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CLIMATE CHANGE IMPACTS ON TRANSPORT ON THE RHINE AND DANUBE A MULTIMODAL APPROACH (ABRIDGED VERSION)

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ABSTRACT

Rainfall, melted snow and evaporation affect the rivers water level and periods of drought may impair freight transport by inland navigation during a number of days. Indeed, water depth conditions the loading of vessels, hence their transport cost and their competitive position versus alternative modes, rail and trucking. The ECCONET research project funded by the European Commission[1] endeavored to measure the potential effects of these phenomena on the Rhine and Danube navigation in the context of the observed weather variability and expected climate change scenarios. Many inter-disciplinary issues and methodologies are involved in such an analysis. These were tackled in several technical reports on statistical data, climate evolution prognoses, vessels specifications, adjustment strategies, etc. The present paper uses as inputs part of the wealth of information gathered during that project.

The paper presents a long-term multimodal transport analysis over the period 2005-2050, which is based on two climate impact scenarios on the Rhine and Danube hydrology. The geographic multimodal transport model NODUS is calibrated with respect to transport costs on estimated 2005 and forecast 2050 matrixes of freight transport flows between origins and destinations within Continental Europe per mode and per type of commodities. The model is used to analyze the effects of climate induced changes in the distributions of water depth on transport costs and on the resulting modal splits between the three competing modes, rail, road and inland waterway transports. The model integrates the effects of planned future European investments in the networks' infrastructure, and gives some insights on the cost savings that some improved vessels designs and operations could provide.

Keywords: inland waterways, network models, climate change
JEL: L91, L92, Q54, R41, R42

1. INTRODUCTION

For this analysis of the climate-induced impacts on the freight transport navigation on the Rhine and Danube, the NODUS software (Jourquin, 1995; Jourquin and Beuthe, 1996; Jourquin and Limbourg, 2007) is used for assigning transport traffics between modes and means over the multimodal trans-European network of roads, rails and rivers or canals. The assignment algorithms are based on the minimization of the generalized transport costs and the model calibration is done with respect to the modal shares estimated in 2005 and forecast in 2050. The simulated outcomes are given in terms of

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transport modal shares and costs under different climatic conditions observed in the past or forecast by two long term climate scenarios over the period 1977 to 2050.

Given the spatial scope of the research, traffics on the Rhine and Danube, the network includes all the regions potentially involved in these traffics from France and Benelux countries to Bulgaria and Romania. Transport costs include variable and fixed costs of carrying goods by the three modes, road costs to places of loading/unloading on wagons or vessels, plus the costs of these operations. However, our analysis had to separate the Rhine and Danube markets, because of differences in operating conditions on the two rivers and in the vessels costs, and differences in water depths as measured in specific places. . As will be explained in the following, four cities, corresponding to spots on the Rhine and the Danube were the water levels are at the lowest during dry periods, will draw our attention. These are Kaub and Ruhrort on the Rhine and Hofkirchen and Wildungsmauer on the Danube, as illustrated in Figure 1.1, which only represents the inland waterways network in order not to clutter the map:

Figure 1.1: Critical points on the Danube and the Rhine rivers

Source : Nodus

The outputs from simulations are the changes induced by the waterways conditions in the modal split and costs of transport for the three modes as well as for different commodities. These outcomes are computed for the reference years as well as for a set of water depth distributions that are selected from two modeled climate scenarios extending to 2050. Further on, some simulations show what could be the global impact of the climate change on the use of the different types of waterway vessels.

After this introduction, Section 2 of this paper gives a general description of the NODUS methodology. Section 3 describes the three modes' trans-European networks, the 2005 transport demands that can possibly make use of waterway transport on the Rhine, and the cost data. Section 4 explains the modeling of the effects of water level variations. Then, Section 5 presents the analysis of the Rhine market, the outcomes of simulations relative to the reference period 1977-2006, the impacts of climate change over the period 1977-2050, and some results on the use of the different types of vessels. Section 6 presents a similar analysis for the Danube market. The concluding remarks underline some limitations inherent to that type of modeling, and sum-up the research main results.

2. THE NODUS TRANSPORT MODEL

The NODUS approach permits the simultaneous handling of modal split and assignemnt. Given an OD flows matrix, output of the two first steps, it directly assigns the traffics on the networks by selecting the modes, the transport means as well as the itineraries that minimize the generalized transport cost for each origin and destination. The OD matrixes, at the Nuts 2 level in this case, pragmatically aggregate transport flows from/to many different places into a limited number of origins and destinations. Hence, for the most part, NODUS here applies a "multi-flows" assignment procedure whereby each OD flow is spread among the best available transport solutions.

This more comprehensive and detailed approach is made possible by constructing the transport networks as a virtual network. This concept differs from the usual geographic definition as it replaces each single infrastructure, like a specific waterway segment, by a set of "virtual" waterways corresponding to the different types of vessels that can navigate on that river segment. Additional virtual links can also be used to model within the networks all technical operations involved in transportation, like loading/unloading, transferring from one mode or means to another, locks or border operations, etc. Also, each centroid in a zone is linked to the road, rail and waterway networks by 'connectors'. As they are distinctively identified, each virtual link can be linked to its specific cost of operation. This set-up conveniently allows the computing of the total cost of every chain of transport operations that could be considered as part of the overall solution.

3. NETWORKS, OD MATRIXES AND COST FUNCTIONS

The European geographic networks in NODUS extend from Scandinavia to Spain and Italy, from Ireland and United Kingdom to Greece, Romania and the Baltic countries. Altogether, the entire physical network counts more than 40,400 segments on the railroad transport network, 67,800 on the road network and 1,180 segments on the inland waterways.

The OD flow matrixes for the 10 NST-R commodity classes and, separately, for rail, road and waterway transports at the NUTS2 level, were prepared by Panteia-NEA for the year 2005 chosen as reference year, as well as for the year 2050, the horizon year of this analysis. They correspond to the freight transport estimated demands over Continental Europe during these years. They are based on previous NEA's work with TRANSTOOLS (NEA *et al.*, 2009 and 2010) for the European Commission project TEN-CONNECT2 (Tetraplan *et al.*, 2011). The model presented in this paper is thus to be considered as a strategic transport model rather that a logistic optimisation model, in the sense that the flows are not disaggregated at the firm level, but are aggregated at a regional level. As a consequence, the specific logistic conditions or the contractual arrangements that lead the firms to choose one or another mode of transport are not explicitly taken into account. Only the calibration process ensures that the market shares (per group of commodities) correspond to the observed ones (at the NUTS 2 regional level).

We pruned the matrixes in order to retain only traffics that could possibly make use of at least one critical segment of the Rhine or the Danube. That was done by a first NODUS traffic assignment of all the OD flows on the waterway network only, which identified which flows could, if at all, use some segments of the Rhine or Danube.

The next step was to separate the Rhine and Danube transport markets. This partition is necessary because vessels with different operational costs are used on the two rivers. Also, different water level thresholds at different periods of the year will be used for the two rivers in our later analyses. Geographically, the separation between the two markets is taken, somewhat arbitrarily, at the Western end of the Main canal that links the Rhine to the Danube. In the Rhine market, we naturally include all transport flows on the Rhine from/to The Netherlands to/from Basel, but also navigating partly on its tributaries (Mosel, Schelde, Maas and Neckar, etc.). However, some transport flows on both the Rhine and Danube raise an assignment problem between the two markets. As a larger part of these traffics are upstream going East on the Rhine, all these traffics are included within the Rhine river analysis with selected Rhine vessels. Indeed, it is rarely the case that goods in these traffics are transferred at some point from/to Rhine vessels to/from Danube vessels. As to the traffics on the Mosel, the Neckar or the Southern part of the Rhine that also involve navigating on the Danube, there is no significant difference between the volumes going upstream and downstream. The volume of these traffics is relatively small and is also included in the Rhine market. Furthermore, an examination of the principal OD pairs involving navigation on the Rhine and Danube showed that these traffics mostly operate on the Rhine. In the end, this partition allocates to the Rhine market 88% of the total inland waterway volume in 2005 (82% in 2050), in which less than 4 could possibly be affected by the water level conditions on the Danube.

As developed within NODUS, four types of cost functions are needed that are associated with the corresponding virtual links. They relate to the costs of travelling, of transit, transhipment and loading/unloading. They include all the costs related to moving a vehicle between an origin_and destination, like labour, fuel, insurance, capital and maintenance costs, and, in some cases, equivalent tariffs; handling and storage costs, including packaging, loading and unloading and services directly linked to a transport; all residual indirect costs like general administrative services which may be assigned to transports on an average basis. Transport speed and time taken for various operations are important factors for determining some of these costs, like the travelling cost and the cost of inventory of the goods during transportation - an element of the generalized cost. For waterway transport, the speed is a function of the characteristics of each waterway and the ships that are allowed to navigate on them. Rivers or canals are categorized according to six classes of vessels, CEMT II to IV, Va, Vb, and VIb. The vessels' speeds are adjusted according to whether they navigate upstream or downstream, and their loading is influenced by the categories of transported goods: dry and wet bulk, pieces or containers. It is also taken into account whether the vessel is loaded or empty.

Besides these costs, a full account of the generalized transport costs in a multi-modal multi-means context should include some relative costs of transport quality differences, like differential reliability, safety, etc., if it is at all possible. These relative costs may vary from one category of goods to another, since transporting containers or coal requires different types of organisation and care. Also, congestion level on the different networks may also influence the costs and the transport service quality. Unhappily, information about these factors is rather scarce if one considers that the associated equivalent costs are specific to each type of commodity, transport modes and industrial organization (Beuthe and Bouffioux, 2008), and may vary through the spatial scope of the present research. Hence these additional costs are not introduced in the present study, but can be taken into account to some extent by the adjustments made to the cost functions at the stage of the model calibration, which is done separately for each category of commodity.

Real prices for transport services are very difficult to obtain in many cases, so that we mainly use transport production costs as an approximation. From a socio-economic point of view these are certainly the relevant parameters. In some cases, they can also be taken as acceptable approximation of prices or tariffs at least on marginal contestable markets where modes compete for market share. The trucking and inland navigation markets should not be very far from that model. Hopefully, some possible divergences that could affect the markets are also taken into account at the calibration stage of the model. Note, however that Jonkeren *et al*. (2007, 2009), who also have worked on this problem, based their analysis on a statistical analysis of the relationship between transport price per ton and the level of water for traffic going through the Kaub pass, which has the most severe effect on the loading of inland ships on the Rhine. As a consequence, they restricted their analysis to the Kaub-related Rhine market. In contrast, in the present analysis all traffics on the Rhine are taken into account, traffic through Kaub as well as through Ruhrort, another difficult pass, and traffic not subjected to any loading constraint.

4. MODELLING THE EFFECTS OF WATER LEVEL VARIATIONS ON WATERWAY TRANSPORT

The model was calibrated separately for each commodity group with respect to the 2005 modal shares in tonnage. The model shows a good fit of the calibration both in terms of tons and tons-km. Indeed, the global correlation coefficient between the modal shares (per commodity) in the 2005 data basis and the estimated modal shares from the calibration is above 0.99. Very similar results were obtained in the calibration of the Danube market model. Note that this calibration does not take into account any capacity constraint of the fleet, and also that it proceeds as if the transports volumes are evenly spread over the year since it is based on yearly data.

Two problems had to be dealt with for introducing the effects of water level into the model. To begin with, the rivers water levels vary over their successive segments. However, modelling the water depth and its variations in a quasi-continuous way along the Danube and the Rhine would create a serious computational problem. In the case of the Rhine, an analysis of the more shallow parts of the river and the practices of the inland navigation industry indicate that the water depths at two critical points on the Rhine, Kaub and Ruhrort, are mainly used as references for loading and pricing the transport of vessels going through their shallow waters. Hence, the water depth yearly distributions at these two passes are used as indicators of the hydrologic situation over the entire Rhine river.

Furthermore, the comparison of the daily water depth at Kaub and Ruhrort showed that water depth at Ruhrort was practically always higher than at Kaub, with a linear relationship between the two. Hence, it was decided to proceed in three steps: firstly, analyse separately the traffic going through Kaub and, in some cases, also through Ruhrort with reference to the water depth measured at Kaub (49.4% of the tonnage in the Rhine matrix for the year 2005); secondly, analyse the traffic through Ruhrort only with reference to the water levels measured at Ruhrort (18.6% in 2005); thirdly, analyse separately the remaining traffic at average loading, as if it was not encountering any serious shallow water difficulty. This led to the partitioning of the Rhine matrix in three sub-matrixes named “Kaub”, “Ruhrort” and “no critical point”. The same procedure is also applied to the Rhine 2050 data. Likewise, a similar analysis is applied later on to the Danube market data with respect to the critical passes at Hofkirchen and Wildungsmauer.

Secondly, the rivers water level varies from day to day during a given year, and this variability must betaken into account for simulating the impacts of the climate and weather variation. We are grateful to B. Zigic (DST, DE) for providing a relationship (practically linear) between the possible loading of each type of vessel and its draught, which gives the necessary information for computing the (maximum) feasible loading at any given water depth level. Thereby, it is possible to run the NODUS model for any given water depth taking into account the corresponding loading of each type of vessel and their associated operational cost. Again, to avoid running the model up to 365 times for every day of a year, seven intervals of water depth are pragmatically defined which fitted well the frequency distribution of water levels in 2005. Next, for the number of days within each interval it is assumed that the vessels are loaded according to what would be feasible at the mid-water depth of that interval. For a given year simulation of one commodity group, the total cost and modal split are then computed for each interval, and a weighted sum of the results of each interval gives an estimate of a year expected total cost of transport and modal split. In the case of the Rhine market analysis, the partitioning of the water level analysis into seven intervals requires a total of 165 runs of the calibrated model for simulating the effects of one year water depth distribution. As explained in the following paragraph, this computation is only made with respect to the average water depth distributions during the two 1977-2006 and 2021-2050 periods.

Climatologists define a (statistical) climate by reference to a set of average weather parameters over a number of years. For this research, the standard convention of a thirty years period was applied; it is also adopted for the hydrological parameters whose sensitivities to climate change are evaluated. The climate of reference for the 2005 economic data is then defined over the observed period 1977-2006, whereas the long-term climate forecast toward 2050 is set with reference to the time span 2021-2050. In order to take into account the uncertainty about the future climate situation, two long term climate scenarios were developed over the full period 1977-2050, to which the rivers’ hydrologic situations were linked: a ‘dry’ and a ‘wet’ scenario, which together represent the range of possible future conditions of navigation with special attention given to low water levels. These scenarios are based on a number of recent international studies on climate change on rivers, like the KLIWAS research on the Rhine, the GLOWA project on the Danube and a few others reviewed in the ICPR’s Report 188 (2011). They translate into distributions of daily water depths, which can be used, as previously explained, within the two reference periods. These water depth distributions obviously vary from year to year, but, with such small samples of 30 years from a wide range of possible outcomes, it is very hazardous to identify and compare two water depth distributions from two different climate sequences (observed or simulated) that could have the same probability of realization as could be measured on these samples. Hence, in what follows, all comparisons within and between scenarios will be made more reliably in terms of average outcomes over the two climate sequences, assuming that each year distribution in a sequence has the same probability.

5. CLIMATE CHANGE IMPACT ASSESSMENT FOR THE RHINE

The first step is to handle the 2050 demand matrixes in a way similar to the one used on the 2005 matrixes, selecting the useful data and splitting them between the two markets. The resulting data for 2050 appear in Table 5.1 with a comparison with the 2005 data.

The table shows a relatively strong increase of 48.07% of all traffics over the period, with a 2.27% increase in road transport share, whereas IWW and Rail shares decrease respectively by 0.84 and 1.43 %. When looking at the geographical spread of origins and destinations over Europe on the following two maps in Figure 5.1, we note a higher concentration around harbors in 2050, particularly in Germany, and a measured shift towards Eastern Europe countries.

Then, the 2050 model was calibrated by adjustment of the initial 2005 cost functions, hence without any additional assumption about modes' performance changes that could occur by 2050, some of these changes being already taken into account for estimating the 2050 matrixes. However, the calibration was made on the assumed 2050 network of infrastructures. These include all the projects in France and Belgium programmed in the framework of the Seine-Nord canal project, also the works on the river Meuse, the Albert and Juliana canals, works on the Betuwe railway and the rail lines between Athens and Nürnberg, as well as on the motorway between Budapest and Constanza). As before, we obtained a rather good fit of the model to the 2050 reference data, with as good a correlation coefficient between 2050 reference flows and flows assigned by the calibrated model.

Table 5.1: Modal split comparison-2005 and 2050 Rhine matrixes

		T (Millions T)	%	T.km (Millions)	%
2005	**IWW**	140.26	9.45%	82,779.66	12.53%
	Rail	196.50	13.24%	123,267.29	18.66%
	Road	1,147.52	77.31%	454,633.72	68.81%
	Total	**1,484.28**	**100.00%**	**660,680.67**	**100.00%**
2050	**IWW**	189.12	8.61%	123,534.49	10.74%
	Rail	259.72	11.82%	182,425.50	15.86%
	Road	1,748.93	79.58%	844,207.21	73.40%
	Total	**2,197.78**	**100.00%**	**1, 150,167.20**	**100.00%**

Source : Nodus computation

Before proceeding with the impacts analysis of the climate change, it is instructive to evaluate the impacts that the new 2050 infrastructures would have on the modal split in 2005. This can be done using the calibrated 2005 model. Table 5.2 indicates a slight increase of both IWW and Road to the detriment of Rail and suggests that the new infrastructures planned for the three modes would not induce any substantial modal shift within the given demand matrix. Several reasons can explain this result: the individual effects of the infrastructure should roughly cancel each other in the aggregate, and there should be some amount of routing and vehicles' switch inside each mode. Also, the volumes of commodities that can be efficiently transported by inland navigation impose a limit on modal substitution. Such a limit is actually embedded in the calibrated cost functions. At a more individual level, some of these new infrastructures, like the Seine-Nord-Europe, could not play an important role in the present context since only traffics that could possibly use the Rhine were kept into our basic matrix. In contrast, the Betuwe line is certainly a strong competitor to waterway navigation and trucking for transports on this East-West corridor, and we observed a clear increase of rail shipments along this corridor. Likewise, we observed a substantial increase of traffic on the upgraded Juliana canal, where larger class Vb vessels will be able to navigate after its completion.

Table 5.2: Rhine market - Effects of 2050 infrastructures (Matrixes 2005, cost functions 2005)

Network	Mode	Volume (Millions T)	%	Performance T.km (Millions)	%	Costs (Millions €)	%
2005	IWW	146.70	9.88%	82,652.52	12.57%	2,082.14	5.67%
	Rail	251.43	16.94%	122,097.75	18.57%	4,736.33	12.91%
	Road	1,086.15	73.18%	452,780.97	68.86%	29,882.98	81.42%
	Total	**1,484.28**	**100.00%**	**657,531.28**	**100.00%**	**36,701.46**	**100.00%**
2050	IWW	147.25	9.92%	83,053.87	12.61%	2,080.45	5.69%
	Rail	248.38	16.73%	121,406.45	18.44%	4,629.81	12.66%
	Road	1,088.65	73.35%	454,000.60	68.95%	29,854.53	81.65%
	Total	**1,484.28**	**100.00%**	**658,858.57**	**100.00%**	**36,564.79**	**100.00%**

Source: Nodus computation

In any case, these results are not sufficient to bear a judgment on the usefulness of these projects. This can be assessed only by a proper cost-benefit analysis of each project, taking into account the investment costs, all external costs, and some small and local traffic missing in our matrixes, as well as the full transport cost savings. Still, if all these investments had already been realized in 2005, the computed total cost of transport, including all modes, would have decreased by a non-negligible 137 M€ (in 2005 €).

Given the 2005 and 2050 calibrations it is possible to proceed to an analysis of the climate change impacts on the modal split and the costs of transports. Table 5.3 gives, as an example, the average water depth distributions at Kaub as observed during the 1977-2006 period and as estimated by the long term dry and wet scenarios in the same period; it also gives the distributions estimated by the two long term scenarios in the period 2021-2050.

It appears that the two "dry" distributions are hardly different, whereas the "wet" distribution in 2050 indicates a somewhat more humid climate. It also appears that there are no substantial differences between the 'dry' and 'wet' distributions in 2005 and also in 2050.This similarity between these distributions suggests that there is not a great deal of uncertainty about the future average water levels of the Rhine. The distributions at Ruhrort are very similar except that the water depth is (practically) always higher than at Kaub.

The calibrated models are then applied, using cost functions that are successively adjusted at the maximum loading allowed by the mid-point water depth of each interval. A weighted average of these results provides the average outcome for each scenario. This is separately applied on the so-called 'Kaub' and 'Ruhrort' subsamples, as explained in Section 4. For the third sub-sample of traffics, which does not go through these two passes, a straight application of the calibrated models at average loading is applied. In Table 5.4, aggregate results are given for the average observed period 1977-2006 and for the two long term scenarios average distributions over the two periods of reference, successively with respect to the demand and network data in 2005 and 2050.

Table 5.3: Rhine market - Distributions of average water depth at Kaub

Water depth	Days frequency									
	Average observations 1977-2006		Climate scenario 1977-2006				Climate scenario 2021-2050			
			Dry		Wet		Dry		Wet	
	#Days	%	#Days	%	#Days	%	#Days	%	#Days	%
x > 4.3 m	55	15.07%	58	15.89%	49	13.42%	57	15.62%	67	18.36%
3.6 < x ≤ 4.3	97	26.58%	97	26.58%	87	23.84%	96	26.30%	112	30.68%
3.1 < x ≤ 3.6	129	35.34%	105	28.77%	127	34.79%	106	29.04%	114	31.23%
2.8 < x ≤ 3.1	55	15.07%	59	16.16%	69	18.90%	56	15.34%	50	13.70%
2.5< x ≤ 2.8	20	5.48%	30	8.22%	26	7.12%	29	7.95%	18	4.93%
2.2 < x ≤ 2.5	7	1.92%	10	2.74%	5	1.37%	13	3.56%	4	1.10%
x ≤ 2.2	2	0.55%	6	1.64%	2	0.55%	8	2.19%	0	0.00%
Total	**365**	**100.00%**	**365**	**100.00%**	**365**	**100.00%**	**365**	**100.00%**	**365**	**100.00%**

Source: BfG and own computation

In this table, the relevancy of the climate modeling comes out from the comparison of the results obtained for the observed period and the results of the climate model in average over the period 1977-2006 for the 'dry' and 'wet' scenarios. We see that the modal split of the simulated average of the 'wet' scenario corresponds closely to the observed period situation. The 'dry' scenario's results are hardly different, as expected, even though they indicate a slight decrease of the inland waterwaysshare to the benefit of both Rail and Road. This rather small difference between the 'dry' and 'wet' scenarios can be seen in all the successive comparisons of these two scenarios presented in the table.

The table also allows the comparison of the results of the average climate situation over the period 2021-2050 with the results of the average over the period 1977-2006, while keeping unchanged the 2005 networks and demand matrixes. This shows that there is no serious climate impact on the model shares computed for the 'dry' and 'wet' scenarios.

A similar comparison can be made between the results of the estimated average climate situation over the periods 1977-2005 and 2021-2050 when applied to the 2050 demand matrixes and networks. We observe again very small changes similar to those shown in the previous paragraph. Again, there are practically no climate impacts on market shares.

Indeed, the changes that occur during the 2021-2050 period must be mostly attributed to the changes in demand, the general economic evolution, the changes in relative costs as well as the change in the geographic spread of origins and destinations. This is well illustrated by the comparison of the results of the 2021-2050 average scenario when applied to the different demands and infrastructures.

Table 5.4 also gives information on the total transport costs of successive simulations. It can be seen that costs changes are parallel to the changes in transported volumes, which indicates that the strong cost increases when 2050 demands and infrastructures are applied cannot be the result of a climate change.

Jonkeren *et al*. (2009) obtained similar results at least for two of the four year-scenarios that they formulated in terms of price levels for the Netherlands and Kaub-related traffic. Compared to our (30 years) average scenarios, the other two years were much more extreme, with 37 and 79 days of water level below 2.60 meter that induced average price increases of 3.4% and 8.5% respectively. There is not denying that such extreme years may happen, but their occurrence is rather rare and highly uncertain. Still, as a result of inelastic demand, the impacts of these specific scenarios on the waterways modal share were limited to decreases of 2.3% and 5.4% for the respective years.

The previous Table 5.2 indicated that the new infrastructures should not much influence the modal split between modes at this aggregate level, whereas Table 5.1 showed that IWW and Rail are forecast to lose some market shares in 2050, even though their transport volumes would increase. This is exactly what appears in Table 5.4. Again, this does not mean that the planned investments should not be realized. Additional simulations of the 2050 climate situations with and without the new infrastructures showed that, if the modal shares were hardly influenced by the assumed networks improvements, the latter would contribute sizable transport cost savings of about 737 M€ (2005 €) on the flows included in the 2050 Rhine matrix. However, as previously emphasized, a proper assessment of their usefulness would require a full-fledged cost-benefit analysis of each planned investment.

Table 5.4: Rhine market - Simulations of the climate impacts over the period 2005-2050 (with average water depth distributions)

Mode	Average Observations 1977-2006	Climate scenario 1977-2006		Climate scenario 2021-2050		Climate scenario 1977-2006		Climate scenario 2021-2050	
	2005 Data	2005 Data		2005 Data		2050 Data		2050 Data	
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Modal share (%)									
IWW	10.82%	10.79%	10.82%	10.78%	10.84%	9.39%	9.42%	9.38%	9.45%
Rail	16.67%	16.68%	16.67%	16.68%	16.66%	11.52%	11.51%	11.52%	11.50%
Road	72.51%	72.53%	72.52%	72.54%	72.50%	79.09%	79.07%	79.10%	79.05%
Volume (Million T)									
IWW	160.66	160.18	160.57	159.97	160.95	206.43	207.03	206.12	207.73
Rail	247.36	247.52	247.37	247.58	247.28	253.13	252.87	253.25	252.70
Road	1,076.26	1,076.58	1,076.34	1,076.74	1,076.05	1,738.22	1,737.87	1,738.41	1,737.34
Total	**1,484.28**	**1,484.28**	**1,484.28**	**1,484.28**	**1,484.28**	**2,197.78**	**2,197.78**	**2,197.78**	**2,197.78**
Total costs (Million €)									
IWW	2,168.43	2,170.19	2,169.52	2,170.87	2,166.43	3,202.81	3,207.61	3,201.19	3,208.71
Rail	4,667.72	4,670.16	4,667.96	4,671.14	4,666.51	5,914.71	5,910.57	5,916.73	5,907.62
Road	29,599.67	29,608.93	29,602.15	29,612.94	29,593.67	54,888.22	54,874.24	54,895.36	54,856.39
Total	**36,435.82**	**36,449.28**	**36,439.63**	**36.454.95**	**36,426.60**	**64,005.75**	**63,992.42**	**64,013.28**	**63,972.72**

Source: Nodus Computation

It is also interesting to have a look at the relative use of the different types of vessels. As indicated earlier, six classes of vessels are included in this analysis, with specific cost functions and capacities. The representative vessels in each class are the Kampine (class II), Gustav Koenigs (III), Johann Welker (IV), GMS 110 (Va), GMS 110 + one E-II Rhine barge (Vb) and PB with 2X2 E-II Rhine barges (VI). For this more detailed analysis, a second model was developed for analyzing the 2005 OD matrix relative to inland navigation only. The calibration of the model was made with respect to the fleet operating on the Rhine, as given by the Economic and Social Council of the United Nations (2010). Note that this reference is not perfect, as it concerns the whole Rhine market, and not only the submarket that could possibly be affected by low water levels, and which is analyzed in this paper, but no better data was available. Assuming, then, that the least cost vessel must be mostly used on a given OD relation, a simpler "all-or-nothing" assignment technique available in NODUS was applied. Admittedly, this analysis is closer to an optimisation procedure than to a simulation made with the multi-flows assignment technique, but, as such, it provides useful information about the extent to which the fleet should be adjusted in the long run.

Table 5.5 shows the impacts of the two climate scenarios on the use of the different vessels. Without any change of infrastructure the use of class II vessels remains unchanged, but the "wet" scenario allows the substitution of larger boats to the smaller class III and IV vessels.

Table 5.5: Rhine market - Climate impacts on the use of the different types of vessels

2005 Demands, Infrastructures and Costs			
Class of ship	Average Dry scenario (Millions T)	Average Wet scenario (Millions T)	Difference (%)
II	10.51	10.51	0%
III	19.03	16.69	-12.28%
IV	40.11	39.49	-1.54%
Va	34.37	36.51	6.23%
Vb	12.47	12.94	3.70%
VI	23.76	24.11	1.48%

Source: Nodus computation

This model as well as the initial multi-flows model can also be used to assess the cost savings that an improved design of vessels or some change in their operations could generate. As an example, such an analysis was made to test the possible use of Johan Welker ship (class IV) in a convoy configuration with a barge. This combination would substantially increase the tonnage transported and reduce its transport cost by about 20% while providing a better performance in situations of low waters. In that case, the multi-modal multi-flows model showed that the modal share in tons transported on waterways would increase by 1.69%, with the effect that the total cost of transport (all modes) would decrease by 1.03% (378 M€) in 2005.

To sum up this analysis of the Rhine market, we can state that the possible climate changes from 2005 to 2050 and their impacts on the Rhine hydrology, as modelled by the two long term 'dry' and 'wet' scenarios, are not strong enough to induce any significant shift in modal shares. Indeed, the induced variations in the number of days of low water between the 2005 and 2050 scenarios, as well as between the 'dry' and 'wet' scenarios, are not significant enough to make much difference. Actually, the computed variations of modal shares between 2005 and 2050 appear to result mostly from the forecast changes in demands and in their spatial spread throughout Europe. But it also comes out that a drier climate would justify maintaining small vessels in operation.

6. CLIMATE CHANGE IMPACTS ON THE DANUBE MARKET

The analysis of the Danube market follows the same steps as the one on the Rhine market. The general methodology and the costs definitions are nearly identical. The only change is that only four classes of vessels are included into the analysis: Gustav Koenigs (class III), GMS 95 (Va), GMS95 + one DE-II barge (Va) and PB +2X2 DE-II barges (VIb). Their specific characteristics and costs are taken into account for the model calibration. The analysis on the Danube market bears upon the transport of 198.27 million tons included in the Danube matrix, which amounts to only 11.78% of the total tonnage included in the total matrix, all traffic common to the two rivers being included in the Rhine market. As mentioned earlier, as far as our initial data basis is concerned, transport activity on the Danube really amounts to about twice as much as what is included in the Danube matrix.

The 2050 networks incorporate all the new projected infrastructures included in the Rhine analysis. To that list, we added the planned improvements of the Straubing–Vilshoffen stretch in Southern Germany and of the Danube East of Wien in Austria. These two projects aim at guaranteeing a higher minimum water depth during a larger part of the year. However, they cannot be incorporated as such into the modeled 2050 networks, but are separately handled through specific simulations with adjusted water levels distributions. The calibration of the Danube transport model for the years 2005 and 2050 was realized with as good a fit as obtained in the Rhine analysis.

Table 6.1 compares the estimated 2005 Danube matrix with the projected 2050 matrix. It shows a relatively strong increase of 40% of waterways transport over the period, like in the case of the Rhine market. However, in contrast with the evolution on that market, there is a sizable decrease of -5% of the share of road transport. IWW increases its share by 5.5%, whereas the share of rail slightly decreases (-0.5%). These evolutions are stronger when measured in ton-km. On the other hand, as seen in the two maps given in Figure 6.1, it is forecast that the geographical spread of origins and destinations over Europe is extended in 2050 towards the Eastern countries and Romania.

Table 6.1: Modal split comparison in 2005 and 2050 in Danube matrixes.

	Mode	**Volume (Millions T)**	**%**	**Performance T.km (Millions)**	**%**
2005	IWW	19.13	9.65%	4,913.55	10.07%
	Rail	9.99	5.04%	4,244.35	8.70%
	Road	169.15	85.31%	39,632.75	81.23%
	Total	**198.27**	**100.00%**	**48,814.81**	**100.00%**
2050	IWW	43.26	15.15%	16,085.75	18.44%
	Rail	13.03	4.56%	6,782.04	7.77%
	Road	229.34	80.29%	64,367.85	73.79%
	Total	**285.62**	**100.00%**	**87,235.65**	**100.00%**

Source: Nodus computation

The modeling of the water depth and its variations is handled in a way similar to what is done in the Rhine case. Here, the two critical water segments of reference are Hofkirchen, within the Danube stretch between Straubing and Vilshoffen in Germany, and Wildungsmauer, East of Wien. Their distributions of water depth are pretty much correlated but they tend to often intersect each other at low waters levels. Hence, no simplification can be used in the handling of the various traffics going through these two points. The flows which could possibly go through Hofkirchen only are separated from the traffics which could go through Wildungsmauer. The vessels loading for these two sub-matrixes of flows are then affected only by the water depth at their respective critical passes. The flows which would go through both passes are successively analyzed with respect to the distributions of water depths at Hofkirchen and Wildungsmauer. The remaining flows are analyzed using the calibrated average cost functions.

Table 6.2 presents the water depth distributions at Hofkirchen[2]. Furthermore, the distributions for 2021-2050 are adjusted to take into account the deepening of the fairways planned for 2050. To that effect, an additional 60 cm depth is added between Straubing and Vilshofen, and 50 cm East of Wien. These adjustments approximate the targets assigned to the planned improvements. In the dry scenario, they lead to 305 days of water depth above or equal to 2.5 meters at Hofkirchen and 314 days at Wildungsmauer. However, these adjustments can only be taken as working hypotheses since they bear in the same way on every water level, whereas dredging and other infrastructural works for deepening rivers have a decreasing effect as the water level increases.

In this Danube analysis, the available data and methodology unfortunately did not allow extending these scenarios to the 1977 -2006 span of years. In what follows, therefore, we will be obliged to compare the 2021 - 2050 results for these scenarios to the observed situation during the period 1977-

[2] A similar table exists for Wildungsmauer

2006. There are only minor differences between the results obtained for the four subsamples, and, space lacking in this paper, Table 6.3 presents the aggregated results of the simulations realized on the four sub-samples. For the simulations on flows going through both critical passes, the aggregation results are based on the distributions at Hofkirchen, as the results obtained with the Wildungsmauer distributions were not significantly different.

Table 6.2: Danube market
Distributions of average water depth at Hofkirchen

Water depth	Days frequency					
	Average Observations 1977-2006		Model 2021-2050 all infrastructure projects			
			Dry		Wet	
	# Days	%	# Days	%	# Days	%
> 4.3 m	14	3.84%	33	9.04%	44	12.05%
3.6 < x ≤ 4.3	52	14.25%	85	23.29%	105	28.77%
3.1 < x ≤ 3.6	83	22.74%	89	24.38%	96	26.30%
2.8 < x ≤ 3.1	59	16.16%	54	14.79%	47	12.88%
2.5 < x ≤ 2.8	58	15.89%	44	12.05%	35	9.59%
2.2 < x ≤ 2.5	47	12.88%	32	8.77%	22	6.03%
1.8 < x ≤ 2.2	37	10.14%	28	7.67%	16	4.38%
x ≤ 1.8	15	4.11%	0	0.00%	0	0.00%
Total	**365**	**100.00%**	**365**	**100.00%**	**365**	**100.00%**

Source: BfG and own computation

This table firstly shows a very small decrease of the waterways share when applying the 2021-2050 distributions on the 2005 data. Likewise, it shows that the impacts of the 'dry' scenario, compared to the 'wet' scenario, are minimal. This suggests again that the limited climate change should not make much difference to the waterways navigation. Secondly, there is a substantial increase of the volumes transported by the three modes in 2050, but with a strong increase of the inland navigation's share to the detriment of rail and road transports. This evolution from 2005 to 2050 is entirely in line with the forecast volumes for the three modes (Table 6.1), which are partly influenced by the changes in the geographical spread of origins and destinations. Thus, this increase is most likely attributable to the general economic evolution over the period 1977-2050.

Table 6.3 also gives some information about the transport cost changes. They are roughly parallel to the changes in transported volumes. Additional simulations on the 2050 data with the 2005 networks, compared to the above results with the planned new infrastructures, indicated that the networks improvements by 2050 would contribute a transport cost savings of about 410 M €2005 on the flows included in the 2050 Danube matrix. At this point it is worth remembering that the actual traffic on the Danube is higher than what appears in Table 6.3. This means that the above cost saving is likely underestimated since it does not take into account some savings made on the flows common to both the Rhine and Danube, flows that are included in the Rhine matrix but which also benefit from some specific network improvements on the Danube. Again, this partial information is not sufficient to pass a judgment on the usefulness of the planned investments. A full-fledged cost-benefit analysis of every project would be needed for such an assessment.

Finally, the impacts of climate and infrastructure change on the use of the different types of vessel on the Danube can also be analysed with the same "all-or-nothing" methodology as applied for the Rhine market. The calibration of the model was not an easy task, as no official data was available on the respective usage of the different ships. Therefore, we have tried to set-up a reasonable hypothesis about the existing fleet, and calibrated the model on that basis. Table 6.4 shows the aggregated tonnage impacts of the two climate scenarios on the use of the different vessels in the four main sub-

2050 demand and networks impacts

Climate impacts of demand & networks remain identical (2005)

markets all together, with and without infrastructure improvements. These simulations are applied only on the 2005 demands and costs data and used the Hofkirchen distributions. The results obtained with the Wildungsmauer distribution are hardly different.

Table 6.3: Danube market - Aggregate average results of the climate impacts simulations

Mode	Average Observations 1977-2006	Climate scenario 2021-2050		Climate scenario 2021-2050	
	2005 data	2005 Data		2050 Data with all infrastructure projects	
		Dry	Wet	Dry	Wet
Modal share (%)					
IWW	9.62%	9.55%	9.57%	15.10%	15.12%
Rail	5.18%	5.21%	5.20%	4.61%	4.60%
Road	85.20%	85.24%	85.22%	80.29%	80.28%
Volume (Million T)					
IWW	19.07	18.93	18.98	43.14	43.19
Rail	10.28	10.34	10.31	13.15	13.14
Road	168.92	169	168.97	229.33	229.3
Total	**198.27**	**198.27**	**198.26**	**285.62**	**285.63**
Total costs (Million €)					
IWW	247.43	247.88	247.48	558.64	556.7
Rail	385.39	387.18	386.53	467.16	466.29
Road	3,494.01	3,497.98	3,496.40	5,449.55	5,447.56
Total	**4,126.83**	**4,133.04**	**4,130.41**	**6,475.35**	**6,470.55**

Source: Nodus computation

Table 6.4: Danube - Climate impact on ships usage

Aggregated results with Hofkirchen's distributions

2005 Demands and Costs						
Class of ship	Climate scenario 2021-2050 2005 Network			Climate scenario 2021-2050 2050 Network, all infrastructure projects		
	Average Dry scenario (Millions T)	Average Wet scenario (Millions T)	Difference (%)	Average Dry scenario (Millions T)	Average Wet scenario (Millions T)	Difference (%)
III	2.009	1.936	-3.60%	1.816	1.816	0.00%
Va	4.007	4.101	2.35%	4.273	4.333	1.40%
Vb	10.830	10.683	-1.35%	10.417	10.281	-1.31%
VIb	2.285	2.409	5.45%	2.623	2.700	2.93%
Total MT	**19.13**	**19.13**		**19.13**	**19.13**	
Total Cost (M€)	**239.54**	**235.60**	**-1.64%**	**226.21**	**225.13**	**-0.48%**

Source: Nodus computation

First, when the networks are not improved, the use of class III and Vb vessels decreases in case of a wet scenario to the benefit of the other two classes. In addition, a wet scenario allows a cost decrease of about 3.94M€ (1.64%). With improved networks, the same two classes decrease in use whereas classes Va and VIb gain in use. This is particularly the case with a 'wet' scenario occurrence, which corresponds to a transportation cost decrease of approximately 1.08M€ (0.48%). Class Va and VIb vessels also gain in share in a 'wet' scenario, but the smaller class III vessels keep their tonnage share.

This analysis of the Danube market leads to conclusions that are very similar to those obtained for the Rhine market. The climatic evolution up to 2050 as forecast does not appear sufficiently strong to induce much change in the modal shares. It seems that the general economic evolution and its spread throughout Continental Europe would more affect the activities of the three modes than their modal shares. However, we noted that the use of different types of vessels could be affected in the long run by the type of climate that develops. Similarly, the impacts on modal shares of the set of infrastructure projects planned for 2050 appear rather limited, but they would still determine sizable transport costs savings, amounting to at least to 410 M €2005 during the year 2050.

7. CONCLUSIONS

To conclude this analysis of the Rhine – Danube corridor it is important to underline some of the methodology limitations. First, the basic data about freight transport activities in 2005 2050 are themselves derived from a modelling of European freight transports. These are not really observed data, which, actually, do not exist at this level of detail. Furthermore, they are yearly data, which means that the analysis proceeds as if the corresponding traffics are equally spread over the year, whereas, in reality, economic activities as well as water levels are marked by seasonal variations. Secondly, the NODUS model in its general application does not fully integrate the capacity constraint of the fleet. Only the model specific to the waterway flows and the use of vessels is calibrated with respect to the fleet operating on the rivers. Lastly, the modelling and simulations assume that transport costs are minimised. This hypothesis is quite reasonable in the framework of a freight transport analysis, but does not take into account the full complexity of shipping decision making. Hopefully, the calibration of the cost functions integrates to some extent the missing factors into the model.

The main conclusion that can be drawn from this analysis is that the possible climate changes from 2005 to 2050 and their impact on both the Rhine and Danube hydrology, as modeled by the two long term 'dry' and 'wet' scenarios, are not likely to be strong enough to induce any significant shift in modal shares. This conclusion is quite similar to the one reached by Jonkeren *et al*. (2009), who were working on a small set of water depth yearly scenarios and concluded on limited effects of forecast climate changes. However, we should note that a drier scenario would justify maintaining small vessels in operation, regardless of the planned improvements in infrastructures. They would remain useful in situation of low waters and for transports on smaller waterways that feed into the Rhine and Danube.

In contrast, it appears that the general economic evolution and its spread throughout Continental Europe will more affect the level of activities of the three transport modes than their modal shares. Similarly, the impacts on modal shares of the set of infrastructure projects planned for 2050 appear very limited, but these projects are shown to induce substantial transport cost savings.

These global results, obtained in both the Rhine and Danube analyses, cannot be taken as implying anything negative or positive about the possible economic usefulness of these planned investments. Modal shares changes are not appropriate indicators of investments worthiness. After all, these projects concern the three modes and their individual effects compensate each other in the aggregate; also, there are some routing and vehicles switches within each mode after improvement of specific links, and the volume of commodities that can be efficiently transported by inland navigation or rail imposes a limit on modal substitution. On the other hand, our analysis has shown that substantial transport cost savings would likely result from these investments. A complete assessment of these investments would require a full-fledged cost-benefit analysis at a global level as well as separate assessments of each project in terms of operational costs, capital investments and external costs.

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