A General Model to Support Transport Planning

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0. Abstract

This paper examines a transportation model which is to be used as a support in planning and whose main requirement is general applicability in terms of both geographical area and user levels.

The model treats the transport network as a system of finite elements characterized by a transit delay. These elements are nodes, legs or links, and carriers.

The model consists of a series of cores, each of which applies to a different commodity. Integration in the network takes place on the legs at carrier level. The elements of each core are characterized by both operational and economic performance.

The dynamics run on two time scales: day-to-day and year-to-year.

The model is implemented by discrete-event, object-oriented languages and provides a scenario for decision-making problems, which are typically approached using System Dynamics methods[1].

1. Introduction

1.1 Navigation, Traffic, Transport

The conduct of a carrier represents a navigation problem, interaction between carriers is a traffic problem, while the flow of carriers creates transport.

The models that correspond to these processes lie at different hierarchical levels, meaning that they may be incorporated into a shell framework where the transport model creates the background conditions for the traffic model and this in turn does the same for the navigation model.

In functional terms, the navigation model defines the requirements for the traffic model, which in turn establishes the transport model. Hence, the shell framework is related to a pyramidal layout of the models: the transport model may be used as a scenario for a number of traffic models, each of which can be applied to a range of navigation models.

However, in practical application the only models of interest are those which can serve as a tool for exploring possible solutions to critical situations. Irrespective of the specific problem, a suitable approach requires definition of a scenario, namely a transport model.

The main objective pursued in the design of the model under discussion is wide-ranging application; in other words, the goal is to obtain a single transport model which may be applied to

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[1] This model has been developed with funding from the Italian National Research Council as part of the "Progetto Finalizzato Trasporti 2" targeted project.

any specific application problem within the above-mentioned shell framework. This generality not only allows the model to be applied to any transport network but also enables the user to conduct planning at any level.

One further project requirement concerns the explicit introduction of information and telecommunications systems, i.e. technological support for handling the flow of information other than cargo and carriers. There is also a need to focus more closely on interfaces with maritime traffic models for the study of local and regional Vessel Traffic Services[2].

Progress to date has seen the design of a general model framework composed of cores or similar submodels, each of which relates to a commodity. A similar type of core can be used for passenger transportation.

A prototype sample core has been produced which uses as an example the transportation of petroleum products in Italy.

1.2 Conceptual Considerations and Time Scales

The most interesting application for the transport model described here concerns support in decision-making at all levels of planning. For this purpose, it is necessary to compare the impact of a certain decision (which is supposed to produce its full effects in a given future year) with the way the transport network would have performed from that particular year onward had the decision not been taken. Therefore the model must contain its own "natural dynamics", i.e. mechanisms that adjust transport supply in response to evolution in transport demand, and this demand is to be explicitly introduced.

The supply and demand subsystems operate in slow, or year-to-year, mode. Yearly transport demand is converted into daily terms to produce fast, day-to-day mode; in this way, the model produces:

- the flow of cargo moving within the network
- the flow of carriers entering each leg;
- updating of transit times;
- collection of input data for slow dynamics
- exchange of data with a traffic model

The simulation interval has been set at a quarter of a day. The interface with the traffic model operates on a day-to-day basis as this model is the one responsible for flow modulation within its simulation interval.

2. Model Structure

2.1 The Transport Network

The transport process begins at a source and terminates in a sink (fig. 1a). The source encompasses in a single flow the local cargo collection gravitating around a node, in the case where this collection is below the resolution level established for the model. The flows to the node from outside the geographical area in question are also attributed to the source; likewise for flows from within the area but on legs which are not taken into consideration in the model.

The sink functions in a similar fashion in terms of local distribution, as well as for flows leaving the area or those hauled over legs not considered in the model.

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[2] Vessel Traffic Services were the subject of the EC COST 301 research programme.

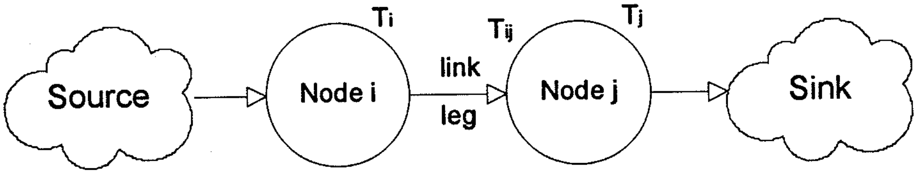

Fig. 1a: The transport process (transport time = ΣT)

Generally speaking, a sink-source pair is associated to each node. From the point of view of cargo, the node may be terminal, namely a point of either origin or destination, or intermediate, where the carrier and/or mode of transport change.

The node is affected both by inbound flow (from sources and legs - or links) and outbound flow (to sink and legs) (fig. 1b) and has the capacity to stock cargo or provide storage.

Nodes are connected by unidirectional links; in general, the number of links in either direction is equal to the number of existing link types: sea routes, internal waterways, railways, roads, pipelines and airways.

A cargo flow exits the node and is converted into a flow of carriers which enter the leg.

Each shipment is treated by the model as indivisible and is identified according to the specific commodity, quantity, origin, destination and routing. It moves instantly in day-to day mode from the source to the node and encounters delays when crossing the borders between node/leg, leg/node and node/sink.

Hence, the transport network is organized as a distributed system of finite elements, which are represented by transit times (fig. 1a)

Dead times, or transit delays, are updated in fast mode and calculated for every cargo load or carrier the moment it enters the element. Transit times therefore vary over time according to cargo type and transit direction (the latter will be examined in detail further on).

Each core in the model deals with one commodity and operates independently. In other words, a certain geographic node generally appears in the various cores with different characteristics, which correspond to different commodities (the node i in Fig. C belongs to the cores from a to m). Similarly, each core produces differing cargo flows on the legs according to commodity.

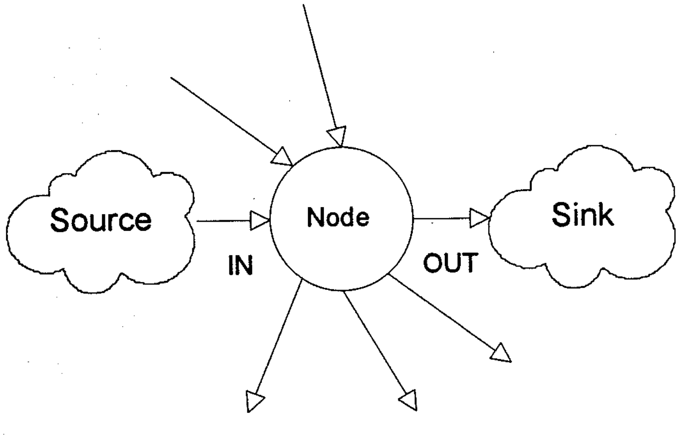

Fig. 1b: Flows in and out of a node

For simplicity's sake, the carriers for each core and leg are assumed to be homogeneous and therefore their performance is standard. On the leg, the carriers are not differentiated according to their starting core. The total number of necessary or available carriers is not explicitly stated in the model but can be determined indirectly[3]. One fundamental assumption is that cargo leaving the node always finds the required carriers immediately available and that further delays only occur with modest flows which do not reach the carrier's minimum stowage coefficient.

The cores operate independently until carriers entering the legs are generated. Network integration takes place on the legs through the summing of carriers produced by each core (figure 1c). Exiting the leg, carriers are converted back into load and reassigned to the various cores.

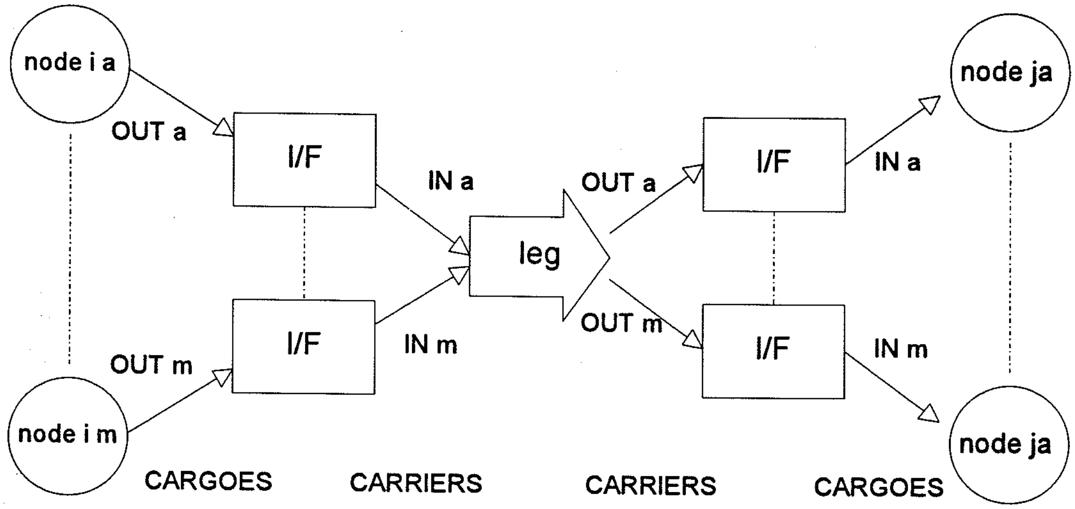

Fig. 1c: Core integration in terms of carrier flow on leg

2.2 Model Core

The transport model core reproposed for each commodity may be considered as a set of six blocks, three of which are dedicated to user interface as outlined in Figure 2.

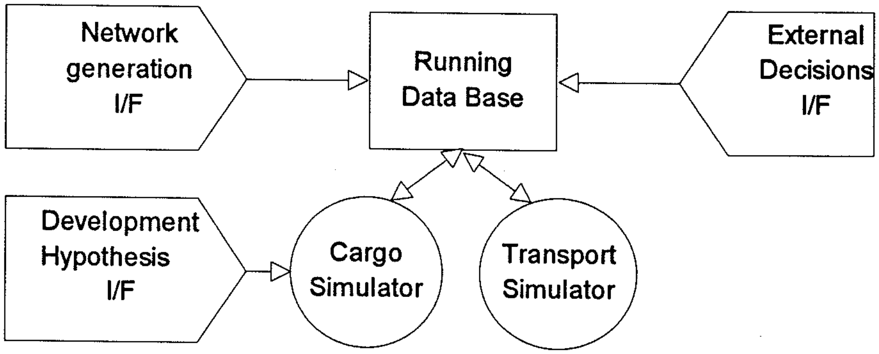

Fig. 2: Simplified scheme of model core

Concerning typical transport model functions, the demand model is initialized by the database and updated by the Development Hypothesis I/F. The supply model is initialized by the database

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[3] The number of carriers associated to a leg is obtained from the flow at the saturation threshold multiplied by transit time and divided by standard load capacity and the stowage coefficient.

and updated by the Transport Simulator. The cargo and transport simulators represent the interaction between demand and supply in both slow and fast modes.

2.3 User Interfaces

- Network generation I/F. Together with the related transport network, this is defined by the model user by means of keys, which are equal in number to the information categories contained in the available external database. The main keys are:
  - geographical area;
  - commodities, and annual demand thresholds above which the sources are to be considered (this fixes simulation resolution).
  - load unit to be used
  - types of link to be considered.

  In the example used to set the core, the keys chosen are: Italy; 300,000 cargo tons per year; 25 tons; sea; inland waterways; railway; road; pipeline. The result was a 38-node network.

  Generally speaking, the geographical area and link type to be considered should be identical for all cores. The load unit is determined by the capacity of the smallest carrier operating on the network, which in practice also fixes the relation between the various thresholds.

  The model may be used in a preliminary fashion to verify and adjust the choice of keys. In any case, the I/F produces the working database (see Figure 2) for each core via the keys applied to an external database.
- External I/F Decisions. These are made outside the model and are introduced in the form of modifications occurring in a particular year. These modifications regard the performance in the working database of either one or more network elements or of the network structure itself. Examples include: the doubling up of a motorway, the raising of railway speed limits, variation in public funding of a section, construction of a new port, establishment of a specialised computer network, etc.
- Development Hypothesis I/F. The working database contains the annual flows for the year of model initialization and this interface updates the values for successive years. Possible development models are external to the transport model examined here. In their absence, as seen in the example when setting the core, a historical series supplied by the external database is used for extrapolation. Development hypotheses relate only to the extrapolation algorithm and any correction filters applied.

At this point, it is worth introducing a consideration that will be examined in greater detail later on: the validity of the model as a simulation tool is not strictly related to the point made above but rather depends on the external systems that supply the databases, the formulation and evaluation of decisions and the development model to be used as a reference.

2.4 Working Database

The network generation I/F accesses pertinent information contained in an external database and produces the working database for the model core and initialization year. This working database contains two types of information:

- the origin/destination matrix with cargo quantity expressed in load units for that particular year and commodity, together with the routes; the generation of the database includes the allocation of flows that are not considered in the network to sources and sinks.
- the initial nominal performance of all the elements contained within the transport network, which is the object of the model.

The origin/destination matrix then comes under the control of the development hypothesis I/F for year-to-year updates, while the load simulator handles conversion into day-to-day basis.

Performance is updated year-to-year by the transport simulator or determined by external I/F decisions.

2.5 Cargo Simulator

This block performs a number of coordinated functions:

- adjustment of the annual matrix through transfer of a constant quota[4] from a less profitable to a more profitable route[5]. This adjustment constitutes part of the model's "natural" adaptation mechanisms;
- conversion of the annual matrix into a daily one, considering days of operation, annual trend and stochastic modulation;
- tracking of single daily shipments and generation of events related to their transit across the borders between network elements, in accordance with transit times calculated by the transport simulator;
- calculation of flows at the borders adopted by the transport simulator;
- collection of transport time and cost data on each route, calculation of the annual averages for the aforementioned adaptation mechanism; these data are also available for external processing.

It should be noted that the various network elements generally feature asynchronous operation mode.

Sea navigation is carried out 24 hours every solar day. Restrictions are imposed on daytime truck movement on weekends, public holidays and the day preceding public holidays. Collection and local distribution is suspended on weekends and public holidays. These holidays may not be the same for all nodes.

The task of managing all these factors lies with the cargo simulator.

2.6 Transport Simulator

On a day-to-day basis, this simulator performs:

- transit time calculation as described in detail in 3.1;
- collection of performance data used as input for the slow mode.

In year-to-year mode, the transport simulator updates performance at each network element and each core. Updating of performance on legs is obviously carried out only once and is valid for all cores.

Performance characteristics subject to updating are as follows.

- For the node: nominal flow, storage capacity, basic transit time, level of information and telecommunications systems, tariff rate.
- For the leg: nominal carrier flow, maximum speed, tariff rate[6].
- For the carriers: average capacity, operational speed, tariffs (the loading coefficient is invariant).

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[4] This proportion, like those that establish borderline modifications of performance, has been tentatively set at 3.5%.

[5] The performance criterion is determined by a combination of trasportation time and cost, which provides a scale for the attractiveness of alternative routes.

[6] The reduction of leg length, which is possible on some types of leg, is considered an external intervention.

2.7 Implementation Difficulties and Simulation Languages

Conceptual problems undermine the validity of the transport model as a tool to support planning. However, these problems are kept outside the model, thus permitting model generality. Some of the model's intrinsic problems are examined in point 3.

Model complexity is a result of the considerable number of objects/events to be dealt with. For example, a ten-node network with an average transit time of five days deals each day with around 500 loads per core and if we consider 10 cores or commodities the number increases to 5000. Hence the load simulator should adopt a suitable language for this scenario and for management of events. It was for these reasons that MODSIM II was chosen.

The transport simulator manages joint flows and its complexity depends on the number of borders within the network. In addition, it calculates transit times which require a degree of logic, as does performance updating. This aspect is presently handled in MATLAB[7].

DYNAMO-like languages do not appear to be suitable for the transport model but are useful for conceptual aspects lying outside it, particularly in the areas of development hypotheses and formulation and evaluation of decisions.

COSMIC-COSMOS was adopted for these areas in tests carried out to set the core for petroleum products in Italy.

Languages and aims are obviously correlated. One area of interest is the possibility of coupling models like the transport one, which can handle a range of objects/events separately, with models that operate on a small quantity of aggregated data according to System Dynamics principles. Consider, for example, the use that the manager of a particular node would make of the transport model. The specific problem faced by this operator will produce a node model of equivalent complexity and which can typically be developed through System Dynamics techniques. This can substitute the one adopted in the transport model, which provides a scenario for the new model.

The only constraint relates to interface conditions, in terms of input/output.

3. Conceptual Problems Within the Transport Model

3.1 Transit Time Calculation

The value of delay resulting from transit across the borders between network elements is valid for a minimum of one year and is updated by the transport simulator in slow mode for every model core.

The current delay value is updated with respect to the day the cargo entered each element of the network. Transit delay increases at the node/leg border in the following circumstances:

- flow saturation, above the threshold applied to the nominal value, with a quadratic effect on the excess;
- storage saturation, as above but with linear effect and only in the absence of flow saturation;
- where the node of origin's telecommunications level is lower than that of the node in question (stating delayed access to information and official documentation);
- waiting time for the carrier to reach minimum shipload (in the case of minimal flow on the leg).

With the exception of this last condition, all these circumstances apply to the node/sink border.

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[7] The choice of languages is not the result of an exhaustive study: we adopted the most suitable languages available to us.

As to the leg/node border, the carriers related to each core have their own operational speed, which determines basic transit time; this value will in no case be lower than that fixed by maximum speed on the leg. Flow saturation beyond the threshold produces a longer delay which, here again, is a quadratic function of the surplus.

3.2 Economic Considerations

Tariff rates are used to calculate transport costs and are fixed annually. Rates paid by carriers to leg managers are summed, without any mark-up, to the rates that the carrier charges for shipments in relation to quantity.

Tariff rates are public-domain data, meaning they are openly accessible to all. They can be regarded as the sum of a cost element and a profit element, the latter set as a percentage of revenue.

The conceptual problem regards the share of costs to be allocated to the services, a notion which is necessary to update the economic values following changes brought about by the network's natural dynamics or by external intervention.

In practice, cost sharing data are difficult to obtain but even if they were easily accessible, calculating them for every network element would prove too complicated. For this reason, we have preferred to introduce an "arbitrary" submodel which splits costs among the various services, as well as into fixed and variable components related to flow.

In the end, an expected cost is obtained that depends on nominal performance and tariff rates are calculated accordingly. The economic outcome of management depends on how much current values diverge from the nominal values adopted in order to set tariff rates. The system runs at a loss where flows are too low, as fixed costs weigh more heavily on it; the same is true of excessive flows because extra costs like overtime are introduced in order to reduce the increasing in transit times. Unlike nodes, legs do not run at a loss in conditions of excess flow.

3.3 Strategy for the "Natural" Evolution of the Network

The transport model is expected to provide a suitable scenario for testing decisions and traffic models. Optimum strategies at whatever level are therefore dealt with externally, while the model should operate in a perspective of "realistic mediocrity".

In this respect, it does not appear necessary to differentiate strategies for individual managers of nodes, legs or carriers. This realistic mediocrity is introduced by an economic criterion that modifies the performance of each and every network element to obtain the desired profit; this is determined on the basis of previous year's results and on expected demand in the coming year.

The magnitude of change is limited in order to allow for technical feasibility in the span of a year. Changes are introduced with a year's delay, while tariff rate updating is carried out immediately.

In accordance with realistic mediocrity, changes made by the individual managers of network elements or sectors do not take into consideration the decisions of others, nor the mechanism for transferring cargo to a more profitable route. The latter is conducted at the level where origin/destination matrices are generated.

Changes imposed by external decisions take effect immediately upon introduction. Neither these nor internal modifications take into consideration a possible decrease in service performance for work in progress.

Although the logical procedure governing these modifications may be of interest, it has been excluded because of space restrictions.

3.4 Unique Features of the Maritime Sector

One of the transport model's requirements is the necessity to focus on interfacing with both local and wide-ranging maritime traffic models. Sea links are atypical because, apart from exceptions like Panama and Suez, they do not entail artificial infrastructure and so have no managers, costs or rates (the same as for air travel). In addition, there are no artificial limits on absorbable flow or operational speed.

For land transport, carriers face infrastructure constraints imposed by roads, canals and railways but no such limitations exist at sea and this represents the principal conceptual problem. Reference routes obviously do exist, and these generally coincide with the minimum distance between points, but for the influence of climatic factors. In actual fact, adverse weather conditions generally cause navigation to deviate from these routes in a significant, stochastic manner, which ultimately means that any area of sea may feature a multitude of sea links. The end result is that sea traffic in a particular area always depends on the global, or worldwide, transport network.

This characteristic[8] has led to applications which have not been able to utilise global transport models and have had to rely on alternative principles. In safety at sea, for example, the Global Maritime Distress and Safety System is not grounded on the possibility of reconstructing a traffic image, but rather on the guarantee that a distress signal is sent, received and its position fixed. This approach appears to be in keeping with the low probability of accidents occurring and their dispersion throughout the globe.

Similarly, the global transport model is unsuitable in congested local areas such as the English Channel, where the likelihood of accidents occurring is significant. Here, Vessel Traffic Services work in real time and begin tracking ships the moment they enter the monitored area.

In theory, the application to the whole sea surface of techniques used for infrastructure-bound traffic and of procedures currently used by local VTS systems would improve the efficiency and safety of maritime traffic and hence also of sea transport. Many steps have been taken in this direction: international regulations for hazardous cargo constitute but one example.

Practical problems are posed by technology and the cost/benefit ratio. However, the transport model described here should permit evaluation of new developments in the maritime field with respect to these two factors.

4. Conclusions

This paper has presented a transport model to be used as a practical tool for defining transport networks of interest and for supporting decision-making at various levels of operation.

Its practical application, however, is conditioned by outside factors which are concerned with the availability of:

- databases which should cover all types of commodities, including passengers, from a global level down to the resolution required at the level of specific local problems;
- a global development model from which future transportation demand for all commodities can be extrapolated;
- a model capable of making decisions in line with predefined goals and evaluating their impact.

The problem of the databases does not appear to pose constraints if the model is designed for use in a specific geographical area such as Italy or the European Union. Similarly, the number of commodities, subject to systematic statistics, is restricted to around a dozen.

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[8] It should be remembered that around 75% of the Earth's surface is covered by sea water. For a more detailed examination of this characteristic, see the literature on Seapower.

Conversely, the problem which is typical of a System Dynamics approach remains open in the case of development, decision-making and evaluation models. It can be observed, however, that even when there is no reference development model, nor any general model for action planning, the transport model presented here can still be employed with remarkable results, providing that aims are unambiguous, well-defined and limited in time (i.e. given appropriate application).

An example of this is the problem faced both in Italy and in Europe when seeking to divert the ever-increasing demand for land transport towards carriage by sea.

Finally, it should be noted that the model described here does not strictly fall into the category of System Dynamics. Nevertheless, it appears to be relevant in that it permits the development of System Dynamics models by providing necessary simulation tools in the transport sector, where the high number of objects and events renders traditional System Dynamics approaches unsuitable.

5. References

Cascetta E., Cantarella, G. E. 1993. Modelling dynamics in transportation networks: State of the art and future developments. *Simulation Practice and Theory.* 1(2): 65-91.

COSMIC and *COSMOS.* 1994. The COSMIC Holding Co., 8 Claycourt Road, Shrivenham, Swindom, Wilts SN6 8BN, U.K.

Coyle, R. G. In press. *System Dynamics Modelling. A practical approach.* London: Chapman & Hall.

Deo, N. 1974. *Graph Theory with Applications to Engineering and Computer Science.* Englewood Cliffs, N.J.: Prentice-Hall.

Drew, D. R.. 1991. Transportation impact methodology for measuring user and non-user benefits. In *Proceedings of the 1991 System Dynamics Conference*, 163-172, Bangkok, Thailand.

MATLAB. 1992. The Math-Works Inc., Cochituate Place, 24 Prime Park Way, Natick, MA 01760, U.S.A.

MODSIM II. 1993. CACI, 3333 North Torrey Pines Court, La Jolla, CA 92037, U.S.A.

Reggiani A., Nijkamp P. 1995. Competition and complexity in spatially connected networks. *System Dynamics Review.* 11(1): 51-66.