Private Transport and the European Emission Trading System: Revenue Recycling, Public Transport Subsidies, and Congestion Effects

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Abstract:

From 2012 onwards, the European Emission Trading System regulates the carbon emissions of electricity generation, refineries, energy intensive production, and aviation. Beside the fuel efficiency regulation of cars, there exists no European approach of carbon regulation in the private transport sectors. However, half of the income of allowance auctioning has to be used for implementing environmental improving policies including public transport subsidies. Using a Computable General Equilibrium model of the German economy, we show that exempting transport from carbon pricing but recycling revenues via public transport subsidies is welfare enhancing. By including congestion effects into the model we show that such a recycling scheme has the potential of negative gross cost of carbon regulation by reducing congestion and global pollution externalities.

Keywords: Transport, Carbon Regulation, European Emission Trading System, Public Transport Subsidies

JEL-codes: D58, H23, Q58, R41

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1 Introduction

The European Emission Trading System (EU ETS), introduced in 2005 (EC, 2003), is the world largest emission trading system. Designed as a classical cap-and-trade instrument, it currently regulates the carbon emission of electricity generation, energy intensive production, and refineries.[2] From 2012 onwards aviation will also be included (EC, 2008). In contrast to aviation, the carbon emissions of automobiles are not regulated under this system but by using mandatory carbon efficiency standards of new cars (EC, 2009a). While carbon allowances are currently mainly allocated by grandfathering, from 2013 onwards most of the allowances have to be auctioned. At least half of the income of allowance auctioning has to be used for policies improving the environment. One explicitly mentioned policy alternative is the promotion of public transport subsidies (EC, 2009b).

We analyze different carbon pricing approaches to reduce emissions of automobiles, i.e. carbon taxes, the inclusion into the EU ETS, and the complete exemption of automobiles from any carbon pricing. Furthermore, we examine the possibility of recycling the income of allowance auctioning using public transport subsidies. As congestion is the main externality related to automobiles, we explicitly evaluate the role of congestion effects. Using a Computable General Equilibrium (CGE) model of Germany with a detailed representation of electricity generation, private transport, and congestion effects, we find, that the preferable approach is to exempt transport from carbon pricing. Furthermore, recycling the revenues of carbon regulation via public transport subsidies provides welfare gains as this induces a shift from automobile transport towards environmentally friendly public transport modes. Moreover, if congestion effects are included an additional positive effect is induced as the congestion externality is decreased. These positive effects of public transport subsidies have the potential to exceed the negative effect of carbon regulation, i.e. the gross cost of carbon regulation become negative.

In general two carbon pricing approaches for automobile emission exist: Fuel taxes and emission trading. As European fuel taxes are already high (Sterner, 2007), a further tax increase faces political feasibility problems (Raux and Marlot, 2005). Furthermore, due to the low own-price elasticity of fuel demand (e.g. Graham and Glaister, 2002), the additional fuel tax needed to provide a given carbon reduction has to be high. The problem of political feasibility amplifies as fuel taxes are considered to be regressive (West, 2004). An alternative way of pricing carbon in the transport sector is to include transport into the EU ETS by means of upstream emission trading (e.g. Stronzig et al., 2002; Ellerman et al., 2006). However, numerical simulation suggest that the inclusion of automobiles into the EU ETS is not beneficial due to the already high fuel taxes in Europe (Paltsev et al., 2005a; Abrell, 2010a). If the fuel tax is attributed to carbon, then there already exists a carbon price on transport fuels. Consequently, the exemption of transport from further carbon pricing leads to carbon prices closer to uniform across sectors, i.e. to a more cost-efficient carbon policy. However, relating current fuel taxes solely to carbon is incorrect as road transport exerts multiple externalities including

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[2] For some activities, nitrous oxide and perfluorocarbons are also included into the system.

congestion, accidents, local and global pollution, and noise (e.g. Verhoef et al., 1995; 1997) and empirical estimates show that congestion is by far the largest externality (Jeger et al., 2001; Link et al. 2001; Tweddel et al., 2001). Thus, the above mentioned studies have estimated the fuel tax too low since they neglect the congestion externality.

CGE models have become a standard tool in estimating the economy-wide effects of environmental and transport policies. Energy related models are mainly concerned with the effects of carbon pricing on electricity production and, thus, with a detailed modeling of electricity production (see Conrad, 1994; Bergman, 2005; Wing, 2009 for literature surveys). In contrast, the transport related CGE literature mainly focuses on a detailed representation of different externalities and the evaluation of road pricing approaches and infrastructure investments (e.g. Meyeres and Proost, 1997; Parry and Bento, 1999; Conrad and Heng, 2002; Kalinowska et al., 2007). Recently there have been some studies analyzing the effects of carbon pricing in the transport sector with both, a detailed representation of electricity production and transport. Schäfer and Jacoby (2005, 2006) include transport into the MIT Emission Prediction and Policy Analysis (EPPA) model (Paltsev, et al. 2005b). They use a mode choice model (Schäfer and Victor, 2000) linking the EPPA CGE model to the MARKAL (Loulou et al., 2004) energy system model which represents the transport system. Berg (2007) extends the EMEC model (Östblom and Berg, 2006) by detailed representation of household transport. While both of these studies incorporate details of electricity production and transport, they still neglect the impact of congestion.

Our contribution to the existing literature is threefold: First, we complement the studies of Paltsev et al. (2005a) and Abrell (2010a) by showing that the welfare enhancing effect of excluding private road transport from carbon pricing is still present even if congestion effects are included. Second, we provide a preliminary assessment of the recycling of allowance auctioning under the rules of the EU ETS. Third, we present an approach on how to incorporate details of electricity production and transport introducing a simplified version of the TREMOVE demand module into a hybrid top-down/bottom-up CGE model allowing us the evaluation of congestion effects. In the following section, we describe our modeling approach and the construction of the underlying database. Afterwards, we describe the scenario setting and evaluate the results. The final section concludes.

2 Model Description

2.1 Model overview

The model presented is a static small open economy CGE model of the German economy designed to analyze carbon policies especially in the electricity or private transport sector.[3] On the producer side we model 18 sectors which are assumed to be perfectly competitive. The seven energy sectors include coal, crude oil, natural gas, refined oils, and nuclear inputs as well as gasoline and diesel as

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[3] A detailed algebraic model description is given in Abrell (2010b).

transportation input. Electricity is modeled in a detailed bottom-up manner using 13 generation technologies as described below. Non-energy sectors, energy-intensive sectors and motor vehicle production as well as other sectors are aggregated along the NACE Rev. 2 classification scheme (Eurostat, 2009). The four transport sectors include aviation, water, rail, and other land transport which mainly consisting of road transport. For a detailed listing of all sectors see Table 4 in the Appendix. Final consumption is modeled using a representative agent with a detailed representation of private transport including different transport modes as well as congestion effects on different road networks. The household is endowed with capital and labor which are assumed to be constant and inelastically supplied. Both primary factors are intersecotrally mobile but not internationally. Government demand is assumed to be constant and modeled using a Leontief function. Domestic and imported commodities are assumed to be differentiated and aggregated using a Constant Elasticity of Substitution (CES) function (Armington, 1969). The trade deficit of the economy as well as investment demands are constant.

2.2 Production

Non-electricity production is described by a nested-CES function depicted in Figure 1. Outputs to the domestic and international market are modeled using a Constant Elasticity of Transformation (CET) function. At the top level, a Leontief function combines material inputs with an aggregate of energy and primary factors and a transport aggregate. The transport aggregate consist of a combination of the non-road transport services and road transport which subdivides into own provided and purchased road transport. Own provided transport is represented by the use of road transport fuels. The value-added/energy aggregate combines the value-added aggregate together with a energy composite consisting of fossil fuels and electricity. In order to represent the more easy substitution of liquid and gaseous fossil fuels, refined oil and natural gas are combined to the liquid fossil fuel aggregate, which is then enters the fossil fuel composite together with coal. Each of the fossil fuels is associated with a carbon content causing emissions when used.

Electricity production is depicted in Figure 2. At the top level, a Leontief function aggregates a value-added composite together with the transport composite described above. Electricity generation is characterized by three different load segments: base, middle, and peak load. Depending on their technological specification, generation technologies produce in different load segments. A list of the generation technologies is provided in Table 4 and the technological characteristics are given in Table 5 in the Appendix. The differentiation of load segments is important to avoid unrealistic substitution patterns between technologies. From an economic perspective, base load power plants are often characterized by high investment and low variable cost. Consequently, these plants need to run for a large number of hours per year in order to cover fixed costs. From a technical point of view, base load plants often exhibit a long-start up time, i.e. are limited in their flexibility. On the other hand, peak load power plants are less expensive in terms of investment cost but more flexible regarding the start-up time. Within a load segment, technologies are perfect substitutes. Technologies are either active or inactive in the benchmark equilibrium. For active power plants, capital is technology specific expressing the effect of installed capacities.

Figure 1: Non-electricity production

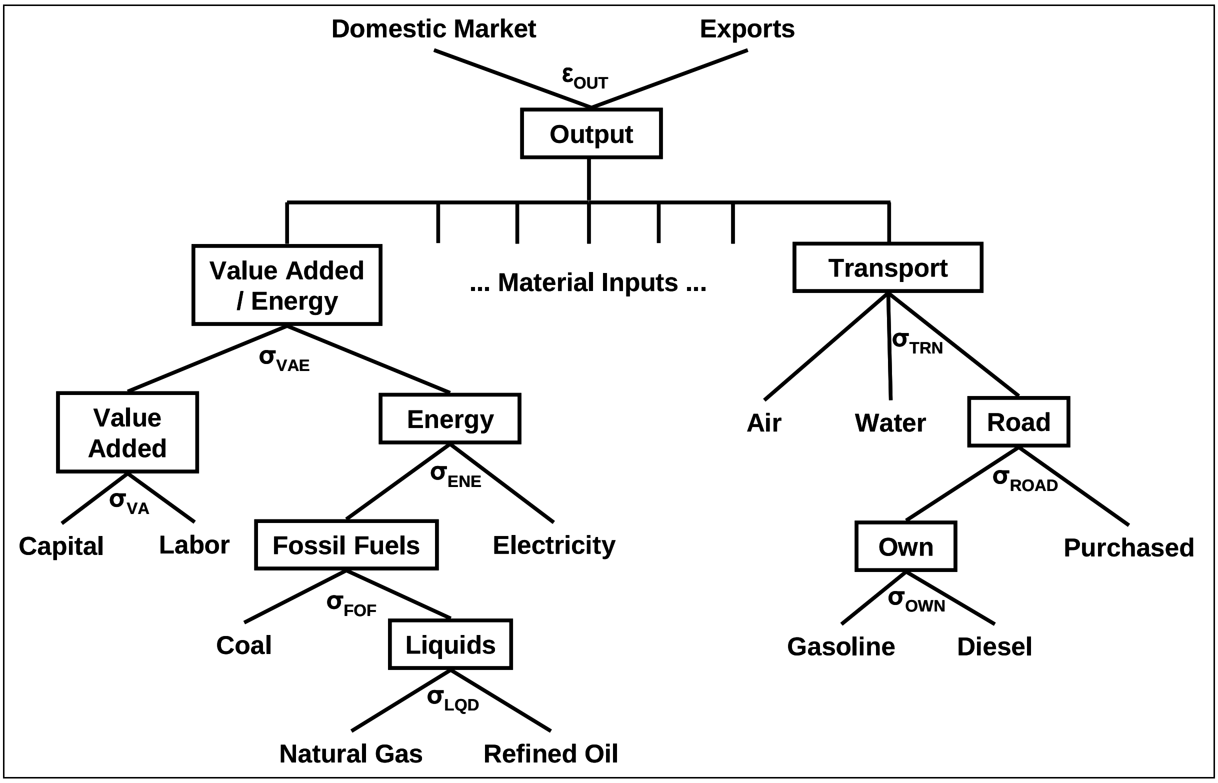
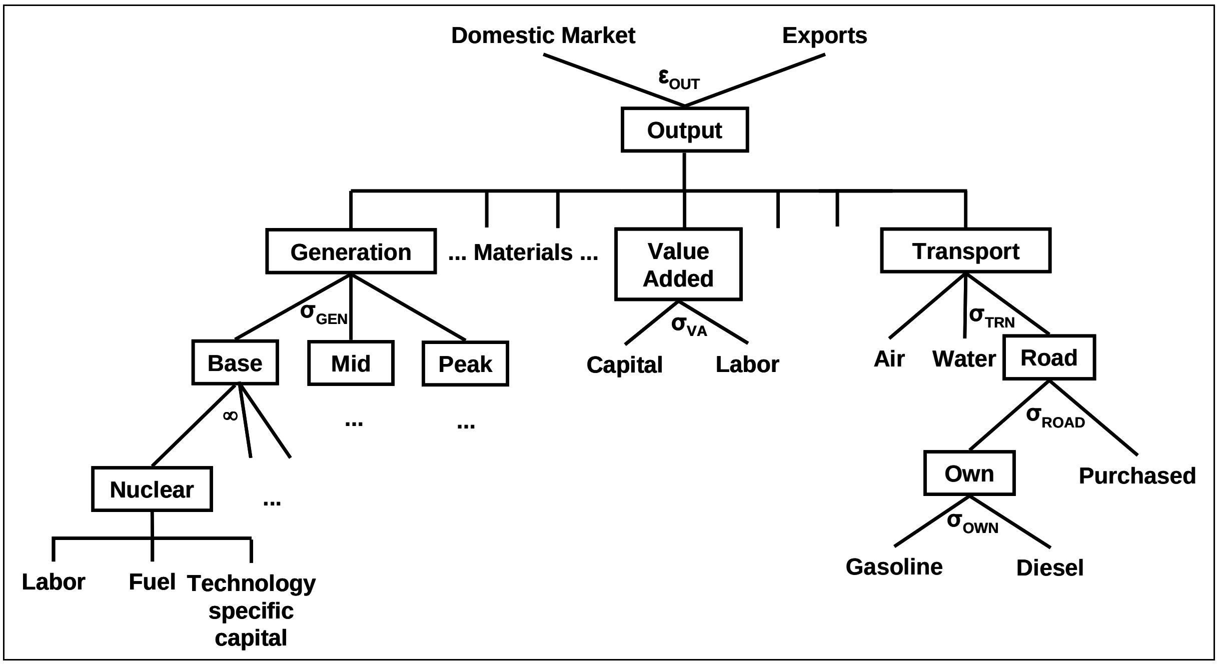


Figure 2: Electricity production



In order to control the malleability of installed capacities, i.e. allowing deconstruction of existing power plants, the approach of Wing (2006, 2008) is used: a CET function uses perfectly economy-wide malleable capital endowment of the representative agent providing technology-specific capital stocks. The capital stock of inactive technologies is not technology-specific.

The implementation of discrete generation technologies builds on previous work of Böhringer (1998) and Wing (2006, 2008). Böhringer (1998) treats technologies as perfect substitutes with technology specific resources to limit unrealistic flip-flop behavior of technologies. However, this approach does not allow for the deconstruction of installed capacities. Wing (2006, 2008) controls for the malleability of capital by introducing the CET transformation and uses a nearly linear CES function to combine the output of power plants. However, using the CES aggregator for power plants' output is not feasible if new technologies are included: due to the zero-value share in the benchmark equilibrium, inactive technologies cannot be calibrated into the CES aggregate. Consequently, the only possibility is to model them as perfect substitutes to the CES aggregate of existing technologies. However, this approach favors the adoption of new technologies since they do not use technology-specific capital. Additionally, the change in the generation of existing technologies is restricted by the share preserving character of the CES aggregator leading to unrealistic results. The approach presented has the advantage that it implements realistic technology substitution by modeling them as perfect substitutes and allows controlling the malleability of existing installed capacities using the CET transformation of technology specific capital.

2.3 Representative household

The representative household inelastically supplies capital and labor. Utility is derived from commodity and leisure consumption as well as from leisure trips.[4] Labor also induces private trips but these do not yield utility. The nested CES utility function is depicted in Figure 3. At the top-level of the tree, leisure is combined with an aggregate of commodity and private trips consumption. Commodity consumption is distinguished by energy and non-energy commodities. The composition of trips, which applies to leisure as well as labor trips, is given in Figure 4. Trips are subdivided into long (above 500 km) and short-distance trips. Within the distance categories we distinguish between peak and off-peak travel periods with a high and low transport volume, respectively. Within each of these periods, the consumer can choose among the different mode alternatives: busses, metros, planes, trains, own provided road transport, i.e. car trips, and slow mode representing bicycles and pedestrians. Each of the transport modes (except the slow mode) requires some commodity input causing monetary cost and some time input. For trips occurring on road – busses and own provided transport – we further differentiate between urban and non-urban streets in order to account for different congestion effects on these networks.

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[4] We assume that labor supply is constant but include leisure into the model in order to represent the time input necessary to provide trips allowing to introduce congestion effects into the model. The assumption of constant labor time input is primarily to clearly separate the effects from congestion effects from labor market effects in the scenarios described below.

Figure 3: Utility structure

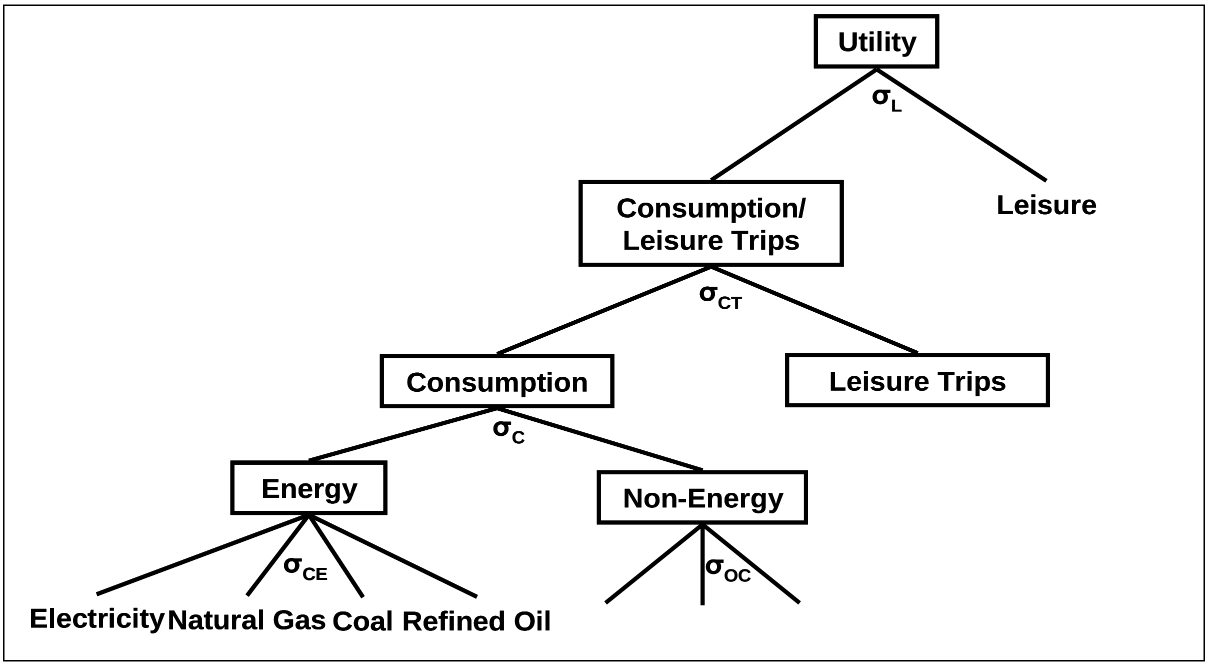
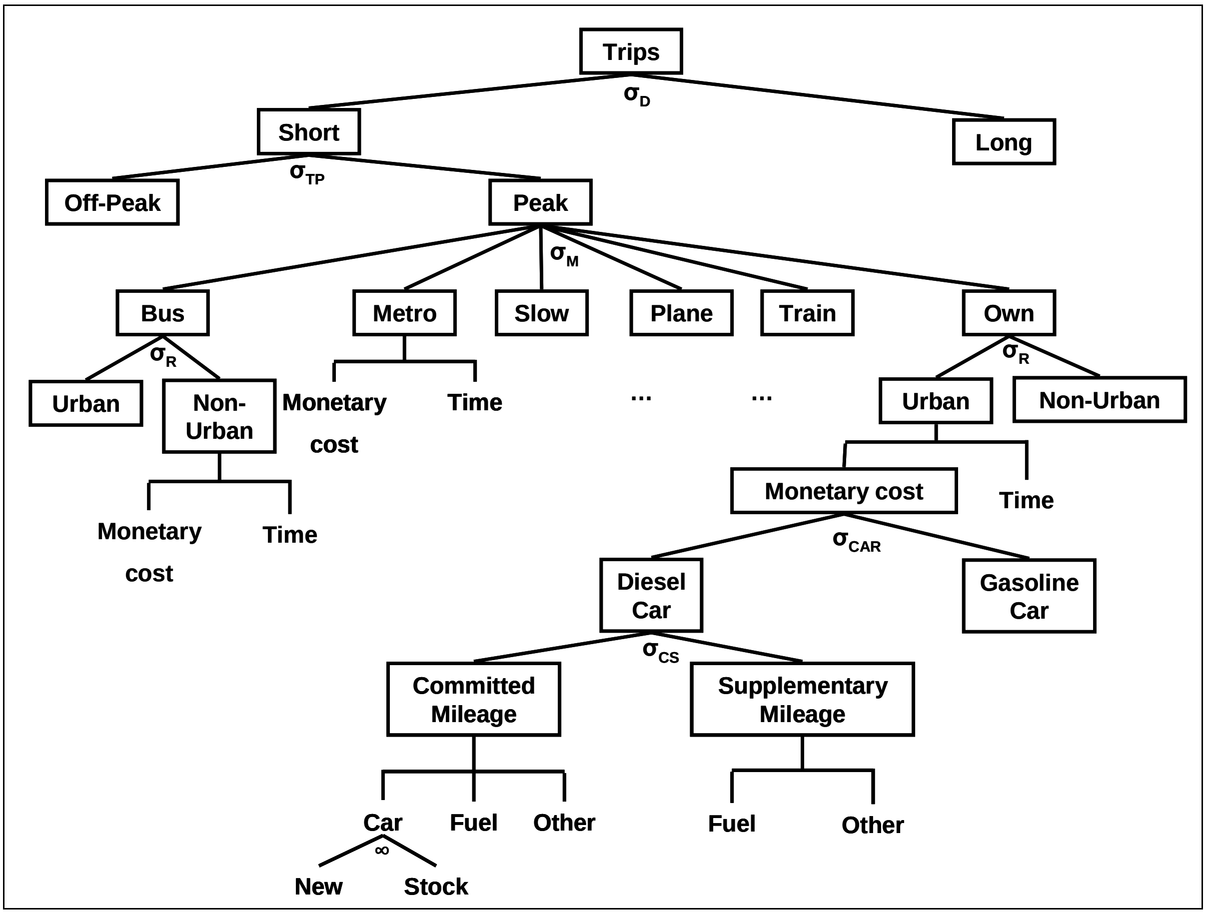


Figure 4: Private transport structure



Either gasoline or diesel cars can be used for own provide car trips.[5] Each of these cars causes use of the vehicle fleet, use of the respective fuel, and some other cost representing maintenance and insurance cost. Note that the time input is the same for both car classes but the monetary cost differ. Following the approach of Koopman (1995) in the EUCAR model, we distinguish committed and minimum mileage of cars expressing the fact that consumers can react in two ways to rising fuel prices. First, reducing supplementary mileage to save the variable cost and keeping the number of available cars constant. Second, the consumer can reduce the number of car purchases reducing committed mileage. The approach is based on the assumption that buying an automobile implies a certain minimum of kilometers driven per year. Consequently, the committed mileage is characterized by the rental cost for the car and the variable cost implied by minimum kilometers driven. In addition, it is possible to drive more kilometers – the supplementary mileage – which are only characterized by variable cost.

Congestion impacts the time input necessary to travel one kilometer. With an increasing use of cars or busses on a specific network the traffic flow is rising and, consequently, the time needed increases. This expressed with an exponential function (O'Mahony et al., 1997):

$$time_{m,n} = A^1_{m,n} \left[A^2_n + A^3_n e^{A^4_n flow_n} \right]$$

The indexes *m* and *n* respectively denote the travel mode and network used, *time* is the necessary time input for travelling a kilometer and *flow* the traffic flow on a network expressed in person car equivalents. The *A* parameters have to be calibrated as explained below. The congestion impact of freight related road transport is not explicitly model. We assume that traffic flow from industrial sectors is constant.

2.4 Parameterization

The model is based on four main data sources: the German input-output (IO) table of the year 2004 (Destatis, 2008a), the corresponding physical IO table (Destatis, 2008b), and transport data of the TREMOVE (de Ceuster et al., 2007) demand module and the German Institute for Economic Research (DIW, 2006).[6] The carbon content of fossil fuels is taken from IPCC (2006). The IO tables are used to construct the underlying social accounting matrix (SAM). The TREMOVE demand module incorporates physical data on travel demand by different networks and periods including the travel speed. DIW (2006) contains household expenditure data on transport including taxes, new car purchases, and the existing vehicle fleet.

Generation technologies are incorporated into the database using a two-step procedure. First, the detailed engineering data listed in the appendix are converted into a three dimensional unit input vector of capital, fuel, and labor input. Following Wing (2008), we use a least square minimization to match the input sectors of the single technologies to the aggregated input values of the electricity

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[5] The base year of the simulation is 2004. Therefore, we do not included electricity vehicles.

[6] A detailed description of the construction of the underlying database and results of a sensitivity analysis over the assumed elasticities is given in Abrell (2010b).

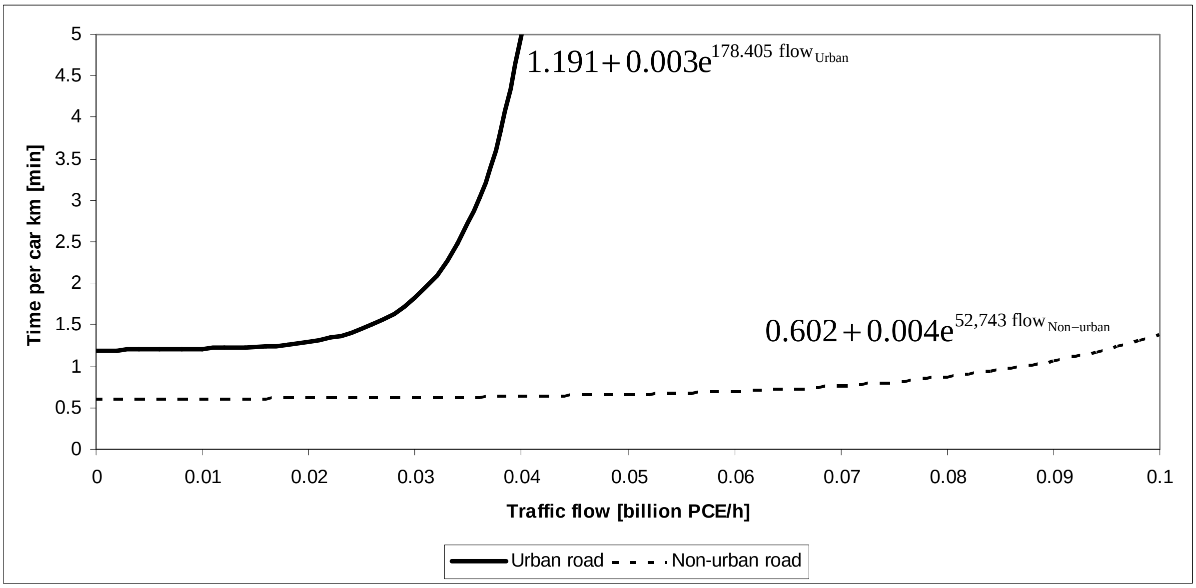
sector given in the SAM. The result of this procedure is given in Table 6 in the Appendix which also lists the technological potential of renewable generation technologies and the price markup of technologies inactive in the benchmark. Note that the technological potential of nuclear power plants is assumed to be equal to the benchmark as we do not allow for further expansion of nuclear power.

Data for the calibration of the congestion function are taken from the TREMOVE model and are listed in Table 7 in the Appendix. The resulting congestion functions for the different networks are given in Figure 5.

Substitution elasticities are listed in the Appendix (Table 8-10). For the value-added and value-added/energy composites estimated values from van der Werf (2008) are taken. Following Böhringer (2005) the substitution elasticity between load segments is assumed to be small. Substitution elasticities in the transport module are based on a literature review (Berg, 2007; Koopman, 1995; Mayeres, 1999; Munk, 2003, 2005; de Ceuster et al., 2007). Armington elasticities have been estimated by Welsch (2007). Other elasticities are adopted from Paltsev et al. (2005). According to de Jong (1991) the share of committed mileage in observed kilometers driven is around 65%.

The model is formulated in GAMS (Brook et al., 2008) using MPSGE (Rutherford, 1999) as a subsystem and the PATH solver (Dirkse and Ferris, 1995).

Figure 5: Calibrated congestion functions for automobiles



3 Results

3.1 Scenario description

The benchmark scenario (BAU) replicates the German economy in the year 2004. In the counterfactual experiments, we generally assume that the German economy has to reduce 12% (108 Mt) of its carbon emissions in the benchmark year. These 12% stem from the fact that the allocation to the EU ETS sectors is reduced by around 21% until the year 2020 which amount to around 10% of the total emissions. The remaining reduction has to be achieved by additional measures for non-EU ETS sectors. We further assume a moderate reduction target for automobile travel which is required to reduce its emissions by 2% of the benchmark emissions. As a consequence, the total amount of emission to be reduced is approximately 12% of the total benchmark emissions. As aviation is included into the EU ETS from 2012 onwards, we include it in the emission trading system. Consequently, the emission trading sectors are electricity generation, refineries, energy intensive sectors, and aviation.

Three basic simulations are performed: First, the emissions of the private road transport sector are reduced by 2% using a tax on the carbon content of transport fuels. The remaining necessary reduction burden is carried by the ETS sectors. Second, private road transport is included into the EU ETS. Third, private road transport is exempted from carbon pricing and the reduction burden in the EU ETS is increased accordingly.

Each of the basic simulations is carried out for two different revenue recycling schemes. First, the income of allowances auctioning is passed to the final consumer using a lump-sum transfer. Second, the total income of carbon regulation is used to uniformly increase the subsidies on public transport modes, i.e. on bus, metro, and train use.[7]

In order to identify the role of congestion, each of the described scenario variations is performed with and without the congestion effect. In the case without congestion, we keep speed on the different road networks constant. We proceed by separately describing the result of each variation of the basic scenarios. Afterwards the base scenarios are compared against each other.

3.2 Taxing transport fuels

In this scenario private road transport emissions are reduced by 2% using a tax on the carbon content of fuels. In order to reduce total emissions by 12% the remaining reduction burden is carried by the ETS sectors. The results of the different scenario variation are given in Table 1. We measure the gross cost of carbon regulation, i.e. the cost of carbon regulation without incorporating the benefit of less carbon emissions, in terms of Hicksian Equivalent Variation (HEV).

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[7] We have to note, that this kind of revenue recycling is an extreme case, as the EU ETS Directive only dictates that 50% of the income has to be recycled via policies aiming to improve the environment.

Table 1: Results EU ETS and transport tax

Recycling Congestion	Lump-Sum No	 Yes	Public Transport Subsidy No	 Yes
Welfare (% HEV)	-0.498	-0.492	-0.016	0.008
ETS Reduction (%)	21.27	21.27	21.30	21.30
ETS Carbon Price (€/t)	8.32	8.32	8.41	8.40
Transport Reduction (%)	2.00	2.00	2.00	2.00
Transport Carbon Price (€/t)	293.17	301.02	15.66	16.19
Gasoline Tax Increase (€/l)	0.67	0.69	0.04	0.04
Diesel Tax Increase (€/l)	0.78	0.88	0.04	0.04

In general, the gross costs of carbon regulation are relatively low. This is a typical feature of hybrid bottom-up/top-down models introducing more technological flexibility than comparable top-down models. The ETS sectors jointly reduce around 21% of their emissions mainly in the electricity sector. This reduction occurs in two ways (see Abrell and Weigt, 2008, for a more detailed description): First, electricity output is reduced by 10.5%. Second, the generation portfolio changes by reducing the output of carbon intensive coal plants which are partly substituted by an increase of on- and offshore wind power and coal plants using carbon capture and storage in the base load segment.

Emissions in the private transport sector are reduced by substituting automobile trips with public transport modes. In the case of lump-sum recycling, the carbon tax becomes very high and the difference in the carbon price indicates cost saving potentials by equating marginal abatement cost, i.e. including private transport in the emission trading system. If the revenues of allowances auctioning are recycled using public transport subsidies, a significant drop in the carbon tax is observed. The public transport subsidy affects relative prices in private transport favouring busses, trains, and metros. Consequently, this instrument already sets incentives to switch to environmentally friendly transport modes which reduces the carbon tax for transport fuels.

The effect of congestion on the gross cost of carbon regulation is negative, i.e. the inclusion of congestion is beneficial in terms of welfare. This is explained by the induced shift to non-road modes and busses with a higher occupancy rate. In consequence, the traffic flow is decreasing which reduces the congestion externality by increasing travel speed, i.e. decreasing travel time. In the case of revenue recycling via public transport subsidies, this welfare enhancing effect is amplified by the subsidy induced shift to public modes. Hence, the welfare effect even becomes positive, i.e. there are negative gross costs of carbon regulation.

We do not observe an impact of congestion effects on the EU ETS allowances price. However, the carbon price in the transport sector increases with the congestion effect. The increase in the fuel tax induces a substitution away from automobile travel. Traffic flow on the different networks is reduced which decreases the congestion effect, i.e. increases the average speed on the networks. This increase in the automobile travel speed provides incentives to increase private road transport, and, thus, counteracts the increased carbon tax. Therefore, the carbon price is slightly increasing.

3.3 Transport under emission trading

In this scenario automobile fuels are incorporated into the EU ETS. The results are shown in Table 2.

Table 2: Results private transport under emission trading

Recycling	**Lump-Sum**		**Public Transport Subsidy**	
Congestion	**No**	**Yes**	**No**	**Yes**
Welfare (% HEV)	-0.035	-0.035	-0.007	0.014
ETS Reduction (%)	21.56	21.56	21.34	21.34
ETS Carbon Price (€/t)	8.41	8.41	8.39	8.39
Transport Reduction (%)	0.03	0.03	0.17	0.17
Gasoline Tax Increase (€/l)	0.02	0.02	0.02	0.02
Diesel Tax Increase (€/l)	0.02	0.02	0.02	0.02

The main reduction occurs in the original ETS sectors, mainly in electricity generation. In the case of lump-sum recycling there is nearly no reduction of carbon emission in automobile travel. Using public transport subsidies, the change in relative prices in private transport supports the shift to environmentally friendly public modes and induces a slight increase in the reduction of automobile emissions. Therefore, the price of carbon allowances under public transport subsidy revenue recycling is decreasing.

The effect of congestion on welfare is again positive. Also, public transport subsidies under congestion effects have a positive welfare effect. We do not observe an effect on the allowances prices as these are mainly determined by the marginal abatement costs in the electricity sector.

3.4 No carbon price for transport

In this scenario automobile fuels are completely exempted from carbon policy and the reduction burden is shifted to the EU ETS. The results are shown in Table 3.

Table 3: Results no carbon price for transport

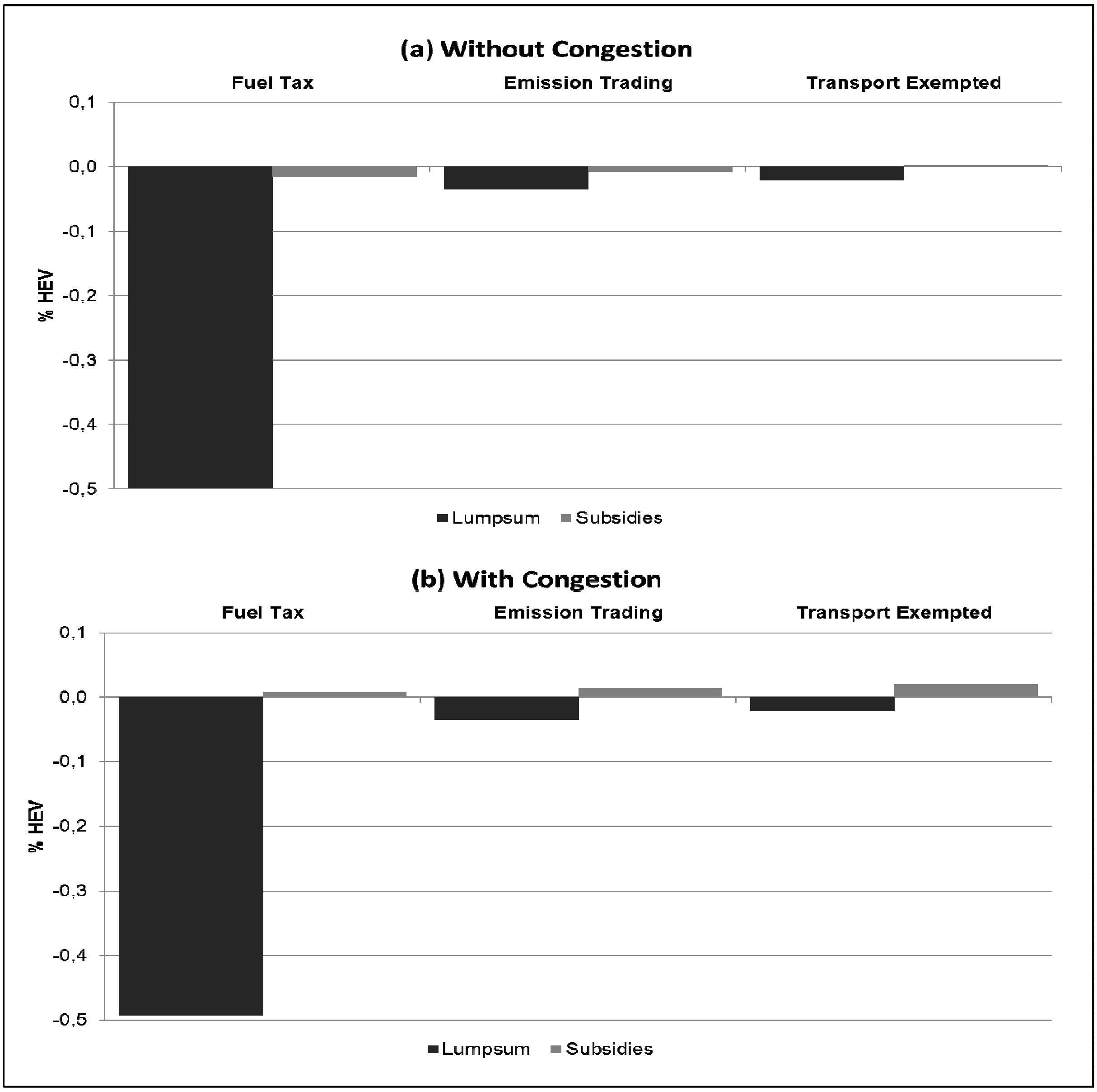
Recycling	**Lump-Sum**		**Public Transport Subsidy**	
Congestion	**No**	**Yes**	**No**	**Yes**
Welfare (% HEV)	-0.021	-0.021	0.003	0.02
ETS Reduction (%)	21.56	21.56	21.38	21.38
ETS Carbon Price (€/t)	8.41	8.41	8.41	8.41

The results are similar to those described above: congestion has no impact on welfare as long as the revenues of carbon regulation are lump-sum recycled and a positive impact if public transport subsidies are used. Note that the reduction in the EU ETS is decreasing if public transport subsidies are used. This is caused by the constant overall target of 12% carbon emission reduction. The public transport subsidy induces a decrease in automobile travel and, in turn, a decrease in automobile emissions. As the overall target of emission reduction is constant, this leads to a reduction of the reduction burden in the EU ETS.

3.5 Comparison

Figure 6 summarizes the gross cost of carbon regulation in terms of welfare results for the cases with and without congestions. Independently whether congestion effects are included, the highest welfare cost occur if automobile emission are reduced by using a tax on the carbon content of transport fuels. Due to the high difference in the marginal abatement cost of automobile travel and those of the EU ETS sectors, the inclusion of transport in the EU ETS is beneficial. However, there is an additional gain by excluding transport from carbon pricing and shifting the reduction burden to the EU ETS. This effect is caused by the high pre-existing taxes on transport fuels which already cause a difference in carbon prices between the transport and EU ETS sectors in the benchmark equilibrium. The exemption of transport from carbon pricing reduces this difference in carbon prices, the marginal abatement cost become closer to uniform across sectors, and welfare is improving. This confirms the results of Abrell (2010a) and Paltsev et al. (2005a). However, in contrast to their work, we also show that this effect is even robust againgst the inclusion of congestion effects.

Figure 6: Welfare Results



4 Conclusion

We analyzed the effect of different carbon policies for automobile travel in the presence of an emission trading system. A small-open economy CGE model of the German economy was used. The model includes a detailed representation of the electricity sectors by displaying discrete generation technologies. Private transport is modeled in detail by including different transport modes and different car technologies. Furthermore, we included congestion effects on different road networks.

The best policy alternative for carbon pricing in the transport sector is a carbon price of zero, i.e. excluding private transport from carbon pricing. This is justified by the already high taxes on transport fuels. By reducing the gap in effective carbon prices there is a beneficial effect on welfare. This result is invariant to the inclusion of congestion.

Revenue recycling using public transport subsidies, as suggested by the EU ETS Directive, is clearly superior to lump-sum recycling. Public transport subsidies induce a shift to environmentally friendly public transport modes. As a result, the emissions of automobile travel and the congestion externality are reduced. In the extreme case of fully recycling the allowances auctioning income via subsidies to public transport, this even leads to a welfare enhancing effect of carbon regulation, i.e. the gross cost of carbon regulation become negative.

We concentrated on the role of revenue recycling and public transport subsidies. However, the EU ETS Directive also allows for revenue recycling supporting advanced technologies in the electricity sector. Therefore, in future work we will compare this possibility against subsidies in the transport sector. The employed model shows that it is possible to incorporate technological details of electricity generation and detailed private transport behavior into a general equilibrium framework. However, we did not yet incorporate a detailed link between electricity consumption and automobile transport. In future work, we include such a link by allowing for electro mobility.

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Appendix

Table 4: Model dimensions

Description	Abbreviation	Description	Abbreviation
Non-energy:		**Vehicle classes:**	
Agriculture	AGR	Diesel car	DIESEL
Energy intensive industries	EINT	Gasoline car	GASOLINE
Manufacture	MAN		
Mining	MIN	**Generation technologies:**	
Motor vehicle production	MVH	Combined cycle gas turbine	CCGT
Services	SER	Hard coal power plant	HCOA
Electricity	ELE	Hydro power plant	HYDRO
		Lignite power plant	LIGN
Energy:		Lignite CCS	LIGNCCS
Coal	COA	Natural gas CCS	GASCCS
Crude oil	CRU	Nuclear power plant	NUCLEAR
Diesel transport fuel	DIESEL	Open cycle gas turbine	OCGT
Gasoline transport fuel	GASOLINE	Open cycle oil turbine	OCOT
Natural gas	GAS	Other technologies	OTHER
Nuclear inputs	NUC	Photovoltaic	PV
Refined oils	P_C	Wind onshore	WINDON
		Wind offshore	WINDOFF
Transport:			
Air transport	ATP		
Rail transport	RAIL		
Road and other transport	OTP		
Water transport	WTP		
Transport modes:		**Trip distances**	
Airplanes	PLANE	Long distance trip	LONG
Bicycles, pedestrians	SLOW	Short distance trip	SHORT
Busses	BUS		
Metro and tram	METRAM	**Trip time periods**	
Own private road transport	OWN	Off-peak transport	OPEAK
Private train	PTRAIN	Peak period transport	PEAK
		Road networks	
		Non-urban roads	NURBAN
		Urban road	URBAN

Table 5: Data on electricity generation technologies

	Size [MW]	Investment [10^6 €/MW]	Variable operation and maintenance costs [€/MWh; % of investment for renewables]	Fixed operation and maintenance costs [€/MW; 10^3 €/year for renewables]	Heat efficiency [%]	Fuel price[d] [€/MWh]	Availability [hours/year]	Lifetime [years]	Production 2004 [TWh]
Combined cycle gas turbine[a]	400	0.6	1.9		55	15	7500	30	30.7
Hard coal power plant[a]	400	1.1	4.9		48	6	7500	30	140.8
Hydro power plant[c]	2.5	1.5	5%	50			5400	60	26.9
Lignite power plant[a]	1050	1.1	5.2		44.5	3.5	7500	35	158
Lignite CCS[a]	450	1.4	4		44.5	3.5	7500	35	0
Natural gas CCS[a]	425	1	2		55	15	7500	35	0
Nuclear power plant[a]	1450	1.8	5.8		36	2.2	7500	60	167.1
Open cycle gas turbine[b]	160	0.4	4	9.98	45	15	7500	30	30.7
Open cycle oil turbine[b]	160	0.4	4	9.98	45	17.7	7500	30	10.3
Other technologies[b]	100	1.7	2.89	44.88			7500	30	25.3
Photovoltaic[c]	2	3.7	1.05%	50			1000	20	0
Wind onshore[c]	2.5	0.9	6.12%	50			1900	20	15.5
Wind offshore[c]	3.6	2.1	10%	50			3500	20	0

Sources: (a) EUSUTEL project (2006); (b) Wing (2008); (c) Reichmuth et al. (2007); (d) BP (2007) for natural gas; Wissel et al. (2008) for hard coal, lignite, and nuclear fuel; IEA (2008) for oil

Table 6: Generation technologies in the benchmark equilibrium

	Load	Markup [%]	Capital share			Labor share			Fuel share			Technical potential [TWh]
			predicted [%]	used [%]	deviation [%]	predicted [%]	used [%]	deviation [%]	predicted [%]	used [%]	deviation [%]	deviation [%]
Combined cycle gas turbine	mid		19.41	19,72	1.61	5.22	5.25	0.43	74.37	75.03	-0.45	∞
Combined cycle gas turbine	base	19		19,72			5.25			75.03		∞
Hard coal power plant	mid		38.84	35.66	-8.19	13.90	13.49	-2.93	47.27	50.86	7.59	∞
Hard coal power plant	base	19		35.66			13.49			50.86		∞
Hydro power plant	base		53.89	53.89	0	46.11	46.11	0				26.9
Lignite power plant	base		50.29	49.92	-2.74	19.78	19.57	-1.08	29.92	31.51	5.31	∞
Lignite CCS	base	25		27.12			4.86			68.02		∞
Natural gas CCS	mid	15		57.70			14.42			28.08		∞
Nuclear power plant	base		59.37	60.62	2.12	19.79	19.93	0.71	20.85	19.45	-6.70	167.1
Open cycle gas turbine	peak		11.47	11.60	1.16	9.49	9.58	0.96	79.04	78.82	-0.28	∞
Open cycle oil turbine	peak		10.02	10.11	0.85	8.29	8,35	0.70	81.68	81.54	-0.17	∞
Other technologies	base		87.81	87.81	0	12.19	12.19	0				25.3
Photovoltaic	mid	150		77.88			22.12					105
Wind onshore	mid		33.81	33.81	0	66.19	66.19	0				68
Wind offshore	mid	10		63.72			73.72					235

Sources: Own calculations; Capital shares are derived by continuous annuity method with an interest rate of 7.5% over the lifetime of the plant.

Table 7: Data for the calibration of the congestion function

	Urban road	Non-urban road
Peak period speed [km/h]	68	40
Off-peak period speed [km/h]	84	47
Freeflow speed [km/h]	99	50
Peak traffic flow [billion PCE/h]	0.083	0.026
Off-peak traffic flow [billion PCE/h]	0.066	0.018

Source: TREMOVE and own calculations. The TREMOVE model does not include data on the freeflow speed. However, three point are necessary to calibrate the parameters of the exponential function. Using the Bureau of Public Roads formula (e.g. Small, 1992) which only depends on two parameters the freeflow speed is derived.

Table 8: Production substitution elasticities

Elasticity	Description	Value
	Non-electricity production	
ε_{OUT}	Exports vs. domestic production	2
σ_{TRN}	Different transport modes	1
σ_{VAE}	Value added and energy	0.33
σ_{ROAD}	Own and purchased road transport	1
σ_{VA}	Labor and capital	0.43
σ_{OWN}	Own transport with diesel and gasoline	0.9
σ_{ENE}	Electricity and fossil fuels	0.25
σ_{FOF}	Coal and liquid fossil fuels	0.5
σ_{LQD}	Natural gas and refined oils	1
	Electricity production	
σ_{GEN}	Load segments	0.1
ε_{KE}	Transformation elasticity for technology-specific capital	1

Table 9: Utility substitution elasticities

Elasticity	Description	Value
	Utility function	
σ_L	Leisure and commodity and leisure trips	0.7
σ_{CT}	Commodity consumption and leisure trips	0.75
σ_C	Energy and non-energy commodities	0.25
σ_{CE}	Energy commodities	0.4
σ_{OC}	Non-energy commodities	0.5
	Transport module	
σ_D	Short and long trips	0.1
σ_{TP}	Peak and off peak period	0.9
σ_M	Different modes	Peak: 2.2 Off-peak: 1.9
σ_R	Urban and non-urban roads	0.1
σ_{CAR}	Diesel and gasoline cars	2
σ_{CS}	Committed and supplementary mileage	0.15

Table 10: Armington elasticities

Commodity	Elasticity	Commodity	Elasticity
Agriculture	0.575	Mining	1.5
Air transport	0.5	Motor vehicles	2
Coal	0.37	Other transport	0.5
Energy intensive industries	0.8	Refined oils	0.37
Electricity	0.3	Rail transport	0.5
Natural gas	0.37	Services	0.5
Manufacture	1.5	Water transport	0.5

Source: Welsch (2007)