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# TRANSPORTATION POLICY ANALYSIS WITH A GEOGRAPHIC INFORMATION SYSTEM: THE VIRTUAL NETWORK OF FREIGHT TRANSPORTATION IN EUROPE

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**Abstract**—This paper presents a multi-modal freight transportation model based on a digitized geographic network. A systematic analysis and decomposition of all the transport operations, i.e. moving, loading and unloading, transshipping and transiting, leads to the development of a virtual network where each virtual link corresponds to a specific operation, and all transportation modes and means are inter-linked. Software, called NODUS, automatically generates the virtual network so that the model can be conveniently applied to large networks. The analytical structure of the links notation makes it easy to attach specific cost functions to each virtual link. The model is applied to the trans-European freight network of roads, railways and inland waterways for the transportation of wood. Cost functions are built up for each operation by each mode/means combination. A detailed point-to-point origin–destination matrix, calibrated on Eurostat statistics, is generated by a Monte-Carlo technique. Then, the total transportation cost is minimized with respect to the choices of routes, modes and means. This provides estimations of transportation services demands as well as modal splits, to the extent that the two hypotheses of demand based on generalized cost minimization and market contestability are accepted. A sensitivity analysis on the relative road cost is made, which provides measures of arc-elasticities. 

## 1. INTRODUCTION

The computing facilities which are available nowadays, their speed and power as well as their programming ease, have led to the development of Geographic Information Systems (GIS) which can provide a number of services to geographers, urban planners, geologists and engineers, as well as to economists working in the fields of spatial analysis and transportation. Most of them have been developed by consultants or firms for specific purposes, but they are often not well documented and include black boxes with programs and information which remain "confidential".

For these reasons, the purpose of this paper is not to review the field of GIS software applied to transportation, which would be a worthwhile but rather difficult task, but to provide an exposé of a systematic GIS analysis for freight transportation over long distances, which has been recently developed for the trans-European network in the Mons Facultés (Jourquin, 1995a–c). As will be explained below, it has the advantage over other systems that it is completely open and flexible: it can be used with external programs designed to solve particular problems. Moreover, its detailed analytical structure permits an easy set-up of all its parameters. It is also one of the very few GIS which focuses on the transportation of goods.[1]

Based on a full decomposition of all transport operations over a multi-modal geographic network, i.e. loading, moving, unloading, transshipping and transiting, it creates an expanded virtual network which gives a mono-modal version of a complex multi-modal network. Different types of virtual links correspond to moving goods by different

[1]The most interesting one is STAN by Crainic *et al.* (1990), which provided useful insights for the present research. We thank also T. G. Crainic for his many stimulating comments.

modes and by transportation means of different sizes or characteristics; some others correspond to the possibilities of transferring the goods from one mode or means to another. Hence, the alternatives of combined transports can be taken into account. Specific generalized cost functions, in terms of distance, time and cost, can be attached to each virtual link. Then, given a transportation task, it is possible to minimize, for instance, its total cost by choosing the best combination of mode, means and route.

This model of analysis, with its associated software, constitutes a powerful tool for evaluating the impacts of new transportation infrastructures and policies. Actually, this was the motivation behind its development and it partly explains the emphasis on the costs of the means and modes of transportation. Obviously, savings in the costs of transports are one important benefit of new infrastructures; with this model they can be easily computed in a comprehensive way over a complete national or international network. Actually, this model has already been used for that purpose in evaluations of public investments in waterways (Beuthe and Jourquin, 1994b). In the same spirit, it was used for estimating the additional cost of transportation resulting from the state-controlled organization of inland waterways transports in Belgium (Beuthe and Jourquin, 1994a). Within the context of the European governmental discussions over the improvements needed for the trans-European network, the present paper illustrates the proposed methodology by an analysis of the relative competitive situations and potential market shares of three inland transportation modes: railways, roads and waterways.

We start with a presentation of the virtual network and its methods for defining the network links and generating automatically the full virtual network. The second section will discuss the cost functions which are attached to each link of the network and the method of total cost minimization which is applied. The third section will present the trans-European network and the market shares analysis. Finally, a short discussion of further possible developments will be proposed.

## 2. THE VIRTUAL NETWORK

Transportation of goods on a real geographic network may be realized by various means on the same infrastructure. For instance, the same large canal can be used by small and large boats. Transportation also involves many different operations which do not appear in a normal geographic representation of the network, i.e. loading, moving, unloading, transshipping and transiting. In particular, the operations of transferring goods from one means or mode to another are not represented. However, in order to properly analyse a transportation problem with all its alternative solutions and operating dimensions, it is necessary to identify and separate each transport operation. This can be achieved by creating a network—a virtual network—linking all the possible successive operations in the geographic space in a systematic way.

In the context of freight transportation models, the idea of virtual links was initiated by Harker (1987), who extended its general spatial price equilibrium model with additional links corresponding to different levels of services. It was further developed by Crainic *et al.* (1990) in order to define a multi-modal network with links connecting the various modes. Jourquin's recent contribution (1995b) is to propose an automatic generation of all the virtual links on the basis of a well-structured notation of the real nodes and links. His method makes it possible to deal rather easily with very large networks like the trans-European one, and greatly facilitates any ensuing sensitivity analyses. It uses a particular structured notation that provides a convenient matching of each specific link with the appropriate weight or cost functions.

The software, called NODUS, was especially designed for implementing the virtual network. It is a PC, Windows based GIS which uses ASCII or ANSI files to allow the development of external programs in any convenient programming language without special interfacing. These files can also be imported into the most popular databases or spreadsheets. As no pre-defined algorithms are included in the package, application-specific programs can be included in the main software through a user-defined menu.

Since the files relate to three types of objects—nodes, links and paths—their structure is very simple. A great variety of results can be plotted by the appropriate use of different fields of the database. A node represents a point in a two-dimensional space. A link represents a segment joining two nodes. Nodes and links are therefore sufficient to give a planar representation of a network. A path (or route) corresponds to a set of links. These three basic objects can be defined by a restricted set of fields in the database. A node is identified by a node number and its coordinates. A link is identified by a link number, a begin and an end node number. A path is identified by an alpha-numerical label and a set (vector) of link numbers.

Beside these basic fields, the links are characterized by the mode $t$ and means $m$ which can be used on the links; the nodes also have a special attribute which indicates whether they are available for loading, unloading and transshipping. In addition to these attributes needed for the generation of the virtual network, NODUS lets the user specify as many user-defined fields as he wants. Each field can be defined as an integer, a floating-point, a single character or a string.

On the basis of this information, NODUS automatically generates a virtual link for each possible mode $t$ and means $m$ on each real link. As the real geographic network is tabulated as $G = (X, U)$, which enumerates the links $U_j$ of the network graph and their associated end-nodes $X_i$ and $X_k$, these virtual links are defined by their two virtual end-nodes $X_i^{jtm}$ and $X_k^{jtm}$. But, because the cost of moving goods in one direction may well be different from the cost of moving in the other direction, two separate arrows must be generated for all virtual links.

The next step is to create virtual links corresponding to transshipping operations. This is done by a systematic comparison of the virtual nodes that can be linked by such an operation: transshipping at a node $i$ is possible between all virtual nodes pertaining to that node, if they relate to different real links. No transshipping can be allowed between nodes which relate to the same link $j$, since it would correspond to a transshipment between two means of the same mode before turning back on the same real link.

Besides these transshipment virtual links, it may be convenient to include transit virtual links for the simple passage from one virtual node to another without changing the mode or the means of transportation. These links will connect virtual nodes with same $i$, $t$ and $m$, but different $j$.

The last step deals with the operations of loading and unloading at the real nodes. This problem is handled by the creation of virtual nodes $X_i^{000}$ for each real node $X_i$. It is then possible to create a set of virtual links for these operations between $X_i^{000}$ and every virtual node $X_i^{jtm}$, with separate arrows for loading and unloading.

In some cases this method of automatic and exhaustive generation of virtual nodes and links may create virtual links corresponding to operations which cannot be made at some nodes, such as the handling of containers in some places without adequate facilities. This problem is handled by defining a list of exclusions for each real node, which is checked during the process of creating the virtual links and nodes. The procedure that automatically generates a virtual network from a real one can be formalized in the following way:[2]

**ASSUME**: I = number of real nodes and J = number of real links
**DEFINE**: tab1[ ], tab2[ ]: virtual nodes arrays and z1, z2: indexes in these arrays
**BEGIN**
z1 ← 1
**FOR** j = 1 → J
    t ← *transport mode on link j*
    M ← *number of transport means accepted on link j*
    **FOR** m = 1 → M
        i ← *begin node of link j*
        k ← *end node of link j*

[2]The symbol # is used for concatenation.

```
                node1 ← i#j#t#m
                node2 ← k#j#t#m
                Save link(node1, node2)
                Save link(node2, node1)
                tab1[z1] ← node1
                tab1[z1 + 1] ← node2
                z1 ← z1 + 2
        END FOR m
END FOR j

FOR i = 1 → I
        tab2[ ] ← tab1[ ] elements generated from real node i
        z2 ← number of elements in tab2[ ]
        FOR p = 1 → z2
                FOR q = p + 1 → z2
                        IF "j" part of tab2[p] ≠ "j" part of tab2[q] THEN
                                IF (not a transshipment node
                                  AND "t" part of tab2[p] = "t" part of tab2[q]
                                  AND "m" part of tab2[p] = "m" part of tab2[q])
                                OR transshipment node THEN
                                        IF no exclusions at node i THEN
                                                Save link(tab2[p], tab2[q])
                                                Save link(tab2[q], tab2[p])
                                        END IF
                                END IF
                        END IF
                END FOR q
        END FOR p

        FOR p = 1 → z2
                IF transshipment node THEN
                        IF no exclusions at node i THEN
                                Save link(i#000, tab2[p])
                                Save link(tab2[p], i#000)
                        END IF
                END IF
        END FOR p
END FOR i
END
```

As an example, Fig. 1 presents a very simple real network made of railways ($R$) and waterways ($W$). To illustrate the difference which exists between transportation modes

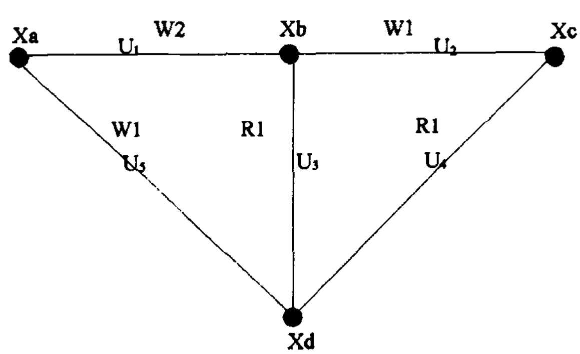


Fig. 1. Simple real network.

and transportation means, link $U_1$ of this simple network represents a canal ($W_2$) large enough for small (1) and large (2) boats, while links $U_2$ and $U_5$ correspond to smaller canals which can accept only small boats; links $U_3$ and $U_4$ are non-electrified rail-lines.

Figure 2 presents the corresponding virtual network (separate arrows are not represented in order not to clutter the diagram). At real node $b$, for instance, five virtual nodes are created: $X_b^{000}$ represents the former real node where freight can be loaded or unloaded, while the other nodes correspond to the four possible combinations of $j$, $t$ and $m$. An arrow from $X_b^{000}$ to $X_b^{2W1}$, for example, would represent the loading of a small boat on link 2; an arrow on link $U_2$ from $X_b^{2W1}$ to $W_c^{2W1}$ would represent the moving of the (small) boat from $b$ to $c$. An arrow on the dotted line between $X_b^{1W1}$ and $X_b^{2W1}$ would indicate a simple transit operation, while an arrow on the line joining $X_b^{1W2}$ to $X_b^{3R1}$ would correspond to a transshipment operation from a large boat on link 1 to a train on link 3.

Now, it can be seen how this notation is convenient for matching the virtual links, which correspond to a particular operation, to the relevant cost functions. Actually, the two end-nodes which define a link provide the necessary information:

1. When two virtual end-nodes relate to different real nodes $i$ and $k$, the virtual link corresponds to a moving operation between $i$ and $k$, to which must be attached the relevant cost function for mode $t$ and means $m$.
2. When the nodes refer to different real links $j$ and $l$, but to the same mode $t$ and means $m$, it is a simple transit operation to which must be attached the relevant cost, if any.
3. When the nodes refer to different real links and different modes $t$ and $t'$ and/or to different means $m$ and $m'$, it must be a transshipping operation for which there is a special set of cost functions.
4. When one of the nodes is $X_i^{000}$, it must be a loading or unloading operation for which there are some other particular functions.

## 3. COST FUNCTIONS AND TOTAL COST MINIMIZATION

### *3.1. General considerations on cost minimization*

The main objective of this network model is to predict the choices of modes, means and routes which would result from the minimization of the total cost of transports for a given transportation task defined by a matrix of origins–destinations.

This total cost, which must be minimized with respect to the choices of mode/means

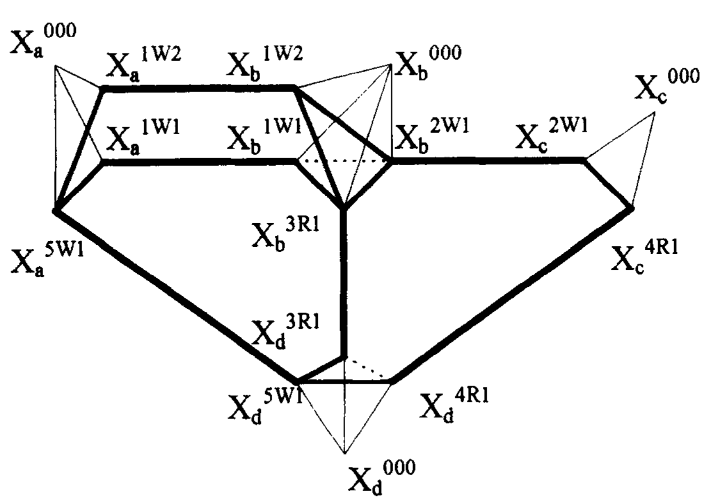


Fig. 2. Corresponding virtual network.

combinations $\theta$ and routes $l$ can be defined as

$$TC = \sum_{l} \sum_{\theta} TC_{l\theta},$$

where $TC_{l\theta}$ is the sub-total cost for the traffic on a particular route $l$ with a vehicle of type $\theta$. $TC_{l\theta}$ is the sum of all the costs over the successive links (or operations) of the virtual network over route $l$, and it is supposed that all these costs are proportional to the total quantity transported $Q_{l\theta}$. This means that the minimization will result in an all-or-nothing assignment procedure, so that all the traffic flow of a particular origin–destination will be assigned to the same combination of mode, means and route which minimizes the total cost of transporting 1 ton.

Defining a route $l$ by a set $l_i$ of "handling" virtual links and another set $l_j$ of "moving" virtual links, if the cost per ton for any link is either constant or proportional to the distance $s_j$:

$$TC = \sum_{l} \sum_{\theta} Q_{l\theta} \left( \sum_{i \epsilon l_i} A^{\theta i} + \sum_{j \epsilon l_j} B^{\theta} s_j \right)$$

This is the total cost which must be minimized with respect to $l$ and $q$. After attaching the relevant cost functions to all the links, this operation can be realized by applying the algorithms of Moore-Dijkstra (1959) or Johnson (1973) to the virtual network.

This general framework of analysis deserves a few comments. As explained in Section 1, the present paper aims at a global analysis of the competitive positions of rail, road and inland waterway on the trans-European network. It follows that different cost functions will be used for different operations by different means and modes in different regions, but that no company specific cost functions, nor tariffs, are introduced in the model, with the exception of railways. Naturally, the basic elements of NODUS could be used, with some adjustments, for other purposes, such as an analysis of spatial competition between companies with different networks and costs.

Given the choice of a transportation means on a specific route, costs are proportional to the quantity transported. This is equivalent to an assumption of no capacity constraint. While it is clear that there are many congestion problems on the trans-European network, we think that, for the present analysis of long distance transports over a very large network, congestion is adequately dealt with by an appropriate setting of the transport average speed which is an input of the cost functions.[3]

Finally, the assumption of total costs as linear functions of distance is a prerequisite for this type of network modelling. However, it will be seen presently that the computation of the various costs takes into account many different factors, the combination of which leads in a rather reasonable way to linear functions.

### *3.2. The cost functions*

The vehicle's costs for transporting 1 ton over a distance $s$ with a vehicle of type $q$ is made up of two elements:

1. The sum of loading and unloading costs plus the possible transshipping costs; they correspond to some of the $A^{\theta i}$ parameters in the above formula.
2. The sum of the costs of moving the goods over the links which make up the route; these costs correspond to the $B^{\theta} s_j$ elements.

The basic formulas used for vehicle costs on route $l$ for a vehicle of type $q$ are:

$$A^{\theta i} = a^{\theta} \cdot H_i^{\theta} = \frac{F^{\theta} \cdot H_i^{\theta}}{u \cdot T^{\theta}} \quad \text{and} \quad B^{\theta} \cdot s_j = \frac{F^{\theta} + b^{\theta} \cdot u}{u \cdot v^{\theta} \cdot T^{\theta}} \cdot s_j$$

[3] If we had the appropriate information we could have introduced, at some points of the network, an additional transit operation with the cost of congestion at that point. Note that it is possible to use an algorithm with NODUS which would compute an equilibrium solution spreading a given flow between several routes if transport costs are made a function of the total traffic on a link.

where $F^\theta$ is the annual fixed cost of the vehicle (capital annuity, insurance, maintenance and wages of the crew), $H^\theta{}_i$ is the time taken for a particular handling operation on virtual link $i$, $u$ is the number of working hours per year, $T^\theta$ is the average load of the vehicle in tons, $b^\theta$ is the cost of energy consumption per hour and $v^\theta$ is the vehicle average speed. Thus, the vehicles' total cost on a route $l$ can now be written as

$$\sum_{i \in l_i} a^\theta \cdot H_i^\theta + \sum_{j \in l_j} B^\theta \cdot s_j.$$

Note that the real distance may be adjusted to take into account various delays which may be encountered on a link. The times $H^\theta{}_i$ for loading and unloading are estimated by the Deming's formula (Deming, 1978) whereby the handling time $= a + b \times \text{quantity}^c$, a non-linear relation between handling time and handled quantity. The coefficients estimated by Deming for the different operations are used.

Besides these vehicles' costs, the labour costs of handling the goods at points of origins and destinations, or when the goods are transferred from one mode or means to another, are estimated by

$$a^\lambda \sum_{i \in l_i} H_i^\theta$$

where $a^\lambda$ is the labour cost per unit of time.

Finally, there is the opportunity cost of the capital tied into the goods during transportation. It is proportional to the time taken by the handling operations and travelling:

$$a^\rho \cdot \left( \sum_{i \in l_i} H_i^\theta + \sum_{j \in l_j} \frac{S_j}{V^\theta} \right) = p \cdot r \cdot \left( \sum_{i \in l_i} H_i^\theta + \sum_{j \in l_j} \frac{S_j}{v^\theta} \right),$$

where $p$ is the value of the transported commodity and $r$ is the rate of interest.

Using this more detailed notation for a given origin–destination matrix, the total cost function which must be minimized with respect to $\theta$ and $l$, i.e. $l_i$ and $l_j$, can be written as:

$$TC = \sum_{i \in l_i} \sum_{j \in l_j} \sum_{\theta} \left[ \left( B^\theta + \frac{a^\rho}{v^\theta} \right) \cdot s_j + (a^\theta + a^\lambda + a^\rho) H_i^\theta \right] \cdot Q_{l\theta}$$

The reader will find all the parameters in Table A2.

## 4. APPLICATION TO THE TRANS-EUROPEAN NETWORK

### *4.1. The distribution of the global flows*

The concepts and techniques described in the above sections were applied to the trans-European transportation network of the 12 countries which were members of the European Union in 1991. The digitized geographic network is based on the *Trunk Lines of Communication of International Importance* published by the European Conference of Ministers of Transport (ECMT). Data of global transport flows within and between these countries are provided by Eurostat for the different modes and categories of goods.[4] In this paper we have chosen to present the case of wood transports. However, the data available do not give any indication about specific points or regions of origins and destinations.

In order to solve this problem, a set of centroids was created as additional nodes of the network. They can be defined as regional centres of gravity, which are taken as points of origins and destinations of the goods. In order to obtain these centroids, each real node of the network was assigned to the closest harbour and to the closest railway station. A centroid was created for each of these clusters of nodes as a point of unique origin or destination. Moreover, a road link was also created between the centroid and the nearest

[4]Eurostat publishes all the statistics available on the European Union. No data are given for combined transports. Only transports of more than 50 km were taken into account.

harbour or railway station. The distance assigned to that link was the average distance of the nodes in each cluster to the harbour or railway station.

Obviously, these centroids are not evenly distributed over the network, but they are more numerous in industrialized areas where the density of the network is greater. To that extent it is likely that their distribution over the geographic space corresponds to the distribution of the real origins and destinations. The total flows of goods were assigned among all the centroids by 5000 random drawings of centroids for small bundles of goods. By this Monte-Carlo procedure, a detailed origin–destination matrix was obtained which can be thought to be very similar to the real one.

To validate this distribution method a lot of disagregated data on the flows of commodities throughout Europe would be needed, which is not, unfortunately, available. However, some Italian data on national and international traffic over 20 regions are available. Hence, in the case of Italy at least, it was possible to compare the generated origin–destination matrix with the "real" flows estimated by the Ministero dei Transporti a della Navigazione (1995).

In Table 1 the first column gives the percentage of the total traffic which was allocated to the centroids in each region; the second column gives the corresponding "real" percentages. The correlation coefficient between these two columns is 0.731, which suggests that the method proposed, as a stopgap measure, deserves consideration.

Obviously, had we such additional information for every European regions, it would have been possible to calibrate the generated origin–destination matrix accordingly. As it was, with information only about Italy we could not attempt any calibration.

### 4.2. *The impact of a cost variation on the modes' market shares*

At this stage, given this origin–destination matrix and all the cost functions for the various operations, it is possible to minimize the total cost of the transportation tasks by choosing the cheapest combinations of modes, means and routes and to compute the market shares predicted by the network model. They could be taken as estimates of the real market shares under two hypotheses: first, that shippers are actually minimizing their generalized transportation costs, a rather weak hypothesis; second, that the carriers' tariffs bear a close relationship with the operating costs presented in the above sections. This second hypothesis could be justified, to some extent, by the contestable character of each mode's market, at least for their marginal traffic. In any case, they can be taken as estimates of the market shares which would be obtained if these conditions

Table 1. Distribution for Italy

| | Distribution of traffic in % | |
|---|---|---|
| Italian regions | Generated matrix | "Real" matrix |
| Piemonte | 8.14 | 10.05 |
| Valle d'Aosta | 0.74 | 0.24 |
| Lombardia | 11.85 | 20.63 |
| Liguria | 3.70 | 3.57 |
| Trentino Alto Adige | 2.22 | 2.03 |
| Veneto | 4.44 | 11.87 |
| Fruili Venezia Giulia | 3.70 | 2.37 |
| Emilia Romana | 11.11 | 12.00 |
| Toscana | 9.62 | 6.19 |
| Umbria | 2.22 | 1.66 |
| Marche | 5.18 | 2.69 |
| Lazio | 5.18 | 6.80 |
| Abruzzo | 3.70 | 2.32 |
| Molise | 0.00 | 0.82 |
| Campania | 3.70 | 5.16 |
| Puglia | 4.44 | 4.37 |
| Basilicata | 0.74 | 1.08 |
| Calabria | 3.70 | 1.31 |
| Sicilia | 8.88 | 3.22 |
| Sardegna | 6.66 | 1.65 |

were satisfied. As such, they provide a useful information on the mode's competitive situation.

By simple additions of the quantities transported by each of the three modes, including the quantities they move in combined transports, the results of the cost minimization provides a global modal split which can be compared with the modal split computed on the basis of the Eurostat data: 3% of transports by inland waterways, 7% for the railways and 90% of transports by trucks.[5]

It was also possible to compute the effects on the modal split of some cost variations. Here, the impact of relative cost variations of road transports was estimated. To that effect, an iterative procedure which modifies, at each step, the relative operation costs of road transports from 60% to 140% of the actual cost was implemented. As a progression by steps of 10% was used, 9 iterations were needed for 9 successive assignments of the origin–destination matrix. Table 2 presents the market shares of the three modes and their evolution as a consequence of successive increases or decreases of road transport relative operating costs. The market shares are computed on the basis of the tons transported by the different modes.

At the 1991 level of costs, i.e. at the relative level 1, these market shares can be compared to the shares recorded by Eurostat. As they appear to be very similar, this comparison suggests a rather good fit of the network cost model and gives some support for its use in the present context. If we accept the two hypotheses that shippers are minimizing their generalized transport costs and that the three modes' markets are contestable, at least at the margin, these successive values can be taken as expressions of the demand functions for the different modes.

In any case, railway transports appear much more sensitive to a cost variation of road transport than inland waterway transports. This phenomenon could partly be the result of the characteristics of the networks. Indeed, the flows were assigned on the whole European network, but the hydraulic network is only widely developed in the Benelux

Table 2. Estimated relative market shares (tons)

| Wood | Relative market shares | | |
|---|---|---|---|
| Relative operation costs for road (1 = 100%) | Road | Waterways | Railways |
| 0.6 | 94.8 | 2.2 | 3 |
| 0.7 | 93.8 | 2.7 | 3.5 |
| 0.8 | 92.4 | 3.2 | 4.4 |
| 0.9 | 90.1 | 3.7 | 6.2 |
| 1 | 87.7 | 4 | 8.3 |
| 1.1 | 86.1 | 4.1 | 9.8 |
| 1.2 | 84.5 | 4.1 | 11.4 |
| 1.3 | 82.5 | 4.5 | 13 |
| 1.4 | 81.3 | 4.6 | 14.1 |

Table 3. Estimated relative market shares (tons) in the Benelux and Germany areas

| Wood | Relative market shares (tons) | | |
|---|---|---|---|
| Relative operation costs for road transport (1 = 100%) | Road | Waterways | Railways |
| 0.6 | 95.1 | 4.9 | 0 |
| 0.7 | 94.6 | 5.4 | 0 |
| 0.8 | 93.9 | 6.1 | 0 |
| 0.9 | 93.1 | 6.8 | 0.1 |
| 1 | 92.2 | 7.2 | 0.6 |
| 1.1 | 91.8 | 7.5 | 0.7 |
| 1.2 | 91 | 7.8 | 1.2 |
| 1.3 | 90.3 | 7.9 | 1.8 |
| 1.4 | 89.5 | 8.2 | 2.3 |

[5]Market shares were computed for transports of more than 50 km.

countries, the northern part of France and Germany. Hence, in the other countries the only competitors of road transportation are often the railway companies, and the total market share for inland waterway transportation in Europe could never be highly affected by variations of cost. In order to clear up this question, the market shares were also computed for the countries which were mostly concerned by waterway transports, i.e. Germany, Belgium and the Netherlands. They are shown in Table 3.

As can be seen, the share of inland waterway transports in these three countries is much larger than in the whole of the European market, while the railways share is substantially reduced. Again, the modal split at cost level 1 can be compared to the modal split computed on the Eurostat data: 87% for road transports, 6% for waterways and 7% for railways. Thus, when these countries are taken separately, the model does not fit as well. This may be caused by a distribution of origins–destinations which does not correspond enough to the real distribution. Only additional information, which is not available for the time being, could solve that problem. It may also be the result of the approximation used for estimating the railway costs in the different countries. A thorough study of the cost structure and operations of the various European railways is probably needed in order to improve the specification of the cost functions. On the other hand, the railway tariffs are rarely set up on a competitive basis and they are characterized by cross subsidies between traffics.

The values given in these two tables can be used for computing direct and cross arc-elasticities for a variation of 10% around the road cost of 1991 (level 1). These elasticities are given in Table 4.[6] They show that, in relative terms, the variations of road costs do not substantially affect the market share of inland waterways, even in countries where waterways are available. The cross-elasticities of railway services are much higher; it is particularly the case in Benelux and Germany, but this is the result of the small market share of railways in these countries. As could be expected, road transportation "demand" is inelastic with respect to its own cost. Altogether, these results indicate that railways could increase substantially their market shares in Europe if the costs of road transports were to increase provided, naturally, that they have the capacity to do so.

Table 4. Estimated elasticities

| | Europe | | Germany, Belgium and The Netherlands | |
|---|---|---|---|---|
| Elasticity | Tons | Tons/km | Tons | Tons/km |
| Road (direct) | −0.22 | −0.77 | −0.07 | −0.27 |
| Waterways (cross) | 0.50 | 0.66 | 0.49 | 0.80 |
| Railways (cross) | 2.16 | 2.34 | 5.00 | 5.19 |

Table 5. Estimated relative market shares (tons/km)

| Wood | Relative market shares (tons/km) | | |
|---|---|---|---|
| Relative operations costs for road transport (1 = 100%) | Road | Waterways | Railways |
| 0.6 | 97.6 | 1.8 | 0.6 |
| 0.7 | 93.8 | 2.7 | 3.5 |
| 0.8 | 88.4 | 3.6 | 8 |
| 0.9 | 80.8 | 4.7 | 15.5 |
| 1 | 74 | 5.3 | 20.7 |
| 1.1 | 69.4 | 5.4 | 25.2 |
| 1.2 | 65.4 | 5.5 | 33.5 |
| 1.3 | 61 | 33.5 | 5.5 |
| 1.4 | 5.7 | 35.9 | 58.4 |

[6]Note that these market share elasticities are equal to quantity elasticities, since the total quantities remain constant through the simulation. But, obviously they do not take into account the impact of the cost variation on the total quantities. Keep in mind, though, that they are based on a discrete "all-or-nothing" mode choice model.

Table 6. Estimated relative market shares (tons/km) in the Benelux and Germany areas

| Wood | Relative market shares (tons/km) | | |
|---|---|---|---|
| Relative operation costs for road transport (1 = 100%) | Road | Waterways | Railways |
| 0.6 | 94 | 6 | 0 |
| 0.7 | 92.9 | 7.1 | 0 |
| 0.8 | 90.8 | 9.2 | 0 |
| 0.9 | 88.4 | 11.3 | 0.3 |
| 1 | 84.9 | 12.4 | 2.7 |
| 1.1 | 83.7 | 13.3 | 3.1 |
| 1.2 | 80.7 | 14.1 | 5.1 |
| 1.3 | 78.6 | 14.4 | 6.9 |
| 1.4 | 76.2 | 15.3 | 8.5 |

As indicated above, the modal splits of Tables 2 and 3 are based on the tonnages transported by each mode, without taking into account the distances of transportation. A more accurate way to measure the impacts of a cost variation is to examine the results of the sensitivity analysis in tons/km. These results are presented in Tables 5 and 6.

In Table 5 it is seen that, in tons/km, the market shares of inland waterways and railways are quite naturally larger than when computed in tons transported. Going back to Table 4, it is seen also that the elasticities of waterways and railways are just slightly larger, but that the elasticity of road transports is much larger in absolute value (from −0.22 to −0.77). When attention is restricted to the traffic within the Benelux countries and Germany, Table 6 shows again that the market shares of railways and waterways are larger. On the other hand, Table 4 indicates a much higher elasticity for waterways (from 0.49 to 0.80) as well as for the use of roads (from −0.07 to −0.27).

## 5. CONCLUDING COMMENTS

As an illustration of the use of the network model, Section 4 has presented a very global analysis of the competitive positions of the three inland modes of transportation: rail, road and waterways. One of the conclusions suggested by this exercise is that it should be possible to increase substantially railway transports of commodities just by increasing the cost of road transports through taxation. Waterway transports would increase much less. Given the weak direct elasticity of road transportation, the taxation proceeds accruing to the states would increase.

Obviously, this is only the first step of an ongoing research project which should progressively add more precision and details to the network and cost functions, so that very specific types of transportation, like container transports for high value goods could be dealt with. It would also be interesting to examine separately and in more detail different transportation corridors characterized by different competitive situations. For instance, a specific analysis should be made of the corridor between the North Sea harbours and Germany, where waterways can compete for some goods with road and rail transportation. The conditions of competition via the various types of transports between the Baltic and the North Sea harbours should also deserve a particular analysis, like the problem of the Alpine crossing routes, the links between the North Sea countries and southern Europe,··· etc. Combined transports, roll-on, roll-off and piggy-back transports on some routes would also require specific analyses.

All these problems could be the object of simulations with this network model, provided that, in some cases, more detailed data be available. This is because the virtual network is based on an exhaustive representation of all the transports movements and operations on the multi-modal network. Hence, it is possible to vary any parameter of the cost functions attached to the virtual links. Detailed and comprehensive sensitivity or scenario analyses, such as those used in evaluations of transport new infrastructure and policies, are thus made much easier.

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## APPENDIX

*Parameters of the cost functions: Remarks*

1. An interest rate of 15% was used for the opportunity costs calculation.
2. On the basis of prices published by the OECD, the value of the transported wood per ton is 4954 BF.
3. The fixed costs for the trucks do not include the maintenance, which is included in the variable costs.
4. Fixed costs for the locomotive ($F_m$) and for the wagons ($F_w$) are separated: $F_m$ includes a constant capital annuity, insurance cost and wages; $F_w$ includes a constant annuity, insurance cost and maintenance.
5. The parameters for the railways (Table A1) are based on the published statistics of the Belgian railway company (S.N.C.B.). As there exists an infinite number of engine–carriage combinations, we have defined a standard diesel train and a standard electric train. Note that the Belgian cost data have been adjusted for each national railway company in order to take account of their varying efficiency. These adjustments are based on the work of Gathon (1991).

*Values (1991)*

$A$ is expressed in BEF per ton.
$B$ is expressed in BEF per ton/km (Table A2).

Table A1. Relative productivities of the different railway companies

| Railway company | Productivity index | Relative index to Belgium |
|---|---|---|
| SJ | 1 | 0.592 |
| NS | 0.762 | 0.777 |
| SNCF | 0.7 | 0.846 |
| RENFE | 0.69 | 0.858 |
| VR | 0.675 | 0.877 |
| CFF | 0.667 | 0.888 |
| CH | 0.666 | 0.889 |
| BR | 0.653 | 0.907 |
| CFL | 0.637 | 0.929 |
| SNCB | 0.592 | 1 |
| FS | 0.583 | 1.015 |
| CP | 0.563 | 1.052 |
| DB | 0.528 | 1.121 |
| TCDD | 0.352 | 1.682 |

Table A2. Costs (in BEF) for the different parameters

| Parameter | $A$ (loading) | $A$ (unloading) | $B$ |
|---|---|---|---|
| 300-ton boat | 41.2 | 86.0 | 0.62 |
| 1350-ton boat | 50.4 | 135.8 | 0.21 |
| 4500-ton boat | 25.7 | 72.8 | 0.11 |
| Diesel powered train | 99.6 | 145.0 | 0.80 |
| Electric powered train | 103.6 | 151.1 | 0.78 |
| 40-ton truck | 101.1 | 144.3 | 1.64 |