.

The STREAMS model was the first pan-European network-based multi-modal transport model, consisting of independent passenger and freight demand model components, and having the year 1994 as a base year (see Leitham et al. 1999). The geographical coverage was the EU, at that time consisting of 15 countries. The underlying zoning system was based on the NUTS2 classification, resulting to around 200 internal zones. The STREAMS model has been the basis of the SCENES model which was developed in the period of time 1998-2002. The geographical scope was extended to eight Central and Eastern Europe Countries (CEEC), resulting to 250 zones in Europe (see ME&P, IWW, INRETS et al. 2002)

The VACLAV model developed at the IWW[1] has been developed continuously since its inception in the 1990s. Its structure represents a classic four-stage transport model

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consisting of the following sub-models: trip generation, trip distribution, modal choice and trip assignment. It covers the whole of EU, including most of the neighbouring countries, by a NUTS3 zoning system resulting to around 1,300 traffic cells.

A specific strength of the VACLAV passenger transport model is its capability of modelling intra-zonal road traffic demand, i.e. passenger traffic flows within a NUTS-3 region. A brief documentation of the model is provided within section 3.2.

On behalf on the EU, VACLAV has been applied – together with the NEAC freight demand model – in projects such as TEN-STAC (NEA et al. 2004), the Feasibility Study on the Rail Baltica railways (COWI et al. 2006) and the TINA-Turkey project (TINA transport strategies et al. 2007).

TRANS-TOOLS is a network-based European transport and assessment model which has been being developed on behalf of the European Commission since 2004, and represents a tool which contains methodologies of several European transport and assessment models. The model's most recent version is model version 2. Its geographical scope is the whole EU and the neighbouring countries. The zoning system of the traffic cells is mainly in line with the regional structure used by the European Union's statistical authority EUROSTAT, and represents NUTS-3 region (freight/ logistics partly NUTS-2).

The model consists of following sub-modules (see e.g. Burgess et al. 2008):

- Passenger module
- Freight module
- Logistics module
- Assignment module
- Regional economic module
- External impact module

The TRANS-TOOLS model is hosted by the European Commission's Joint Research Centre (JRC/ IPTS) in Seville and is subject to continuous further development and extensions. It represents the designated transport demand and impact assessment model of the European Commission.

Certain elements of the VACLAV model have been included in the first version of the TRANS-TOOLS model.

3 BRIEF OVERVIEW OVER THE MODELS INVOLVED

This chapter gives a brief overview to the System Dynamics model ASTRA and the network based transport model VACLAV.

3.1 Methodological description of ASTRA

ASTRA (Assessment of Transport Strategies) is applied for Integrated Assessment of policy strategies. The model is implemented as System Dynamics model. The ASTRA model has been developed and applied in a sequence of European research projects by three Institutions since 1998: Fraunhofer-ISI, IWW and TRT. The ASTRA model consists of nine modules that are all implemented within one Vensim© System Dynamics software file:

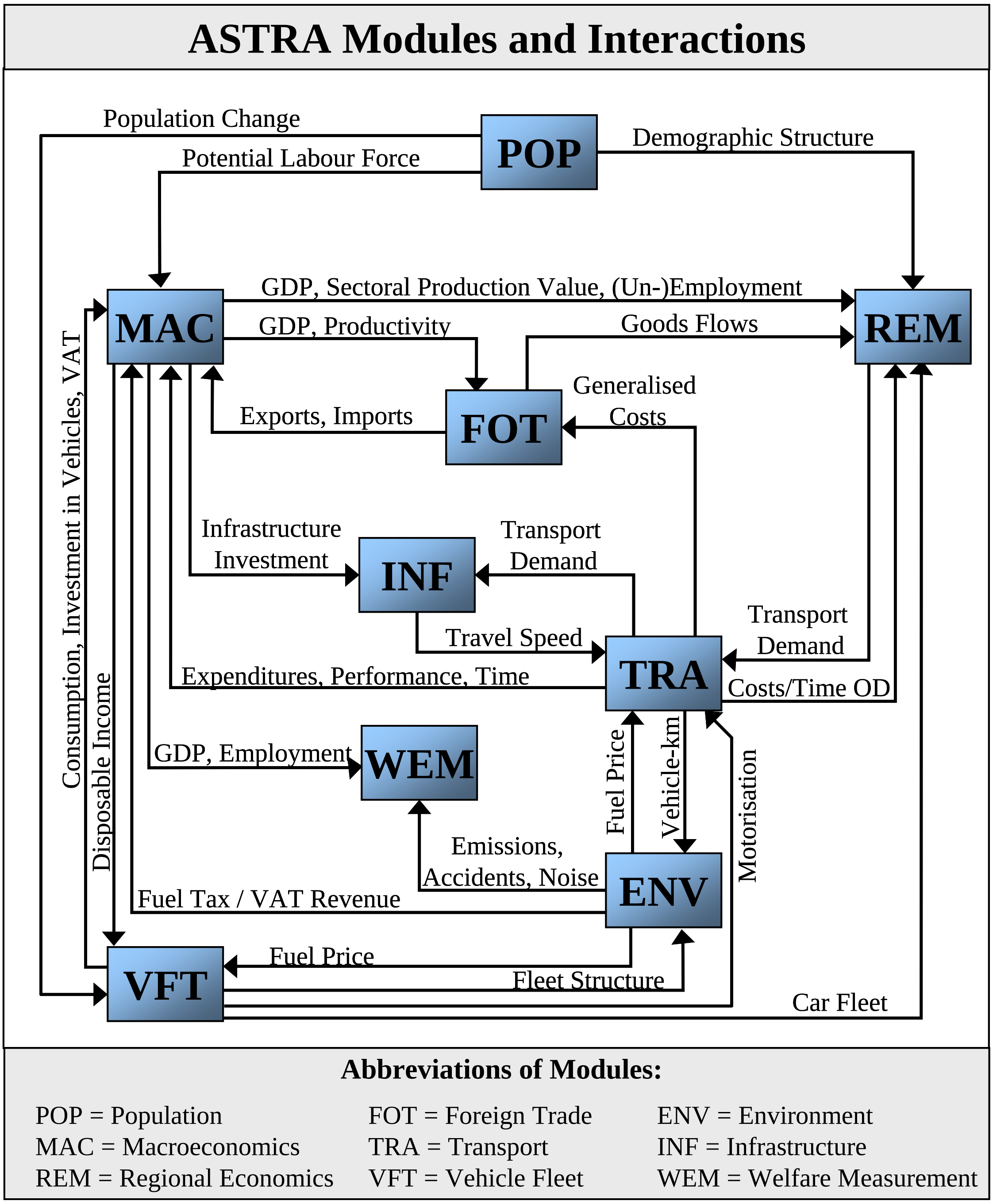
- Population module (POP),
- Macro-economic module (MAC),
- Regional economic module (REM),
- Foreign trade module (FOT),
- Infrastructure module (INF),
- Transport module (TRA),
- Environment module (ENV),
- Vehicle fleet module (VFT) and
- Welfare measurement module (WEM).

An overview on the nine modules and their main interfaces is presented in Figure 1.

The Population Module (POP) provides the population development for the 29 European countries with one-year age cohorts. The model depends on fertility rates, death rates and immigration of the EU27+2 countries. Based on the age structure, given by the one-year-age cohorts, important information is provided for other modules like the number of persons in the working age or the number of persons in age classes that permit to acquire a driving license.

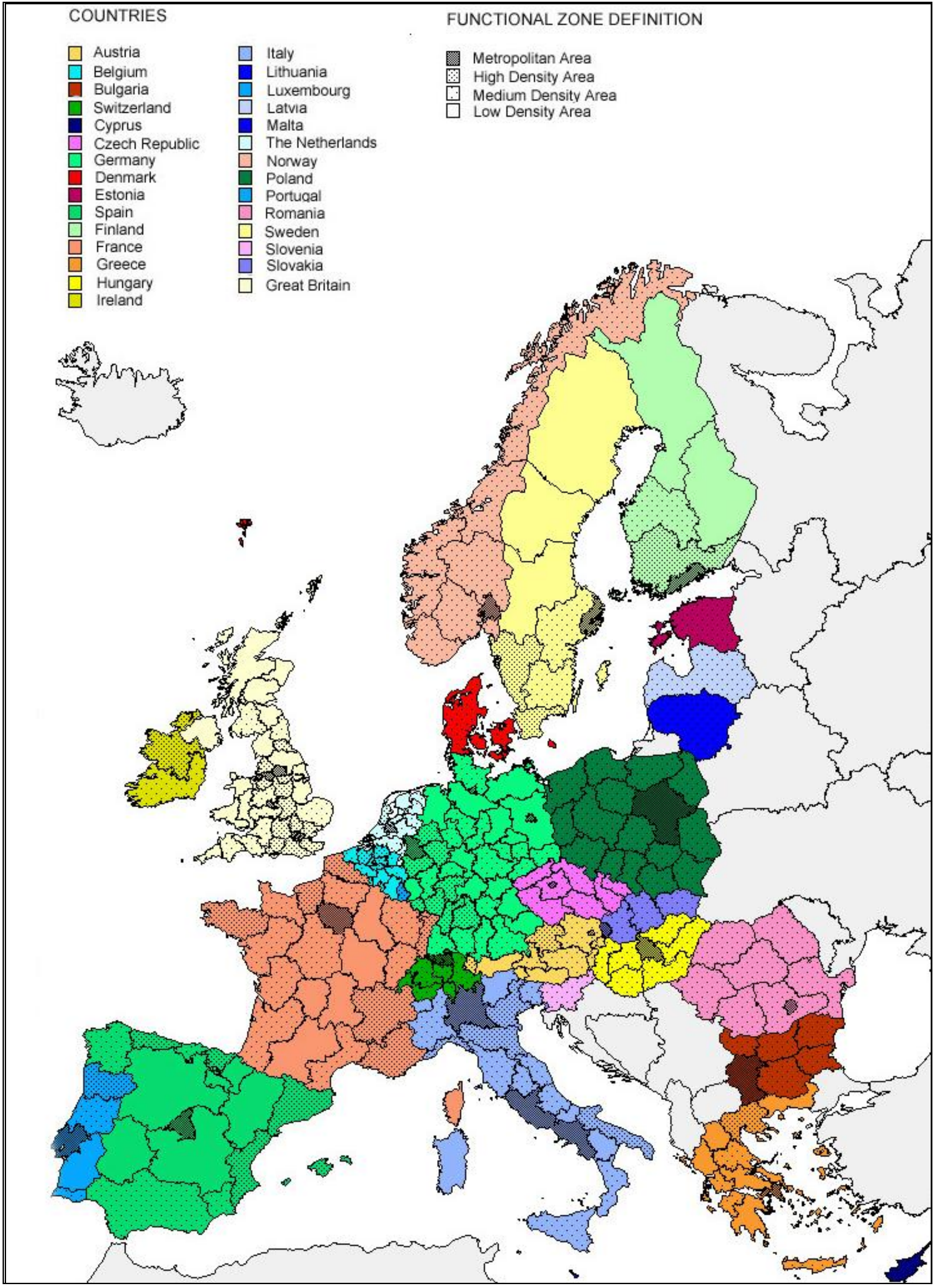
The Macro-economic module (MAC) provides the national economic framework, which imbeds the other modules.

The Regional Economic Module (REM) mainly calculates the generation and spatial distribution of freight transport volume and passenger trips. The number of passenger trips is driven by employment situation, car-ownership development and number of people in different age classes. Trip generation is performed individually for each of the 76 zones of the ASTRA model (see Figure 2). Distribution splits trips of each zone into three distance categories of trips within the zone and two distance categories crossing the zonal borders and generating OD-trip matrices with 76x76 elements for three trip purposes. Freight transport is driven by two mechanisms: Firstly, national transport depends on sectoral production value of the 15 goods producing sectors where the monetary output of the input-output table calculations is transferred into volume of tons by means of value-to-volume ratios. For freight distribution and the further calculations in the transport module the 15 goods sectors are aggregated into three goods categories. Secondly, international freight transport i.e. freight transport flows that are crossing national borders are generated from monetary Intra-European trade flows of the 15 goods producing sectors. Again, transfer into volume of tons is performed by applying value-to-volume ratios that are different from the ones applied for national transport. In that sense the export model provides generation and distribution of international transport flows within one step on the base of monetary flows.



Source: KRAIL (2009)

Figure 1 ASTRA Modules, Main Outputs and their Interactions



Source: KRAIL (2009)

Figure 2 Overview of Spatial Differentiation in ASTRA

The Foreign Trade Module (FOT) is divided into two parts: trade between the EU27+2 European countries (INTRA-EU model) and trade between the EU27+2 European countries and the Rest-of-the-World (RoW). Since transport cost and time are not modelled for transport relations outside EU27+2, transport is not considered in the EU-RoW model. The resulting sectoral export-import flows of the two trade models are fed back into the macroeconomics module as part of final demand and national final use respectively.

Secondly, the INTRA-EU model provides the input for international freight generation and distribution within the REM module.

The Infrastructure Module (INF) provides the network capacity for the different transport modes. Infrastructure investments derived both from the economic development provided by the MAC and from infrastructure investment policies alter the infrastructure capacity. Using speed flow curves for the different infrastructure types and aggregate transport demand the changes of average travel speeds over time are estimated and transferred to the TRA where they affect the modal choice.

Major input of the Transport Module (TRA) constitutes the demand for passenger and freight transport that is provided by the REM in form of OD-matrices (i.e. matrices linking origin and destination of transport activities). Using transport cost and transport time matrices the transport module performs the modal-split for five passenger modes and three freight modes. The cost and time matrices depend on influencing factors like infrastructure capacity and travel speeds both coming from the INF module, structure of vehicle fleets, transport charges, fuel price or fuel tax changes. Depending on the modal choices, transport expenditures are calculated and provided to the macroeconomics module. Changes in transport times are transferred to the macroeconomics module such that they influence total factor productivity. Considering load factors and occupancy rates respectively, vehicle-km are calculated.

Major outputs of the TRA provided to the Environment Module (ENV) are the vehicles-km travelled (VKT) per mode and per distance band and traffic situation respectively. Based on these traffic flows and the information from the vehicle fleet model on the national composition of the vehicle fleets and hence on the emission factors, the environmental module calculates the emissions from transport. Besides emissions, fuel consumption and, based on this, fuel tax revenues from transport are estimated by the ENV. Traffic flows and accident rates for each mode form the input to calculate the number of accidents in the European countries. Expenditures for fuel, revenues from fuel taxes and value-added-tax (VAT) on fuel consumption are transferred to the macroeconomics module and provide input to the economic sectors producing fuel products and to the government model.

The Vehicle Fleet Module (VFT) describes the vehicle fleet composition for all road modes. Vehicle fleets are differentiated into different age classes based on one-year-age cohorts and into different emission standard categories. The car vehicle fleet is developing according to income changes, development of population, fuel prices, fuel taxes, maintenance and purchase cost of vehicles, mileage and the density of filling stations for the different type of fuels. Considered car vehicle technologies include conventional vehicles (3 gasoline types, two diesel types), CNG, LPG, bio ethanol, hybrid, battery electric and hydrogen fuel cell cars. Vehicle fleet composition of buses, light-duty vehicles and heavy-duty vehicles mainly depends on travelled kilometres and the development of average annual mileages per vehicle of these modes. The purchase of vehicles is translated into value terms and forms an input of the economic sectors in the MAC that cover the vehicle production.

Finally, in the Welfare Measurement Module (WEM) major macro-economic, environmental and social indicators can be compared and analysed.

For more details on ASTRA, the most comprehensive description of the model can be found in SCHADE (2005) and KRAIL (2009).

3.2 Methodological description of VACLAV

The VACLAV model is a network-based passenger transport model whose European roots lie in the STEMM[2] project (EBERHARD ET AL. 1998), and which has been developed continuously since its inception. Its structure represents a classic four-stage transport model consisting of the following sub-models (e.g. ORTÚZAR AND WILLUMSEN 2001; MCNALLY 2000):

- trip generation, in which the total number of trips originating in a traffic cell is calculated

- distribution, in which the destinations of the trips are defined, so that the elements of the origin/destination matrix (O/D matrix) are determined,

- modal split, in which the share of modes (rail, road, air, coach) are calculated for each O/D pair,

- and trip assignment, in which the demand for each O/D pair per mode is assigned to the referring network on a route r.

The model's geographical scope is the whole European continent, with Russia, Belarus, Ukraine and the Balkan countries considered as external zones. The zoning system of the traffic cells is mainly in line with the regional structure used by the European Union's statistical authority EUROSTAT, and represents NUTS[3] 3 regions.

The current version of the zoning system with about 1350 zones which models EU27+2 and its neighbours is shown by Figure 3.

Freight traffic is not modelled by VACLAV. To include congestion effects for road exogenous freight matrices with trucks and tonnes are assigned together with the passenger car matrices.

A specific strength of the VACLAV passenger transport model is its capability of modelling intra-zonal road traffic demand, i.e. passenger traffic flows within a NUTS-3 region. For this purpose, land cover grid data is joined with socio-economic data at the level of statistical regions, in order to generate "geographical base units", which in the next step are subjected to a cluster analysis. Finally "sub-zones" or "access zones" are identified, which are treated as additional cells within a NUTS-3 traffic cell, and whose estimated demand is taken into account by an adapted assignment procedure.

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[2] STEMM: Strategic European multi-modal modelling
[3] NUTS: Nomenclature of Territorial Units for Statistics

Figure 3 NUTS3 traffic zones used in VACLAV

VACLAV is scenario oriented and used for point forecasts with the focus on infrastructure measures or network related pricing policies.

The model is developed under Linux and is able to use multiple processors to speed up the assignment. Current runtime for computation is about one hour per scenario using several computers.

The most detailed documentation of the VACLAV model is provided by SCHOCH (2004).

4 MAIN CHALLENGES

The challenges to link both models are to bridge the different computer platforms, to convert the different data structures and make use of the forecasting properties of both models.

4.1 Communication between the models

ASTRA is implemented in the System Dynamics Tool Vensim©, which is only available for the Windows platform. VACLAV on the other hand has been developed in C/C++ under Unix/Linux and uses parallel algorithms to make use of multiple processors to reduce the running time.

Because both models run on different platforms using different operating systems a framework for the communication and process control is needed. The current approach uses PVM (Parallel Virtual Machine (2010)) (SUNDERAM ET AL. 1990 & 1994) which is a software framework available for Windows and Unix/Linux that allows message-passing, task and resource management for a heterogeneous computer network.

The Vensim© software which is used to run ASTRA offers the use of an external library (DLL) for external functions which can be developed by the user. Within this library a set of functions have been implemented to start and stop VACLAV on the Linux cluster and send and request data sets between both models.

4.2 Bridging the gap between functional and NUTS representation

The zoning differences between ASTRA with 76 functional zones (see Figure 2) and VACLAV with about 1350 zones (see Figure 3) create an asymmetrical situation for the data flows between both models. The data has to be aggregated and disaggregated depending on the direction. Data has been transferred between the models in earlier projects by mapping the functional zones to their corresponding NUTS2 and NUTS3 regions. Since there are revisions to the NUTS3 layer every few years, this mapping has been updated to the latest version used for the base year 2005 of VACLAV.

Relations between regions in ASTRA are furthermore classified into distance bands as shown in Table 1 and Table 2.

The NUTS3 O/D relations of VACLAV can be sorted accordingly. Due to the zonal diameters of the NUTS3 zones, which are in many cases greater than 40km (for instance in Spain), there is only a reliable mapping for the O/D relation to the distance bands for distance bands greater than 40km. Thus only MD and LG are applicable for passenger and REG, MED and LGD for freight.

Table 1 ASTRA distance bands for passenger traffic

Code	Name	Distance band
LC	Local	0 - 3.2km
VS	Very Short	3.2 - 8km
ST	Short	8 - 40km
MD	Medium	40 - 160km
LG	Long	160km and more

Table 2 ASTRA distance bands for freight traffic

Code	Name	Distance band
LOC	Local	0-50km
REG	Regional	50-150km
MED	Medium	150-700km
LGD	Long	700km and more

The data transferred between VACLAV and ASTRA is mainly of the following structure:

$$Data_{VACLAV}[o_{n3}, d_{n3}] \rightarrow Data_{ASTRA}[o_c, o_{fz}, d_c, d_{fz}, db]$$

or

$$Data_{ASTRA}[o_c, o_{fz}, d_c, d_{fz}, db] \rightarrow Data_{VACLAV}[o_{n3}, d_{n3}]$$

with

o_{n3}	origin as NUTS3
d_{n3}	destination as NUTS3
o_c	country of origin (EU27+2)
o_{fz}	functional zone of origin
d_c	country of destination (EU27+2)
d_{fz}	functional zone of destination
db	distance band.

The arrow “→” denotes the transformation of the data output of one model into the format of the other model.

In the first case a weighted aggregation of impedance values is performed. For passenger data the population of the two NUTS3 zones relatively to the whole population of the belonging functional zones is used. GDP weights are applied for the aggregation of freight data accordingly. This is done to reflect the varying importance of different zones.

The disaggregation is more complex, since the VACLAV matrices are much more detailed compared to ASTRA matrices. To preserve the level of detail, the data from ASTRA is used as trend input to generate the detailed forecast matrix. The growth factors from the ASTRA matrices are applied to the corresponding parts of the VACLAV matrices and adjusted with the Furness algorithm (see ORTÚZAR AND WILLUMSEN 2001)

The classification of NUTS3 relations to the distance bands is done only for the base year and then kept constant since the distance bands are constant within ASTRA itself and changing them dynamically with different distances through changing infrastructure or changing congestion situations would cause further problems.

For the neighbouring countries not considered in ASTRA, a business-as-usual scenario (i.e. default growth values) is applied.

4.3 Combining path and point forecast

A further difference between both models lies in the scope of the forecast. ASTRA results in a forecasted path whereas VACLAV computes point forecasts.

The idea is to deliver demand trend forecasts from ASTRA to VACLAV to facilitate scenario creation for future scenario years and to feed back the impact of the assigned demand trends from VACLAV to ASTRA.

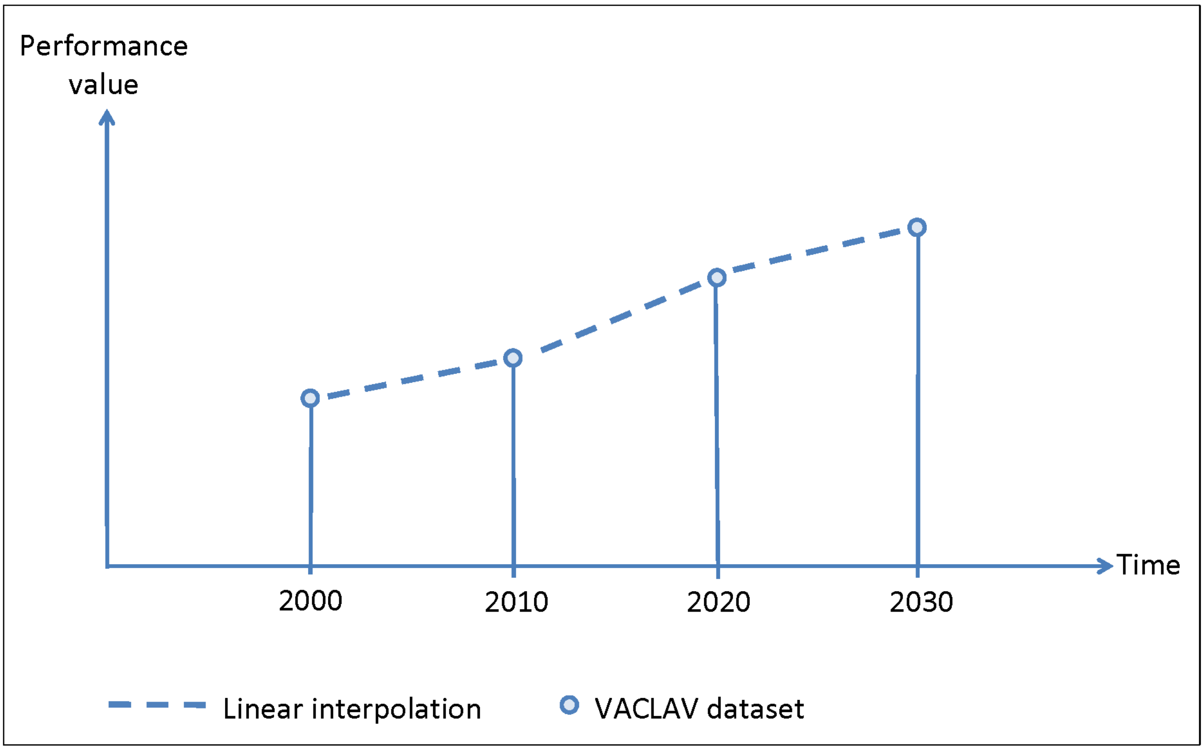


Figure 4 Interpolation of data between VACLAV datasets

The demand trend matrices can easily be transferred at the right time from ASTRA to VACLAV. But the other way round is more difficult. Since the VACLAV running time per scenario is about one hour, it is not feasible to have more than four to eight scenarios for a complete run. Currently the setup uses only four VACLAV calls.

Using only four data points for the whole ASTRA run would induce shock-like moments to the dynamic system. To avoid this, linear interpolation is used between those data points. To estimate the interpolation in a current run, the data points of a previous iteration are used as shown in Figure 4.

5 MODEL LINKAGE

This chapter describes in the first part the scope of linkage and introduces two linkage variants, while the second part is devoted to a technical description of the interfaces.

5.1 Scope of linkage

The proposed linkage offers two possibilities to have both models interact: a passive (or weak) linkage where pre-computed data from the one model is fed into the running model and an active (strong) linkage with both models running and interacting with each other.

The weak linkage variant allows for stand-alone models which still benefit of the data outputs of the other model while preserving the current running time of each model, whereas the strong linkage creates a framework in which both models influence each other directly.

5.1.1 Weak linkage

With the passive/ weak linkage only one model runs actively and gets fed with pre-computed data from the other model. The running time of both variations does not differ significantly from the running time of the stand-alone models.

For the weak linkage, there are two possibilities of model configuration:

1. VACLAV is run, pre-computed datasets from ASTRA are used
2. ASTRA is run, pre-computed datasets from VACLAV are used

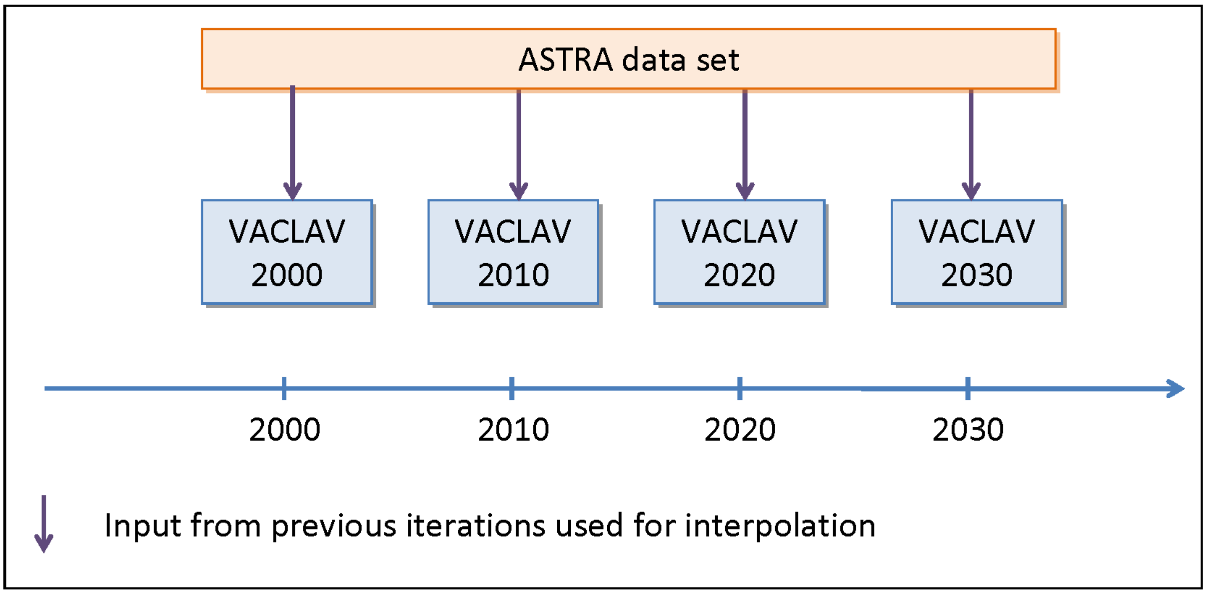


Figure 5 Weak linkage between ASTRA data and VACLAV running

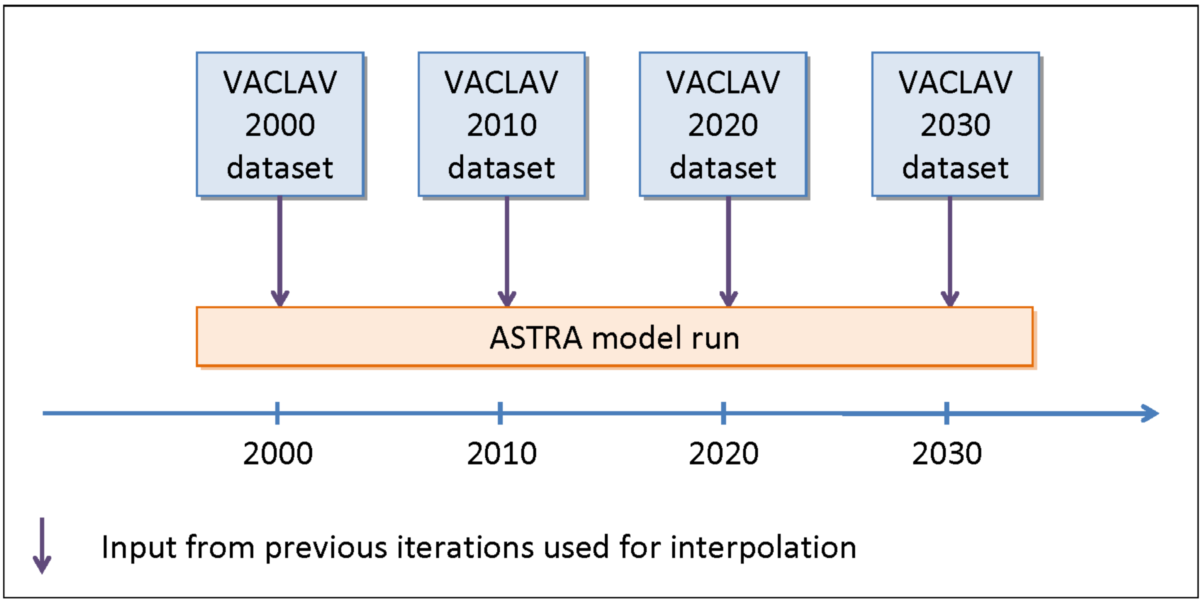
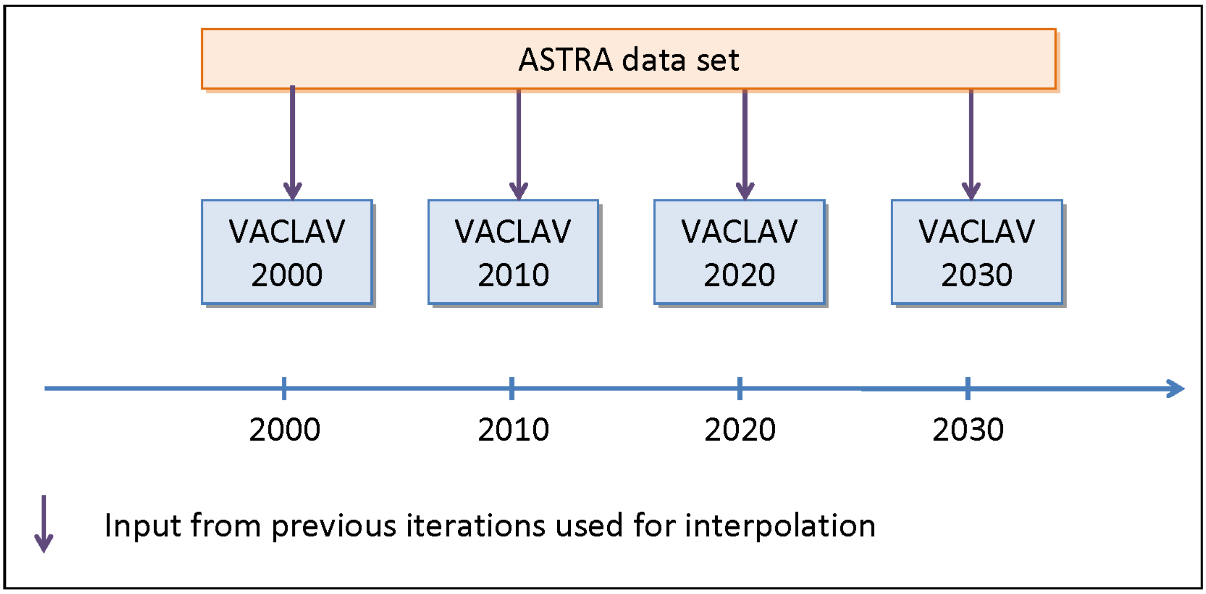


Figure 6 Weak linkage between VACLAV data and ASTRA running



Alternative (1) with only VACLAV running (Figure 5) uses pre-computed ASTRA output to create the passenger and freight demand matrices used for single VACLAV scenarios. This setup allows also variable VACLAV scenario years regarding the demand matrices and minimizes the work needed to create forecast demand matrices for VACLAV. It can also be used for comparing several ASTRA scenarios at assignment level.

One run of this weak linkage is also needed to bootstrap the strong linkage described in the following subchapter.

Applying alternative (2) implies using four pre-computed VACLAV datasets for the years 2000, 2010, 2020 and 2030 as input for a complete ASTRA run (Figure 6). Currently only four datasets are used because the available infrastructure scenarios of VACLAV are limited to these years and the running time of VACLAV.
ASTRA is started and the impedance datasets from VACLAV are used to interpolate the development path of the impedances for each time step of ASTRA (see chapter 4.2).

This approach makes it possible to compare multiple ASTRA runs with different infrastructure datasets.

The pre-computed datasets used for the weakly linked runs are results from several iterations of a strongly linked run to make use of the mutual impact.

Weak linkage offers the possibility to use each model as a stand-alone tool while still using the output of the other model.

5.1.2 Strong linkage

In case of an active/ strong linkage, ASTRA is started and VACLAV is run every ten years (see Figure 7).

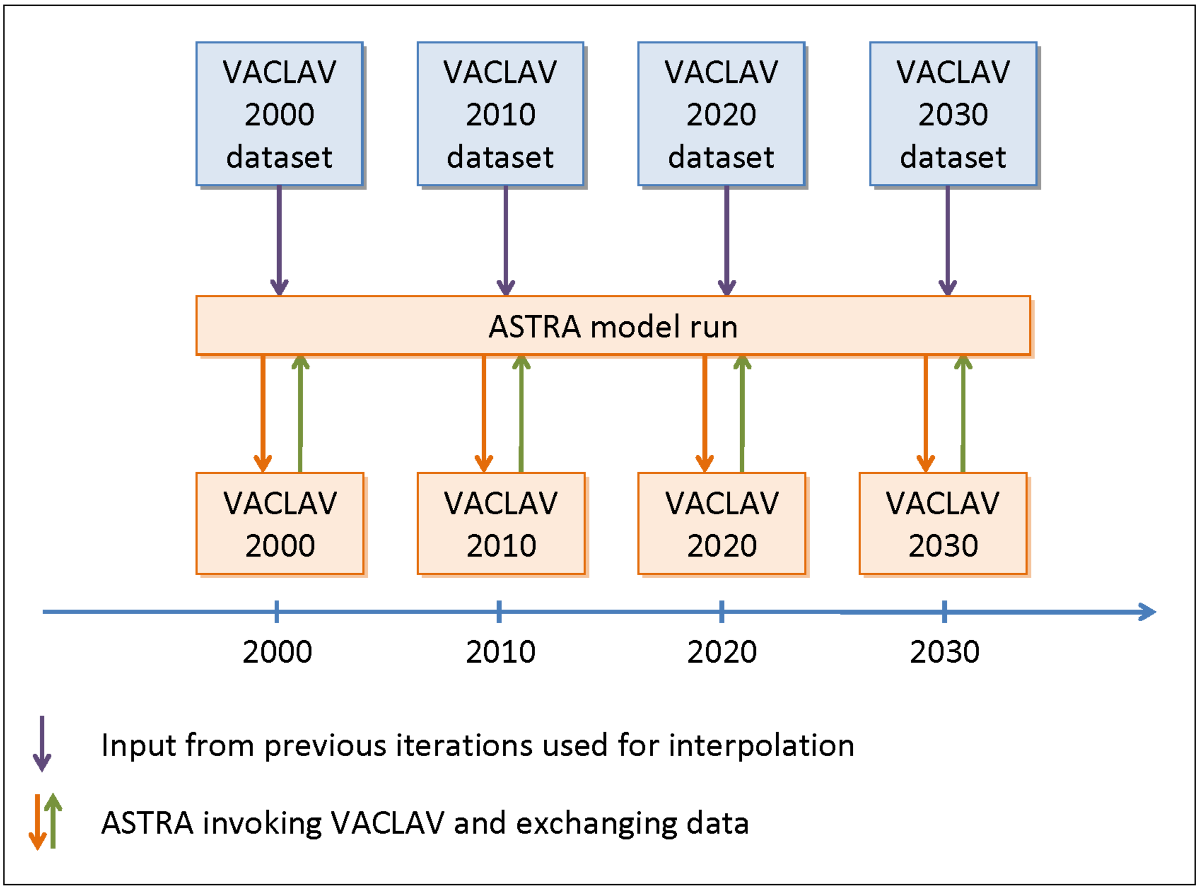


Figure 7 Strong linkages between ASTRA and VACLAV with both models active and datasets from previous VACLAV runs

The NUTS3 demand matrices for passenger and freight are constructed from the base matrices and the demand trends from ASTRA (see chapter 4.2) and then VACLAV does the assignment. In the next step impedance data is computed, aggregated and transferred back to ASTRA.

To avoid system shocks for ASTRA, data in between those data points is extrapolated with growth factors resulting from a previous iteration or a weak linkage computation (see chapter 4.3).

Several complete iterations are performed in order to ensure a proper feedback of the impacts of both models on each other. Two or three iterations are expected to be sufficient.

The running time of the run with the strongly linked models takes about 4.5 hours mainly due to the involvement of the VACLAV model.

Output of strongly linked runs can be used as input for weakly linked runs so weak linkage runs benefit from the mutual impact of both models.

5.2 Technical description of the interface

The following sub-chapters describe the data flows between both models.

5.2.1 Data flow from ASTRA to VACLAV

Currently the main inputs from ASTRA for VACLAV are the passenger and freight demand trend matrices for both passengers and freight for different years.

The ASTRA passenger trip matrix is extracted after the distribution step, right before the modal split. The matrix is used to generate the demand trends, which are applied to compute the NUTS3 demand forecast matrix (see chapter 4.2)

The model split is computed with VACLAV to take advantage of the detailed model information for all 1.8 million O/D relations. Flows in the distance bands below 40km are not considered yet since VACLAV uses pre-computed data for the intrazonal trips which has been adjusted to the modelled network and special distribution of settlement areas.

The data transformation can be characterized as

$$\text{PassengerData}_{\text{ASTRA}}[p, o_c, o_{fz}, d_c, d_{fz}, db] \rightarrow \text{PassengerData}_{\text{VACLAV}}[p, o_{n3}, d_{n3}]$$

with

p	purpose (business, private or holiday)
o_c	country of origin (EU27+2)
o_{fz}	functional zone of origin
d_c	country of destination (EU27+2)
d_{fz}	functional zone of destination
db	distance band (MD or LG)
o_{n3}	origin as NUTS3
d_{n3}	destination as NUTS3.

The freight matrix of ASTRA is extracted after the modal split and the demand trends are transferred for the freight modes rail and road. VACLAV uses only exogenous freight data and has currently no modelling capabilities which makes it necessary to use the modal split of ASTRA. Freight flows below 50km are not considered yet. Also intrazonal freight flows are not modelled by VACLAV.

The freight data is transformed according to

$$\text{FreightData}_{\text{ASTRA}}[gc, m, o_c, o_{fz}, d_c, d_{fz}, db] \rightarrow \text{FreightData}_{\text{VACLAV}}[gc, m, o_{n3}, d_{n3}]$$

with

gc	goods category (bulk, general cargo or unitized)
m	mode (rail or road)
o_c	country of origin (EU27+2)
o_{fz}	functional zone of origin
d_c	country of destination (EU27+2)
d_{fz}	functional zone of destination
db	distance band (REG, MED or LGD)
o_{n3}	origin as NUTS3
d_{n3}	destination as NUTS3.

5.2.2 Data flow from VACLAV to ASTRA

The data generated by VACLAV and used in ASTRA are mainly impedance data. Values are given for travel time (in hours), distance (in km), tolls (in €). Furthermore, information about the average travel speed (in h/km), average trip length affected by congestion (in km) and average motorway shares per country (in %) for each relation are given.

The impedance data is calculated after the assignment of VACLAV and is used as input in the TRA module of ASTRA for the modal split computation.

For all passengers purposes impedance data for the modes rail, road and air are aggregated from NUTS3 to the functional zone representation (see chapter 4.2). Only distance bands over 40km are considered.

Passenger impedance data is aggregated within the following structure:

$$\text{PassImpedanceData}_{\text{VACLAV}}[m, p, o_{n3}, d_{n3}] \rightarrow \text{PassImpedanceData}_{\text{ASTRA}}[m, p, o_c, o_{fz}, d_c, d_{fz}, db]$$

with

m	mode (rail, road or air)
p	purpose (business, private or holiday)
o_{n3}	origin as NUTS3
d_{n3}	destination as NUTS3
o_c	country of origin (EU27+2)
o_{fz}	functional zone of origin
d_c	country of destination (EU27+2)
d_{fz}	functional zone of destination
db	distance band (MD or LG)

Freight impedance data is generated and aggregated for the modes road and rail. The ship mode (sea and inland waterways) is currently not implemented in VACLAV. Only distance bands greater than 50km are considered.

The aggregation of freight impedance data is performed within the subsequent structure:

$$\text{FreightImpedanceData}_{\text{VACLAV}}[m, o_{n3}, d_{n3}] \rightarrow \text{FreightImpedanceData}_{\text{ASTRA}}[m, o_{c}, o_{fz}, d_{c}, d_{fz}, db]$$

with

m	mode (rail or road)
o_{n3}	origin as NUTS3
d_{n3}	destination as NUTS3
o_{c}	country of origin (EU27+2)
o_{fz}	functional zone of origin
d_{c}	country of destination (EU27+2)
d_{fz}	functional zone of destination
db	distance band (REG, MED or LGD)

5.3 Synthesis

We have seen a framework for ASTRA and VACLAV (see Figure 8) in which complementary data for both models are passed between both models.

Demand trends from ASTRA are disaggregated and prepared for point scenarios of VACLAV. VACLAV uses these trends to generate demand matrices which in the next step are assigned. The loaded networks are evaluated and impedance datasets are generated which subsequently are aggregated and transferred to ASTRA. The point forecasts of VACLAV are converted with interpolation methods to path forecasts, which are fed into ASTRA.

The strong linkage variant allows the models to interact and influence each other directly. The running time and model setup with different computer environments for both models needed is limiting the portability and usage. These limitations are mitigated with the weak linkage variants, but at the cost of direct interaction between the models.

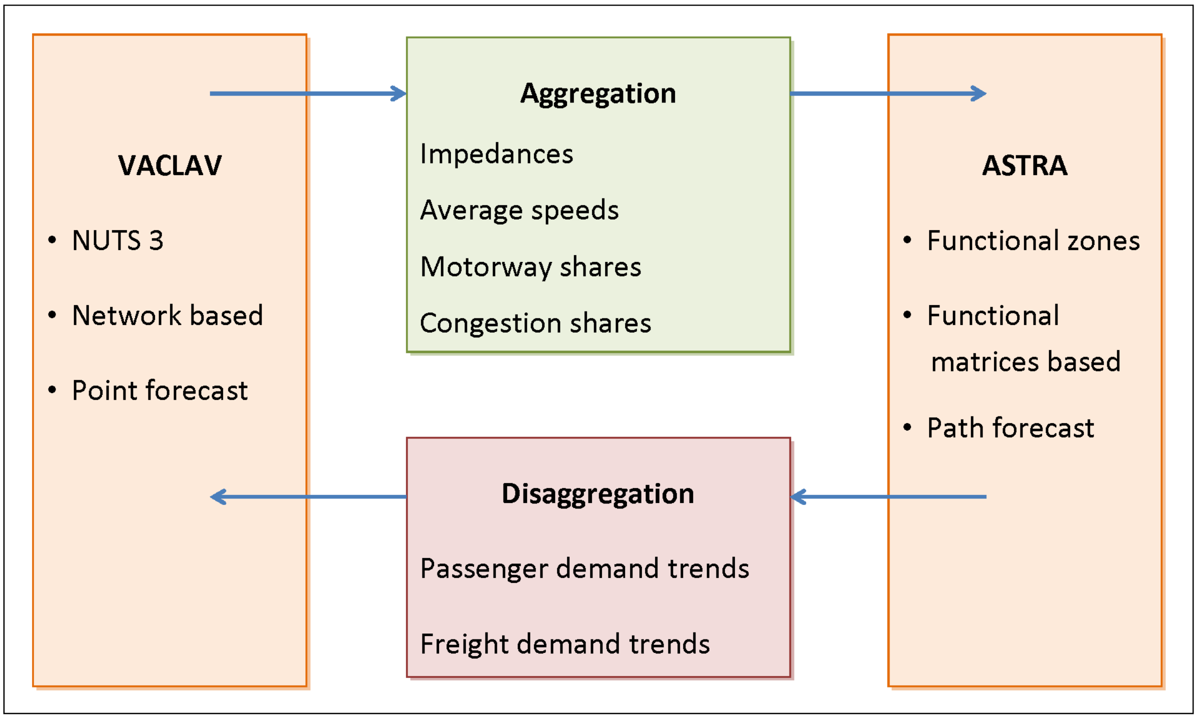


Figure 8 Interactions between ASTRA and VACLAV

Two different types of linkages between these models have been sketched and discussed. With these linkages both models can benefit from each other. The first variant of the weak linkage allows an easy creation of forecast demand matrices for VACLAV and visualization of ASTRA results, the second weak variant enables better impacts of routing or infrastructure measurements in ASTRA. The strong linkages combines both weak linkage approaches and creates a framework in which the impacts of both models on each other can be harmonized and more versatile policy and infrastructure scenarios can be analyzed.

6 CONCLUSIONS

The paper has drafted an approach to combine and integrate a network-based transport model with a System Dynamics model, in order to join the intrinsic advantages of both modeling philosophies. While network-based transport models are capable of predicting transport demand at the level of network within a detailed geographical reference, System Dynamics models can be used for simulating the evolution paths of impact variables beyond the transport domain.

With special focus on the European network-based transport model VACLAV and the European System Dynamics model ASTRA, certain methodological and technical challenges were dealt with. The linkage allows overcoming some disadvantages of both models: ASTRA gains direct access to network modelling results and impedance changes at origin/ destination level, while VACLAV gains the feedback to demography, economy and employment trends. The combination creates a coherent holistic assessment approach for infrastructure policies for impact on the regional and macro-economic level and the environment. The regional model feeds back into the transport model and allows to capture indirect effects and medium- and long-term impacts (LAIRD (2005) and TAVASSZY (2004)).

After the finalization of the implementation of the presented linkages between both models, it has to be explored which further outputs of each model can be used for the other model. For instance, using vehicle fleet data from ASTRA allows refined corridor analysis with restriction on vehicle types allowed on certain links. Adding sea and inland waterways assignments for freight to VACLAV would allow VACLAV to utilize the freight trends from ASTRA. Intra-zonal freight traffic is another area in VACLAV's scope which can be improved by using input data from ASTRA, since intrazonal freight traffic is currently not modeled in VACLAV.

Concluding, the paper has outlined a method for holistic assessment of most types of transport policies, by combining and integrating models of different philosophies in a complementary way. The designed approach establishes the basis for completing the technical implementation and, after a careful assessment of obtained results, for a future extension of the scope of data transfer between the two models.

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