Transport under Emission Trading
A Computable General Equilibrium Assessment

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Abstract

This thesis analysis the impact of private road transport under emission trading using two different Computable General Equilibrium models. A static multi-region model with special emphasis on the European Union, addresses the welfare impact of road transport under the European Emission Trading System. Including terms-of-trade effects, this model does not account for congestion which is the main externality of road transport. Furthermore, technological details of electricity generation which are an important factor in evaluating climate policies are not included. Therefore, the second model is a static Small Open Economy model of the German economy including congestion effects and detailed technological characteristics of electricity generation. The results of both models highlight the important role of already existing taxes on transport fuels for the evaluation of carbon mitigation measures in road transportation.

JEL-code: D58, Q43, Q52

Keywords: Climate policy, emission trading, road transport, carbon dioxide emissions, European Emission Trading System

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List of Abbreviations

AGE	Applied General Equilibrium
CAFE	Corporate Average Fuel Economy
CCS	Carbon Capture and Sequestration
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium
CO_2	Carbon dioxide
COICOP	Classification of Individual Consumption by Purpose
EPPA	Emission Prediction and Policy Analysis
EU	European Union
EU ETS	European Emission Trading System
GAMS	General Algebraic Modeling System
GTAP	Global Trade Analysis Projekt
h	Hour
HEV	Hicksian Equivalent Variation
IPCC	Intergovernmental Panel on Climate Change
IO	Input Output
ISIC	International Standard Industrial Classification
km	Kilometer
MARKAL	MARKet ALlocation
MCP	Mixed Complementarity Problem
MIT	Massachusetts Institute of Technology
MPEC	Mathematical Program with Equilibrium Constraints
MPSGE	Mathematical Programming System for General Equilibrium
MT	Megaton
MW	Megawatt
TW	Terawatt
NO_x	Nitro oxides
PCE	Person Car Equivalent
POLES	Prospective Outlook on Long-term Energy Systems
SAM	Social Accounting Matrix
SO_2	Sulfur dioxide
t	Ton
TJ	Tera Joule
UNFCCC	United Nations Framework Convention on Climate Change
UNITE	UNIfication of accounts and marginal costs for Transport Efficiency
VKM	Vehicle Kilometers

List of Mathematical Notation

Chapter 3

Sets and Indexes

F, f	Factors	H, h	Households
J, j, i	Producers	L, l	Commodities
Y	Production set	T, t	Technologies

Functions

U	Utility function	F	Production Function
z	Excess demand function	C	Cost function
d	Demand function	c	Unit cost function

Parameters and Variables

a	Technology input vector	γ	Households' dividend share
δ	Distribution parameter	θ	Cost share
ρ	Substitution parameter	σ	Substitution elasticity
Π	Profit	Φ	Efficiency parameter
ω	Initial endowment	a	Technology input vector
B	Technology production level	cap	Capacity
I	Investment	M	Income
p	Price	Pi	Investment price
$pcap$	Capacity rent	pot	Technological potential
$ppot$	Scarcity rent on potential	r	Choice in MCP formulation
x	Consumption and intermediate demand	y	Production (plan)

Chapter 4

Subscripts

car	Cars	$fuel$	Transport fuel
i,j	Commodities and production sectors	K	Capital
km	Kilometer	L	Labor
$other$	Other	own	Own provided transport
pur	Purchased transport	p_c	Refined oils
R	Resources	r,s	Regions
RA	Representative agent	$total$	Total
trn	Transport		

Superscripts

a	Armington composite	d	Domestic market
e	Export	m	Import
ma	Import composite	mt	Import transport margin
t	International transport pool		

Functions

C	Representative agents' demand functions	c	Unit cost functions
EFF	Fuel efficiency depending on fuel price	$FUEL$	Fuel expenditure depending on fuel price
KM	Kilometers driven depending on fuel price	r	Unit revenue functions
U	Utility function		

Parameters and Variables

α	Required transport margin for import	β	CO$_2$ emission coefficient
ε	Transformation elasticity	η	Price elasticity of demand
θ	Cost share	σ	Substitution elasticity
bop	Balance of payment deficit	CON	Consumption
$emax$	Emission limit	ES	Share of transport in total expenditure
EXP	Expenditure	G	Government demand
inv	Investment demand	K	Capital endowment
L	Labor endowment	OS	Share of transport in refined oil expenditure
p	Net prices	$pcarb$	National emission price
pt	Transport margin price	q	Gross input prices
R	Natural resource endowment	t	Demand taxes
te	Export taxes	tm	Import taxes
to	Output taxes	tr	Transport margin
$trans$	Direct transfer from government to household	v	Gross output prices
$wcarb$	International emission price	x	Demand
y	Outputs		

Chapter 5

Subscripts

i,j	Commodity set	g	Electricity generation technologies
K	Capital	L	Labor
m	Transport classes	n	Road networks
RA	Representative agent	v	Vehicle types

Superscripts

a	Armington composite	d	Domestic
e	Export	ELE	Electricity
fx	Exchange rate	GEN	Electricity generation
im	Import	L	Labor trips
l	Leisure trips	new	Purchases for new automobiles
$Stock$	Vehicle stock	Var	Variable input for own road transport

Functions

C	Final demand function	c	Unit cost function
D	Combination of automobiles and variable commodity purchases for own road transport	r	Unit revenue function
$time$	Congestion function	U	Utility function
V	Combines commodity purchases to new cars		

Parameters and Variables

β	CO$_2$ emission factor	δ	Time requirement for trips
ε	Transformation elasticity	σ	Substitution elasticity
A	Coefficient in congestion function	a	Armington supply
b	Unit input coefficient electricity generation	bop	Balance of payment deficit
$emax$	Emission limit	$flow$	traffic flow on road types
G	Government demand	inc	Income
K	Capital endowment	L	Labor endowment
p	Net prices	$pcarb$	CO$_2$ price
pot	Technological potential	$ppot$	Scarcity price of technological potential
q	Gross input prices	t	Demand taxes
to	Output tax	tr	Trips
$trans$	Direct transfer from government to the representative agent	TRL	Total amount of labor trips
v	Gross output prices	VEH	Vehicles
x	Demands	y	Output
Z	Congestion index		

1 Introduction

Global warming has become one of the most serious environmental problems for current and future generations. In consequence, countries agreed to stabilize "…greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992, Art. 2) and signed the United Nations Framework Convention on Climate Change (UNFCCC) in Rio de Janeiro in 1992. Following this agreement, industrial countries implemented the Kyoto Protocol in 1997 and agreed to reduce greenhouse gas emissions by an average of 5.2% as compared to 1990 within the period 2008-2012 (UNFCCC, 1998).

The main greenhouse gas is carbon dioxide (CO_2) which is mainly produced by the combustion of fossil fuels in the electricity and transport sectors. In 2007, energy industries were responsible for 32% of the total emissions in the European Union (EU), followed by the transport sector emitting 19.5% (Eurostat, 2009a). With more than 90% road transport is the main polluter in the transport sector followed by aviation (ECMT, 2007).

In the line of the Kyoto Protocol, the EU started regulating CO_2 emissions of electricity generation, energy-intensive production, and refineries implementing the world largest emission trading system in 2005 (EC, 2003). The European Emission Trading System (EU ETS) is a classical cap and trade system setting an upper bound on total emissions and allowing the trade of emission allowances. The design of the EU ETS allows including further sectors and greenhouse gases in the future development. Aviation will be included into the EU ETS from 2012 onwards (EC, 2008a). In contrast, concerning private road transport the EU has released mandatory carbon efficiency standards for new cars from 2012 onwards (EC, 2009c).

From an economic point of view, mandatory standards are suboptimal since they do not allow equal marginal abatement cost of carbon across the economy, i.e. do not implement carbon reduction at lowest cost. Thus, the central question of this thesis is whether the inclusion of road transport into the EU ETS lowers the cost of carbon regulation in Europe. The question is numerically analyzed using two different computable general equilibrium (CGE) models.

The remainder of this thesis is structured as follows: Chapter 2 provides the theoretical background of carbon regulation in a first and second-best setting and under environmental tax reform concerns. Furthermore, the complications of regulating road transport, namely multiple externalities of different dimensions and the large number of polluters, are analyzed and possible strategies of carbon regulations are derived. This chapter also provides the basic arguments in favor and against the inclusion of road transport into the EU ETS. Chapter 3 provides the methodological background of computable general equilibrium modeling. Special emphasis lies on the integration of technological details into the CGE modeling framework. Furthermore, a review of the environmental-energy and transport related CGE literature is given. Chapter 4 employs a multi-region CGE with a detailed representation of the EU 27 countries analyzing the effects of transport under the EU ETS, a European fuel tax increase, and the total exemption of transport from carbon regulation. The results indicate that the most preferable strategy is exempting transport from regulation. The analysis in this chapter is unique in the sense that the question is investigated on a detailed European member state level. Chapter 5 presents a small open economy model with a detailed representation of electricity generation technologies and private transport. Against the background that congestion is the most important externality of transport, different time periods and road types are introduced to include the impact of travel flow changes. Again, the results show that exempting transport from carbon regulation is favorable to its inclusion into emission trading or increases in fuel taxes. Moreover, using the income of carbon regulation to increase subsidies on public transport shows large positive effects in two directions: the cost of carbon regulation decrease and the congestion externality is partly decreased. The analysis in this chapter is unique in bringing together a detailed representation of electricity generation and private transport. Moreover, the details of the private transport representation including different road types based on empirical data have not been investigated for Germany, yet. Chapter 6 summarizes the results, concludes, and suggests future research topics.

2 Regulation of Road Transport Carbon Emissions

This section analyzes approaches on how to regulate carbon emissions with a focus on the transport sector. First, the theory of environmental regulation in a first and second-best setting and the effects of environmental tax reforms are examined. Second, the special needs of regulation in road transport are reviewed and different approaches to carbon emission regulation of road transport are analyzed.

2.1 Regulating externalities

2.1.1 Regulation in a first-best world

Internalization of external effects requires choosing an appropriate target level of the externality and an adequate regulation instrument. Having implemented the instrument, it needs to be enforced and monitored.

Theoretically, the optimal target level equates the marginal external cost to the marginally benefit (see e.g. Baumol and Oates 1988). In the case of greenhouse gas regulation, the target level in terms of emissions for a certain time period is predetermined by international climate agreements: The Kyoto Protocol commits participating countries to reduce average yearly emissions for the period from 2008 to 2012 by a certain percentage as compared to the emission level of the year 1990. Accordingly, the EU15 has to mitigate CO_2 emissions by 8 %. In consequence, the EU has released the Burden Sharing (EC, 2002) and more recently the Effort Sharing Agreement (EC, 2009a) which regulate the member states' mitigation requirements in a way to reach the overall European target. Therefore, the target level of emissions is taken as given in the following analysis.[1]

A variety of policy instruments for the regulation of GHG exist. These can be classified into three main categories: public spending, market-based instruments, and command and control policies.[2] The performance of instruments is compared in terms of costs and environmental effectiveness, dynamic efficiency, implementation and monitoring costs, and political feasibility. Cost efficiency is given (i.e. the environmental target is reached at lowest costs) if the marginal abatement costs equalize across pollution sources (see e.g. Perman et al., 2003). Environmental effectiveness measures the distance between the target pollution level and the level induced by the instruments. Dynamic efficiency evaluates the incentives to invest in research, development, and adaptation of new technologies.[3]

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[1] In 2009 the EU committed to reduce emission by 20% below the 1990 level in the period 2012 to 2020 (EC, 2009b). While the burden sharing relates to t EU 15 countries, the new reduction commitment and the effort sharing agreement also includes new member states, i.e. relates to EU 27. In the case that the negotiations for a post-Kyoto climate agreement will be successful, the EU announced to reduce 30 % of its emission in this period.

[2] Additionally, there exist informational policies like e.g. energy efficiency labelling or educational programs. Since the effectiveness of such measures can hardly be controlled, they should be seen as important additional policies to overcome transaction costs in the form of information costs on the final demand side.

[3] A general statement about the dynamic efficiency of different instruments is not possible. Downing and White (1986) show that the innovation incentives are independent from governments' reaction to adaptation of new technologies. However, adaptation depends on the reaction of other market participants, i.e. if they also adapt the technology. The study of Downing and White (1986) only examines the adaptation stage of technological progress. In subsequent analysis the problem is examined in terms of game theoretic analysis and considerations about research and development. Jaffe et al. (2002a, b) provide a survey.

Public spending policies could take place in the form of direct mitigation actions of the government or in the form of subsidies. In the case of GHG, direct mitigation actions hardly exist. Subsidies can take place in production or final demand sectors. A prominent example on the production side is the support of electricity generation technologies from renewable energy sources (EC, 2008b); subsidies for environmental friendly public transport are a demand side example. The fundamental problem of public spending policies is the refinancing issue since the increase in the spending has to be rebalanced by additional taxes.

Command and control policies are obligations which are introduced in the production process. Possible measures are to constrain the upper emission level of every production site or firm, to dictate technologies which may be used, or to put quotas on input commodities. These policies generally can be shown to be highly ecologically efficient but lack cost effectiveness.

Economists favor the use of market-based instruments. Two classes exist: Pigouvian taxes (Pigou, 1920) and tradable permits (Dales, 1968). Pigouvian taxes implement taxes on polluting commodities equal to the social marginal cost. The idea of tradable permits builds on the work of Coase (1960) who noted that externalities are caused by lacking property rights. Consequently, property rights are established by allocating pollution rights (i.e. the permits) to agents and allowing the trade of these rights. Mitigation of pollution is achieved by either allocating only a limited number of permits, i.e. setting an upper bound on pollution, or by open market policy, i.e. governments buy permits on the market and hence avoid pollution. Both instruments are cost efficient in the sense of equating marginal abatement costs across polluters (Montgomery, 1972). If the social marginal costs are correctly estimated and the overall pollution target is optimally determined, the permit price will be equal to the Pigouvian tax and both instruments achieve the same environmental target. However, under a given target level of pollution, as is the case for GHG, the Pigouvian tax requires estimating the correct tax rate in order to implement the imposed environmental target. Therefore, the aggregated marginal cost curve needs to be determined. Thus, Cropper and Oates (1992) see the major advantage of an emission trading system in gaining direct control over the emission quantity.

However, tradable rights systems raise the question of the initial allocation of permits. Two extreme possibilities exist: The government can use grandfathering, i.e. allocate permits to installations for free, or sell or auction permits. Montgomery (1972) proves that the initial distribution of permits does not affect post-trading allocation and efficiency of the instrument. However, economists favor auctioning of permits for at least two reasons. First, auctioning permits implements the polluter-pays principle, i.e. polluting firms have to pay for emissions. Second, auctioning reveals a permit price at the beginning of the trading scheme which improves liquidity of the permit market. Nevertheless, grandfathering is an important option especially in the first establishment of trading schemes since this improves the political acceptance of the system (Tietenberg, 2006).

2.1.2 Regulation in a second-best world

The basic theory of environmental regulation as described in the last section builds on a first-best framework which is characterized by the absence of other distortions. Obviously, this assumption is unrealistic since economies are full of distortions mainly due to governments' needs to finance the provision of public goods and non-convexities in the form of imperfect competition (Hahn, 1984; Liski and Montero, 2008). The theory of second-best states that if one set of efficiency conditions is violated, it is not necessarily optimal to achieve the remaining ones (Lipsey and Lancaster, 1956). Thus, deviation from the basic assumptions may lead to optimal carbon taxes which are no longer uniform across the economy, i.e. deviation from the Pigouvian tax.[4]

Generally, governments need to raise taxes in order to finance the provision of public goods. As long as taxes do not correct for market failures, they are necessarily distortionary in the sense that raising one dollar of public revenues causes a loss in welfare greater than one dollar. The cost of raising one additional unit of government revenues is known as the marginal cost of public fund consisting of the direct tax burden plus the associated welfare cost by distorting prices in the economy (Browning, 1976). The direct burden is the cost of raising one unit of revenue. The excess welfare costs are referred to as excess burden of taxation. The theory of optimal taxation analyzes the optimal tax structure under the need of raising public revenues by imposing taxes, i.e. in the absence of non-distortionary lump-sum taxation (see Auerbach and Hines, 2002 for a survey). In a world without externalities, optimal indirect taxes on commodity consumption rates are characterized by the Ramsey or inverse elasticity rule: the more inelastic the commodity demand, the higher will be the tax rate (Ramsey, 1927; Boiteaux, 1956). Furthermore, Diamond and Mirrlees (1971 a,b) show that taxes on intermediate inputs are non-optimal as long as production exhibits constant returns to scale.

The presence of externalities alters these results. Sandamo (1975) shows that in the presence of externalities optimal tax rates are the weighted average of the optimal tax and the Pigouvian tax rate. The optimal tax schedule exhibits a property known as additivity property: in the presence of externalities the optimal commodity tax rate in final consumption is the weighted average of the optimal Ramsey tax and the Pigou tax equal to the marginal social cost caused by the consumption of the commodity. Weights depend on the government's budget need. In the case where corrective taxation is able to fully finance the budget, the Ramsey component of the optimal tax becomes zero. With increasing revenue raising requirement, the Ramsey tax component becomes more and more important and the Pigou tax term vanishes. Bovenberg and van der Ploeg (1994) extend the result for the more general case of interdependent demand functions and endogenous labor supply decisions. Sandamo (1993) addresses distributional concerns considering consumers who differ in their preferences and income and shows that weighted average property of optimal taxes still holds. However, distributional considerations additionally influence the weighting factors: If the share of high income consumers' consumption for a commodity is high, the Ramsey tax component increases.

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[4] In the ongoing, Pigouvian taxes are discussed. Due to the inverse relation of environmental taxes and tradable rights schemes differentiated taxes offer arguments for exemptions of sectors from carbon regulation or rebate systems.

Similarly, if a high valuation of environmental quality is concentrated among high income consumers, the Pigouvian tax component tends to be higher.

Bovenberg and Goulder (1996) show that in the presence of externalities it is also optimal to tax dirty intermediate commodities at the Pigouvian tax rate corrected for the marginal cost of public fund, i.e. with increasing excess burden of taxation the dirty intermediate input tax vanishes.

2.1.3 Environmental tax reforms

The optimal taxation approach faces two main criticisms: First, it assumes the existence of a welfare function which generally does not exist (Arrow, 1950). Second, it assumes that policy makers newly design tax systems. However, generally they do not create new tax systems but are confronted with altering existing schemes, i.e. with tax reforms Feldstein (1976). In the light of environmental regulation, governments impose environmental regulation on top of a pre-existing tax schedule. This raises two questions: First, if environmental regulation raises revenues, how to spend the income optimally? Second, what are the interactions of pre-existing taxes and the additional corrective tax measures? Consequently, the occurring effects are known as revenue recycling and tax interaction or intermediate effect (Parry, 1995; Goulder, 1995).

Generally, the revenue recycling effect is analyzed under the assumption that the provision of public goods is constant in order to separate the question of environmental regulation from the topic of the optimal size and composition of public spending.[5] The double dividend hypothesis states that using the additional government income to lower pre-existing distortionary taxation provides an additional welfare gain beside the improvement of environmental quality (Pearce, 1991). Consequently, the gross costs of environmental regulation, which are defined as the welfare loss of regulation without the benefit of improved environmental quality, decrease. In order to maximize the double dividend the lowered tax should be preferably broad based. Accordingly, the literature most often considers cutting labor taxes. As a consequence, the double dividend hypothesis is often stated in terms of unemployment: using the income of environmental regulation lowering existing labor taxes stipulates labor demand and subsequently reduces involuntary unemployment (e.g. Bovenberg and de Mooij, 1994; Bovenberg, 1999). A survey of empirical evidences on the double dividend hypothesis is given by Galeotti and Carraro (1996) and Bosquet (2000) which show that it holds in the short and medium term but is uncertain in the long run.

Tax interaction has two direct aspects. First, raising the price of a commodity by environmental taxation reduces commodity demand as long as the commodity is a normal good. This happens naturally, since the aim of environmental regulation is to reduce the social cost associated with commodity consumption. If the commodity is already taxed, a loss in the income of the pre-existing tax results. This is known as tax base erosion effect. The tax base erosion effect counteracts the

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[5] Bovenberg and van der Ploeg (1994) investigate both issues in a single framework.

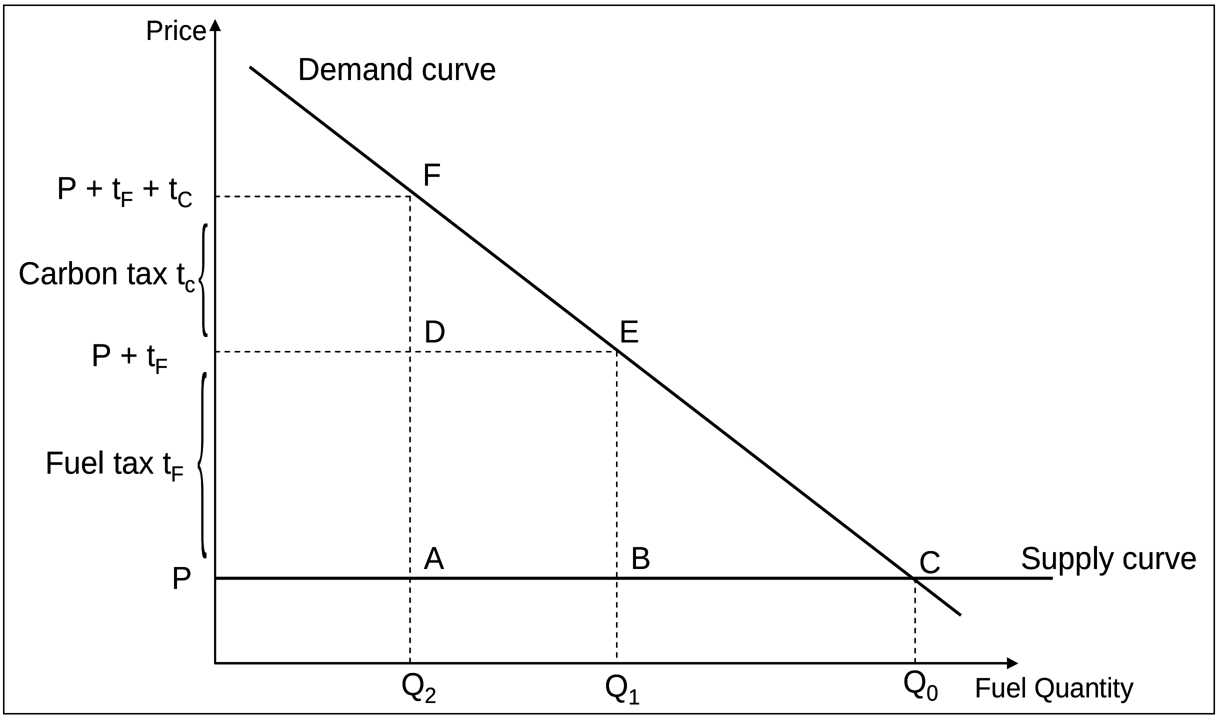
revenue recycling effect since it lowers tax income and, accordingly, the amount to be recycled in a welfare enhancing way.

Environmental taxes also directly interact with the pre-existing tax schedule. For illustrative purpose, assume that the regulator imposes an economy wide tax on carbon at the marginal rate of social cost and abstract from the marginal cost of public fund. If the pre-existing tax scheme is optimal in the sense that all commodities are taxed at their Ramsey tax rate in final consumption and intermediate inputs are untaxed, the uniform carbon tax rate will be optimal since it implements an additional Pigou tax term equal for all consumers and sectors. Now assume that the initial tax schedule is non-optimal, for concreteness, taxes on final consumption are above the Ramsey tax. Imposing the uniform carbon tax raises input prices of all sectors and consumers by the same amount. Consequently, taxes on final consumption are also too high after the introduction of carbon regulation. By lowering the carbon tax on final consumption the regulator can reduce the cost of carbon regulation since the after-regulation tax schedule is closer to the optimal tax scheme, i.e. the distortionary effect of taxation is reduced. The essential point is that a tax rate above the Ramsey tax already implies corrective taxation of the externality. Consequently, the reduction of the carbon tax in final consumption leads to effective carbon tax rates effectively closer to uniform across the economy.

Figure 1 illustrates the tax interaction effect. The demand curve is given by the straight line FC. Supply is assumed to be price inelastic and is given by the line AC. The welfare costs of tax introduction are the area under the demand function net of production costs. Accordingly, the introduction of a fuel tax t_F is associated with welfare costs equal to the triangle BCE. Adding the carbon tax t_C results in an additional welfare loss equal to the triangle DEF and the rectangle ABDE. The triangle DEF is equal to the area under the marginal abatement cost curve for carbon. On the one hand, the rectangle ABDE represents the tax base erosion effect as the loss income of taxation. On the other, it also represents the loss in consumer surplus due to the pre-existing fuel tax.

A lower carbon tax on some commodities translates into (partial) exemption in emission trading schemes. In contrast to Pigou taxes, trading schemes set an upper bound on total quantity of emissions. Accordingly, the question about which sector should carry the additional abatement burden resulting from the exemption arises. Theoretical results on this issue do not exist.

Figure 1: Tax interaction effects



Source: Following Paltsev et al. (2004, 2005b) and Raux and Marlot (2005)

Böhringer and Rutherford (2002a) numerically analyze optimal differentiation of carbon taxes. They maximize welfare under the equilibrium conditions of a CGE model.[6] The government imposes environmental regulation in the form of a 20% reduction requirement by choosing carbon taxes differentiated by commodity and sectors and final consumption. The results show that it is optimal to differentiate carbon taxes across sectors and final consumers. Due to high energy taxes in final consumption it becomes optimal to exempt consumers from carbon regulation moving the reduction burden to industries (mainly electricity generation).[7] The results are decomposed into the effects of energy and non-energy taxes. While the tax interaction with non-energy taxes only justifies a small differentiation of the environmental levy, the exemption of the household sector is caused by pre-existing energy taxes mainly mineral oil taxes (IEA, 2007).[8]

2.2 Regulation of road transportation

2.2.1 Externalities of road transportation

Three classes of external cost related to road transportation can be distinguished: i) cost resulting from actual driving, ii) external cost arising when vehicles are not in motion such as parking externalities, and iii) cost occurring from the presence of infrastructure such as visual annoyance (Verhoef et al.

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[6] This is an MPEC problem (Mathematical Program with Equilibrium Constraints) (Luo, Pang, and Ralph, 1996) since the objective function is optimized under a set of complementarity conditions which characterize the equilibrium. An introduction into the use of MPECs for the investigation of optimal taxation problems is given in Light (1999).

[7] In the study carbon taxes are constraint to be positive, i.e. subsidies for carbon are ruled out.

1997). In the ongoing, I concentrate on the first category. External cost of actual driving are further subdivided into intrasectional cost that road users impose on each other and social cost which are imposed on the rest of the society (Mayeres et al., 1996).

Social cost come in two different forms: pollution damages and noise (Bickel et al., 2005).[9,10] Pollution cost can occur either on a local or on a global level. On a local level pollutants like carbon monoxide, nitro oxides (NO_x), volatile organic compounds, particulate matter, sulfur dioxide (SO_2), polycyclic aromatic hydrocarbon, and heavy metals cause health damages in the form of mortality or morbidity and environmental damages in the form of negative bio-system impacts (Bickel and Friedrich, 2005).[11] On a global level, pollutants add to global warming. Most important in this class are carbon dioxide emissions. However, nitrogen dioxide and troposphere ozone also exhibit a positive radiative forcing effect. Furthermore, SO_2 and NO_x lead to the creation of aerosols that have a negative impact on the Earth's energy balance (IPPC, 2007).[12]

Intrasectional external costs are congestion effects and increases in private resource cost. Congestion occurs since average speed is negatively related to the traffic flow (measured in personal car equivalent per hour; PCE/h). Consequently, each additional road vehicles increase the time cost of traffic users since the travel flow raises (e.g. Walters, 1961; Vickery, 1963). Furthermore, monetary vehicle operating costs per kilometer depend on the speed level (Mayeres, 1993). Since users only care about their own cost and not about the effect on the speed-flow relationship, congestion implies external cost.

Marginal accident costs relate to both classes, intersectional and social. Additional vehicles raise the likelihood of medical and material cost (Button, 1990). Link (2005) subdivides external accident costs into production loss due to accidents, the cost of medical treatment and rehabilitation if provided by the public health system, cost of associated police and rescue services not covered by transport users, and public material damage as not covered by insurances. Accordingly, the precise definition of the external accident cost varies between countries depending on the insurance system, especially regarding the payment of medical services.

Table 1 depicts the dependency of different externalities on trip characteristics. Even though it only includes qualitative rankings it will prove useful in the discussion of regulation approaches.

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[8] The authors also analyzed other motive of carbon tax differentiation. Other arguments of differentiation come in form of carbon leakage (Hoel, 1996) and terms-of-trade effects (Krutilla, 1991)

[9] Noise is sometime also regarded as intrasectional externality in the form of annoyance of other traffic participants. Additionally, in the case of heavy vehicles, social cost in the form of road damage occur which cause road repair and increased vehicle operating cost of other traffic participants (Newbery, 1988).

[10] Parry et al. (2007) also mention the external cost of oil dependency in the form of military and geo-political cost imposed on the society and the vulnerability to oil price volatility and market power in the oil market.

[11] For a detailed description of the impacts of the single pollutants see Bickel and Friedrich (2005, Table 1.1 p. 3). Most pollutants have a direct effect. However, NO_x and VOC also have secondary effects in increasing troposphere ozone concentration. The oxidation products of SO_2 lead to the acid rain problem.

[12] While the level of scientific understanding of radiative of carbon dioxide is high, the role of ozone and aerosols is still at medium and low level respectively. For an assessment of the level of scientific understanding and radiative impacts see IPPC (2007, pp. 32 ff.).

Table 1: External cost of road transportation and trip characteristics

	Mileage	Time of driving	Area of driving	Vehicle used
Accidents	+	0	0	-
Congestion	+	+	+	-
Global pollution	+	-	-	+
Local pollution	+	-	0	+
Noise	+	0	+	+

Source: Verhoefen et al. (1995, 1997) extended by the distinction between global and local pollution.
Legend: + high dependence, 0 moderate dependence, - low dependence.

In general, all external cost categories show a high correlation with vehicle kilometers (VKM) travelled. While congestion is nearly independent of the car used, it is highly dependent on the spatial and time dimension. Pollution strongly correlates with the car technology determining fuel efficiency and consequently fuel use. By definition, global pollution does not depend on the area of driving while local pollution does. The noise externality correlates to all trip characteristics. Safety may depend to some extend on the area and time of driving but is mainly determined by mileage.

Table 2 shows the total external cost of road transportation for France, Germany, and the United Kingdom in 2005 as derived by the UNITE Project (UNIfication of accounts and marginal costs for Transport Efficiency). The general lesson is that congestion cost, which are differentiated by pure time and resource cost, are the greatest externality imposed by road transport. Beside external accident cost, the externality generated by global pollution, i.e. global warming shows the lowest value. Differences in the external accident costs are difficult to compare across countries, since they depend on the high accident rate and difference in the insurance system (Link, 2005). The ranking between local pollution and noise externalities is non-homogenous among countries. However, the general point is clear: Congestions is the main concern of regulation in the transport sector. Adopting a partial transport sector view, global warming motives are of minor concern.

Table 2: External cost of road transport in 2005 [Million €$_{1998}$]

	France	Germany	United Kingdom
Accident	1 818	17 324	1 716
Congestion (time)	18 803	20 484	23 981
Congestion (fuel)	1 778	1 102	264
Global pollution	2 700	4 555	2 741
Local pollution	9 394	7 030	3 952
Noise	4 747	7 825	7 592

Source: France: Jeger et al. (2001, p. 53); Germany: Link et al. (2001, p. 157); United Kingdom: Tweddel et al. (2001, p. 92)

2.2.2 Regulation in the road transport sector

Regulation of private road transport is complicated due to five major reasons (Verhoef et al., 1997): First, the number of externalities is large and they additionally correlate. Second, externalities differ with respect to the time and spatial dimensions. Third, the number of externality generators is large and, in addition, mobile. Fourth, generally demand is derive and, consequently, quite inelastic Fifth, equity aspects are highly relevant.

Naturally, this translates into a number of general questions regarding the regulation of road transportation. Does one single instrument exist which is able to internalize all externalities or is it better to follow the Tinbergen rule, i.e. one instrument for each policy target. And following the Tinbergen rule, what are the interactions with newly imposed carbon regulation? What to regulate? Essentially, road transportation needs three complementary components: networks, cars, and fuel. Consequently, there are three options where regulative measures could be imposed. However, the number of traffic users is high and mobile, implying large implementation and monitoring cost and, the number of suppliers of cars and fuels (and networks if privately supplied) is lower: Who to regulate? After making these basic decisions: How could an optimal regulation be designed? Finally, from a political perspective one has to ask whether the optimal strategy is politically feasible. Naturally, these decisions are highly interdependent.

2.2.2.1 Optimal regulation

Reducing vehicle kilometers is the only way to address all externalities within a single framework. Parry and Small (2005) derive the optimal fuel tax rate in an analytical model including local and global pollution, accidents, congestion feedbacks, and endogenous feedbacks of cars' fuel efficiency. They show that the optimal fuel tax consists of three terms: the Ramsey tax, a modified Pigouvian tax, and congestion feedback.

In line with earlier results, the modified Pigouvian tax is equal to the marginal external cost divided by the marginal cost of public funds. The marginal external cost are the sum of the global pollution damage, that is directly related to fuel consumption, and marginal local pollution, accident, and congestion cost. Since the latter are determined by kilometers driven, they only indirectly correlate with fuel consumption via the cars' fuel efficiency. Consequently, the kilometer-dependent component of the quasi Pigouvian tax is negatively related to the price elasticity of fuel demand since a high elasticity implies a high reaction in form of less driving. However, the remarkable point compared to earlier studies (e.g. Newbery, 1990) is that fuel efficiency is endogenous. Thus, there is a positive relation of the kilometers driven component to the fuel price elasticity of energy efficiency. To put it differently, people have two alternatives to react on higher fuel taxes:[13] driving less or buying more efficient cars. Driving less reduces fuel consumption and kilometers driven. Consequently, the kilometers driven externality component is reduced. Buying more fuel efficient cars reduces fuel consumption but does not affect kilometers driven. Therefore, the kilometer-dependent externalities are not reduced and the modified Pigouvian tax increases inducing less driving. In short, calculating the optimal modified Pigouvian tax rate, kilometer-dependent externalities enter with a weighting factor determined by the ratio of the fuel price elasticity of fuel efficiency and fuel demand. Empirical work suggests a value of around 0.5 (Parry and Small, 2005).[14] Neglecting endogenous fuel efficiency

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[13] A third option in small countries is fuelling abroad (Mayeres, 1999).

[14] Schäfer and Jacoby (2005) estimate a fuel efficiency elasticity of -0.126 using the MARKAL model. According to Graham and Glaister (2002) the short run price elasticity of fuel demand is between -0.2 and -0.5.

implicitly assumes that both elasticities are equal resulting in a ratio of one. Consequently the modified Pigouvian tax rate is overestimated.

The congestion feedback term in Parry and Small (2005) increases the optimal fuel tax since labor supply is endogenous and taxed. Transport is modeled as a consumption commodity. Reduced congestion lowers the price of transportation relative to leisure. Consequently, people substitute transportation for leisure which is welfare improving since labor is taxed (also see Parry and Bento 2001).

Calibrating the model to the US and the UK, Parry and Small (2005) show that gasoline taxes in the US should be increased while in the UK taxes are more than twice as high than the optimal tax. A single fuel tax has the problem that kilometer-dependent externalities are only indirectly included via fuel efficiency. Furthermore, fuel taxes do not change the pattern of driving time and location.

In contrast, imposing road pricing measures allows addressing the spatial and time dimension of externalities but only indirectly addresses fuel efficiency of cars (Newberry, 2004). Thus, it is more promising to regulate single externalities with different instruments and accounting for interactions. For congestion the possibility of road pricing schemes, kilometer-dependent taxes, or infrastructure policy exist. Such instruments also address other kilometer-dependent externalities. Emissions of cars can be regulated by technology standards, fuel quality regulation, or fuel taxation. Newberry (2004) calculates the optimal tax rates on fuels and equivalent road user charges for the United Kingdom.

Policy options to reduce carbon emissions including taxes of private transport are discussed in the next section.

2.2.2.2 Options to regulate carbon emissions in the transport sector

Three main options to reduce carbon emissions of private cars are considered: regulating fuel composition, fuel efficiency regulation of cars, and increasing fuel taxes. Further options that require different regulation approaches are changing driving behavior and imposing speed limits. Furthermore, subsidies on public transport can reduce private road transport by inducing transport mode switches altering relative prices.

2.2.2.2.1 Fuel composition regulation and fuel switching

In general, a regulation of the transport fuel composition cannot change the direct emissions of private transportation since the energy value of fuels is determined by the carbon content combusted.[15] One liter of gasoline (diesel) contains 0.640 kg C/l (0.734 kg C/l) with a net calorific value of 32.44 MJ/l (35.87 MJ/l) (US Environmental Protection Agency, 2005). Assuming 99% of carbon oxidized and multiplying with the ratio of molar weights of CO_2 and carbon (~44/12) yields average CO_2 emission of 2.30 kg CO_2/l (gasoline) and 2.66 kg CO_2/l (diesel).

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[15] To be more precise: the energy content is determined by the carbon content and its oxidation state. However, changing the oxidation state would require a different composition of hydrocarbons which is not possible without altering combustion technologies (e.g. Archer, 2007).

The only way of to reduce total carbon emissions per liter combusted fuel is blending with biofuels which are regarded as carbon neutral since the carbon content is absorbed from the atmosphere.

While biofuel blending regulation is able to reduce the net emissions of cars and, additionally, has the advantage of reducing economies' oil dependency, three major problems arise. First, blending is restricted in the short run since changing the fuel composition requires adjustments in combustion technologies, i.e. car technologies (Schallaböck et al., 2006). Second, the production of biofuels causes interactions with food markets due to the changed use of agriculture areas and the use of food crops for energy production. The second point may be overcome by using second generation biofuels based on cellulose (UN, 2007). Third, increased biofuel production causes nitrogen dioxide emissions of fertilization. Consequently including the whole lifecycle, biofuels are not carbon neutral (Crutzen et al., 2008). Nevertheless, the EU aims to increase the biofuel share in transportation above ten percent (EC, 2008b).

Another option on the fuel level is switching to alternative energy sources. The main opportunities are natural gas, hydrogen, or electric cars. A problem arising for all new fuels is the dependency on a service station network (Achtnicht et al., 2008). The problem can be addressed by using bivalent cars and extending fuel station networks. Natural gas vehicles are already market mature while hydrogen cars are not competitive today. Furthermore, hydrogen cars are only improving environmental quality if the fuel is produced using renewable electricity generation, since hydrogen production is energy-intensive (Sandoval, 2008). Electric cars are critical in terms of battery performance, limiting driving range, and cost (Duvall, 2004). Karplus et al. (2009) show that even under very strict climate policies, the adaptation of hybrid electric cars, that are additionally able to run on conventional fuels, requires further research in battery design to lower costs. As in the case of hydrogen cars, carbon emission reduction depends on electricity generation technologies.

2.2.2.2.2 Fuel efficiency regulation

Fuel efficiency improvements can be achieved by altering car design and improving combustion and gearbox technologies. Altering car design takes place by either aerodynamic resistance improvements for new designs or reducing the weight of automobiles. Weights can be reduced using light-weight interiors or, more costly, using more aluminum in the autobody (Schäfer and Jacoby, 2006). Combustion engines can be improved by various technological measures improving energy efficiency. Schallaböck et al. (2006) estimate the technical potential to improve energy efficiency of gasoline (diesel) cars from currently around 15% (18%) to 21% (24%) in the near term. In the long term, further enhancements are possible to around 26% (30%). The main options are the introduction of start-stop systems, hybrid cars, and downsizing. Start-stop systems, which stop the motor at zero speed and start again without using the starter, are already observed on the market. Also, hybrid cars which store dragging energy in batteries and use it for acceleration are on the market, yet. Downsizing is the possibility to decrease fuel consumption by scaling down the cubic capacity of cars. For most cars the most fuel efficient speed does not coincide with the average speed driven. Consequently, fuel efficiency is improved by adjusting the cubic capacity such that the most fuel efficient speed coincides with the average driving patterns. Although downsizing is regarded as one of the most promising options to decrease fuel consumption, it conflicts with consumer preferences since the motor performance is also scaled down.

Successfully improving fuel efficiency by regulatory measures depends on the right incentives for technology adoption at the demand side and technology innovation at the supply side. Consequently, the question is who and how to regulate. On the supply side, technological standards (possibility tradable) concerning the carbon efficiency can be imposed. Besides increasing fuel prices, carbon-dependent motor vehicle or sales taxes can be imposed on the demand side in order to alter relative prices in favor of environmentally friendly technologies.

Recently, the EU has released mandatory carbon efficiency standards for new cars from 2012 onwards (EC, 2009c).[16] Manufactures average specific emission of newly sold cars may not exceed 130 CO_2 g/km. This corresponds to an average fuel efficiency of around 5.7 l gasoline/100 km and 4.9 l diesel/100 km. Emission targets for single cars are weight dependent, i.e. heavier cars are allowed to emit more CO_2. Elmer and Fischer (2009) show that the weight dependency of emission standards leads to inefficiencies. Exceeding the specific emission target causes fines: 5, 15, and 25 € for the first three excess grams, respectively, and 95 € for each additional gram.[17] The directive implements additional innovation incentives: given the use of environmental friendly innovations, manufacturers' specific targets are reduced by up to 7 g CO_2/km. The European approach allows pooling of manufacturers, i.e. manufacturers are allowed to jointly fulfill their average specific emission targets. Therefore, it imposes some flexibility of carbon mitigation but full flexibility using tradable permits is not achieved.

A tradable permit approach would require specifying the unit of rights. This could be either specific emission rights in g CO_2/km or emissions over the whole lifetime cycle of the car (t CO_2). The former, has the disadvantage that trading is restricted to automobile manufacturers. The latter option, which has been termed midstream trading, requires estimating lifetime emissions of a sold automobile. This could be done bases on a representative driving cycle e.g. European Driving Cycle. Choosing the lifetime emissions of cars has the advantage that it is consistent with the unit of carbon accounting in the EU ETS. Accordingly, permit trading between automobile manufactures and EU ETS sectors can be implemented. Albrecht (2000, 2001) proposes such an open midstream approach for the regulation of private road transport emissions.

However, open midstream trading has some disadvantages. Generally, driving cycles are only an approximate estimate of the real lifetime emissions which leads to uncertainties about reaching the overall target. But such uncertainties are a general problem of fuel efficiency regulation since the ex

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[16] The most prominent example of fuel efficiency regulation is the US Corporate Average Fuel Economy (CAFE) program which was established in the wake of the 1973 oil crisis and imposes a 27.5 miles per gallon (~8.6 l/100 km) standard for passenger cars (e.g. Small and van Dender, 2007).

[17] From 2019 onwards each excess gram will cost 95 €. The period 2008-2018 is regarded as the phase in of the regulation, which is characterized by only partly including newly sold cars (2012: 65%; 2013: 74%; 2014: 80%; 100% from 2015 onwards).

ante determination of carbon mitigation depends on the reactions of drivers. For example, fuel efficiency improvements are considered to exhibit a rebound effect, i.e. an increase in kilometers driven due to lower fuel cost, which partly offsets the carbon mitigation effect. Furthermore, increased mileage increases other externalities like congestion and accidents (Fischer et al., 2007). A second concern regarding open midstream trading arises from the design of the EU ETS: time inconsistency. Currently, the EU ETS is divided into four year periods. Selling a car in one period it is unclear to which period the required emission permits belong to due to the longer lifecycle of cars. The problem is weakened by the extension of the EU ETS period to 8 years from 2013 onwards (EC, 2009b). A general unsolved concern of fuel efficiency regulation at the supply side in the case that car prices increase is the eventual delay of new car purchases due to decreased scrapping.

Additionally to the European directive, Germany has adopted CO_2 dependent motor vehicle taxes (Deutscher Bundestag, 2009). Every car initially registered after the July 1st, 2009 has to pay a yearly tax of 2 € for every gram above 120 g CO_2/km. The threshold level is decreased in 2012 (2014) to 110 (95) g CO_2/km. Such an instrument additionally increases adoption incentives on the demand side.

2.2.2.2.3 Pricing transport fuels

Due to the one-to-one connection of fuel use and carbon emissions, fuel price regulation approaches are the most direct measure to regulate carbon emissions of the private transportation sector. It is possible to either use taxes or include emissions into the EU ETS.

Taxes can either uniformly increase or can be differentiated by fuels. The latter approach is more sophisticated since differentiation can be oriented towards the carbon content of fuels. As a price oriented measure, taxes hardly implement given reduction targets since future driving patterns are uncertain (Raux, 2004). Furthermore even if the target could be reached for sure, due to the low own-price elasticity of fuel demand, taxes have to be very high (Graham and Glaister, 2002; Sterner, 2007). This contrasts the high consumers' sensitivity to fuel price increases leaving political feasibility in doubt (Raux and Marlot, 2005). Political feasibility is further restricted by equity aspects. Due to the high share of fuel spending in low income groups, a tax on fuels is regressive (West, 2004). Fuel tax rates across Europe are already at a high level. Sterner (2007) reports an average tax rate of 80% on gasoline for West-Europe in 2007. The already high tax level restricts further tax increases due to the high responsiveness of the public opinion to fuel taxes (Hammar et al., 2004).

Implementing emission trading has the advantage of reaching the carbon target for sure and allowing equalization of marginal abatement cost, i.e. implementing cost efficiency. Beside the midstream option, two further options exist to include road transportation into the EU ETS (e.g. Ellerman et al., 2006; Stronzig et al., 2002): downstream and upstream trading.

In downstream trading the polluters, i.e. drivers, are obliged to hold emission allowances for every ton of CO_2 emitted. Due to the large number of polluters such a system is expected to incur high transaction and information cost. Raux and Marlot (2005) argue that an electronic system for permit sales and purchases can minimize transaction costs if the system is compatible with automatic teller machines already existing at service stations. Information costs can be overcome by market intermediaries like banks or service station operators. Even though the possibility of downstream trading exists, it has never been regarded as a valid option for private transportation.

In upstream trading, the suppliers of fuels are required to hold emission allowances. For every sold liter of fuel the resulting carbon emissions can be calculated and have to be deposited with permits. Since the number of upstream fuel suppliers is far below the number of vehicle users, transaction costs decrease. This argument is of particular importance for the EU ETS: Refineries are already part of the EU ETS. Consequently, administrative costs are lowered since monitoring mechanisms already exist and only need to be extended. Furthermore, refinery operators have experience in permit trading since the beginning of the EU ETS in 2005. Therefore, information costs are lower, too.

Under prefect competition up- and downstream trading lead to equivalent results. Dobes (1999) remarks that the equivalence breaks down if the fuel market is characterized by imperfect competition. This is a serious point which has to be considered if upstream trading should be implemented.

2.3 Summary

This chapter laid out the theory of environmental regulation in a first and second-best setting and the effects of environmental tax reforms. Both, environmental theory in a first and second-best setting, state that it is optimal to impose Pigou taxes uniform across sectors and commodity since cost efficiency is achieved by the equalization of marginal abatement costs. Consequently, they provide the theoretical argument for the implementation of unrestricted emission allowances trade across the economy. Following this argumentation, the emissions of road transport should be regulated by integrating road transport into the EU ETS most favorably using an upstream approach. Since refineries are already part of the EU ETS and since the number of refinery operators is far smaller than the number of road transport users, such an approach incurs lower information, transaction, and monitoring costs.

However, the theory of environmental tax reforms claims that the structure of the pre-existing tax system is important. If initial taxes on some commodities are too high, lower carbon taxes or exemption from emission trading decrease the cost of regulation since the after-regulation tax schedule is closer to the optimal one. Observing high excise taxes on transport fuels across Europe, it can be argued that the exemption of road transport from further carbon is optimal. On the other hand, the existence of other externalities justifies high taxes on road transport. Congestion is the major concern in the regulation of road transport followed by local pollution, accidents and noise. In the consequence, the effect of an additional increase of fuel taxes crucially depends on the pre-existing tax. If the tax is too high in the sense that it already includes a carbon tax component, a further increase in the fuel tax will lower welfare.

3 Methodological Background

This chapter describes the methodological background of computable general equilibrium modeling. I start by reviewing the basic theory of general equilibrium. Afterwards, the CGE format and its representation as mixed complementarity problem are introduced; functional forms and empirical specification are discussed. Finally, the inclusion of technological details is described.

3.1 Theoretical basics of applied general equilibrium models

Consider an economy with *L* commodities (indexed by *l)* which are traded at a single positive price p_l. *J* producers (indexed by $j \in J:=\{1 \ldots J\}$) are characterized by technologies, represented by the set of feasible production plans Y_j which are part of the commodity space $\mathbb{R}^L$. The set of feasible production plans is assumed to be strictly convex, compact and includes the possibility of inaction ($0 \in Y_j$).[18] Producers are assumed to behave profit maximizing. Furthermore, markets are assumed to be perfectly competitive, i.e. every agent takes the price vector as given. Consequently, observing the price vector *p* every producer chooses his production plan y_j such that his profit is maximized and the production plan is feasible:

$$\begin{aligned} \Pi_j(p) &= \max_{y^j}\left[p y_j\right] \\ \text{s.t.} \quad & y_j \in Y_j \end{aligned} \tag{1}$$

The *H* households (indexed by $h \in H:=\{1 \ldots H\}$) are characterized by a utility function which associates nonnegative consumption plans x_h with utility levels $U_h(x_h)$. Utility functions are assumed to be strictly quasiconvex, continuous, and nonsatiated.[19] Each consumer receives income from two sources: First, he is initially endowed with a positive commodity vector ω_h being sold at the market price and second, he owns nonnegative shares γ_{hj} of firm *j* for which he receives dividends $\gamma_{hj}\Pi_j$. Profits are fully distributed to households, i.e. the shares of firm *j* sum to one over all households. Households are assumed to maximize utility under the constraint that consumption plans are feasible, i.e. are within the budget set:

$$\begin{aligned} &\max_{x_h \geq 0}\left[U_h(x_h)\right] \\ &\text{s.t.} \;\; p x_h \leq p\omega_h + \sum_j \gamma_{hj}\Pi_j(p) \end{aligned} \tag{2}$$

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[18] These assumptions imply a well-defined, nonempty, continuous point-valued supply function. The assumption of strict convexity can be relaxed to weak convexity. However, the supply function generally becomes set-valued, i.e. results in a supply correspondence (e.g. Starr, 1997).

[19] These assumptions ensure that the associated demand functions are homogeneous of degree zero in prices and single valued. As in the production case, relaxing the strict quasiconvexity assumption leads to a demand correspondence (e.g. Mas-Colell, Whinston, and Green, 1995).

A general competitive equilibrium is then defined as production plans y_j^* and consumption plans x_h^* and a price vector p^* such that given the equilibrium price vector the programs (1) and (2) are fulfilled. Furthermore, markets are either cleared or in excess supply:

$$\sum_j y_j^* + \sum_h \omega_h \geq \sum_h x_h^* \tag{3}$$

Equation (3) is commonly referred to as market clearing or material balance equation. It relates to the concept of the excess demand function, which is defined as:

$$z(p) := \sum_h x_h - \sum_j y_j - \sum_h \omega_h \tag{4}$$

Under the above formulated assumptions, the excess demand function is a continuous, single valued function of prices. Furthermore, it is homogenous of degree zero in prices. Thus, the absolute value of prices does not affect outcomes. Therefore, it is possible to normalize prices by choosing a numéraire commodity for which the price is fixed to some arbitrary number (normally one). In addition, strict Walras' law holds, i.e. the value of excess demand is equal to zero:

$$p \cdot z(p) = 0 \tag{5}$$

As long as the assumption of satiated preferences is satisfied, the first fundamental theorem of welfare economics holds which states that every equilibrium is Pareto efficient.

The existence of the equilibrium under the given assumption has been proven by Arrow and Debreu (1954). Consequently, the described model format is often denoted as Arrow-Debreu format. Alternative names are Walras' or competitive general equilibrium model. An extensive discussion of the underlying assumptions and the existence proof is given in Debreu (1959) and Arrow and Hahn (1971).

3.2 Computable general equilibrium modeling

From a policy analysis point of view, the described economy is seen as a controlled system (Munk, 2009). Decision makers – generally governments – impose policies using instrument variables to influence the value of goal variables in a desired way. For example, the goal of governments is to reduce greenhouse gases in order to mitigate the consequences of global warming. As described in the last chapter, various policy instruments exist, among them carbon taxes or emission trading schemes. Possible choices of a goal variable are consumer welfare or total abatement cost. Applied general equilibrium (AGE) models simulate the controlled system based on the Arrow-Debreu framework.

This involves setting up a parameterized model, i.e. choosing functional forms for production and utility functions and determining the mathematical format. Parameters of these functions are determined based on empirical data in order to obtain a fully specified model. The model is then used to carry out comparative static exercises by quantifying the effect of a change of the instrument variables on the goal variables. Since closed form solutions for higher dimensional models generally do not exist, this involves solving the model using numerical methods.

3.2.1 Mathematical format

CGE models are AGE models adopting additional assumptions and a special mathematical format (Ginsburgh and Keyzer, 1997)[20]. The commodity vector is divided into goods (index by $i,j \in J$) and factors (index by $f \in F$). Factors are characterized by the fact that they are provided solely by households. Furthermore, production functions are characterized by constant returns to scale. Additionally, it is assumed that every firm produces one specific good, i.e. only firm j produces commodity j.[21] Let $F(x_{ij},x_{fj})$ be the production function of firm j with x_{ij} as intermediate input $i \in J$ and factor inputs x_{fj} and $C(p,y_j)$ the associated cost function. Since the production is homogenous of degree one, the cost function also exhibits constant returns (e.g. Mas-Colell et al., 1995). Consequently, the profits optimization problem can be stated using the unit cost function $c(p)$:

$$\max_{y_j} \Pi_j = p_j y_j - c(p) y_j \qquad \forall j \in J \tag{6}$$

The first order condition yields:[22]

$$p_j \le c_j(p) \qquad \perp \qquad y_j \ge 0 \qquad \forall j \in J \tag{7}$$

These conditions are known as zero profit conditions since the complementarity implies that the price of commodity j is equal to the unit cost – the firm makes zero profits – and the corresponding production level y_j is positive or costs exceed the price and the production level drops to zero since the firm otherwise would make losses.

Let $U_h(x_{ih},x_{fh})$ be the consumer h's utility function with consumption x_{ih} of commodity i and x_{fh} of factor f. Additionally, let M_h be the income of the consumer defined as:

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[20] Another approach is to use the Negishi format which formulates AGE models as welfare optimization problems based on the Negishi theorem (1960).

[21] This assumption is only for the ease of notation since it allows using the set J for firms and goods. The extension to multi-product firms is straightforward but requires introducing an additional set for goods.

[22] The symbol $\perp$ is used to express complementarity. In full notation the conditions reads as $p_j \le c_j(p) \qquad (c_j(p)-p_j) y_j = 0 \qquad \forall j \in J$

$$M_h = \sum_{k \in J \cup F} p_k \omega_k \qquad \perp \qquad M_h \geq 0 \qquad \forall \quad h \in H \tag{8}$$

The Walrasian demand functions are defined in means of the utility optimization problem:

$$d_{kh}\left(p, M_h\right) := \underset{x_{kh} \geq 0}{\arg\max} \left[U\left(x_{kh}\right) \quad \text{s.t. } M_h = \sum_{k \in J \cup F} p_k x_{kh} \right] \qquad \forall \quad k \in J \cup F, h \in H \tag{9}$$

where the assumption of non-satiated preferences is used to impose strict equality on budget constraints.

Walras' law implies complementarity between market clearing conditions and associated prices. Using Shepard's lemma the market clearing equations become:

$$\begin{aligned} & y_i + \omega_i \geq \sum_{j \in J} \frac{\partial c_j}{\partial p_i} y_j + \sum_{h \in H} d_{ih} && \perp \quad p_i \geq 0 \quad \forall i \in J \\ & \omega_f \geq \sum_{j \in J} \frac{\partial c_j}{\partial p_f} y_j + \sum_{h \in H} d_{fh} && \perp \quad p_f \geq 0 \quad \forall f \in F \end{aligned} \tag{10}$$

These complementarities express the fact that either the market clearing condition holds with strict equality (i.e. the commodity is scarce) and the respective price is positive, or supply exceeds demand and the corresponding price drops to zero.

The equilibrium conditions (7), (8), and (10) specify a square system of equations which can be solved for the unknown prices, production, and income levels. Furthermore, the system imposes complementarity between equilibrium conditions and variables. In mathematical programming such programs are known as mixed complementarity problems (MCP) which are generally defined as (e.g. Cottle et al.,1992; Rutherford, 1995):[23]

$$\begin{aligned} & \text{given } f : \Re^n \to \Re^n \\ & \text{find } \; r \in \Re^n \\ & \text{s.t. } r \geq 0 \;\; f(r) \geq 0 \;\; r^T f(r) = 0 \end{aligned} \tag{11}$$

In the case of CGE models, r is defined as the vector of prices, incomes, and production levels and *f(r)* are the equilibrium conditions. In contrast to welfare optimization formulations, which do not represent dual variables (i.e. prices) explicitly in the formulation, the MCP format has the advantage of the representation of these variables and, consequently, allows restrictions on dual variables. Put

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[23] For a survey of the use of MCP in economics and engineering applications see Ferris and Pang (1997).

differently, the MCP overcomes the integrability restriction of optimization formulations (Mathiesen, 1977, 1985).

3.2.2 Functional forms

The underlying assumptions restrict the choice of functional forms to the class of linear homogenous ones. Most applied studies employ the Constant Elasticity of Substitution (CES) function (Arrow et al., 1961):[24]

$$
\begin{aligned}
& y_j = \phi_j \left[\sum_{k \in J \cup F} \delta_{kj} x_{kj}^{-\rho_j} \right]^{-\frac{1}{\rho_j}}; \quad \sum_{k \in J \cup F} \delta_{kj} = 1 \\
& \sigma_j = \frac{1}{1+\rho_j}
\end{aligned}
\tag{12}
$$

with $\Phi_j > 0$ being called the efficiency parameter, δ_{kj} Є]0,1[are distribution parameters, and $\rho_j > -1$ is the substitution parameter which determines the constant substitution elasticity σ_j. The CES function includes the Leontief ($\sigma_j = 0$) and Cobb-Douglas functions ($\sigma_j = 1$) as special cases (e.g. Chiang and Wainwright, 2005). However, the CES function imposes equal substitution elasticities between all inputs. In order to overcome the problem of equal substitutability of all inputs, nested CES functions (Strotz, 1957) are used which can be depicted in the form of a nesting tree.[25] Figure 2 shows an arbitrary nesting tree for four inputs and a two level production function of firm *j*. Both nests (aggregates, composites) at level 1 (i.e. N_{11} and N_{12}) are single level CES functions as given in (12) with the respective substitution elasticities combining the commodities. At level zero, these composites are combined with the elasticity σ_0. A discussion about nested CES functions, their properties, and derivation of elasticities is given in Keller (1980, 1976).

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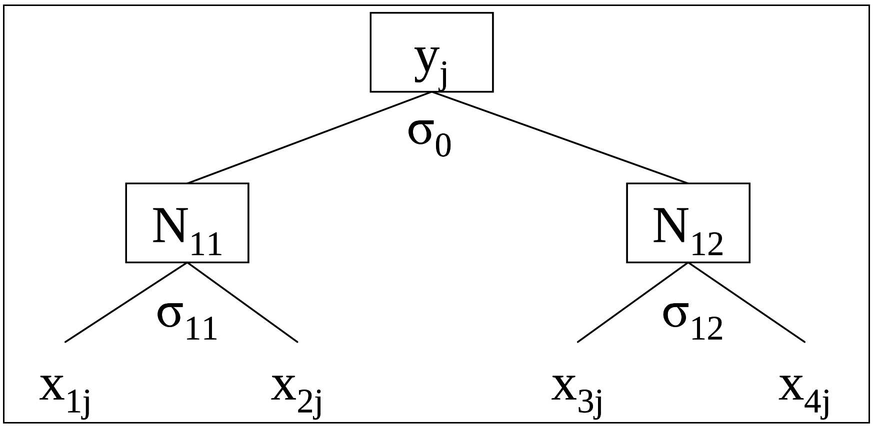
[24] More flexible functional forms within this class are the Translog (Christensen et al., 1971), Generalized Leontief (Diewert, 1971), or Normalized Quadratic (Diewert and Wales, 1987) function. Perroni and Rutherford (1998) compare the performance of flexible function forms in AGE modeling. They find that these function often fail to preserve desired global curvature properties which causes computational difficulties.

[25] In the ongoing, I discuss separable nested CES functions. Even though non-separable CES function are more flexible (Perroni and Rutherford, 1995), they are rarely used in applied work since especially in large application with extensive nesting empirical specification becomes complicated.

Figure 2: Nesting tree



3.2.3 Empirical specification

The implementation of CGE models involves choosing functional parameters based on empirical data. The most preferable approach would be to estimate all parameters of the model based on macroeconomic data on prices and quantities. However, this approach is usually impossible for two reasons. First, CGE models are large systems of equations. Thus, system estimation procedures have to be employed. However, error terms in the system are not independently distributed which leads to likelihood functions which are generally not well defined. Second, with a growing number of sectors and consumers the number of parameters to be estimated increases rapidly. In consequence, the number of independent parameters to be estimated exceeds the number of data points (Mansur and Whalley, 1984; Shoven and Whalley, 1992). Modelers react to the situation by involving a procedure referred to as calibration and borrowing estimates from the literature (usually elasticities).

Calibration assumes that the economy under consideration is in equilibrium – the benchmark equilibrium. Data for a specific year usually are given in the form of a Social Account Matrix (SAM) (Pyatt and Round, 1985). A SAM is a square matrix which includes data on production and income generation of different sectors and institutions like governments and households; columns represent input vectors, rows refer to income generation. The assumption of an underlying equilibrium implies that earnings and spendings add up to zero. Thus, a SAM has to be balanced. A general starting point for the construction of a SAM are national input-output tables. These have to be combined with additional data such as taxes, trade, consumer income, and physical data.

Under the equilibrium assumption, the CES function can be transformed into the calibrated share form (Rutherford, 2002):

$$y_j = \overline{y}_j \left[\sum_{k\in J\cup F} \theta_{kj} x_{kj}^{-\rho} \right]^{-\frac{1}{\rho}}; \qquad \sum_{k\in J\cup F} \theta_{kj} = 1$$

$$\theta_{kj} := \frac{\overline{p_k}\,\overline{x_{kj}}}{\sum_{l\in J\cup F} \overline{p_l}\,\overline{x_{lj}}} \qquad (13)$$

Benchmark parameters are denoted by upper bars and θ_{kj} is the share of input k's cost in the total cost of firm j. The calibrated share form has the advantage of avoiding calibrating the efficiency parameters. Given a balanced SAM, all cost share parameters can be calibrated. Often SAMs do not report prices and quantities separately but the product of them, i.e. are given in monetary units. In this case, it is common to assume that all prices are equal to one. The assumption does not affect the conclusions from the model results since the benchmark equilibrium is compared to the equilibrium outcome resulting from a change of an instrument variable – the counterfactual equilibrium outcome. Thus, relative changes to the benchmark equilibrium are relevant for the interpretation of the results and the choice of prices is arbitrary as long as the cost shares are correctly specified.

The curvature of functions is determined by the substitution elasticity. These elasticities have to be taken from additional econometric estimates. However, estimates of substitution elasticities are rare. The lack of empirical estimates suggests including additional estimates of price and income elasticities into the procedure. However, partial equilibrium elasticities often do not interact very well with general equilibrium elasticities. Bergmann (2005) concludes that substitution elasticities are generally "guesstimates". Therefore, sensitivity analysis of the results with respect to substitution elasticities is needed.

Correctness of the calibration procedure is validated in form of a replication check, i.e. without any change in the instrument variables the model reproduces the benchmark equilibrium as given by the SAM.

3.2.4 Computational implementation

Solving CGE models naturally involves numerical algorithms. This puts restrictions on the use of models along two dimensions. First, computational performance restricts model size. Second, besides specification of the models, modelers must also be able to implement efficient solution algorithms.[26] Since computer performance has rapidly increased during the last decades, dimensionality is rarely considered nowadays. Concerning the implementation of solution algorithms, modelers greatly benefit from modern mathematical programming applications like the General Algebraic Modeling System (GAMS) (Brooke et al., 2008). GAMS allows the modeler to write down the model equations and the software provides standardized solution procedures in the form of solvers. All models in this thesis are formulated as MCPs and are solved using the PATH solver (Dirkse and Ferris, 1995; Ferris and Munson 2000). Models are implemented using the Mathematical Programming System for General Equilibrium (MPSGE) developed by Thomas Rutherford (1999). MPSGE is a meta language implemented on top of the GAMS system. The modeler provides a description of (nested CES) cost and expenditure functions together with benchmark data and substitution elasticity in tabular form. MPSGE evaluates functions and the corresponding Jacobian matrix and implements the model in

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[26] See Scarf (1984) and Todd (1984) for a survey of earlier solution algorithms.

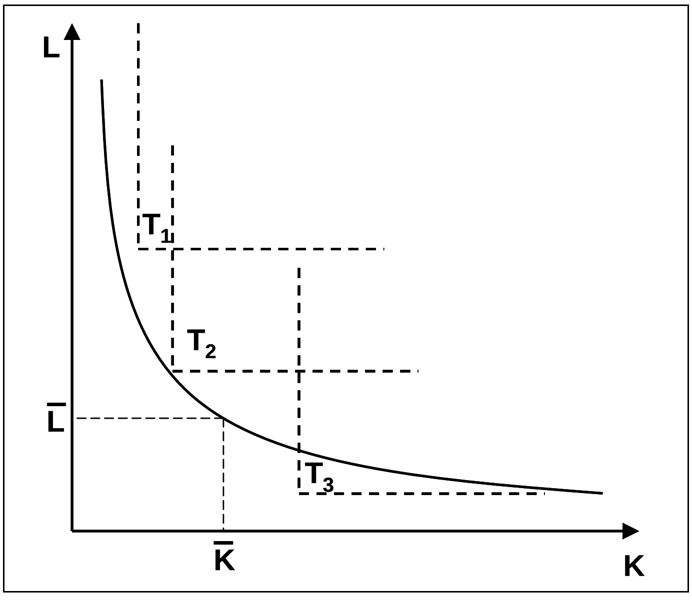
MCP format. After generation of the model's equations it is solved using the PATH solver.[27] Beside the advantage of avoiding the error prone explicit programming of nested CES function, MPSGE has the benefit of automatically deriving demand functions as partial derivatives of provided functions (Shepard's lemma).

3.3 Technological details

3.3.1 The bottom-up/top-down discussion

Applied general equilibrium models have the advantage of capturing price interdependencies of economic sectors by a comprehensive assessment of the circular flow of commodities and incomes. However, especially in energy policy analysis, CGE models are often criticized for the lack of detailed representation of technological details of the energy system. In this discussion, AGE models are often termed top-down models since they adopt a view on the whole economy from the top and neglect details of single sector representations. In contrast, bottom-up models adopted a technological rich engineering view of single sectors but approximate macroeconomic changes in a rough manner, i.e. do not capture macroeconomic feedbacks (Hourcade et al., 2006). Usually bottom-up models characterize sectors in terms of different production technologies represented by Leontief technologies. A change on relative input prices then leads to a switch from one technology to another. Such models are implemented as linear programs. Prominent examples of bottom-up models of the energy system are the MARKet ALlocation (MARKAL) (Loulou et al., 2004) or the Prospective Outlook on Long-term Energy Systems (POLES) (Criqui et al., 1999) model.

Figure 3: Top-down versus bottom-up technology representation



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[27] Alternatively the MILES Solver (Rutherford, 1993) can be used.

The discussion about technology representation is best explained in terms of Figure 3 which depicts production function using capital K and labor L as inputs. From a bottom-up view, the sector is best characterized in terms of three distinct technologies represented by dashed lines. The parameter specification of the technologies' cost functions is derived using engineering data. Under a given demand for the output, the firm seeks to minimize production cost by choosing the output level of different technologies, i.e. the technology mix. In contrast, the top-down approach describes the sector's cost by a smooth cost function depicted by the solid isoquant. The described calibration procedure implies that the isoquant's locus in the production space is determined by the sector's benchmark input of capital and labor. The substitution possibility among inputs is determined by the curvature of the isoquant, i.e. by choosing the substitution elasticity. However, only by incident, a substitution elasticity which correctly determines factor substitution as implied by detailed technology analysis exists. Furthermore, even if the isoquant succeeds in replicating technology substitution, other restrictions like pre-installed production capacities and technological potential which imply limited technology substitution are not represented.

Generally, three different approaches exist to overcome the top-down/bottom-up problem. The softlink approach links independently developed models using a convergence algorithm. Such approach used for example in the MESSAGE-MACRO model (Messner and Schrattenholzer, 2000). This approach often faces problems of different behavioral assumptions and accounting schemes (Böhringer and Rutherford, 2008). In contrast the hardlink approach formulates a highly aggregated reduced form macro model with a detailed deciption of the energy system in a single optimization problem. This approach is followed for example in the REMIND model (Bauer et al., 2008; Leimbach et al., 2009). Finally, using the MCP format, both model formats can be fully integrated. This thesis follows the integrating approach which is described in detail in the next section.

3.3.2 Integrating bottom-up and top-down

Böhringer (1998) and Böhringer and Rutherford (2008) propose exploiting the MCP format in order to overcome the problem of technology representation. The basic idea is to set up the bottom-up linear programming model, deriving the first order complementarity conditions, and adding them to the CGE model in MCP format.

Consider a specific sector $s \in J$ being subject to the bottom-up representation. The sector uses T different technologies ($t \in T:=\{1,2,\ldots,T\}$) to produce one homogenous output y_j. Technologies are characterized by unit inputs a_{kt} and installed capacities cap_t. Additionally, technologies' production levels are bounded from above by technological potentials pot_t.[28] Imposing perfect competition, the firm seeks to minimize production cost given commodity prices p_k, prices for capacity investments pi_t

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[28] The term technological potential is a bit misleading since the potential also might be restricted by policy. For example, in the electricity sector the use of hydro power is naturally restricted by possible production sights. However, the potential of nuclear power might be restricted by the government's intention for nuclear phase out.

and demand d_s for output by choosing technologies' production levels B_t and investment in new capacities I_t:

$$\begin{array}{llllll}
\min\limits_{\substack{B_t \geq 0 \\ I_t \geq 0}} & \sum\limits_{\substack{t \in T \\ k \in J \cup F}} p_k a_{kt} B_t + \sum\limits_{t \in T} pi_t I_t & & & & \\
\text{s.t.} & \sum\limits_{t \in T} B_t \geq & d_s & \perp & p_s \geq 0 & \forall t \in T \\
 & cap_t + I_t \geq & B_t & \perp & pcap_t \geq 0 & \forall t \in T \\
 & pot_t \geq & B_t & \perp & ppot_t \geq 0 & \forall t \in T
\end{array} \tag{14}$$

The dual variables have natural economic interpretations: p_s is the dual on the market clearing equation and interpreted as the price earned per unit of output, i.e. the price of commodity *s*; $pcap_t$ is the capacity rent of technology *t*; and $ppot_t$ are rents stemming from the technological potential restriction of technology *t*. The first order conditions for technologies' production levels become:

$$\sum_{k \in J \cup F} p_k a_{kt} + pcap_t + ppot_t \geq p_s \qquad \perp \quad B_t \geq 0 \qquad \forall t \in T \tag{15}$$

On the left hand side, the cost of producing one unit of output with technology *t* is given. They consist of the costs of intermediate and factor inputs and possible capacity and potential rents. On the right hand side, the earnings of one unit in terms of the output price are given. The complementarity is interpreted as zero profit condition: the technology production level is positive iff unit cost equal unit income.

The condition for optimal capacity investment results as:

$$pi_t \geq pcap_t \qquad \perp \quad I_t \geq 0 \qquad \forall t \in T \tag{16}$$

Again, this has the natural interpretation of a zero profit condition: investment in production capacity of technology *t* is positive iff the unit income of investment – the capacity rent $pcap_t$ – is equal to the unit cost given in terms of the investment price.

Neglecting pre-installed capacities and investment in new capacities for the moment, integration of the bottom-up model into the top-down framework is easily done by adding the derived zero profit conditions (15) and the restrictions of program (14) to the stylized CGE model described by conditions (7), (8), and (10). The integrated model becomes:

Zero-profit conditions:

$$
\begin{array}{lclcll}
c_j(p) & \geq & p_j & \perp & y_j \geq 0 & \forall j \in J \setminus \{s\} \\
\sum\limits_{k \in J \cup F} p_k a_{kt} + pcap_t + ppot_t & \geq & p_s & \perp & B_t \geq 0 & \forall t \in T \\
pi_t & \geq & pcap_t & \perp & I_t \geq 0 & \forall t \in T
\end{array}
$$

Market clearing conditions:

$$
\begin{array}{lclcll}
y_i + \omega_i & \geq & \sum\limits_{j \in J} \dfrac{\partial c_j}{\partial p_i} y_j + \sum\limits_{h \in H} d_{ih} & \perp & p_i \geq 0 & \forall i \in J \setminus \{s\} \\
\sum\limits_{t \in T} B_t & \geq & \sum\limits_{j \in J} \dfrac{\partial c_j}{\partial p_s} y_j + \sum\limits_{h \in H} d_{sh} & \perp & p_s \geq 0 & s \in J \\
\omega_f & \geq & \sum\limits_{j \in J} \dfrac{\partial c_j}{\partial p_f} y_j + \sum\limits_{h \in H} d_{fh} & \perp & p_f \geq 0 & \forall f \in F \\
pot_t & \geq & B_t & \perp & ppot_t \geq 0 & \forall t \in T \\
cap_t + I_t & \geq & B_t & \perp & pcap_t \geq 0 & \forall t \in T
\end{array}
$$

Income definitions:

$$
M_h = \sum_{k \in J \cup F} p_k \omega_k + \sum_{t \in T} ppot_t pot_{th} \perp \quad M_h \geq 0 \quad \forall \quad h \in H \tag{17}
$$

The technological potential is allocated to households earning the rent if the restriction becomes binding, and, consequently, becomes dependent on the household set.

It is important to note that in this formulation the technologies' outputs are perfect substitutes, i.e. all technologies sell their output at the same price p_s. Thus, small changes in relative prices can lead to extreme shifts from one technology to another. This undesirable property of the model is often called flip-flop behavior (Wing, 2008). The flip-flop problem makes it necessary to include pre-installed capacities (cap_t) and technology investment (I_t). However, the inclusion of production capacities necessarily involves the modelers' non-trivial decision about what exactly the investment commodities I_t and the associated investment prices pi_t are. Generally, the best approach is to specify the investment demand by technology t in terms of commodities represented in the SAM, to introduce an artificial sector producing the investment commodity and selling it to the technology activity, and to add pre-installed capacities to consumers' endowment. However, this can become a data intensive procedure. For example in the electricity sector it requires specifying detailed input vectors for capacity investments into different generation technologies such as nuclear, coal, natural gas, and hydro plants in terms of construction services, materials and labor. Such detailed data are rarely available. Even in bottom-up models investment is not specified in single commodity terms but in terms of an investment price. The problem of the combined, integrated, or hybrid approach is that the top-down framework demands specifying the investment commodity to maintain circular flow of commodities and income. One approach around the problem is to specify sector specific factor inputs.

The stylized models of Böhringer (1998) and Böhringer and Rutherford (2008) specify fossil fuel energy resources (coal, natural gas, and refined oil) as sector specific resources which are solely supplied by consumers, i.e. energy resources are specified as factors which are only demanded by the respective technologies. However, in empirical applications commodities' supply is endogenously determined and, thus, can not be specified as factor. Böhringer (1995) uses the framework for an empirical evaluation of the influences of alternative coal subsidies on carbon taxes in Germany. In this model, capital inputs are partially specified as sector specific leading to the same desired smooth technology substitution. Wing (2008) is the first elaborating the problem explicitly; he proposes the following modeling approach: If technologies are determined as Leontief production technologies, the supply of sector specific capital naturally puts an upper bound on the output level. He introduces an artificial activity taking malleable or intersectoral mobile capital as input and providing technology specific capital stocks as output using a Constant Elasticity of Transformation (CET) function. This corresponds to the view that capacities are partially reversible, i.e. can be retired and converted into malleable capital, which can be used for investments into new technology specific capital. Consequently, the malleability of capacity is governed by the transformation elasticity of the capital activity. Additionally, he uses the share preserving character of the CES function that price changes do not induce extreme deviation in technologies' output shares: Each output unit is rewarded with a technology specific output price. Outputs are aggregate to a homogenous commodity using a CES function with a high substitution elasticity ($\sigma = 10$) which results in a nearly linear isoquant (perfect substitutability).

3.4 Relevant modeling literature

In general, the global pollution externality of transport in AGE models is investigated from two perspectives: On the on the hand, the energy/environmental approach focuses on the emission of greenhouse gases especially from the combustion of fossil fuels. On the other hand, transport economic modeling focuses mainly on the congestion externality and partly includes other externalities such as pollution and accidents. While in the first class of models the main interest lies in an efficient carbon pricing, cost-efficient abatement of emissions and the interaction across polluting sectors, the second perspective is primarily interested in an efficient internalization of transport externalities within the transport sector and the impacts of changed transport prices and infrastructure investments on mode decisions and other sectors.

A detailed modeling of the transport sector in energy/environmental related studies is relatively rare compared to the number of such studies.[29] Paltsev et al. (2004, 2005b) develop a method to integrate private transport into the MIT Emission Prediction and Policy Analysis (EPPA) model. The MIT

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[29] General surveys of the use of AGE models in energy/environment studies are given for example, in Conrad (1994), Bergman (2005), and Wing (2007). Springer (2003) summarizes the literature especially related to tradable greenhouse gas permits.

EPPA model is a large scale, recursive dynamic CGE model of the world economy.[30] Carrying out illustrative emission pricing scenarios, the authors show the critical importance of a disaggregated representation of household transport to improve the representation of substitution possibilities for fossil fuels. While the MIT EPPA model does include transport, it does not differentiate between the durable stock of transport capital and the associated service flow. Such an approach is implemented in the GEM-E3 model of the European Union (Capros et al., 1997). GEM-E3 offers a detailed representation of the EU 15 region and six further aggregated world regions. It is also recursive dynamic but includes cars as a stock variable which depreciates over time, is augmented by investments, and necessary to obtain the service flow of transport.

Berg (2007) extends the EMEC model developed by Östblom and Berg (2006) by a detailed representation of household transport demand. In this static model of the Swedish economy, different transport modes, work and leisure trips are distinguished. Furthermore, households are differentiated representing different income groups and locations of living. Berg analyzes the effect of carbon taxes in the EMEC model with and without the augmented transport modeling. The model with the detailed transport module always shows higher cost of carbon regulation. This result is based on the endogenous labor/leisure choice: carbon taxes on fuels increase the price of work trips and thus, exert a negative pressure on labor supply.

Another stream of the environmental/energy literature is concerned with the penetration of advanced technologies in the automobile market. Schäfer and Jacoby (2005, 2006) implement a softlink approach on the MIT EPPA model with an improved modeling of private transport. They use the model together with a mode choice (Schäfer and Victor, 2000) and the MARKAL model (Louluo et al., 2004). Transport demand is determined in the EPPA model and passed to the mode choice model. The demand for different modes and prices of the EPPA model are processed in the MARKAL model which is calibrated to an existing fleet of automobile technologies and other transport modes. Consequently, MARKAL determines the penetration of advanced vehicle technologies. In order to achieve consistency between the MARKAL energy and the EPPA transport demand, substitution elasticities in the household transport module and the autonomous energy efficiency improvement parameter are adjusted in an iterative procedure. Implementing different time paths for emission reduction, the authors show that advanced technologies such as aluminum intensive vehicles or hybrid drive trains do not play a significant role in emission abatement in the US for the next 30 years.

Sandoval et al. (2008) analyze the prospect of hydrogen cars by introducing a hydrogen production sector in the EPPA model. They estimate that in the absence of any climate policy hydrogen cars become competitive in the US at a purchase price which is 1.3 times the price of conventional automobiles since they are more fuel efficient. In Europe, the technology will become competitive even at a price twice the one of conventional cars since high fuel taxes stimulate the use of more fuel efficient hydrogen cars. However, the penetration of hydrogen cars only slightly reduces carbon

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[30] Recently, a forward looking model version has also been developped (Babiker et al., 2008).

emissions since hydrogen production in mainly based on coal combustion. Imposing carbon constraints favors the adoption of hydrogen vehicles.

Jokisch and Mennel (2009) calculate hydrogen penetration rates in the MARKAL model and impose them exogenously on the PACE model (Böhringer and Vogt, 2003) to assess the macro-economic impacts. PACE is a dynamic, forward looking of international energy use and global trade with a special emphasis on Europe. Since hydrogen vehicles are assumed to have learning effects which drive lifetime cost below the cost of conventional automobiles, the penetration yields positive welfare effects. Karplus et al. (2009) analyze the potential role of plug-in hybrid electric vehicle for the US and Japan by augmenting the EPPA model. They show that even in the presence of a strict climate policy, additional research on battery design is necessary to lower purchase costs and increase driving range.

The transport economic modeling literature is primarily interested in the congestion externality and the welfare impacts of changed transport prices. Accordingly, often road pricing and/or infrastructure investments are assessed. Such models often ignore externalities (e.g. Kalinowska et al., 2007; Kremers and Kalinowska, 2009) or only focus congestion (e.g. Conrad, 1997; Conrad and Heng, 2002). Other studies use the same approach as the environmental/energy literature: they include the generation of externalities, particularly greenhouse gas emissions, but do not model their impact on the economic system (e.g. de Borger and Swysen, 1998; Steininger et al., 2007). Parry and Bento (1999) note the importance of other externalities evaluating the welfare effects of congestion pricing. Including accident and pollution externalities in a linear separable way into the utility function, they show that reduced congestion offers additional positive welfare effects by reducing these externalities and illustrate their results with a stylized CGE model. Non-separable transport externalities in the utility function and the impacts on production sectors have been model by Meyeres and Proost (1997). Mayeres (1999) extends this approach for different household types to assess the equity aspects of transport policies.

4 Transportation under the European Emission Trading System

4.1 Introduction

This chapter employs a multi-region computable generally equilibrium model analyzing the impacts of European-wide regulation measures addressing the carbon emissions of transport. The introduction of a closed emission trading system for transport emissions, the inclusion of the transport sector into the EU ETS, and the exemption of transport from carbon regulation are tested against the performance of the current EU ETS. The results show that exempting transport from carbon regulation, i.e. shifting the reduction burden to the EU ETS, is the most favorable strategy. Concerning fuel pricing strategies, the inclusion of transport into the EU ETS incurs lower cost than a closed emission trading scheme. Furthermore, a closed emission trading scheme performs only slightly better than transport under national carbon taxes.

Multi-region models have the advantage that changes in terms-of-trade are endogenously determined. Analyzing carbon restrictions, terms-of-trade changes occur in two dimensions. First, countries with a lower carbon price gain comparative advantages in the production of energy intensive commodities. Second, carbon restrictions affect the demand for fossil fuels. Consequently, prices change and create substantial spillovers to other countries. The extensive literature on terms-of-trade reaction concludes that fossil fuel price changes are the main determinant of terms-of-trade changes (e.g. Krutilla, 1991; Böhringer and Rutherford, 2002b; Babiker et al., 2004). Analyzing the introduction of the EU ETS compared to purely national regulation on a member state level, the model also shows this result.

Policies are analyzed at the EU 27 level, i.e. new member states with negative reduction burdens. The results show, that these countries incur welfare gains by participating in the EU ETS since they are able to sell excess emission allowances.

4.2 Model description

4.2.1 Overview

The multi-region model employed in this chapter is formulated as a mixed complementarity problem. Three classes of equilibrium conditions exist. No activity makes positive profits (zero-profit condition). Excess supply is weakly positive (market clearing condition). Each household fulfils his budget restriction. Each class is associated to a class of variables. Activity levels are associated with zero-profit conditions. Prices are connected to market clearing equations. Each budget restriction determines the income level of the respective household.

The basic assumptions of the model are:

- The model is static.
- International commodity trade is unrestricted.
- All markets are perfectly competitive, i.e. all agents take prices as given.

- Households' preferences are represented by a representative agent.
- The household is endowed with capital and labor which are intersectoral but not international mobile. Furthermore, an endowment of immobile natural resources exists. All factors are inelastically supplied.
- Investment demand and balance of payment deficits are exogenous and constant.
- The government imposes taxes to finance the provision of public goods which is assumed to be constant.
- Production and utility functions are represented using nested CES functions.

4.2.2 Algebraic description

4.2.2.1 Representative agent

The representative agent (RA) in region *r* derives utility consuming commodities *i* ($x_{i,RA,r}$) according to the utility function $U_r(.)$. The initial endowments of capital (K_r), labor (L_r), and natural resource used in sector *i* ($R_{i,r}$) determine the income of representative agents. Factors are inelastically supplied. While capital and labor are mobile across sectors but not international, natural resources are sector-specific, i.e. immobile across sectors and regions. Given commodity prices $p_{i,r}$, factor prices $p_{K,r}$, $p_{L,r}$, and $p_{R,i,r}$, the tax rate on final consumption $t_{i,RA,r}$, and a direct transfer from the government to the household $trans_r$, the representative agents maximize utility subject to the budget constraint:

$$\begin{aligned}&\max_{x_{i,RA,r}\geq 0} U_r\left(x_{i,RA,r}\right)\\ &\text{s.t.}\quad p_{K,r}K_r + p_{L,r}L_r + \sum_i p_{R,i,r}R_{i,r} + trans_r \geq \sum_i \left(1+t_{i,RA,r}\right)p_{i,r}x_{i,RA,r} + \sum_i inv_{i,r}\end{aligned} \tag{18}$$

$inv_{i,r}$ is investment demand which is assumed to be constant. Solving the problem for each representative consumer yields the demand function depending on prices ($C_{i,r}$).

4.2.2.2 Production

Each production sector *i* produces one commodity which can either be sold to the domestic market at price $p_{i,r}^d$ or be exported at price $p_{i,r}^e$. The respective quantities are denoted $y_{i,r}^d$ and $y_{i,r}^e$ and the activity level by $y_{i,r}$. $x_{j,i,r}$ is the intermediate input of commodity *j* to sector *i* in region *r*. Similar, $x_{K,i,r}$, $x_{L,i,r}$, and $x_{R,i,r}$ are the respective factor inputs. Taxes are imposed on intermediate as well as factor inputs ($t_{j,i,r}$, $t_{K,i,r}$, $t_{L,i,r}$, $t_{R,i,r}$) and on outputs ($to_{i,r}$). Accordingly, tax inclusive input prices are defined as $q_{j,i,r}:=(1+t_{j,i,r})p_{j,r}$, $q_{K,i,r}:=(1+t_{K,i,r})p_{K,r}$, $q_{L,i,r}:=(1+t_{L,i,r})p_{L,r}$, and $q_{R,i,r}:=(1+t_{R,i,r})p_{R,i,r}$. Furthermore, tax inclusive output prices are given as $v_{i,r}^d=(1-to_{i,r})p_{i,r}^d$ and $v_{i,r}^e=(1-to_{i,r})p_{i,r}^e$. Assuming separability of inputs and output and constant returns to scale in production, the unit revenue ($r_{i,r}$) and cost functions ($c_{i,r}$) can be independently determined from a given production function. The profit optimization problems become:

$$\max_{y_{i,r}\geq 0}\; r\left(v^{d}_{i,r},v^{e}_{i,r}\right)y_{i,r}+c_{i,r}\left(q_{j,i,r},q_{K,i,r},q_{L,i,r},q_{R,i,r}\right)y_{i,r} \qquad \forall i,r \qquad (19)$$

The corresponding zero profit conditions become:

$$c_{i,r}\left(q_{j,i,r},q_{K,i,r},q_{L,i,r},q_{R,i,r}\right) \quad \geq \quad r\left(v^{d}_{i,r},v^{e}_{i,r}\right) \qquad \perp \quad y_{i,r}\geq 0 \qquad \forall i,r \qquad (20)$$

Shepard’s lemma and a similar relation on the output side (Ginsburgh and Keyzer, 1997) determine the optimal input and output quantities:

$$\begin{array}{llll} x_{j,i,r}=\dfrac{\partial c_{i,r}}{\partial q_{j,i,r}}y_{i,r} & x_{K,i,r}=\dfrac{\partial c_{i,r}}{\partial q_{K,i,r}}y_{i,r} & x_{L,i,r}=\dfrac{\partial c_{i,r}}{\partial q_{L,i,r}}y_{i,r} & x_{R,i,r}=\dfrac{\partial c_{i,r}}{\partial q_{R,i,r}}y_{i,r} \\ y^{d}_{i,r}=\dfrac{\partial r_{i,r}}{\partial v^{d}_{i,r}}y_{i,r} & y^{e}_{i,r}=\dfrac{\partial r_{i,r}}{\partial v^{e}_{i,r}}y_{i,r} & & \end{array} \qquad (21)$$

4.2.2.3 International trade

International trade is modeled using the Armington (1969) assumption, i.e. commodities are distinguished by region of origin. First, commodities from different regions are combined to an import composite, and second, domestic commodities and the import composite are aggregated.

Furthermore, international commodity trade is associated with a transport margin, i.e. trading commodity i from region r to regions s requires the transport margin $tr_{i,j,r,s}$ of transport service j. The importer of the commodity pays the margin. Transport services are produced by an international transport pool which combines services from different regions.

Two different taxes apply on international trade. The export tax for commodity i shipped from region r to region s, $te_{i,r,s}$, applies on the value of the export. In contrast, the import tax $tm_{i,r,s}$ is levied on the value of the import commodity including the transport margin.

Let pt_i be the price of transport margin i, $c_i^t(p_{i,r}^e)$ the unit cost function of the international transport pool depending on the export prices of commodities coming from different regions, and y_i^t the activity level of the international transport pool. Accordingly, the profit optimization problem becomes:

$$\max_{y^{t}_{i}\geq 0}\left[p^{t}_{i}-c^{t}_{i}\left(p^{e}_{i,r}\right)\right]y^{t}_{i} \qquad (22)$$

The corresponding zero profit condition and the demand functions become:

$$c^{t}_{i}\left(p^{e}_{i,r}\right) \quad \geq \quad p^{t}_{i} \qquad y^{t}_{i}\geq 0 \qquad \forall i \qquad (23)$$

$$x_{i,r}^{t} = \frac{\partial c_i^t}{\partial p_{i,r}^{e}} y_i^t \tag{24}$$

The transport margin is combined with the import commodity in a Leontief manner, i.e. for every unit of imported *i* a certain amount of transport margin *j* is needed. Denoting the amount of the transport margin *j* by $\alpha_{i,j,r,s}$, the import price of commodity *i* imported in region *s* from region *r* is defined as:

$$p_{i,r,s}^{m} := \left(1+tm_{i,r,s}\right)\left[\left(1+te_{i,r,s}\right)p_{i,r}^{e} + \sum_j \alpha_{i,j,r,s} p_j^t\right] \qquad \forall i,r,s \tag{25}$$

Imports from different regions are combined using an activity characterized by a CES unit cost function $c_{i,s}^{ma}(p_{i,r,s}^{m})$ depending on the import prices from different regions. Denoting the price of the import composite as $p_{i,s}^{ma}$ and the activity level by $y_{i,s}^{ma}$, the profit maximization problem of the Armington activity results as:

$$\max_{y_{i,s}^{ma}} \left[p_{i,s}^{ma} - c_{i,s}^{ma}\left(p_{i,r,s}^{m}\right)\right] y_{i,s}^{ma} \qquad \forall i,s \tag{26}$$

The zero profit condition and demand functions for imports from different regions result as:

$$c_{i,s}^{ma}\left(p_{i,r,s}^{m}\right) \quad \geq \quad p_{i,s}^{ma} \qquad \perp \quad y_{i,s}^{ma} \geq 0 \qquad \forall i,r \tag{27}$$

$$\begin{aligned} x_{i,r,s}^{ma} &= \frac{\partial c_{i,s}^{ma}}{\partial\left(1+tm_{i,r,s}\right)\left(1+te_{i,r,s}\right)p_{i,r}^{e}} y_{i,s}^{ma} && \forall i,r,s \\ x_{i,j,r,s}^{mt} &= \alpha_{i,j,r,s} \frac{\partial c_{j,r}^{ma}}{\partial\left(1+tm_{j,s,r}\right)p_i^t} y_{j,r}^{ma} && \forall i,j,r,s \end{aligned} \tag{28}$$

where $x_{i,r,s}^{ma}$ is the demand for import commodity *i* in region *s* coming from region *r*. $x_{i,j,r,s}^{mt}$ is the demand for transport commodity *i* needed to ship commodity *j* from region *r* to region *s*.

A further activity combines domestic produced commodities and the import composite. The unit cost function, depending on domestic production prices and the price of the import composite, is denoted by $c_{i,r}^{a}(p_{i,r}^{d}, p_{i,r}^{ma})$ and the activity level by $y_{i,r}^{a}$. Since the activity level determines the total quantity of commodity *i* available at the market in region *r*, the market price $p_{i,r}$ determines the unit revenues. Consequently, the optimization problem is given as:

$$\max_{y_{i,r}^{a}} \left[p_{i,r} - c_{i,r}^{a}\left(p_{i,r}^{d}, p_{i,r}^{ma}\right)\right] y_{i,r}^{a} \qquad \forall i,r \tag{29}$$

The resulting zero profit conditions and demand functions result as:

$$c^a_{i,r}\left(p^d_{i,r},p^{ma}_{i,r}\right) \quad \geq \quad p_{i,r} \qquad \perp \quad y^a_{i,r} \geq 0 \quad \forall i,r \tag{30}$$

$$x^d_{i,r} = \frac{\partial c^a_{i,r}}{\partial p^d_{i,r}} y^a_{i,r} \qquad x^m_{i,r} = \frac{\partial c^a_{i,r}}{\partial p^{ma}_{i,r}} y^a_{i,r} \tag{31}$$

4.2.2.4 Government

Public consumption of governments, $G_{i,r}$, is constant and financed by collecting tax income. Beside public commodity consumption the government finances the direct transfer to the household and the constant balance of payment deficit bop_r. The public budget constraint is given as:

$$\begin{aligned}
&\sum_i \left[t_{i,RA,r} p_{i,r} C_{i,r} + \sum_j t_{i,j,r} p_{i,r} x_{i,j,r} \right] \\
&+ \sum_i \left[t_{K,i,r} p_{K,r} x_{K,i,r} + t_{L,i,r} p_{L,r} x_{L,i,r} + t_{R,i,r} p_{R,i,r} x_{R,i,r} \right] \\
&+ \sum_{i,s} \left[te_{i,r,s} p^e_{i,r} x^{ma}_{i,r,s} + tm_{i,s,r} \left(\left(1+te_{i,s,r}\right) p^e_{i,s} x^{ma}_{i,s,r} + \sum_j p^t_j x^{mt}_{j,i,s,r} \right) \right] \quad \geq \sum_i p_{i,r} G_{i,r} + trans_r + bop_r
\end{aligned} \tag{32}$$

4.2.2.5 Market clearing conditions

The available quantity of commodity *i* at the market in region *r*, $y_{i,r}{}^a$, and demands by firms, the representative agent, the government, and investment demand, determine the market price:

$$y^a_{i,r} \quad \geq \quad \sum_j x_{i,j,r} + C_{i,r} + G_{i,r} + inv_{i,r} \qquad \perp \quad p_{i,r} \geq 0 \quad \forall i,r \tag{33}$$

Similar, factor prices are determined by the exogenous endowments and sectors' demands:

$$\begin{aligned}
K_r &\geq \sum_i x_{K,i,r} &&\perp \quad p_{K,r} \geq 0 &&\forall r \\
L_r &\geq \sum_i x_{L,i,r} &&\perp \quad p_{L,r} \geq 0 &&\forall r \\
R_{i,r} &\geq x_{R,i,r} &&\perp \quad p_{R,i,r} \geq 0 &&\forall r
\end{aligned} \tag{34}$$

Domestic output and demand established by the Armington aggregation enter the market clearing condition for domestic products:

$$y^d_{i,r} \quad \geq \quad x^d_{i,r} \qquad \perp \quad p^d_{i,r} \geq 0 \quad \forall i,r \tag{35}$$

The price for exported commodities results from the production of commodities for the international market in regions *r* and import demand by all other regions *s*:

$$y^{e}_{i,r} \quad \geq \quad \sum_{s} x^{ma}_{i,r,s} \qquad \perp \qquad p^{e}_{i,r} \geq 0 \qquad \forall i,r \tag{36}$$

The price of the import composite is established by the supply of the composite and the demand by the aggregation of domestic and imported commodities:

$$y^{ma}_{i,r} \quad \geq \quad x^{m}_{i,r} \qquad \perp \qquad p_{i,r}{}^{ma} \geq 0 \qquad \forall i,r \tag{37}$$

All region demand international transport services which are supplied by the international transport pool:

$$y^{t}_{i} \quad \geq \quad \sum_{j,r,s} x^{mt}_{i,j,r,s} \qquad \perp \qquad p^{t}_{i} \geq 0 \qquad \forall i \tag{38}$$

4.2.2.6 Carbon restrictions

In the counterfactual simulation, upper bounds on CO_2 emissions are implemented. The emission factor $\beta_{i,j}$ ($\beta_{i,RA}$) determines CO_2 emissions caused by using one unit of input *i* in sector *j* (by the representative agent). Each region is characterized by an upper emission bound $emax_r$. If emission trading takes place at a national level, the carbon price is region specific and determined by an additional market clearing condition:

$$emax_r \quad \geq \quad \sum_{i}\left[\beta_{i,RA}C_{i,r} + \sum_{j}\beta_{i,j}x_{i,r,r}\right] \qquad \perp \qquad pcarb_r \geq 0 \qquad \forall r \tag{39}$$

where $pcarb_r$ is the regional emission allowances price, or likewise the regional uniform tax on CO_2 emissions.

On the other hand, if international emission trading takes place, the emission price is uniform across regions and the associated market clearing condition becomes:

$$\sum_{r} emax_r \quad \geq \quad \sum_{i,r}\left[\beta_{i,RA}C_{i,r} + \sum_{j}\beta_{i,j}x_{i,r,r}\right] \qquad \perp \qquad wcarb \geq 0 \tag{40}$$

where *wcarb* is the international emission allowances price. Generally, all intermediate forms between the two extreme cases are possible by portioning the regional set, indicating which region is part of international trade, and the set of sectors, declaring which sector is part of national or international emission trading.

The income of carbon regulation accrues to governments. Furthermore, the provision of public goods is assumed to be constant. Consequently, the question of revenue recycling arises. In this chapter, revenues are generally recycled lump-sum. Therefore, the direct transfers from governments to the representative agents are adjusted such that governments' budget restrictions become binding.

4.2.3 Specification

4.2.3.1 Model dimensions

Table 3 defines the dimensions of the model. Member states of the European Union are explicitly represented while non-European countries are aggregated to a region of countries listed in Annex I of the United Nations Framework Convention on Climate Change (UNFCCC) and a rest of the world region. For each region, commodities most relevant for climate and energy policy analysis are modeled in detail, i.e. all energy commodities, energy intensive production, and refineries. To capture the effects of policies in the transport sector, an industrial transport sector combining air, water, road and rail transports and households' own provided transport are included. Modeling private transport requires a detailed representation of motor vehicle production. Other sectors are aggregated to agriculture production and a macro commodity representing manufacture and services.

Table 3: Model dimensions

Production sectors	Name	Regions	Name
Non-energy:		**EU15:**	
Energy intensive industries	EINT	Benelux	BEN
Macro (industries and services)	MAC	Denmark	DNK
Agriculture	AGR	Finland	FIN
Manufacture of transport equipment	CAR	France	FRA
		Germany	DEU
Energy:		Italy	ITA
Coal	COA	Poland	POL
Crude oil	OIL	Spain	ESP
Natural gas	GAS	Sweden	SWE
Electricity	ELY	United Kingdom	GBR
Refined oil and coke products	P_C	Western EU (Austria, Ireland, Greece, Portugal)	WEU
Transport:			
Industrial transport	TRN	Remaining Eastern EU	EEU
Primary factors:		**Other:**	
Capital	CAP	Annex I	ANI
Labor	LAB	Rest of the world	ROW
Natural resources	RES		

4.2.3.2 Functional forms

The utility function of the representative household (Figure 4) combines a CES aggregate non-energy and energy commodity consumption with household transportation at the top level. Allowing different substitution possibilities of energy and non-energy commodities, these commodity classes are separately aggregated. A CES function combines these aggregates. Both, non-energy and energy commodities are also combined using a CES function. Private transportation combines purchased industrial transport services with the household’s own supplied transport which consists of refined oils used as transportation fuels put together with cars and other transport input costs (e.g. repair and assurance services).

Figure 4: Utility function

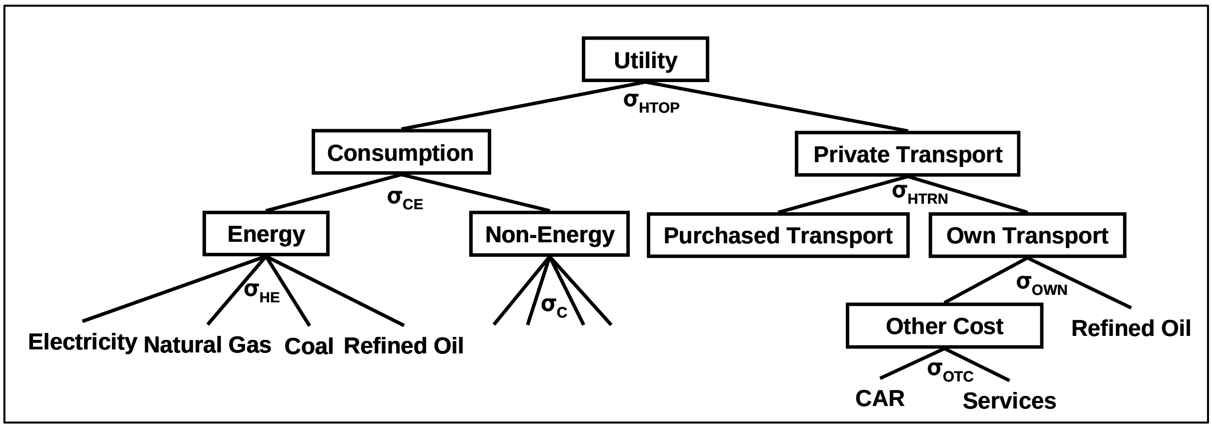
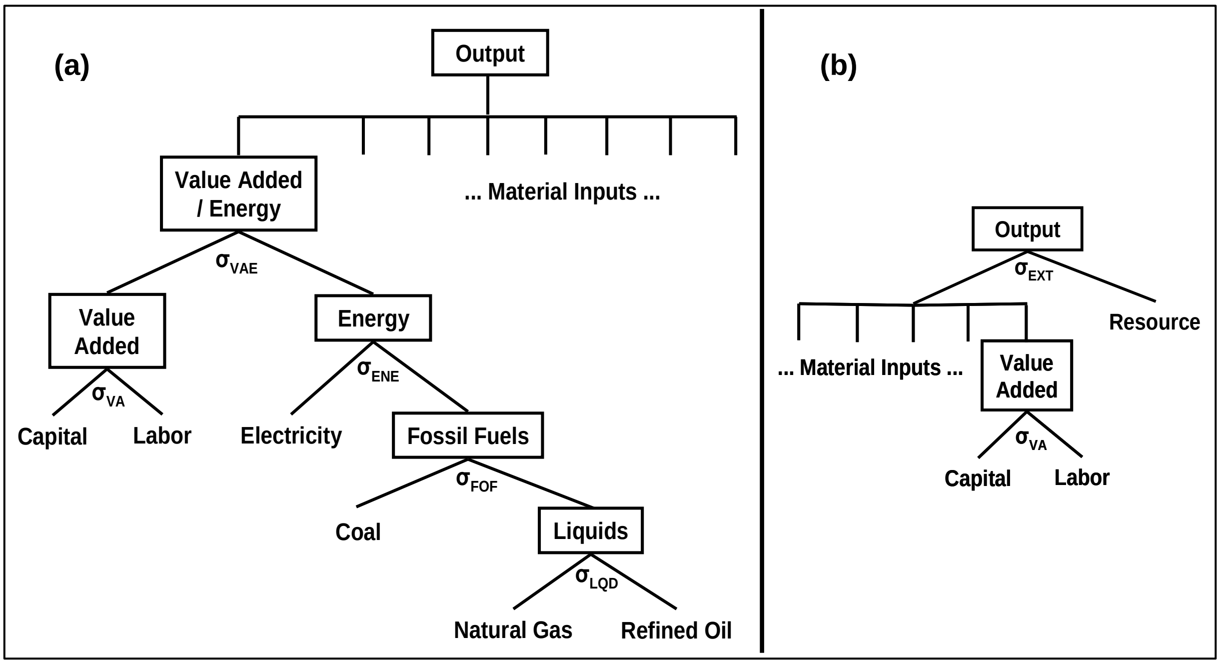


Figure 5 depicts the structure of production functions which are assumed to be equal for all sectors (Panel a) except for extractive industries (Panel b), i.e. coal, natural gas and crude oil extraction.

For non-extractive industries, a Leontief function is used at the top level, combining material inputs and a CES composite of a primary factor value added CES aggregate and an energy composite. The energy aggregate consists of electricity and fossil fuel energy which is a CES composite of coal and liquid fossil fuels (natural gas and refined oil). For all sectors and consumers fossil fuel inputs are associated with CO_2 emissions.

Extractive industries combine the sector specific natural resource and an aggregate of all other inputs at the top level using a CES function. The other inputs are a Leontief composite of materials and the primary factor value added aggregate.

Figure 5: Production functions (a) non-extractive and (b) extractive industries



4.2.4 Parameterization

4.2.4.1 Baseline data

The Global Trade Analysis Project (GTAP) database provides the basic data for the parameterization of the model (Dimaranan, 2006). The GTAP 6 database offers consistent social accounting matrixes for 87 regions including a detailed representation of European countries and 57 commodities based on the year 2001. These data are aggregated to the sectors and regions given above using the GTAP6inGAMS package (Rutherford, 2006). Given the database and normalizing market prices in the benchmark to one, the cost shares of the CES function are derived[31].

The GTAP 6 database does not represent household transport in a detailed way. Separating household transport expenditures out if the final consumption vector of the representative agent is done using the method developed by Paltsev et al. (2004a). Generally, households' transport expenditures (EXP_{trn}) consist of spendings on purchased transport services (EXP_{pur}) and on own provided transport (EXP_{own}):[32]

$$EXP_{trn} = EXP_{pur} + EXP_{own} \tag{41}$$

The GTAP 6 database identifies expenditures on purchased transport but those on own provided and total transport are unknown. However, total consumption expenditures (EXP_{total}) are also known from

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[31] The mapping from the regions and commodities provided by the GTAP 6 database to the model dimensions is given in Appendix A.

[32] For the ease of notation the index for regions is dropped.

the GTAP 6 database. Therefore, given the share of total transport spendings in total consumption (*ES*) only own transport expenditures remain unknown and can be solved for using equation (41):

$$EXP_{own} = ES * EXP_{total} - EXP_{pur} \tag{42}$$

The total transport expenditure share (*ES*) is given in Table 4. It was derived from the European Budget Survey (Eurostat, 1999) by dividing the aggregated transport spending[33] by the sum of all expenditures. For aggregated European regions population-weighted averages are used with population data also from Eurostat (2008a). For non-European regions, the values of Paltsev et al. (2004) are employed.

Table 4: Parameters for household transport and emission calibration

	Emissions in 2001 (Mt)	Share of transport fuels in refined oil expenditure OS	Share of transportation in total consumption expenditure ES
Benelux	313.5	91.28%	10.16%
Denmark	52.7	99.74%	9.06%
Finland	59.8	68.96%	9.73%
France	397.3	77.42%	12.59%
Germany	866.8	84.79%	11.92%
Italy	447	92.33%	12.47%
Poland	297.5	90.20%	9.65%
Spain	307.8	91.91%	11.52%
Sweden	54.5	90.20%	5.99%
United Kingdom	550.9	97.62%	11.73%
Western EU	277.6	82.50%	12.19%
Eastern EU	418.6	90.20%	9.07%
Annex I	9988.9	85.50%	13.40%
Rest of the World	9798.4	90.00%	6.00%

Sources: Own calculations based on European Budget Survey (Eurostat, 1999), population data (Eurostat, 2008a), emission data (World Resource Institute, 2009); share parameter for non-European regions are adopted from Paltsev et al. (2004).

Having derived own provided transport expenditures, one has to split these into different cost categories. Generally, these costs consist of expenditures on cars (EXP_{car}), fuel spendings (EXP_{fuel}), and other costs like insurance, maintenance, and services (EXP_{other}):

$$EXP_{own} = EXP_{car} + EXP_{fuel} + EXP_{other} \tag{43}$$

The GTAP 6 data directly give the expenditure on cars. Fuel spendings are part of the representative agent's refined oil consumption (CON_{p_c}) which consists of transport fuels and other refined oil uses (mainly heating). Applying the share of fuel expenditure in total refined oil consumption (*OS*) to the total refined oil spendings, transportation fuel purchases are derived ($EXP_{fuel} = OS * CON_{p\_c}$). Consequently, only the other costs remain unknown. These are derived residually by fulfilling equation (43) and part of the representative agent's consumption of the aggregated manufacture and service commodity:

$$EXP_{other} = EXP_{own} - EXP_{car} - OS * CON_{p\_c} \tag{44}$$

The share *OS* is also given in Table 4 and derived from the European Budget Survey by dividing transportation fuel expenditure (CP 0722) by the sum of liquid (CP 0453), solid (CP 0454), and transport fuels.[34] As above, for aggregated European regions population-weighted averages are used. Non-European regions' values are adopted from Paltsev et al. (2004).

The resulting cost shares are given in Table 5. The share of purchased transport is between 20 % and 35 %. For all European regions the share of transport fuels is higher than the share of the Annex I region indicating the higher taxes on transportation fuels in European.

Table 5: Cost shares in private transportation

	Purchased transport	**Fuel cost**	**Car purchases**	**Other costs**
Benelux	29.52%	19.00%	17.50%	33.97%
Denmark	32.96%	21.77%	6.18%	39.08%
Finland	36.73%	14.14%	7.60%	41.54%
France	20.13%	23.51%	27.26%	29.10%
Germany	24.46%	19.29%	37.14%	19.12%
Italy	23.47%	20.44%	19.84%	36.25%
Poland	24.84%	20.04%	22.11%	33.01%
Spain	32.99%	13.10%	16.33%	37.58%
Sweden	35.74%	37.30%	26.46%	0.51%
United Kingdom	30.33%	11.42%	17.21%	41.03%
Western EU	26.65%	19.63%	20.27%	33.45%
Eastern EU	30.96%	16.66%	23.57%	28.81%
Annex I	23.12%	6.41%	14.99%	55.48%
Rest of the World	49.00%	15.92%	15.85%	19.24%

Source: Own calculations

The used approach treats car purchases as a pure value flow. This is consistent with the treatment of most durable goods in national accounting practice. However, in reality, automobiles are stock commodities which provide a service flow to the consumers and depreciate over time. Adopting a

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[33] CP07 in the Classification of Individual Consumption by Purpose (COICOP).

[34] Taking solid fuels into account, a classification problem results: the GTAP 6 data report refined oil and coke oven products with a reverence to ISIC 23 (International Standard Industrial Classification). Since there exists no clear cut correspondence between these classifications, I decided to take solid fuels into account in the COICOP. For European countries the spending on solid fuels is small. Therefore the bias, in the estimate of the *OS* is negligible.

stock and service flow based approach requires estimating the service flow of automobiles as well as the implicit rental rate for cars. Such an approach is introduced in the next chapter.

Table 6 lists fuel taxes for transport. Excise taxes in Europe are at a high level. Except for the Benelux countries, fuel taxes in household transport are higher than in industrial transport. Compared to other European countries, Poland and the eastern EU have low taxes.

Table 6 also reveals the net export position in the world markets for fossil fuels and energy intensive products. Generally, the EU is net importer of all energy commodities and net exporter of energy intensive products. Annex I countries are net imports of crude oil and energy intensive products and exporters of natural gas and the major player in the global coal market. The rest of the world region is exporter of all products. It is the largest supplier of crude oil and natural gas. Within Europe, Poland is the only exporter of coal. Denmark and the United Kingdom are exporters of crude oil and natural gas. Germany is the pre-dominant supplier of energy intensive products followed by the Nordic countries Finland and Sweden.

Table 6: Net export positions and fuel taxes in the benchmark

	Net exports [billion $]				**Excise tax on transport fuels [%]**	
	Coal	Crude oil	Energy intensives	Natural gas	Industrial	Household
Benelux	-0.847	-10.491	1.109	0.417	510	320
Denmark	-0.238	1.188	-2.084	0.325	153	500
Finland	-0.219	-1.214	9.754	-0.496	251	317
France	-0.612	-10.542	-3.563	-3.994	307	676
Germany	-1.225	-12.869	11.300	-6.443	283	348
Italy	-0.748	-10.052	1.735	-5.066	341	510
Poland	0.781	-2.029	-0.415	-0.727	59	170
Spain	-0.650	-6.829	-1.493	-1.790	204	367
Sweden	-0.128	-2.315	9.484	-0.086	219	509
United Kingdom	-1.179	5.255	-9.773	1.298	275	368
Western EU	-0.480	-5.185	-2.685	-1.322	226	372
Eastern EU	-0.307	-4.078	-0.035	-3.319	78	116
EU	-5.851	-59.162	16.153	-21.202		
Annex I	3.662	-48.284	-29.488	7.606	31	112
Rest of the World	2.189	107.446	1.109	13.596	14	48

Source: GTAP 6 database

4.2.4.2 Substitution elasticities

Fully specifying the CES function requires to take assumptions on the elasticities of substitution. On the production side, the nesting structure is identical to the one used in Böhringer and Rutherford (2002b). Therefore, their values are adopted. However, the values used in the MIT EPPA model (Paltsev et al., 2005a) or the GTAP energy model (Burniaux and Truong, 2002; Truong et al., 2007) do not substantially differ. Generally, substitution elasticities in production show homogeneity in environmental/energy oriented CGE models. In extractive industries (coal, natural gas, crude oil) the top level elasticity between the sector specific natural resource and the material/value added composited is calibrated to meet price elasticities of supply (Rutherford, 2002: Böhringer and Rutherford, 2002b).

While the used elasticities for energy, value-added, and intermediate input substitution show some homogeneity across the environmental oriented CGE literature, elasticities for private transport are rarely available. Paltsev et al. (2005b) use a value of 0.5 for the substitution between private transport and consumption (σ_{HTOP}). This value is expected to have a significant influence on the impact of transport policies since a higher value means that transport can be substituted by more consumption. Steiniger et al. (2007) calibrated this elasticity together with the elasticity between own and purchased transport (σ_{HTRN}) for a small open economy CGE model for Austria using a mode choice passenger transport model. They use a value of 0.275 for the substitution elasticity between aggregated consumption and private transport. In the core simulation Paltsev et al.'s (2005b) value of 0.5 is adopted and sensitivity is examined afterwards.

Table 7: Substitution and transformation elasticities

	Description		**Value**
	Production elasticities		
ENE	Electricity / fossil fuels		0.3
EXT	Sector specific resource / other inputs in extractive industries; calibrated to supply elasticities	Coal	0.5
		Crude oil	1
		Natural gas	1
FOF	Fossil fuels		0.5
LQD	Liquid and gaseous fossil fuels		1
VA	Labor / capital		1
VAE	Energy / value-added		0.8
	Household elasticities		
C	Non-energy consumption goods		0.5
CE	Energy / non-energy commodities		0.25
HE	Coal / electricity / natural gas / refined oil products		0.4
HTOP	Consumption / transport		0.5
HTRN	Own supplied / purchased transport		0.2
OTC	Motorized vehicles / other transport costs		0.5
OWN	Gasoline / other transport costs – motorized vehicles		~ 0.33
	Trade elasticities		
DM	Domestic / imported commodities		
		Non-electricity commodities	2.5
		Electricity	0.3
MM	Imports from different regions		
		Non-energy goods	5
		Fossil fuels	4
		Refined oil products	6
		Electricity	0.5
	Transformation elasticities		
OUT	Domestic / exported commodities		2

The substitution elasticity between own provided and purchased transport relates to the choice between private and public transport modes. While Paltsev et al. (2005b) use a low value of 0.2 Steiniger et al. (2007) calibrate a value of 0.635. The low value is adopted and implications of parameter changes are explored later on.

The elasticity between the other cost (cars and other transport cost) nest and refined oils for transportation (σ_{own}) expresses households' behavioral response to changing fuel prices. In general, there are two different possibilities to react on fuel price changes: changes in kilometers driven and switching to more fuel efficient cars. Denoting fuel consumption depending on the fuel price as $FUEL(p_{fuel})$, fuel demand can be expressed as:

$$FUEL\left(p_{fuel}\right) = EFF\left(p_{fuel}\right) KM\left(p_{fuel}\right) \tag{45}$$

$EFF(p_{fuel})$ is the energy efficiency of cars in liter per kilometer and $KM(p_{fuel})$ are kilometers driven. Taking logarithmic differentials with respect to the fuel price yields:

$$\frac{p_{fuel}}{FUEL}\frac{\partial FUEL}{\partial p_{fuel}} = \frac{p_{fuel}}{EFF}\frac{\partial EFF}{\partial p_{fuel}} + \frac{p_{fuel}}{KM}\frac{\partial KM}{\partial p_{fuel}} \tag{46}$$

Therefore, the price elasticity of fuel demand (η_{fuel}) is equal to the sum of the price elasticity of energy efficiency (η_{EFF}) and the price elasticity of kilometers driven (η_{km}).

$$\eta_{FUEL} = \eta_{EFF} + \eta_{KM} \tag{47}$$

Having determined the price elasticity of fuel demand, the substitution elasticity between other costs and transport fuels can be approximated as (Hyman et al., 2002):

$$\sigma_{OWN,r} = -\frac{\eta_{FUEL}}{1-\theta^{OWN}_{P\_C,HTRN,r}} \tag{48}$$

Schäfer and Jacoby (2005, 2006) use the MIT EPPA model together with a mode choice (Schäfer and Victor 1999, 2000) and the MARKAL bottom-up model (Loulou et al., 2004) analyzing the impacts of climate policies in the transport sectors on the diffusion of vehicle technologies. In this hybrid model, the aggregated household transport demand is calculated in the MIT EPPA model and passed to the MARKAL model. The MARKAL model determines the mix of vehicle technologies and subsequently the fuel demand for private transportation. Fulfilling the equilibrium conditions in EPPA requires consistency between the fuel demand of MARKAL and the EPPA mode. This consistency is achieved by adjusting the substitution elasticity between transport fuels and other inputs (σ_{OWN}) over time. Since MARKAL only takes technology shifts into account, the procedure implicitly assumes that the price elasticity of kilometers driven is zero. Thus, their price elasticity estimate of around -0.126 can be taken as value for the price elasticity of energy efficiency. Again, since only technology shifts are taken into account, the value can be considered as a low estimate since changes in driving behavior which influence energy efficiency (e.g. slower driving, pressure, more maintenance) are neglected. Greene et al. (1999) estimate the long-term response of kilometers driven to fuel price changes (η_{KM}) for the US. They provide values in the range of -0.2 to -0.3. Together with the MARKAL estimate by Schäfer and Jacoby (2005, 2006) a price elasticity of fuel demand between -0.3 and -0.4 is implied. This is in line with econometric estimates of the price elasticity of fuel demand surveyed by Graham and Glaister (2002). For the core simulation a value of -0.3 is used. The resulting substitution elasticity σ_{OWN} is in the range of 0.31 to 0.37. This similarity between the price and substitution elasticity is caused by the relatively small cost share parameter in equation (48). Sensitivity of the model to changes in this parameter will be performed below.

In the *other cost* nest the substitution elasticity between car purchases and other costs like maintenance and assurances is set to 0.5 following Paltsev et al. (2004).

4.2.4.3 Emissions

The GTAP 6 database offers physical energy flows to the corresponding value flows of fossil fuels. These data are used to derive the sectors' carbon emissions, i.e. the carbon coefficients. This is done by deriving the sectors' emission applying the Tier 1 method (IPCC, 2006). The physical energy flows are multiplied by emission coefficients as given in the IPCC guideline (Table 8). Since for refineries fossil fuel inputs are mainly transformation inputs, emissions of the refined oil sector need to be corrected. Energy consumption, transformation, and production tables as provided by Eurostat (2008b) imply that approximately 7% of the energy input into refineries is used for combustion. This value is employed uniformly for all regions to correct refineries' emissions.

Table 8: Emission coefficients in [t/TJ]

	Sectors/household	**Transport sectors**
Coal	101	
Natural gas	56.1	
Refined oil	79.2	67.5

Source: IPCC 2006

The TIER 1 method only delivers approximate values of a sector's emissions since different production technologies and fuel qualities are not taken into account. Therefore, emission coefficients are adjusted meeting the historical emissions of regions in the base year 2001 as given by the World Resource Institute (2009). The historical emission levels are given in Table 4.

4.3 Simulations and results

4.3.1 Policy scenarios

In all scenarios European regions are obliged to fulfill nominal emission targets as given by the *effort sharing agreement* (EC, 2009a). Table 9 lists the reduction requirements by countries and shows that all western European countries have to reduce emissions while the Eastern countries are allowed to increase emissions. Remaining Annex I countries are assumed to reduce their emissions by 5%. Non-Annex I countries do not conduct mitigation efforts. While the structure of the imposed carbon regulation differs for European regions depending on the scenario, Annex I countries comply with their reduction target using national emission trading, i.e. under the assumed absence of emission trading among Annex I countries, and the EU, the strategy adopted is cost efficient.

Table 9: Reduction requirements

Region	Reduction (% vs benchmark)	Region	Reduction (% vs benchmark)
Benelux	16	Spain	10
Denmark	20	Sweden	17
Finland	16	United Kingdom	16
France	14	Western EU	10
Germany	14	Remaining Eastern EU	-15
Italy	13		
Poland	-14	Annex I	5

Two groups of scenarios are analyzed: the introduction of the EU ETS and different approaches regulating the emissions of transport. Table 10 gives an overview on the scenario settings.

The first group examines the effect of increasing flexibility in European emission abatement and provides the references for further analysis. In the SECTORAL scenario, European regions fulfill their reduction requirements using carbon taxes differentiated by sector. For every sector, the respective region’s total mitigation requirement is assigned. The NATIONAL scenario increases flexibility allowing emission trading across sectors within a region but not across Europe. This results in a region wide uniform emission allowances price which can also be interpreted as a uniform carbon tax.[35] Flexibility is further increased in the FULL scenario by allowing additional emission trade across Europe. The ETS scenario examines the impacts of the introduction of the European emission trading system. Electricity producers, energy intensive industries, and refined oil sectors trade emission allowances across Europe. Other sectors are subject to a national uniform carbon tax. Compared to the NATIONAL scenario the introduction of the EU ETS has two counteracting effect. On the one hand, flexibility is increased by allowing partial trade of permits across Europe. On the other hand, the partition of the emission budgets restricts flexibility by preventing trade between sectors regulated under the EU ETS and others. Partition of emission budget poses the question of how many permits should be allocated to the emission trading sectors. It is assumed that countries with positive reduction requirements split the emission budget according to the NATIONAL scenario.[36] I.e. governments provide emission allowances for the emission trading sectors equal to the emissions generated by theses sectors in the NATIONAL scenario. Countries with negative reduction requirements do not face a reduction burden. Consequently, their emission reductions in the NATIONAL scenario are less or equal to zero. These countries allocate their total excess allowances budget to the EU ETS maximizing the gain from being part of the emission trading system. Put differently: these countries cap the emissions of the non-trading sectors at the benchmark level and allocate the remaining budget to the EU ETS.

The second group of scenarios examines regulation approaches for emissions of the transport sectors. All scenarios in this group build on the ETS scenario. The emission budget of transport is always assigned according to the emissions caused by transport in the NATIONAL scenario. Three different variants are considered.

ETS CLOSED TRN establishes a closed emission trading system for transport sectors. I.e. industrial and household transport sectors are allowed to trade emissions across Europe but not with the emission trading sectors or the national trading schemes. The scenario can be interpreted as a European wide, uniform carbon tax in the transport sector which is set on top of pre-existing national fuel taxes.

ETS TRN includes transport sectors into the EU ETS. Consequently, the emission budget of the EU ETS is changed by adding transport emissions caused in the NATIONAL scenarios.

In ETS EXEMPT TRN transport sectors are exempted from carbon regulation. If transport is exempted the reduction burden must increase elsewhere in the economy. Accordingly, the reduction burden of the emission trading scheme is increased.

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[35] All carbon prices are derived using quantity restrictions ensuring equal ecological efficiency in all scenarios. The resulting emission prices can always be interpreted as a carbon tax applied to all agents included in the respective trading scheme.

[36] Generally, the allocation of permits to the EU ETS depends on strategic consideration of the member states. Strategic partitioning of emission budgets under the EU ETS has been analyzed e.g. by Babiker et al. (2003) and Böhringer and Rosendahl (2009).

Table 10: Overview of scenario settings

Scenario	Regulation approach EU27
BAU	Benchmark equilibrium without carbon regulation
	Group A: Introduction of emission trading
SECTORAL	Carbon taxes differentiated by sector and region
NATIONAL	Uniform carbon tax within regions but not across sectors
FULL	Uniform carbon tax across Europe
ETS	European emission trading for electricity, energy intensive and refined oil production Other sectors are regulated by region specific carbon taxes
	Group B: Regulating transport emissions
ETS CLOSED TRN	Like ETS with additional closed European emission trading for transport
ETS TRN	Like ETS with transport included in European emission trading
ETS EXEMPT TRN	Like ETS with transport exempted from carbon regulation and reduction burden shifted to emission trading system

Welfare changes using the Hicksian equivalent variation (HEV) are adopted as measure for the gross cost of carbon regulation, i.e. the cost of the regulation without the benefit of improved environmental quality and preventing impacts of climate change. HEV is defined as the amount of money which needs to be transferred to the representative agents' benchmark income in order to make them indifferent between the benchmark and the counterfactual situation (e.g. Mas-Colell et al., 1995). Accordingly, a negative (positive) change in the HEV as compared to benchmark indicates a welfare loss (gain). Since the gross cost of carbon regulation does not include the benefit of improved environmental quality, the welfare changes are negative in all scenarios.

4.3.2 Group A: Introducing emission trading

Table 11 lists the welfare changes for scenario group A differentiated by regions. Carbon prices and compliance costs are listed in Appendix A.

4.3.2.1 Sectoral regulation

The SECTORAL scenario imposes the reduction requirements separately on each sector. The welfare loss for the European region in total becomes 1.13 % and the total compliance cost for Europe are around 22.3 billion $.[37]

Welfare impacts on European countries with positive reduction requirements are in the order of around 0.6 (Western EU) to 1.9 % (Benelux). Generally, the results show correlation with the imposed mitigation requirements, i.e. a lower reduction burden implies lower gross cost carbon mitigation.

The carbon prices indicate the marginal abatement cost of different sectors. For all countries these are the highest for household own provided transport followed by industrial transport and refined oil production. The lowest marginal abatement costs always occur in electricity generation.

Countries with negative or no carbon reductions face a zero carbon price. Nevertheless, their welfare is affected in two ways. First, since their carbon price is zero, they gain a comparative advantage on the world market due to lower production costs. Second, carbon restrictions imply decreasing fossil fuel prices spilling over to non-abating countries. While the first effect is positive, the second depends on the net-trade position of countries, i.e. importers of fossil fuels gain from decreasing fossil fuel prices while exports suffer a terms-of-trade loss.

These effects explain the different effects on Poland and the remaining eastern EU region. Both regions are net-importers of energy intensive products in the benchmark. Due to the increased production cost in abating European countries they increase energy intensive production. In consequence, the remaining eastern EU states become exporters. Additionally, this region is also a net-importer of fossil fuels and benefits from falling prices. In contrast, Poland is a net-exporter of coal. Due to the high carbon content of coal, it is the resource which is most affected by carbon policies, i.e. incurs the largest price decrease. Thus, Poland is negatively affected by the carbon policy. The fossil fuel price effect outweighs the positive effect of improved terms-of-trade in energy intensive production explaining the slightly negative welfare impact.

The same line of arguments is true for the rest of the world region. It increases domestic energy intensive production and reduces imports. On the other hand, it is the largest supplier of natural gas and crude oil. In consequence, the welfare impact is negative.

The Annex I region is the largest supplier of coal and the second largest supplier of natural gas. In all scenarios, the carbon price in this region is around 4.30 \$/t CO_2. As a large export of fossil fuels they are slightly negatively affected by abatement measures in the European region

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[37] All monetary units are measured in the benchmark currency, i.e. \$ in the year 2001.

Table 11: Welfare changes scenario group A [% HEV vs. BAU]

	SECTORAL	NATIONAL	FULL	ETS
Benelux	-1.90	-0.91	-0.34	-0.76
Denmark	-1.42	-0.60	-0.34	-0.43
Finland	-1.51	-0.54	-0.24	-0.49
France	-1.46	-0.71	-0.18	-0.65
Germany	-1.25	-0.33	-0.19	-0.30
Italy	-1.26	-0.47	-0.18	-0.38
Poland	-0.02	-0.06	0.59	0.36
Spain	-0.63	-0.14	-0.12	-0.13
Sweden	-1.63	-0.84	-0.26	-0.78
United Kingdom	-1.07	-0.34	-0.18	-0.27
Western EU	-0.60	-0.13	-0.12	-0.12
Eastern EU	0.12	0.12	0.93	0.65
EU 27	-1.13	-0.41	-0.13	-0.33
Annex I	-0.07	-0.06	-0.06	-0.06
Rest of the World	-0.15	-0.13	-0.09	-0.11

4.3.2.2 National uniform carbon prices

In the NATIONAL scenario, carbon prices are uniform across all sectors in a region but differ across regions. The total European welfare loss is around 0.4 % and the compliance cost are 9.3 billion \$. For European countries with positive reduction requirements the welfare loss is between 0.13 (Western EU) and 0.9 % (Benelux). Carbon prices are between 10.23 (Spain) and 43.24 \$/t CO_2 (Sweden). While Poland faces a slight welfare loss, the Eastern EU region incurs a slight gain. Both non-European regions suffer a welfare loss.

4.3.2.3 Full European emission trading

In the FULL scenarios all sectors in European regions are allowed to trade emission allowances across Europe. The total European welfare loss is 0.13 % and the compliance cost are 3.1 billion \$. The uniform European carbon price becomes 8.77 \$/t CO_2.

For countries with positive reduction requirements the welfare loss is between 0.12 % Spain, Western EU) and 34 % (Benelux, Denmark). The welfare of Poland and the Eastern EU significantly increases. These countries have negative reduction requirements. Accordingly, the introduction of European emission trading allows them to sell their excess emission budget to other regions. In fact, these are the only exporters of emission allowances.[38] Non-European regions suffer a slight welfare loss.

4.3.2.4 The European emission trading system

The ETS scenario partitions the emission budget. Electricity, energy intensive, and refined oil production are allowed to trade emissions across Europe while other sectors are only allowed to trade permits nationally. The total European welfare loss becomes 0.33 % and the compliance cost are 5.2 billion \$. The European emission allowances price becomes 6.16 \$/t CO_2.

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[38] Carbon trade results are given in Appendix A.

For countries with positive reduction burdens the welfare loss is between 0.12 (Western EU) and 0.78 % (Sweden). National carbon prices range between 10.81 (Western EU) and 46.73 \$/t CO_2 (Sweden). Countries with negative reduction requirements allocate their excess budget to the emission trading system. Consequently, they are able to export emission allowances and thus, incur a welfare gain. Since emissions of non-trading sectors are capped at the benchmark level, they have slightly positive domestic carbon prices. Again, non-European regions suffer a slight welfare loss.

4.3.2.5 Comparison

The ranking of the scenarios in terms of the European welfare loss is as expected. The SECTORAL scenario shows the highest welfare loss followed by the NATIONAL approach since NATIONAL emission trading increases the flexibility of carbon abatement. Put differently, domestic carbon trade equalizes the marginal abatement costs within regions.

Compared the NATIONAL scenario, the introduction of the EU ETS has two counteracting effects. On the one hand, flexibility is increased by allowing European trade of electricity, refined oil, and energy intensive production. On the other, flexibility is decreasing since trade across sectors is restricted by partitioning the emission budget. The results show that the positive effect of European trade prevails and European welfare improves. Remarkably, the welfare of all European countries improves, i.e. introducing the EU ETS under the effort sharing reduction requirements provides a Pareto improvement.[39]

Since the FULL European emission trading system removes the partition of the emission budget and allows fully flexible emission abatement across sectors and regions, it shows the lowest European welfare loss. Again, the result also establishes at the member state level.

While the Annex I region is nearly unaffected by European regulation approaches, the welfare of the rest of the world region improves with increasing flexibility of carbon abatement in Europe. Coal is the resource with the highest emission factor. Accordingly, it is always favorable to substitute the usage of coal by other energy resources. Increased flexibility in Europe also increases the substitution possibilities of coal usage. Consequently, demand for other energy resources increases. The rest of world region as the largest exporter of natural gas and crude oil benefits from this demand increase. This result can also be seen in the welfare effects for Poland in the SECTORAL and NATIONAL scenarios. Since Poland is an exporter of coal but importer of other resources, it is negatively affected of the increased carbon abatement flexibility of European regions.

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[39] This result depends on the imposed reduction burdens. Using reduction requirements of the Burden Sharing Agreement (EC, 2002), Böhringer (2002) shows that the introduction of full emission trading across Europe does not provide a Pareto improvement. In his study, for some countries (Germany, Austria, France) the loss in comparative advantages in energy intensive production induced by equalization of carbon prices overbalances the positive effect of equalized marginal abatement cost.

4.3.3 Group B: Regulation of transport emissions

The second scenario group analyzes different regulation approaches to the emissions caused by transport. The welfare results are listed in Table 12. As the results of this group are compared against the current EU ETS system, the welfare results of the ETS scenario are repeated in this table.

4.3.3.1 Closed emission trading for transport sectors

The scenario ETS CLOSED TRN introduces a closed emission trading system for transport sectors across Europe. Both, industrial and household transport, are allowed to trade allowances across Europe. However, trade with EU ETS sectors is not possible. This scenario can also be interpreted as a European wide carbon tax in the transport sector. Compared to the ETS scenario, the effects of this scenario group are threefold: First, flexibility is positively influenced by allowing allowances trade of transport sectors across Europe. Second, flexibility is negatively influenced by further restricting trade across national sectors exempting transport sectors from the national strategy. Third, the emission budget under the emission trading scheme alters. Countries with negative reduction requirements allocate permits to the transport system according to the NATIONAL scenario. Since they do not face a carbon restriction in this scenario, transport emissions are rising. Consequently, they allocate part of there excess budget to the transport trading system. Furthermore, since emissions of national sectors in these countries are capped at the benchmark level, the carbon budget of the EU ETS system necessarily decreases compared to the ETS scenario.

The total European welfare loss becomes 0.31 % which is only a slight improvement compared to the EU ETS system. Due to the lower emission budget under the EU ETS, the European allowances price is increasing by 3.65 to 9.81 \$/t CO_2. The carbon price in the transport trading system becomes 17.71 \$/t CO_2 indicating the higher marginal abatement cost in transport sectors.

Although the gross cost of regulation are slightly decreasing, total compliance cost in Europe increase by around 1.2 to 6.4 billion \$. The increase of compliance cost is due to a restriction of the flexibility of carbon mitigation which prevents equalization of marginal abatement cost across transport and other sectors under the national emission trading schemes which overbalances the increased flexibility by trade of transport sectors across Europe. However, refined oil in transport sectors is the commodity which shows the highest tax rate across all inputs. Consequently, the decrease in the carbon price for transport sectors reduces the tax interaction effect of carbon and transport taxes. This positive effect outweighs the negative effect of increasing compliance cost.

The effect can be seen at the member state level. Countries with high national taxes in the ETS scenario (Benelux, France, Italy, Sweden) gain, since for these countries the decline in the carbon price of transport is the highest and, thus the positive effect of reduced tax interaction. Furthermore, some of these countries also benefit from decreasing compliance cost. In contrast, countries with carbon taxes in the ETS scenario below or the carbon price in the transport sector (Germany, Spain, remaining west European countries) all incur a welfare loss, since tax interaction and compliance costs increase. Accordingly, the introduction of a closed emission trading system does not provide a Pareto improvement, i.e. some countries loose welfare while others gain compared to the ETS.

Non-European regions are unaffected by the introduction of the additional trading system.

Table 12: Welfare changes scenario group B [% HEV vs. BAU]

	ETS	ETS CLOSED TRN	ETS TRN	ETS EXEMPT TRN
Benelux	-0.76	-0.64	-0.44	-0.35
Denmark	-0.43	-0.45	-0.32	-0.28
Finland	-0.49	-0.45	-0.31	-0.24
France	-0.65	-0.45	-0.30	-0.22
Germany	-0.30	-0.33	-0.20	-0.13
Italy	-0.38	-0.35	-0.23	-0.17
Poland	0.36	0.34	0.44	0.53
Spain	-0.13	-0.22	-0.10	-0.03
Sweden	-0.78	-0.54	-0.36	-0.28
United Kingdom	-0.27	-0.29	-0.18	-0.13
Western EU	-0.12	-0.20	-0.11	-0.05
Eastern EU	0.65	0.41	0.73	0.86
EU 27	-0.33	-0.31	-0.18	-0.11
Annex I	-0.06	-0.06	-0.06	-0.05
Rest of the World	-0.11	-0.11	-0.10	-0.09

4.3.3.2 Including transport into the European emission trading scheme

The scenario ETS TRN includes transport into the ETS system. Consequently, the two largest emitters – transport and electricity generation – trade emissions across Europe. Therefore, flexibility of carbon mitigation is increased in the EU ETS compared to the ETS scenario. On the other hand, flexibility in national trading schemes decreases. Again, the scenario group comes in three variants distinguishing the effect of industrial and household transport under the EU ETS.

Compared to the ETS scenario the total European welfare loss significantly decreases to 0.18 %. Including transport has two positive effects. First, compliance costs are decreasing by 0.7 to 4.6 billion $, since transport sectors with high marginal abatement costs are allowed to trade emissions with the electricity sector which has the lowest marginal abatement costs. Reduction is shifted to the electricity sector, transport expands and compliance cost decrease.[40] In consequence, the European allowances price increases by 1.11 to 7.27 $/t CO_2.

Second, transport sectors in all regions except countries with negative reduction requirements face a lower carbon price than under the national carbon tax scheme. Consequently, tax interaction also inclines. Therefore, all of these countries incur a welfare gain. For countries with negative reduction requirements, tax interaction increases since the carbon price for transport is increasing in these countries compared to the EU ETS system. However, these countries also allocate more allowances to the emission trading system and increase the export of emission permits. Since furthermore the emission price is increasing, the positive effect of increased allowances export exceeds the negative

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[40] Carbon abatement of different sectors is given in Appendix A.

one of increased tax interaction. Therefore welfare of these countries also improves. Consequently, the introduction of transport provides a Pareto improvement for the European carbon policy.

Again, the effect on non-European countries is negligible.

4.3.3.3 Exempting transport from carbon regulation

The ETS EXEMPT TRN scenario analyzes the full exemption of transport from any carbon policy. Transport sectors are unregulated and the resulting reduction burden is shifted to EU ETS. Other sectors are still regulated under nationally uniform carbon taxes.

Compared to the ETS scenario, the loss in European welfare significantly decreases by 0.22 to 0.11 %. Remarkably, welfare even improves compared to the FULL scenario, which implements full flexibility of carbon mitigation by allowing trade across all sectors and European countries and showed a welfare loss of 0.13 %.

Compared to the ETS scenario compliance costs are decreasing by 0.5 to 4.8 billion $. The decrease of the compliance cost is explained by the increased reduction burden in the EU ETS. In the ETS case, all countries with positive reduction requirements have higher national carbon prices. Since the increased abatement effort in the EU ETS increases the allowances price by 1.94 to 8.10 $/t CO_2, carbon prices getting closer to uniform across sectors. Consequently, the marginal abatement cost are closer to uniform and cost efficiency is improved. Countries with negative reduction burdens again gain by the increase in the emission price since they are exporters of permits. Put differently, shifting the reduction burden of the transport sector to the EU ETS system it is possible to reduce more emissions in the electricity at lower cost. Therefore compliance costs decrease.

The exemption of transport completely removes the interaction effect between transport taxes and carbon prices. Consequently, the positive effect of reducing the difference of effective carbon prices is maximized.

The exemption is Pareto optimal in the sense that all member states benefit compared to the ETS system.

The scenario also has an impact on the rest of the world region. The exemption of transport stipulates the use of transport fuels compared to the ETS scenario. Accordingly, the crude oil price increases. Since the rest of the world region is by far the largest exporter of crude oil, it incurs a welfare gain.

4.3.3.4 Comparison

Comparing the transport regulation approaches shows a clear-cut ranking in terms of welfare: The total exemption of transport improves welfare compared to the inclusion into the EU ETS which performs superior to the closed emission trading approach.

The improvement of emission trading under the EU ETS to the closed emission trading is caused by two positive effects. Flexibility of carbon abatement increases and therefore the compliance cost decrease. Furthermore since the carbon price for transport sectors is decreasing tax-interaction also decreases.

Comparing emission trading under the EU ETS to the full exemption of transport, the effects are counteracting. On the one hand, compliance costs in the ETS TRN case are lower, due to higher flexibility of carbon abatement. On the other, tax interaction is completely reduced. The positive effect of reduced interaction prevails explaining the welfare improvement.

4.3.4 Sensitivity analysis

Substitution elasticities used in production function show homogeneity across the environmental, energy related modeling literature. However, elasticities in the household own provided transport module and the elasticity between aggregated consumption and transport are uncertain. Therefore the impact of these elasticities is examined by solving the model under different values.

The central value of the substitution elasticity between aggregated consumption and household transport used in the core analysis was 0.5. The sensitivity of the model results to a change of this elasticity is examined by varying its value between zero and one. The resulting welfare changes in the mains scenarios (ETS, ETS TRN, ETS CLOSED TRN, ETS EXEMPT TRN) are listed in Appendix A and shows that the model results are insensitive altering the elasticity. The same is true for the elasticity between fuel purchases and other transport cost.

Changing the elasticity between household own provided and purchased transport also does not influences the results in the core scenarios. While this might come as a surprise, it can be explained by the fact that the main scenarios do not differentiate between carbon regulation in industrial and household transport. Therefore, both face the same carbon price. Consequently, relative prices are hardly affected and no substitution occurs.

The magnitude to welfare effects reacts sensitive to a change in the elasticity of fuel demand. However, the qualitative implications are unaffected, i.e. the welfare ranking between imposed policy measures remains stable.

4.4 Conclusion

This chapter employs a multi-region top-down computable general equilibrium model analyzing the effect of different approaches to carbon mitigation in the transport sector. The GTAP 6 database augmented by European data needed to model household transport provides the data necessary to calibrate the model. Three different policy approaches for the transport sector are tested: i) a closed emission trading system beside the EU; ii) the inclusion of transport into the EU ETS; and finally, iii) the full exemption of transport from carbon regulation increasing the reduction burden in the EU ETS.

A closed emission trading system for transport only provides small welfare gains. Furthermore, the political feasibility of introducing such a system is in doubt since it does not provide a Pareto improvement on the member state level.

Both, transport under emission trading and the full exemption of transport, lead to the reduction of the gross cost of carbon regulation. Independently on which approach is chosen, it is possible to shift abatement to the electricity sector which has the lowest marginal abatement costs. Therefore, European cost of compliance with the reduction requirements decrease. Moreover, both approaches provide Pareto improvements on the member state level indicating good political feasibility.

The exemption of transport from carbon regulation shows lower welfare losses than the inclusion into the EU ETS due to high taxes on transport fuels in the benchmark equilibrium. These taxes interact with carbon prices in the transport sector leading to negative welfare impacts. Since the exemption of transport leads to transport carbon taxes of zero, the negative tax interaction effect vanishes. In consequence, the gross costs of carbon mitigation are even lower than in a situation where carbon abatement is fully flexible across Europe and sectors.

However, the model employed in this chapter does not account for externalities in an explicit way. As outlined, transport externalities other than global warming justify a higher tax on transport fuels to internalize external effects auch as congestion, accidents, and noise. Therefore, neglecting these externalities, the model overestimates the beneficial effect of excluding transport from carbon regulation. Thus, congestion as the main externality of transport is explicitly included in the modeling framework in the next chapter.

5 Technology Rich CGE Model of Germany

5.1 Introduction

This chapter employs a small open economy model calibrated to the German economy in the year 2004. Although small open economy models have the disadvantage of abstracting from changes in the terms-of-trade assuming infinitely elastic world demand and supply, they have the advantage of modeling technological details. The model presented is designed to analyze the interaction between electricity generation and carbon measures in road transport, especially private transport. Accordingly, electricity production is represented by different generation technologies and accounts for different load segments. Private transport occurs by either using automobiles differentiated by fuel type or public transport modes. Accounting endogenously for the main externality of transport, congestion is included differentiated by travel period and road type.

The introduction of an emission trading between electricity generation, energy intensive industries, and refineries is analyzed. It is compared to the inclusion of road transport into the trading scheme, a separate fuel tax increase, and a full exemption of road transport from carbon regulation. Moreover, including air transport in the trading system is examined. A further scenario relates to the recycling of revenues raised by the introduction of emission trading increasing subsidies on private transport.

The results show that an increase in fuel taxation leads to large welfare losses. Also the inclusion of transport into emission trading does not provide welfare gains. However, the full exemption of transport and moving the reduction burden to the emission trading system decreases the gross cost of carbon regulation. Including aviation into the trading scheme is a favorable option. Using the income of carbon regulation to increase public transport subsidies shows the best performance of all scenarios.

5.2 Model description

5.2.1 Overview

The model is formulated as a mixed complementarity problem. Three classes of equilibrium conditions exist. No activity makes positive profits (zero-profit condition). Excess supply is positive (market clearing condition). Each household fulfils his budget restriction. Each class is associated to a class of variables. Activity levels are associated with zero-profit conditions. Prices are connected to market clearing equations. Each budget restriction determines the income level of the respective household.

The basic assumptions of the model are:

- The model is static.
- The economy is small compared to the world market, i.e. world market prices are fix and taken as given (small open economy assumption). Furthermore, the balance of payment deficit is fix.

- All markets are perfectly competitive, i.e. all agents take prices as given.
- Households' preferences are represented by a representative agent.
- There are two factors, capital and labor, which are intersectoral mobile but not international. Factors are inelastically supplied by the representative agent.
- The government imposes taxes to finance the provision of public goods which is assumed to be constant.
- Investment demand is constant.
- Production and utility functions are represented by separable nested CES functions.
- Electricity generation is represented by discrete generation technologies.
- Locations of production plants and the representative household are exogenous and fix.

5.2.2 Algebraic description

5.2.2.1 Representative agent

The representative agent (RA) derives utility out of commodity consumption $x_{i,RA}$, leisure, and leisure trips tr_m^l using the different transport classes m according to the utility function U(.).[41] Beside leisure trips, trips complementary to labor tr_m^L need to be financed. However, these trips do not yield utility. Since labor is inelastically supplied, the total number of work trips also needs to be constant and is given by TRL. One trip requires the purchase of commodity ($x_{i,m}^l$, $x_{i,m}^L$) and additionally a certain time requirement, $\delta_m(Z)$ which depend on the congestion index Z.[42] Modeling the emissions of private road transport in detail, a special treatment is given to private road transport trips tr_v^l and tr_v^L which are performed using different vehicle types v. Each of theses trips requires input of durable automobiles VEH_v and variable inputs $x_{i,v}^{var}$. The representative agent is endowed with the stock of vehicles VEH_v^{stock} and is able to buy new cars on the market purchasing commodities $x_{i,v}^{new}$. The function $V(x_{i,v}^{new})$ determines the composition of commodities required for new cars and the function $D(VEH_v, x_{i,v}^{var})$ expresses the combination of vehicles and variable cost. This approach of distinguishing between durable commodities and their associated necessary cost producing the service of the durable good, is based on the theoretical work of Conrad and Schröder (1991).

Beside a (possibly negative) transfer from the government (*trans*), the household receives income from selling capital K (labor L) at price p_K (p_L). If the restriction on the technological potential of an electricity generation technology g becomes binding, the representative agent earns the price $ppot_g$ on that potential which is the rent on scarce potential. Income is spend to finance commodity purchases and investment demands inv_i which are assumed to be constant.

Commodity consumption is taxed at rates $t_{i,RA}$ and market prices are denoted as p_i. Commodities used for transportation, are taxed at different rates $t_{i,m}$. Furthermore, capital and labor income is taxed at

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[41] The approach to include leisure and time allocated to transport is based on the theoretical work of Becker (1965) and subsequent research. A survey of the theory of time allocation is given in Bruzelius (1979).

[42] The time requirement for a trip is always to the minimum trip time required. Therefore, travel is a non-lesire commodity in the terminology of deSerpa (1971).

rates t_K and t_L, respectively. The fleet of existing cars is taxed depending on the car technology at rate t_v. The utility maximization problem of the household is given as:

$$
\begin{array}{lcl}
\multicolumn{3}{l}{\max\limits_{\substack{x_{i,RA},x_{i,m}\geq 0\\ x^{new}_{i,v},x^{var}_{i,v}\geq 0\\ tr^{l}_{m},tr^{L}_{m}\geq 0\\ tr^{l}_{v},tr^{L}_{v}\geq 0}} U\left(x_{i,RA},tr^{l}_{m},tr^{l}_{v},l\right)} \\
\multicolumn{3}{l}{\text{s.t.}} \\
\multicolumn{3}{l}{\left(1-t_K\right)p_K K+\left(1-t_L\right)p_L L} \\
+trans+\sum\limits_{g} ppot_g pot_g & \geq & \sum\limits_{i}\left(1+t_{i,RA}\right)p_i x_{i,RA}+\sum\limits_{i} p_i inv_i \\
 & & +\sum\limits_{i,m}\left(tr^{l}_{m}+tr^{L}_{m}\right)\left(1+t_{i,m}\right)p_i x_{i,m} \\
 & & +\sum\limits_{i,v}\left[\left(1+t_{i,v}\right)p_i x^{var}_{i,v}+\left(1+t_{i,v}\right)p_i x^{new}_{i,v}\right] \\
 & & +t_v\left(VEH_v\right) \\
T & \geq & l+\sum\limits_{m}\left(tr^{l}_{m}+tr^{L}_{m}\right)\delta_m\left(Z\right) \\
\sum\limits_{m} tr^{L}_{m}+\sum\limits_{v} tr^{L}_{v} & = & TRL \\
VEH_v & = & VEH^{Stock}_{v}+V\left(x^{new}_{i,v}\right) \\
D\left(VEH_v,x^{var}_{i,v}\right) & \geq & tr^{l}_{v}+tr^{L}_{v}
\end{array}
\qquad (49)
$$

The first constraint is the budget restriction, the second the time constraint, the third holds labor trips constant and the last two are definitions. Solving the problem under given prices yields the demand functions of the representative agent which are denoted by $C_i(inc)$ where *inc* is the income defined by the left hand side of the budget restriction.[43]

5.2.2.2 Production

Each production sector *i* produces one commodity which can either be sold at the domestic price p_i^d or at the export price p_i^e. The quantities supplied are denoted by y_i^d and y_i^e, respectively, intermediate and factor inputs by $x_{j,i}$, $x_{K,i}$, and $x_{L,i}$, and the activity level by y_i. Taxes are imposed on intermediate ($t_{j,i}$) and factor inputs ($t_{K,i}$,$t_{L,i}$) and on outputs (to_i). Tax inclusive input prices are denoted by $q_{j,i}:=(1+t_{j,i})p_j$, $q_{K,i}:=(1+t_{K,i})p_K$, and $q_{L,i}:=(1+t_{L,i})p_L$, and output prices by $v_i^d:=(1-to_i)p_i^d$ and $v_i^e:=(1-to_i)p_i^e$. Imposing separability of inputs and output and constant returns to scale, the unit cost (c_i) and revenue functions (r_i) can be independently determined from the given production function yielding the profit maximization problem for non-electricity production sectors:

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[43] For the ease of notation, price dependency of demand functions is not explicitly stated. Furthermore, commodity demand also depends on the congestion index.

$$\max_{y_i \geq 0} \; r_i\left(v_i^d, v_i^e\right) y_i - c_i\left(q_{j,i}, q_{K,i}, q_{L,i}\right) y_i \qquad \forall i \backslash \{\text{electricity}\} \tag{50}$$

Solving the problem under given prices results in the firm's zero-profit conditions which determine the optimal activity levels:

$$c_i\left(q_{j,i}, q_{K,i}, q_{L,i}\right) \quad \geq \quad r_i\left(v_i^d, v_i^e\right) \quad \perp \quad y_i \geq 0 \qquad \forall i \backslash \{\text{electricity}\} \tag{51}$$

Given the optimal activity level, optimal input and output quantities can be derived using Shepard's lemma:

$$\begin{aligned} x_{j,i} &= \frac{\partial c_i}{\partial q_{j,i}} y_i & x_{K,i} &= \frac{\partial c_i}{\partial q_{K,i}} y_i & x_{L,i} &= \frac{\partial c_i}{\partial q_{L,i}} y_i \\ y_i^d &= \frac{\partial r_i}{\partial v_i^d} y_i & y_i^e &= \frac{\partial r_i}{\partial v_i^e} y_i & & \end{aligned} \tag{52}$$

The electricity sector is involved in two activities: electricity generation and an activity which represents overhead and transmission and distribution. Electricity generation is represented by different technologies *g*. The technological potentials pot_g restrict the use of technologies. The generation level of technology *g* is denoted as y_g^{GEN} and the associated price p_g^{GEN}. One unit of generation of technology requires $b_{i,g}$ ($b_{K,g}$, $b_{L,g}$) units of commodity *i* (capital, labor). Given the demand for electricity (x^{ELE}), the optimal generation mix is determined by minimizing the generation cost under the constraints that generation may not exceed the technological potential and that demand has to be fulfilled.

$$\begin{aligned} &\min_{y_g^{ELE} \geq 0} \sum_g \left[p_L b_{L,g} + p_K b_{K,g} + \sum_i p_i b_{i,g} \right] y_g^{GEN} \\ &\text{s.t.} \\ &\qquad pot_g \quad \geq \quad y_g^{GEN} \qquad \perp \quad ppot_g \geq 0 \qquad \forall g \\ &\qquad \sum_g y_g^{GEN} \quad \geq \quad x^{ELE} \qquad \perp \quad p^{ELE} \geq 0 \end{aligned} \tag{53}$$

The Lagrangian multiplier $ppot_g$, is the scarcity price of the technological potential. And p^{ELE} is the price of one unit electricity under the optimal generation mix.[44] Consequently, the constraints have the interpretation of market clearing conditions. If potential exceeds generation, the price is zero; if the

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[44] The prices are given in monetary per energy units. For example, if generation is measured in megawatt hours and prices are given in euro, the objective function is measured in euro and the constraints in megawatt hours. Consequently, the multipliers are given in euro per megawatt hour. This implies that the technological potential and total electricity demand are also given in megawatt hours.

potential is scarce, the constraint is binding and the price becomes positive. A similar interpretation is given for the demand constraint. However, the electricity price will never become zero as long as demand is positive since excess generation results in excess cost which contrasts the objective of cost minimization. The general equilibrium concept of circular value flows requires determining the supply of the technological potential and electricity demand. Thus, the potential is added to the representative agent’s endowment. Physical electricity demand is determined by the electricity sector (see below).

The first order condition of the optimization problem (53) is given as:

$$p_L b_{L,g} + p_K b_{K,g} + \sum_i p_i b_{i,g} + ppot_g \quad \geq \quad p^{ELE} \qquad \perp \qquad y_g^{GEN} \geq 0 \quad \forall g \tag{54}$$

Equation (54) is the zero-profit condition for generation technologies. Producing one unit of electricity yields revenues equal to the electricity price. Costs are determined by factor and commodity requirements and rents on scarce technological potential. If costs exceed revenues the technology makes losses and does not generate electricity. Otherwise the generation level becomes positive.

Given the optimal generation levels, the demand of technologies is given as:

$$x_L^{GEN} = \sum_g b_{L,g} y_g^{GEN} \qquad x_L^{GEN} = \sum_g b_{K,g} y_g^{GEN} \qquad x_i^{GEN} = \sum_g b_{i,g} y_g^{GEN} \tag{55}$$

The electricity sector combines factor and commodity demands for overhead and transmission and distribution with electricity generation. Thus, physical electricity produced flows from generation technologies to the electricity sector. Consequently, it produces the composite electricity commodity including generation and overhead and transmission and distribution cost. The rest of the economy demands this composite, i.e. pays a price sufficient to cover generation costs as well as the cost for other activities. Therefore, the profit optimization problem of the electricity sector and the corresponding zero-profit condition become:

$$\max_{y_i \geq 0} \; r_i\left(v_i^d, v_i^e\right) y_i - c_i\left(q_{j,i}, q_{K,i}, q_{L,i}, p^{ELE}\right) y_i \qquad i = \{electricity\} \tag{56}$$

$$c_i\left(q_{j,i}, q_{K,i}, q_{L,i}, p^{ELE}\right) \quad \geq \quad r_i\left(v_i^d, v_i^e\right) y_i \qquad \perp \qquad y_i \geq 0 \qquad i = \{electricity\} \tag{57}$$

The commodity and factor demand functions are equivalent to those stated in equation (52). Physical electricity demand is given as:

$$x^{ELE} = \frac{\partial c_i\left(q_{j,i}, q_{K,i}, q_{L,i}, p^{ELE}\right)}{\partial p^{ELE}} \tag{58}$$

5.2.2.3 International trade and government

Following Armington (1969), imported and domestic produced commodities are combined to the total available quantity on the domestic market a_i with a constant elasticity of substitution function.[45] The corresponding cost function is denoted $c_i^a(p_i^d, p_i^{im})$ and depends on domestic producer prices p_i^d and import prices p_i^{im}. The Armington sector sells the aggregate at the market price p_i. Consequently, the profit optimization problem becomes:

$$\max_{y_i^a \geq 0} \left[p_i - c_i^a \left(p_i^d, p_i^{im} \right) \right] y_i^a \tag{59}$$

The zero-profit condition, which determines the total availability of commodity *i*, is given as:

$$c_i^a \left(p_i^d, p_i^{im} \right) \quad \geq \quad p_i \qquad \perp \qquad y_i^a \geq 0 \tag{60}$$

The demand for domestic and imported commodities is derived using Shephard's Lemma:

$$x_i^d = \frac{\partial c_i^a \left(p_i^d, p_i^{im} \right)}{\partial p_i^d} \qquad\qquad x_i^{im} = \frac{\partial c_i^a \left(p_i^d, p_i^{im} \right)}{\partial p_i^{im}} \tag{61}$$

The public demand of the government is constant and given by G_i. Furthermore, the government finances the balance of payment deficit *(bop*), which is also assumed to be constant, and the transfer to the household. Demand is financed by the imposed taxes. Consequently, if tax revenues are changing, either the transfer or taxes need to be changed in order to balance the budget restriction of the government. This approach allows analyzing refinancing and revenue-recycling effects but neglects influences on the composition of public spending.

5.2.3 Market clearing conditions

The market price p_i is determined by the supply of the Armington commodity and the demand of all agents:

$$y_i^a \quad \geq \quad \sum_j x_{i,j} + x_i^{GEN} + C_i \left(inc \right) + G_i \qquad \perp \qquad p_i \geq 0 \tag{62}$$

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[45] A more sophisticated approach would be to specify an Armington aggregate for every agent in the economy. However, two problems arise. First, the models dimension increases. For example, if the number of commodities and production sectors is ten, it follows with one household and a government that twelve activities have to be modelled. Consequently, the number of Armington aggregates rises from ten to 120. Second and more important, reliable estimates of Armington elasticities differentiated by agent and commodity are not available.

Similar, the market clearing equations for factors are given as:

$$\begin{aligned} K &\geq \sum_i x_{K,i} + x_K^{GEN} && \perp p_K \geq 0 \\ L &\geq \sum_i x_{L,i} + x_L^{GEN} && \perp p_L \geq 0 \end{aligned} \tag{63}$$

Under the small open economy assumption, world market prices are constant. Furthermore, the balance of payments is assumed to be constant. Consequently, the sum of all exports evaluated at fix world market prices equals the sum of all imports at world market prices and the balance of payment deficit:

$$\sum_i \overline{p_i^e} y_i^e \geq \sum_i \overline{p_i^{im}} x_i^{im} + bop \quad \perp \quad p^{fx} \geq 0 \tag{64}$$

Upper bars denote constant world prices. The price p^{fx} is the current exchange rate which adjusts in order to fulfill the trade balance. The import and export prices faced by the economy's agent are connected to world market prices by the current exchange rate:

$$p_i^e = \overline{p_i^e} + p^{fx} \qquad p_i^{im} = \overline{p_i^{im}} + p^{fx} \tag{65}$$

Figure 6 summarizes the full algebraic model formulation:

Figure 6: Algebraic model formulation

Zero-profit conditions:

$$c_i\left(q_{j,i}, q_{K,i}, q_{L,i}\right) \geq r_i\left(v_i^d, v_i^e\right) \quad \perp \quad y_i \geq 0 \quad \forall i \backslash \{\text{electricity}\}$$

$$c_i\left(q_{j,i}, q_{K,i}, q_{L,i}, p^{ELE}\right) \geq r_i\left(v_i^d, v_i^e\right) \quad \perp \quad y_i \geq 0 \quad i = \{\text{electricity}\}$$

$$p_L b_{L,g} + p_K b_{K,g} + \sum_i p_i b_{i,g} + ppot_g \geq p^{ELE} \quad \perp \quad y_g^{GEN} \geq 0 \quad \forall g$$

Market clearing conditions:

$$y_i^a \geq \sum_j x_{i,j} + x_i^{GEN} + C_i\left(inc\right) + G_i \quad \perp \quad p_i \geq 0 \quad \forall i$$

$$K \geq \sum_i x_{K,i} + x_K^{GEN} \quad \perp \quad p_K \geq 0$$

$$L \geq \sum_i x_{L,i} + x_L^{GEN} \quad \perp \quad p_L \geq 0$$

$$\sum_i \overline{p_i^e} y_i^e \geq \sum_i \overline{p_i^{im}} x_i^{im} + bop \quad \perp \quad p^{fx} \geq 0$$

$$pot_g \geq y_g^{GEN} \quad \perp \quad ppot_g \geq 0 \quad \forall g$$

$$\sum_g y_g^{GEN} \geq x^{ELE} \quad \perp \quad p^{ELE} \geq 0$$

Income definition:

$$inc = \left(1 - t_K\right) p_K K + \left(1 - t_L\right) p_L L + trans + \sum_g ppot_g pot_g \quad \perp \quad inc \geq 0$$

5.2.4 Extension of the basic model

Analyzing the impact of carbon policies, the counterfactual simulations extend the model for quantity restriction on emissions. The CO_2 emission factor β_i specifies the carbon dioxide emissions resulting of consuming one unit of quantity i. Denoting the upper emission bound by *emax*, the emission restriction becomes:

$$\text{emax} \geq \sum_i \beta_i \left[\sum_j x_{ij} + x_i^{GEN} + C_i\left(inc\right) \right] \quad \perp \quad \text{pcarb} \geq 0 \qquad (66)$$

Equation (66) implicitly assumes that commodity consumption of the government does not emit carbon since government's demand G_i does not enter the right hand side. The complementary variable *pcarb* is the price of an emission permit which has to be paid by the respective consumer of the commodity. Consequently, the carbon restriction adds another market clearing equation to the model. Therefore, the owner of the emission endowment *emax* needs to be specified. It is assumed that the government owns the emission allowances and sells them to the firms and the representative agent. Thus, introducing carbon regulation creates revenues in the form of sold permits. Under the maintained assumption of constant public good provision, this gives rise to the question on how to recycle this additional income which will be described in the scenario definitions.

5.2.5 Specification

5.2.5.1 Model dimensions

Table 13 summarizes the model dimensions of the model. The two columns on the upper left identify the elements of the commodity and sector set *i* which are divided into three subclasses: non-energy, energy and transport commodities. Since the model is designed to analyze the interactions of carbon regulation approaches in the energy and transport market, non-energy commodities are chosen such that the most important sectors are represented (electricity, energy intensive production, and motor vehicle production). All fossil fuel energy sources, the refined oil, and transport sectors are explicitly represented. The road and other transport sector also includes provision of metro and tram services.[46] Other sectors are represented by industry classes which are aggregated along the NACE Rev. 2 (Eurostat, 2009) classification scheme. The two columns on the upper right of Table 13 define vehicle and generation technologies. Two vehicle classes are considered: diesel and gasoline cars. The model includes all electricity generation technologies used in Germany. The OTHER technology combines mainly biomass and generation from municipal waste. In order to allow for important technology switches resulting from carbon restriction, the most important future technologies which are not already used are included: offshore wind generation and carbon capture and sequestration (CCS) generation based on either natural gas or lignite.[47] The lower part of Table 13 shows the differentiation of transport trips. Five different transport modes are available for private transport: own private transport and public transport in form of trains, busses, metros and trams, or airplanes. Furthermore, a slow mode exists which only requires time input but no monetary cost. Since spatial characteristics are important to account for the substitutability of the different trips, a further set distinguishes between short and long distance trips. A trip above 500 km is classified to be long distance.[48] Modeling congestion, which is done for road trips – busses and own private road transport – the time dimension as well as the area of transport are important. Thus, trips are further classified by the transport periods, which are characterized by their congestion level, and the road network used. Road networks are characterized by different freeflow time requirements and congestion levels. Generally, urban streets have a lower freeflow speed than non-urban streets and are heavier congested.

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[46] It would by preferable to explicitly represent bus and metro and tram transport. However, the underlying SAM does not identify these production sectors and data allowing a disaggregation of the OTP are not available. Using the other road transport sector expresses the fact that choosing the model dimensions can not be done independently of the creation of the underlying empirical base.

[47] The CCS technology based on hard coal is more expensive than based on lignite (Wissel et al., 2008). Consequently, a hard coal technology is not included since cost minimization of the generator implies, that it would never penetratze the market in the presented framework.

[48] The distance classification is adopted from the underlying database.

Table 13: 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

5.2.5.2 Utility function and private transports

Figure 7 depicts the structure of the utility function. On the top level, leisure and commodity and transport consumption are combined. At the next stage leisure trips trade off against commodity consumption subdivided by non-energy and energy commodities. Consequently, utility is partly derived from leisure trips. In contrast, labor trips which are complementary to the labor supplied, do not spend utility.

Figure 8 shows the structure of private transport which combines trips of different distances at the top level. For every distance class, trips are aggregated according to the travel period occurring. Within a travel period, the consumer decides about transport modes which are characterized by monetary costs and time requirements which are combined using a Leontief function. For road transport modes (busses and cars), the additional choice between different road networks is implemented with a composite of the road types. Depending on the congestion level on the networks, the time input differs. The tree's structure expresses the assumption of equal speed levels of different vehicle classes, since time and monetary cost are aggregated for the composite of the different car classes. The latter are a composite of trips occurring on diesel or gasoline cars. Consequently, vehicle classes only differ by their monetary but not by their time cost. Following the approach of Koopman (1995) in the EUCAR model, I 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 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. According to de Jong (1991) the share of committed mileage in observed kilometers driven is around 65%.

Substitution elasticities are based on a literature review (Berg, 2007; Koopman, 1995; Mayeres, 1999; Munk, 2003, 2005; Paltsev et al., 2005a; de Ceuster et al., 2007) and are summarized in Table 14.

Table 14: 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

Figure 7: Utility structure

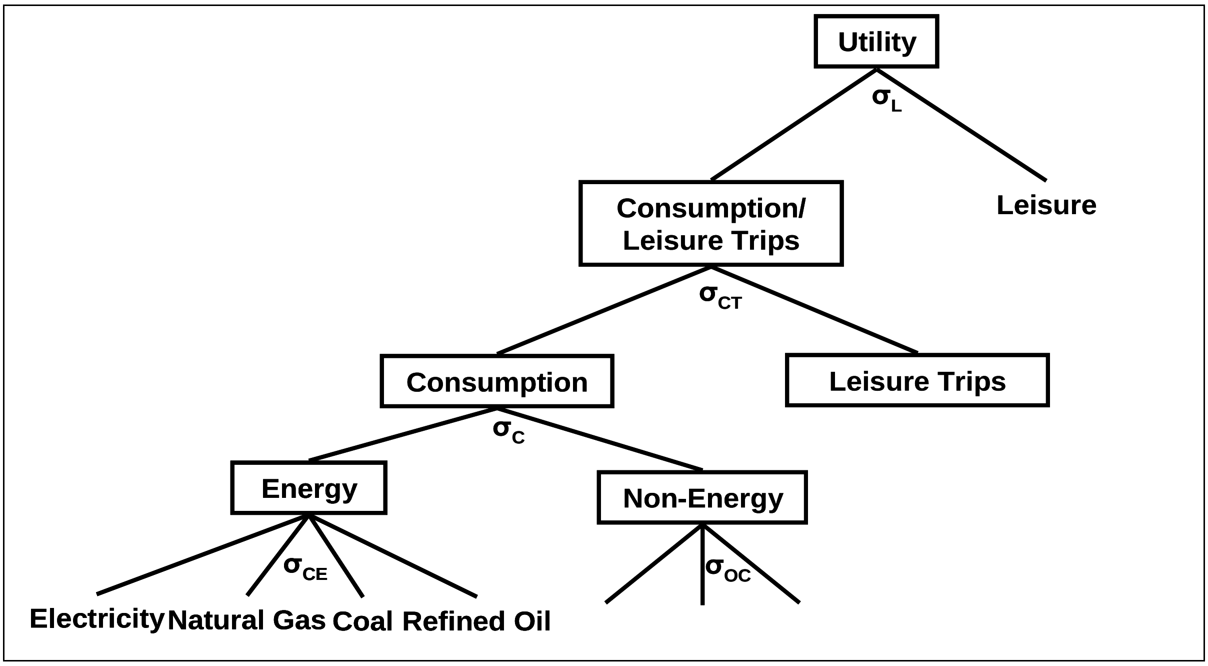
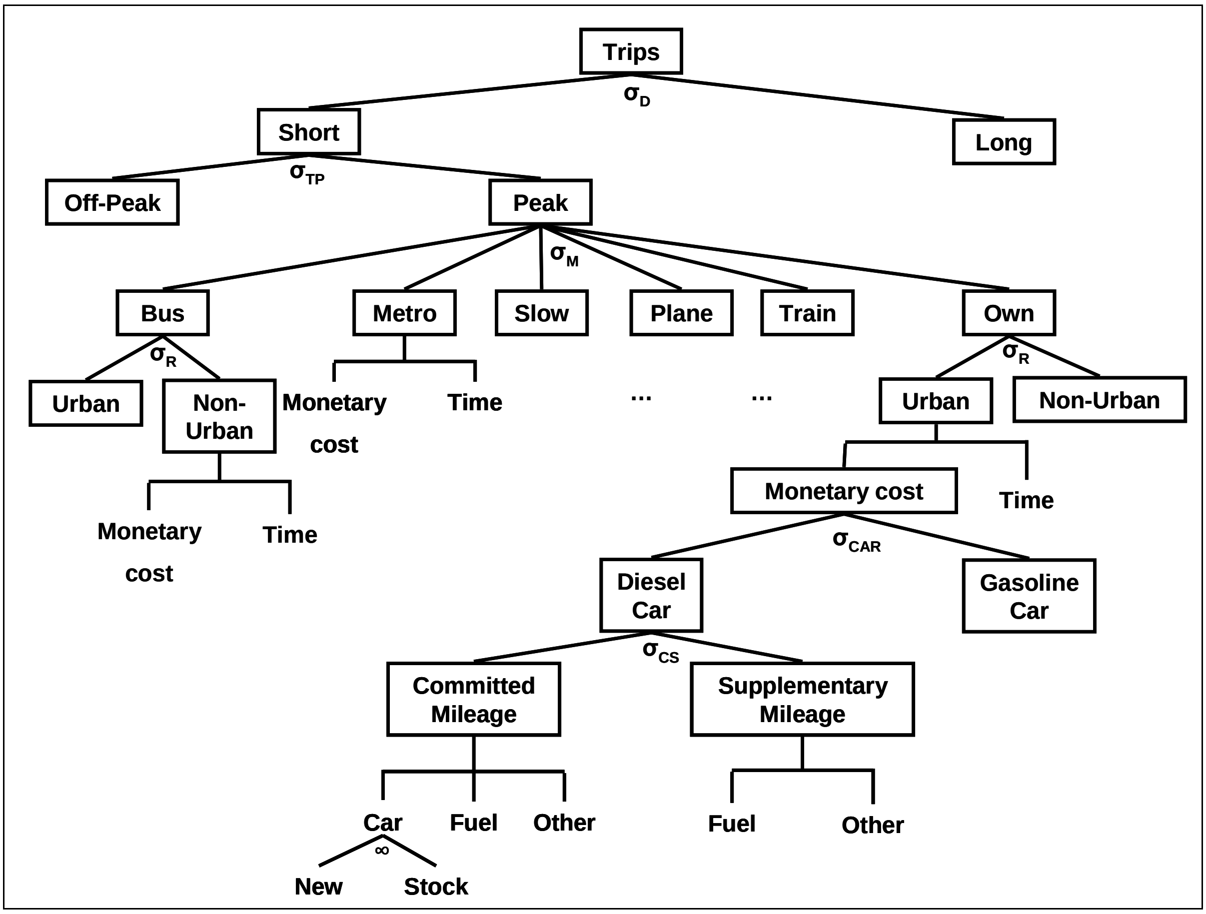


Figure 8: Private transport structure



5.2.5.3 Production functions

Figure 9 shows the production function of non-electricity sectors. Outputs are modeled using a CET function at the output side. At the top-level, material inputs, transport, and an aggregate of factor and energy inputs are combined using a Leontief function. Transportation can either occur on roads or by water or air transport. Road transport can either be own supplied or purchased from the road transport sector. Own provided transport is distinguished by different transportation fuels. However, the transport capital input is not modeled. On the factor and energy side, first a value added composite of primary factors and an energy aggregate are combined. Another approach would be to combine labor with a capital/energy aggregate (Burniaux and Truong, 2002). However, van der Werf (2008) tests different nesting structures of primary factor and energy inputs for twelve OECD countries and shows that the adopted nesting structure performs best in reproducing observed time series. The energy aggregate trades off electricity input versus fossil fuel commodities which are further subdivided by coal and liquid and gaseous commodities.

Figure 10 depicts the electricity production function. At the top level, electricity generation, transport, material and a value added aggregate are combined using a Leontief function. The transport composite is the same as for non-electricity sectors. 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. The differentiation of load segments is important to avoid unrealistic substitution patterns between technologies. From an economic point of view, 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 (e.g. Stoft, 2002). 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. 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.

Figure 9: Non-electricity production

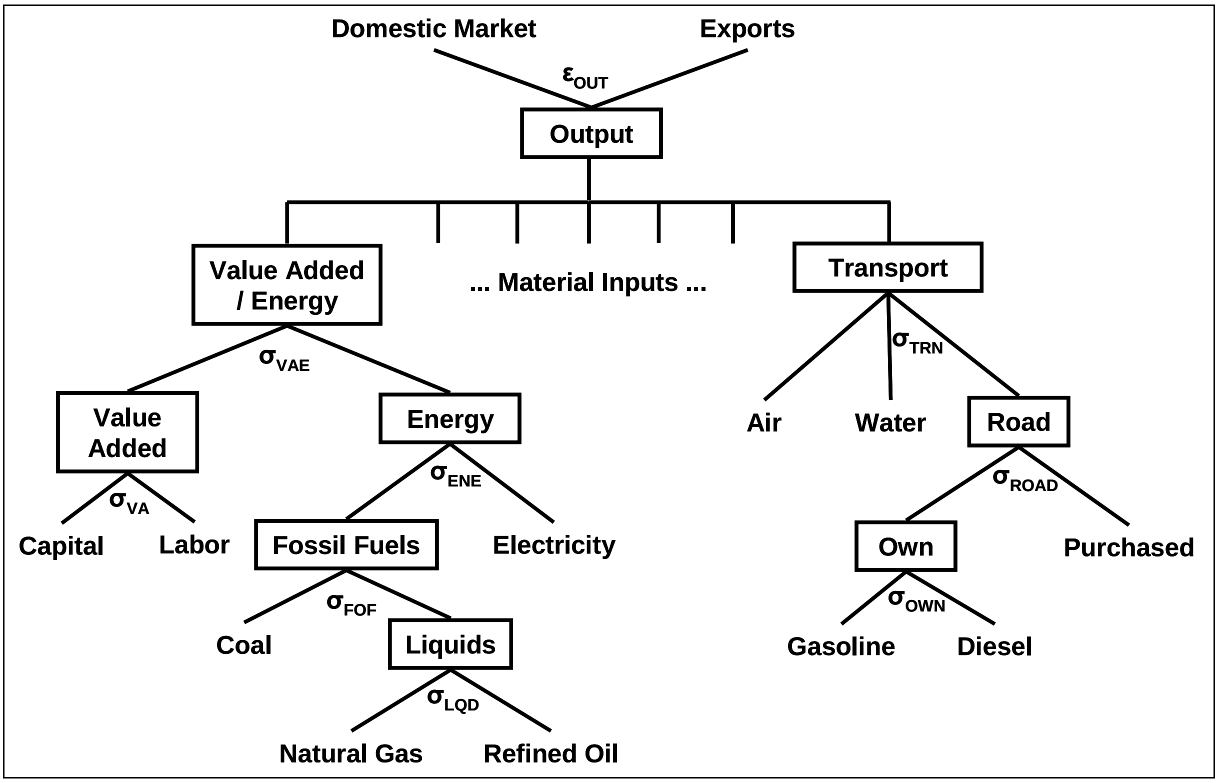
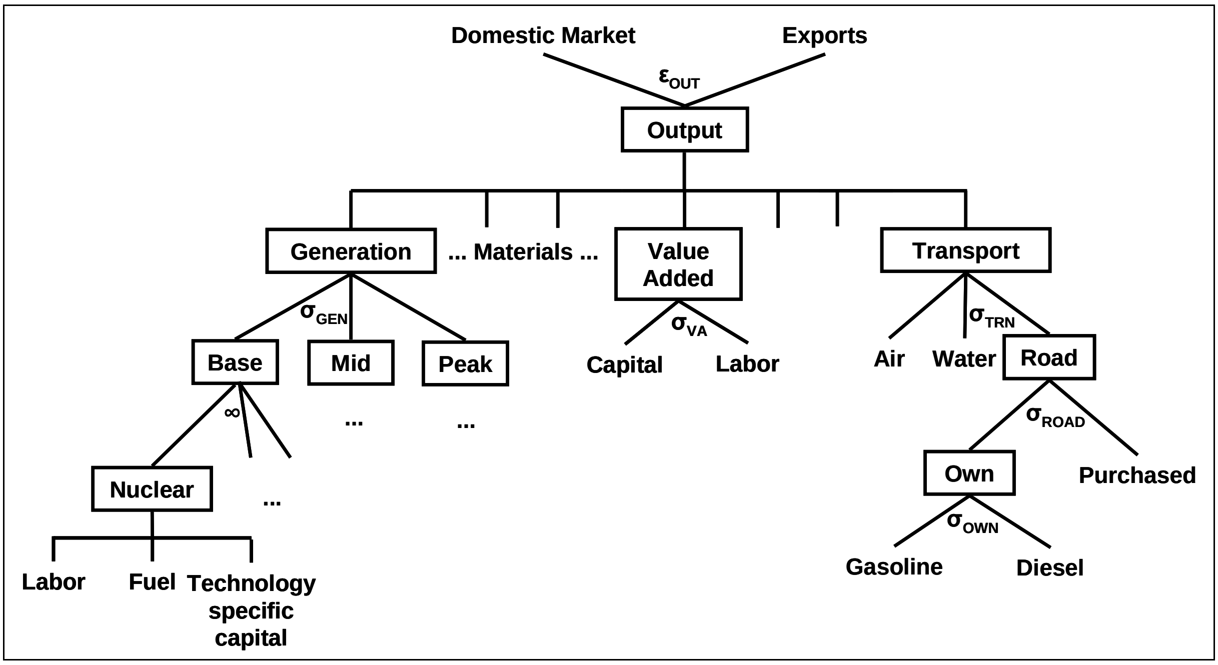


Figure 10: Electricity production



Essentially, the implementation of discrete generation technologies is a combination of the 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, i.e. capacities are not malleable. Wing (2006, 2008) controls the malleability 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 does not work if new technologies are included: due to the zero-value share in the benchmark equilibrium, the 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 used in this thesis 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.

Table 15 lists the substitution elasticities used in the production functions. The substitution elasticities for the value added and value added/energy aggregated have been estimated by van der Werf (2008). Elasticities for the transport module are obtained by a literature review but are generally subject to uncertainty. Following Böhringer (1995), the substitution elasticity between load segments is set to a value near zero. Other elasticities are adopted from Paltsev et al. (2005a) who employ the same production structure. Empirical values for the transformation elasticity of technology specific capital do not exist. Therefore, it is set to one and a sensitivity analysis is performed.

Table 15: 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

Welsch (2007) estimates elasticities for the Armington aggregation for European countries including Germany. The adopted values are given in Table 16.[49] Generally, the values estimated by Welsch (2007) are lower than those used in comparable studies.

Table 16: 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)

5.2.5.4 Congestion function

The congestion function relates the time needed to travel one kilometer ($time_{m.n}$) using the mode *m* on the road network *n* to the travel flow on that network measured in person car equivalents per hour ($flow_n$). The congestion function is assumed to be exponential and given in equation (67) which has been empirically validated by (O'Mahony et al., 1997). The left hand side is the time needed to travel one kilometer using mode *m* on network *n*. The time depends on the total flow in the network, $flow_n$, measured in personal car equivalents per hour. The A parameters need to be calibrated.

$$time_{m,n} = A^1_{m,n}\left[A^2_n + A^3_n e^{A^4_n flow_n}\right] \tag{67}$$

5.2.6 Parameterization

5.2.6.1 Underlying data

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).

The German IO table identifies domestic production and imports for 71 commodities measured at producer prices. Furthermore, labor inputs, depreciation, and net profits for industries as well as tax payments differentiated by production and intermediate input taxes are given. Final demands include consumption of households, the government, and non-profit organizations. In addition, investments, stock changes, and exports are included.

The physical IO table provides energy inputs to the different production sectors and households differentiated by energy commodities. These inputs are given in two forms: total energy and emission

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[49] Since crude oil and nuclear inputs are only imported no elasticity is given.

relevant energy inputs. While the former include transformation inputs, the latter are net of double counted energy flows. The physical IO table also includes total CO_2 emission by production sector.

Transport data are extracted from the TREMOVE demand module which provides data for private and freight transport in the form of person and vehicle kilometers differentiated by travel distance, period, and roads. Furthermore, speeds of different travel modes as well as cost coverage rates of public transport modes are given.

Household expenditures for private transport are given in DIW (2006) and are differentiated by car purchases, fuel spendings subdivided by net cost and different tax categories, and other cost. Moreover, used quantities and prices on different transport fuels and kilometers driven on gasoline and diesel automobiles are provided.

The next sections describe the creation of the database in detail. The corresponding programs are given in Appendix D.

5.2.6.2 Social accounting matrix

The construction of the social accounting matrix is based on the IO table. Intermediate and labor inputs into domestic production, imports and exports as well as household's demand can be directly derived out of the IO table. Capital input is defined as the sum of net profits and depreciation.[50] Total investment demand is taken as the sum of investment demand and stock changes.

Crude oil and natural gas production and consumption are represented in the German IO table in an aggregated fashion. Moreover, gasoline, diesel, and nuclear fuels are included in the refined oil account. In order to disaggregate these accounts, the physical IO table, which identifies input of these commodities in physical energy units except for nuclear fuels, is used. Using prices given in BP (2007), energy inputs are converted into monetary units. The resulting input commodities' shares are applied to each aggregated monetary demand in the IO table. Concerning the supply side, crude oil is assumed to be not domestically produced.[51] Transport fuel sectors are pure transformation sectors, i.e. they take the Armington aggregate of refined oils as inputs and provide diesel and gasoline respectively as outputs.[52] Nuclear fuels are specified as pure import commodities. The demand for nuclear fuels is identified in the creation of different electricity generation technologies described below and separated out of the refined oil imports.

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[50] Net profits may be negative eventually resulting in negative capital inputs with the model formulation. Following Paltsev and Rutherford (1999) in the case of negative capital inputs labor input is adjusted.

[51] This neglects around 2.5% of domestic crude oil production (BP, 2007; Mineralölwirtschaftsverband, 2008). Splitting the aggregated domestic production account requires additional data on the cost structure of natural gas and crude oil. These data are hardly available. Consequently, additional assumptions are necessary. Since domestic crude oil production is small and additional assumptions on cost structures also distort the data basis, I decided to treat crude oil as pure input which essentially facilitates the creation of the SAM.

[52] This implies that production of refined oil can perfectly switch from diesel to gasoline production and vice versa. Choumert et al. (2006) note that this is not possible due to the existing configuration of refineries. They split the outputs of the refined oil sector in the MIT EPPA model into different refined oil products like transportation fuels, heavy fuel oil, and petroleum coke. However, this splitting also comes at cost: beside additional data requirements modeling the refined oil as multi-output sector requires choosing additional transformation elasticities. Moreover, solely splitting outputs under the maintained assumption of separability of the cost and revenue function implies equal cost structure of the production of different refined oil types.

All taxes are derived as ad-valorem taxes. Production taxes are directly derived from the IO table and implemented as output tax on total production. OECD (2007) reports taxes on labor income and social insurance contributions of households and firms. These data are used to derive the labor income tax and a labor use tax which is assumed to be uniform across sectors.

The value-added tax in Germany in the year 2004 was 16 % which applies to all commodities except transportation fuels and refined oils. Consumption tax rates on gasoline and diesel are derived on the base of the DIW (2006) expenditure data which provide net payments for fuels and the tax component separately distinguished by mineral oil tax, eco tax, and value added tax. Other refined oils are tax at a rate of 41.8 % (IEA, 2008). Subsidies on public transport use are derived using cost coverage rates given by the TREMOVE model. Motor vehicle taxes apply on the value of total available cars. The construction of this value and the corresponding tax rate is described below.

Transportation fuel tax rates for intermediate inputs are the same as for final consumption net of the value added tax. IEA (2008) gives a tax of 20 % for refined oil intermediate inputs. In Germany, the aviation sector does not pay taxes on refined oil (kerosene) inputs. Consequently, the tax rate is set to zero. This is also done for the refinery sector since inputs are mainly transformation inputs which are not subject to the mineral oil tax. For the remaining intermediate inputs tax rates are derived residually by subtracting fuel tax payments from total intermediate tax payments given by the IO table and dividing by the total value of intermediate inputs. Generally, these taxes are in the magnitude of 3 %.

A direct transfer from the government to the representative agent is implemented in such that the budget constraints are fulfilled. Selected tax rates are given in Table 17.

Table 17: Selected benchmark tax rates [%]

	Production	Household
Diesel	150	174
Gasoline	234	273
Refined oils	20	42
Labor	15.6	46
Bus		- 18
Metro and tram		- 18
Private train		- 45

As in the previous chapter, emission coefficients are taken from IPCC (2006) and uniformly scaled to meet total emissions by sectors as given in the physical IO table. Table 18 shows the CO_2 emissions differentiated by energy input. The electricity sector is with 40.5 % of the total emission the largest emitter mainly using coal followed by natural gas and oil. The representative agent is the second largest emitter. 45 % of his emissions are caused by transportation and the remaining part by using fossil fuels for heating and cooking. Emissions in the energy intensive sector are mainly caused by fossil fuel use. Transportation fuels only play a minor role. In contrast, in the service sector, which accounts for 11 % of the total emissions, 52 % of the emissions are caused by road transport and the remaining by natural gas and refined oils.

Table 18: CO_2 emissions by sector and energy input [million t]

	Coal	Natural gas	Refined oils	Diesel	Gasoline	Total
Agriculture	0	1	2	5	0	8
Air transport	0	0	4	0	0	4
Coal	2	0	0	0	0	2
Energy intensives	55	39	11	2	0	106
Electricity	323	33	8	0	0	363
Natural gas	0	2	0	0	0	2
Manufacture	4	38	15	5	1	64
Mining	6	0	0	0	0	6
Motor vehicles	0	2	0	1	1	3
Other transport	0	0	0	11	0	11
Refined oils	0	2	16	0	0	18
Rail transport	0	0	0	2	0	2
Services	1	27	20	44	8	100
Water transport	0	0	0	1	0	1
Repr. agent	3	61	50	20	72	206
Total	393	205	125	91	82	896

5.2.6.3 Private transport

Creating the data basis for the private transport module involves three major steps: First, the existing automobile stock and the cost structure of different car types are derived. Second, the monetary inputs into different transport modes need to be determined. Third, the congestion function is calibrated and time inputs to transport modes are derived.

Table 19 provides the data used to derive the cost structure of different car types. The reference cars, which have nearly equal performance data, are an Opel Vectra 1.8 for gasoline and an Opel Vectra 1.0 CDTI for diesel. Purchase prices and new car purchases are used to split consumers' motor vehicle demand given by the SAM and the implied prices per new cars. The stock of automobiles is converted to monetary units using a rental price which is derived as continuous annuity on the purchase price under the given lifetime and an assumed interest rate of 10 %. Given the cubic capacities, the motor vehicle tax rates, and the total motor vehicle tax payments (DIW, 2006) the ad-valorem tax rate on cars is computed. The total monetary annual car costs are given as the sum of the annuity and the motor vehicle tax. Annual fuel costs are directly given from DIW (2006) which also gives the total other spendings on car use. However, the other costs are not differentiated by automobiles. Assuming other costs to be equal for car types and proportional to the number of total cars, the annual other costs per car type are derived. The total other costs are disaggregated to different commodity demands using the consumption transition matrix coming with the German IO table.

Table 19: Basic data for car types

	Diesel car	Gasoline car
Purchase price[a] [€]	26540	24710
Cubic capacity[a] [ccm]	1910	1796
Specific emissions[a] [g CO_2/km]	154	173
Lifetime[b] [years]	12	12
Total kilometers driven[b] [million km]	177589	412820
Total fuel use[b] [million l]	12210	34582
Fuel spending net of tax[b] [million €]	2856	9274
Taxes on fuels[b] [million €]	4970	25250
Motor vehicle tax[c] [€/ 100 ccm]	15.5	6.75
Stock net of scrapping[d] [million]	7620	34479
New cars[e] [million]	1437	1822

Sources: a Motor Presse Stuttgart (2008); b DIW (2006); c BMF (2009); d,e KBA (2005a,b)

Table 20 gives the resulting cost shares of the two car classes. Including the rental costs of the existing car stock and motor vehicle taxes in the car costs results in car expenditure as the main determinant of costs. Diesel cars have a high car cost share than gasoline cars but are more fuel efficient.

Table 20: Cost shares of car types [%]

	Diesel car	Gasoline car
Car	70	53.6
Fuel	10.9	18
Other cost	19	28.5

The described procedure identifies the monetary cost of car use per vehicle kilometer. Using the TEMOVE data, which identify person and vehicle kilometers differentiated by trip type, distance, and period, the costs are converted to a per person kilometer basis. Consequently, occupancy rates differing by trip class are implicitly included. Total private train and aviation consumption are directly given from the SAM and also converted to a per person kilometer basis. The SAM does not offer disaggregated inputs to bus and metro and tram use. These costs are included in the other road transport sector. Under the assumption of equal prices these inputs are converted to the per person kilometer basis.

The TREMOVE model also offers the speed of different transport modes differentiated by trip class. Using the speed data, occupancy rates, and person kilometer traveled the time inputs for different trips purposes are computed. Destatis (2006) reports 81 minutes of transport time per day. Both, working and recreation time are around 8 hours (Destatis, 2002). Consequently, transportation is around 17% of the total leisure time budget which is used to determine the time endowment.

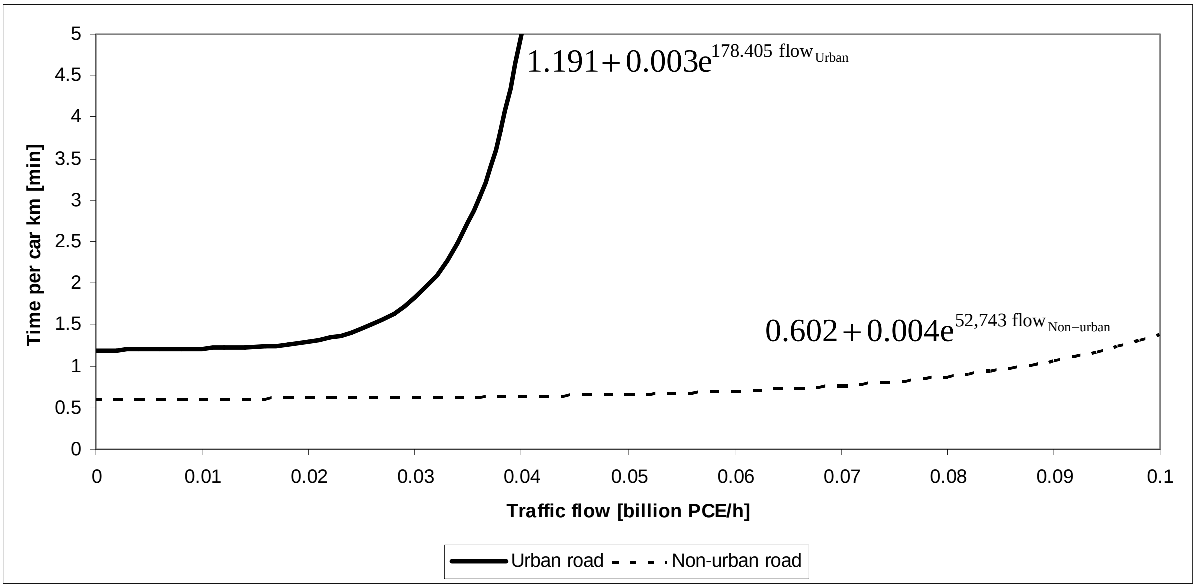
Calibrating the congestion function requires identifying four parameters for each road type. For cars the A^1 parameter in equation (67) is set to one. The TREMOVE data imply that busses are on average 11 % (26 %) slower than cars on urban (non-urban) streets and the A^1 parameter for busses is set accordingly. Consequently, the number of parameters reduces to three. The TREMOVE data give the speed in the peak and off peak period for each road type, the personal car equivalents in different periods, and the duration of periods. Using the Bureau of Public Roads formula (e.g. Small, 1992) which only depends on two parameters the freeflow speed is derived. Given these three points the unknown parameters can be derived. Table 21 gives the input data to the calibration procedure and Figure 11 shows the relation between the traffic flow and time necessary to drive one kilometer using cars.

Table 21: Data for 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.

Figure 11: Calibrated congestion functions for automobiles



The model includes a detailed representation of private transport. However, freight transport is modeled in a typical top-down manner. Consequently, the model is not able to predict the change of traffic flows resulting from freight transport. Therefore, the contribution of trucks to congestion is held constant at the benchmark level.

5.2.6.4 Electricity generation

Extraction of different generation technologies from the electricity account is a two-step procedure: First, data from bottom up engineering studies are used to derive the cost shares of different generation technologies. Second, material and factor demands of technologies are fitted into the SAM format by minimizing the distortion of the derived cost shares.

Table 22 lists the technological characterization of the generation technologies and their physical output levels in the benchmark equilibrium. According to David and Herzog (2000) the CO_2 capture rate of CCS technologies is set to 90 %.

Annualized capital costs are derived using the continuous annuity method on the product of plants' size and investment costs under assumed interest rate of 7.5 %. Operation and maintenance costs are regarded as annual labor cost. Using the plants' availability and size, heat efficiencies, and fuel prices, the annual fuel cost are obtained.

The method of integrating the generation technologies into the SAM framework is described in detail in Wing (2008). The top-down framework requires that the material and factor inputs of all generation technologies and the overhead activity sum to the total demands given by the SAM. Moreover, output also has to equal the output of the electricity sector in the SAM. The sum of squared deviations of predicted cost share and cost shares fitting into the top-down data is minimized. A further restriction is added to minimize the deviation of the heat efficiency from its predicted value.[53] The predicted and used values consistent with the SAM are given in Table 23.

Table 23 also states the respective load segment for technologies. Conventional technologies active in the benchmark equilibrium in the mid load segment, the CCGT and hard coal plant, are allowed to produce in the base load segment, too. This allows substitution of lignite base load production by more environmentally friendly but also more expensive mid load technologies. For inactive technologies, the concept of cost markup over the benchmark price in the load segments is used (e.g. Böhringer, 1998; McFareland et al. 2004). The markup of technologies already active in the mid load but not in the base load segment is equal to the average spread between the respective prices in 2004 (European Energy Exchange, 2004). McFareland et al. 2004 estimate the markup of CCS technologies. The values for offshore wind and photovoltaic are derived using the generation prices as implied by the bottom-up data.

The technological potential given in Table 23 was estimated by BMU (2007) for wind and photovoltaic technologies. For hydro power and other technologies no additional potential is given. Consequently, the limit is set to the benchmark production. Since new installation of nuclear power plants is prohibited in Germany (Deutscher Bundestag, 2002), generation of nuclear power is also capped at the benchmark level.

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[53] See Appendix D for the employed GAMS code.

Table 22: 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 23: 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

5.2.7 Model critics and extension

The presented framework overcomes the bottom-up/top-down discussion of technological details including different electricity generation technologies. Furthermore, private transport is included in detail and congestion is modeled. Although not done in this thesis, representing different road types and congestion also allows analyzing the effect of infrastructure policies determining the effect of infrastructure provision on the congestion function and road pricing policies.

Freight transport is addressed in an aggregated way considering intermediate inputs of transport commodities and energy inputs differentiated by fuel type. Consequently, it is not possible to keep track of the vehicle kilometers traveled by freight transport. Therefore, the contribution of freight transport to the traffic flow in the congestion function is held constant at the benchmark level. Thus, a fruitful extension of the model is the detailed representation of industrial transport. This requires estimation of the transport capital by sector and of trips by travel period, distance and mode. The TREMOVE demand module offers aggregated data on a vehicle and tone kilometer basis distinguished by trip categories. Transport capital in form of the vehicle stock are given in KBA (2005 a,b). DIW (2006) includes data on transit transport in Germany. Given these data, there are two main tasks to solve: First, the aggregated TREMOVE data on traffic use need to be disaggregated to a sectoral basis, i.e. answering the question which sector uses how much of the transport volume. Second, given the transport volume of single sectors it needs to be determined how much of the sector’s transport is own provided and how much is purchased. Obviously, the main effort is in the first task which is a matter of data. The second task might by solved by estimating own provided transport using the data on transport capital and fuel expenditure.

The model treats labor supply as constant. This is done in order to concentrate on the interaction between emission abatement in electricity generation and road transport and to facilitate the interpretation by ruling out labor supply effects. Labor supply effects can be easily included specifying labor as part of the time constraint. Including labor in the time constraint has an additional effect on the private transport decisions since the value of time, which is endogenous in the model, is further linked to the wage rate. Consequently, the decision on the travel mode is further influenced by the model’s reactions on the labor market. Such an analysis has been carried out for example in the empirical analysis of Berg (2007).

The modeling of households using a representative agent is costly in two directions: First, the model does not allow for analyzing important equity aspects. Second, the location of living of households which affects the substitution possibilities across transport modes and roads are not represented. A more detailed representation of households requires splitting expenditure and income data as done for Germany by Kalinowska et al. (2007) and Kremers and Kalinowska (2009).

New technologies for automobiles should be included in future versions of the model allowing for a detailed analysis of fuel efficiency related policies. Modeling new technologies in the car market is more complicated than in electricity generation since cars are not perfect substitutes like generation technologies. Beside the important preferences of consumers, adoption of technologies also depends on the availability of fueling networks (Achtnicht et al., 2008).

Athough the model accounts for the congestion externality, other externalities such as local pollution, accidents, and noise are ignored. Therefore, a future extension of the model should include these externalities, too, as done e.g. in Meyeres and Proost (1997) and Mayers (1999).

5.3 Simulations and results

5.3.1 Scenario description

In all scenarios the German economy reduces 20 % of its CO_2 emissions in the benchmark which amounts to 179.2 million tones. In the ETS scenario, the reduction requirement is achieved using emission trading between the electricity sector, energy intensive industries, and refineries which are referred to as ETS sectors. However, only emissions caused by coal, natural gas, or refined oil combustion are included into the system. Emissions caused by using transport fuels are not covered. Permits are owned by the government which sells them to the emission trading sectors. Consequently, the introduction of carbon regulation increases the government's revenues. The ETS AIR scenario additionally includes the aviation sector. The ETS FUEL and FUEL TAX scenarios include reduction efforts of road transportation. In ETS FUEL, all sectors and the representative agent have to hold emission allowances for emissions caused by gasoline or diesel use. These allowances are tradable with the ETS sectors. The FUEL TAX scenario implements a separated strategy for road transport emissions. It requires road transport to reduce emissions by 5 %. Firms and the representative household are allowed to trade allowances for transport fuels. However, they are not allowed to trade permits with the ETS sectors which fulfill the remaining reduction requirement complying with the overall 20 % reduction target. This closed emission trading system for road transport fuels is equivalent to an increase of the existing fuel tax distinguishing carbon contents of transport fuels. In all of these scenarios the revenues are recycled lump-sum to the representative agent holding the provision of public goods constant. The ETS SUB scenario is the only exemption to this rule. In this scenario, the income generated by the ETS system is used to uniformly increase the subsidies for bus, metro and tram, and private train transport. Table 24 gives an overview over the scenario settings.

Table 24: Scenarios of the small open economy model

	Carbon regulation
ETS	Electricity sector, energy intensive production, and refineries reduce 20% of the total emissions using emission trading Revenues recycled lump-sum
ETS AIR	Aviation sector is additionally included in the ETS system Revenues recycled lump-sum
ETS FUEL	Emissions caused by road fuel use are included in the ETS system Revenues recycled lump-sum
FUEL TAX	Road transport has to reduce 5% of its emissions Remaining reduction requirement is fulfilled by ETS sectors using emission trading Revenues recycled lump-sum
ETS SUB	Like the ETS scenario Revenues recycled uniformly increasing public transport subsidies

The Hicksian equivalent variation is adopted as measure of the overall welfare change. Additionally, the change in the direct transfer to the household and the total abatement cost are listed. Carbon prices reflect the marginal abatement cost of regulation. As an indicator of distortionary extra costs not reflected in the marginal abatement cost the average cost of carbon mitigation are derived as the loss in consumption of representative agent by the total amount of CO_2 abated (Paltsev et al., 2005b). In a partial equilibrium setting, the ratio of average to marginal abatement cost is slightly below one half depending on the curvature of the abatement cost function.[54] If the general equilibrium framework leads to excess welfare costs (gains) the ratio will be above (substantially below) one half.

5.3.2 Introducing emission trading

The ETS scenario introduces emission trading for electricity production, energy intensive industries and refineries. Other sectors are exempted from carbon regulation. With 487 Mt CO_2 the sectors under the trading system account for 54 % of the benchmark emissions and have to reduce 179.2 Mt CO_2. Consequently, the effective reduction rate for these sectors is around 36 %. The welfare change is given as Hicksian equivalent variation and measures the gross cost of carbon regulation: i.e. the gain of environmental regulation in form of improved air quality and reduced impacts of global warming are not included. Furthermore, the changes in direct transfer from the government to the household, total abatement costs, and CO_2 prices, which are interpreted as the marginal abatement cost, are listed in Table 25.

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[54] To see this, consider a linear abatement cost function. If Q is the amount abated and P the resulting price or marginal abatement costs, the total abatement cost (TAC) measured as the area under the abetment cost function are given as: TAC = 0.5*Q*P. Dividing both sides by the quantity abated the average abatement costs are exactly equal to half of the abatement cost. As long as the abatement cost curve is assumed to be convex, the resulting ratio is below 0.5.

With -0.61 ‰ the welfare effect of introducing emission trading is moderate. The total abatement cost amount to 1.76 billion € and the marginal abatement cost become 9.86 €/t CO_2. The ratio between average and marginal carbon cost is around 59 % indicating that cost other than carbon regulation occur. The direct transfer to the household increases by around 2 %.

Table 25: Summery results of the small open economy model

	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB
Welfare change [‰]	-0.61	-0.60	-0.92	-2.30	-0.21
Transfer change [%]	2.11	2.14	2.88	6.26	0.00
Abatement cost [billion €]	1.76	1.76	1.75	2.04	1.75
CO_2 price emission trading [€/t CO_2]	9.86	9.86	9.79	9.42	9.84
CO_2 price transport fuels [€/t CO_2]	0.00	0.00	0.00	53.93	0.00
Average consumption cost [€/t CO_2]	5.86	5.74	8.81	22.38	1.98

As Table 26 shows, the reduction burden is shifted from energy intensive sectors and refineries to the electricity sector which reduces 41 % of its emissions. The main mitigation results from a decreasing use of coal (Table 28). Note that the emission trading sectors avoid only 178.9 Mt CO_2 of the total reduction requirement of 179.2 Mt CO_2. This is due to second order effects which lead via price and demand changes to contraction and expansion of non emission trading sector resulting in changes of their emissions. Since the overall target is to reduce the economy's emission by 20 %, these changes spill over to the emission trading sectors by slightly altering the allowances budget. Due to the reduced usage of coal, emissions in the coal sector are the main determinant of this secondary effect.

Table 26: CO_2 reduction of selected sectors

		ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB
Aviation	[mio t CO_2]	0.00	0.03	-0.02	-0.10	0.01
	[%]	0.05	0.68	-0.44	-2.53	0.34
Electricity	[mio t CO_2]	147.52	147.51	145.85	136.61	146.59
	[%]	40.64	40.64	40.18	37.63	40.38
Energy intensives	[mio t CO_2]	30.99	30.98	30.91	30.47	30.99
	[%]	29.23	29.23	29.16	28.75	29.24
Refineries	[mio t CO_2]	0.36	0.37	0.42	0.63	0.42
	[%]	1.99	2.04	2.31	3.50	2.33
Private cars	[mio t CO_2]	0.00	-0.01	0.05	0.31	1.22
	[%]	0.00	-0.01	0.06	0.34	1.33
Services	[mio t CO_2]	-0.18	-0.19	1.29	6.76	-0.16
	[%]	-0.18	-0.19	1.29	6.76	-0.16
Total	[mio t CO_2]	179.20	179.20	179.20	179.20	179.20
	[%]	20	20	20	20	20

Table 27 shows the impacts on electricity generation. Total generation is decreasing by 12.5 %. Consequently, production in all segments is reduced. In the base load, nuclear and hydro power and the generation of other technologies stay constant since they are upper bounded at the benchmark production level and do not cause emissions. The generation of dirty lignite plants decreases by almost

63 % to 99 TWh. The penetration of lignite CCS plants, which are the only available technology reducing emissions in the base load segment beside the use of CCGT and hard coal power plants, partly balances the decrease in base load generation producing 40 TWh.

In the mid load segment, emissions are mitigated by decreasing the use of hard coal by 54 %. Furthermore, the output of the CCGT technology declines by 40 %. The increase in wind power partly adjusts the offset of mid load generation. Offshore wind energy intensely enters the market with around 31 TWh. In contrast, onshore wind generation only slightly expands by around 5 %. As shown below in the sensitivity analysis, the expansion of onshore generation heavily depends on the degree of capital malleability, i.e. on the transformation elasticity of the capital transformation for technology specific capital.

For peak load generation only OCGT and OCOT plants are available. While the generation of natural gas fired plants (OCGT) stays constant, oil based production (OCOT) is decreasing. This result can be explained by the higher carbon content of refined oil compared to natural gas which leads to higher CO_2 intensity of oil-fired power plants. Consequently, oil based generation is decreases in importance. In order to satisfy peak load electricity demand, generation of natural gas power plants does not decline.

Table 27: Electricity generation [TWh]

	Bench-mark	**ETS**	**ETS AIR**	**ETS FUEL**	**FUEL TAX**	**ETS SUB**
Base load						
Hydro	26.9	26.9	26.9	26.9	26.9	26.9
Lignite	158.0	99.0	99.0	99.9	104.8	99.4
Lignite CCS		40.1	40.1	39.2	34.3	40.3
Nuclear	167.1	167.1	167.1	167.1	167.1	167.1
Other technologies	25.3	25.3	25.3	25.3	25.3	25.3
Total	377.3	358.4	358.4	358.4	358.5	359.0
Mid load						
CCGT	30.7	18.6	18.6	18.8	19.6	18.7
Hard coal	140.8	64.4	64.4	65.1	68.8	64.8
Wind onshore	25.5	26.7	26.7	26.7	27.1	26.7
Wind offshore		30.6	30.6	30.2	28.1	30.6
Total	197.0	140.3	140.3	140.8	143.7	140.7
Peak load						
OCGT	30.7	30.7	30.7	30.7	30.7	30.8
OCOT	10.3	8.6	8.6	8.6	8.6	8.7
Total	41.0	39.4	39.4	39.4	39.4	39.4
Total generation	615.3	538.1	538.1	538.6	541.6	539.2

Table 28: Price and quantity effects [% vs. benchmark]

	Quantity effects					Price effects				
	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB
Agriculture	-0.11	-0.11	-0.14	-0.27	-0.16	0.01	0.01	0.08	0.39	0.13
Air transport	-0.05	-0.29	0.44	2.53	-0.37	-0.01	0.19	-0.02	-0.05	0.10
Coal	-33.11	-33.11	-32.90	-31.66	-32.90	0.39	0.38	0.38	0.34	0.52
Crude oil	-0.85	-0.90	-1.18	-2.40	-1.19	0.11	0.11	0.11	0.12	0.26
Diesel	-0.13	-0.11	-1.24	-5.40	-0.18	0.51	0.51	0.51	0.51	0.65
Energy intensives	-1.31	-1.31	-1.33	-1.39	-1.45	1.01	1.00	1.01	1.02	1.12
Electricity	-3.05	-3.04	-3.05	-3.07	-2.87	7.58	7.58	7.55	7.42	7.69
Natural gas	-4.68	-4.68	-4.66	-4.48	-4.71	0.08	0.08	0.08	0.07	0.22
Nuclear fuel	0.00	0.00	0.00	0.00	0.00	0.11	0.11	0.11	0.12	0.26
Gasoline	-0.12	-0.12	-0.28	-0.97	-1.19	0.51	0.51	0.51	0.51	0.65
Manufacture	-0.20	-0.20	-0.21	-0.26	-0.33	0.07	0.07	0.08	0.09	0.19
Mining	-1.76	-1.76	-1.78	-1.84	-1.79	0.26	0.25	0.25	0.23	0.38
Motor vehicles	0.26	0.27	0.20	-0.06	-1.56	0.01	0.01	0.01	0.01	0.12
Other transport	-0.13	-0.11	0.42	2.76	0.88	-0.05	-0.05	0.15	1.06	0.08
Refined oils	-0.27	-0.32	-0.60	-1.85	-0.63	0.51	0.51	0.51	0.51	0.65
Rail transport	-0.61	-0.61	-0.50	0.02	21.81	0.26	0.25	0.25	0.21	0.39
Services	-0.08	-0.08	-0.08	-0.09	-0.10	-0.14	-0.15	-0.14	-0.12	-0.03
Water transport	1.21	1.24	1.78	4.28	1.37	-1.00	-1.01	-1.04	-1.23	-1.06

Both effects are measured in terms of the Armington composite, i.e. reflect the change of the total quantity used and the market price. Effect on production, intermediate and final demands, and trade are given in Appendix C

Table 29 lists the effects on private transport are listed in. Total private transport is slightly decreasing. The decrease can fully be explained by the declining use of trains. With 4.8 % of electricity in the total cost, the rail sector is one of the most electricity intensive sectors. Consequently, it is indirectly affected by the carbon policy by the change of the electricity price which increases by 7.6 % (Table 28). Accordingly, the price of rail transport rises and therefore, leads to a decrease in private transportation and the substitution of private by air transport, busses, and metro and trams.

Table 29: Private transport

		Benchmark	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB
Bus	billion pkm	91.656	91.727	91.731	91.589	91.007	96.017
	%		0.08	0.08	-0.07	-0.71	4.76
Car	billion pkm	923.849	923.839	923.868	923.276	920.737	914.654
	%		0.00	0.00	-0.06	-0.34	-1.00
Metro /tram	billion pkm	12.101	12.115	12.115	12.080	11.931	12.933
	%		0.11	0.12	-0.18	-1.41	6.87
Plane	billion pkm	43.922	43.926	43.787	43.964	44.135	43.679
	%		0.01	-0.31	0.10	0.49	-0.55
Slow	billion pkm	55.328	55.348	55.346	55.426	55.777	55.175
	%		0.04	0.03	0.18	0.81	-0.28
Train	billion pkm	67.328	66.968	66.974	67.087	67.620	89.466
	%		-0.53	-0.53	-0.36	0.43	32.88
Total	billion pkm	1194.184	1193.923	1193.822	1193.421	1191.207	1211.924
	%		-0.02	-0.03	-0.06	-0.25	1.49

Detailed results distinguishing between trips purposes, distances, and travel period are given in Appendix C.

Since the refineries are part of the emission trading system, the price of transport fuels increases by 0.5 %. The total use of cars only slightly reacts. Table 30 reveals that the change in transport fuel consumption is mainly balanced by a change in the automobile fleet. Since the tax on gasoline fuels is higher than the tax diesel, the representative household decreases purchases on gasoline cars and partly replaces them by diesel cars.

Table 30: Change in new car purchases [% vs. benchmark]

	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB
Diesel	0.05	0.06	0.17	0.69	-1.90
Gasoline	-0.02	-0.01	-0.35	-1.84	-4.36

5.3.3 Including aviation into emission trading

The ETS AIR scenario additionally includes the aviation sector into the emission trading system. Emissions covered by the trading system slightly rise by 4 Mt CO_2. Accordingly, there is no effect on the total or marginal abatement costs compared to the ETS scenario. However, the average costs of carbon mitigation are slightly decreasing and the ratio of marginal to average carbon cost drops to 58 %. The direct transfer to the representative agent is increasing due to an increase in emission allowances. The additional inclusion of aviation leads to a small reduction in the gross cost of carbon regulation. The mitigation effort of the electricity sector is the same as in the ETS scenario. Consequently, electricity generation also shows the same results.

Due to the increased cost, the price of aviation rises. Therefore, private transport reacts with a decreasing number of plane trips. This decline is only partly balanced by switching to private road transport, busses, and trains. As a result the total person kilometer decrease by 360 million person kilometers compared to the benchmark.

The change in new car purchases shows the same qualitative pattern as in the ETS case: since fuel prices rise and diesel is lower taxed, the composition changes in favor of diesel automobiles. Since own private road transport slightly expands, new car purchases are generally higher than in the ETS case.

5.3.4 Fuel based regulation approaches

The scenarios ETS FUEL and FUEL TAX examine fuel-based strategies mitigating carbon emissions of road transport. Road transport has to reduce 5 % of its emissions or 8 Mt CO_2. The remaining mitigation is achieved by emission trading between electricity, energy intensive industries and refined oil production (171.2 Mt CO_2).

The FUEL TAX scenario establishes a price on the CO_2 emissions of road transport fuel use. All sectors have to pay the price except the water and rail transport sectors in which diesel fuel relates to water and rail transport. This is interpreted as an increase in the fuel tax differentiating by the carbon content of fuels. The ETS FUEL scenario also establishes a price of road transport emissions. However, emissions of road transport are included into the emission trading scheme. Consequently, the marginal abatement costs equalize across sectors and a uniform carbon price for road transport and emissions from further fossil fuel use in the trading sectors emerges.

Comparing the FUEL TAX scenario with the ETS scenario, a significant welfare decrease is observed. Since part of the reduction burden is shifted to road transport, the mitigation effort in the emission trading sector is lower. Consequently, the permit price under the trading system is decreasing by 0.44 to 9.42 €/t CO_2. For transport fuels, the carbon price is at a high level of 53.93 €/t CO_2 indicating the high marginal abatement cost of road transport. Due to the coexistence of the emission trading systems, the total abatement costs are increasing being the main determinant of the welfare loss. The hybrid regulation approach which leads to different marginal abatement cost is the main determinant of the significant increase of the average cost of carbon regulation. A large increase in the direct transfer to the representative agent is observed, since the high carbon price of transport results in an increase of the government's income of carbon regulation.

Electricity generation responds to the decrease in the carbon price by increasing production. The generation mix also changes. Since the price of carbon is declining, coal fired generation is increasing compared to the ETS scenario. Accordingly, production of cleaner CCS plants and offshore wind power reduces. To put it clear: Regulating road transport separately, decreases the reduction burden of the emission trading sectors resulting in a lower carbon price which indirectly subsidizes the use of coal plants.

Concerning road transport, industrial sectors carry out the main reduction burden. The service sector, which is the main industrial polluter of road transport emissions, reduces its emissions by 6.8 %. Emissions are mitigated switching from own provided transport to purchased transport.

In contrast, the representative agent only slightly reduces his emissions by 0.3 %. Emissions are decreased in two ways. First, the composition of the new car fleet significantly changes using more carbon efficient diesel cars allowing driving the same distance with lower emissions. Second, total trips are reduced and a mode shift towards private trains, airplanes, and the slow mode is observed. The unexpected result of decreasing use of public transport in form of busses and metro and trams is explained by the model's structure: the monetary costs of both modes are specified in terms of input of the other transport sector. Emissions resulting from diesel and gasoline use in this sector are also addressed by the emission trading system. Accordingly, the cost of this sector increase. Furthermore, increased demand from industrial sectors exerts an upward price pressure. Consequently, the price of the other transport sector is rising by 1 % leading to substitution effects away from busses and metro and tram use.

Comparing the ETS FUEL scenario, which includes road transport into the emission trading system, with the ETS, an additional welfare loss is observed and total abatement costs are slightly decreasing. The carbon price slightly declines, since all sectors are affected by the carbon price on transport fuels leading to decreasing outputs. In consequence, the use of fossil fuels other than gasoline and diesel are also decreasing yielding a decline in these emissions. This second order effect lowers the reduction requirement under the emission trading system since the environmental target is always defined as a 20 % reduction of the economy's emissions. However, the average cost of carbon mitigation increase. The ratio of average to marginal abatement costs raise to 0.9 indicating an increase in the cost of carbon regulation. Due to the high tax on transport fuels, it is favorable to exempt the road transport sector from fuel based carbon regulation. Cost efficiency of carbon regulation requires an equal carbon price for all sectors and commodities, i.e. the effective carbon price should be equalized. However, the high tax on transport fuels is already environmentally motivated; i.e. a price on carbon in the transport sector exists. Consequently, putting an additional carbon price on top of the pre-existing fuel tax effectively induces higher carbon prices in the transport sector, and thus leads to cost inefficiency. In essence, the induced cost inefficiency outweighs the gain of increased flexibility of transport under emission trading.

Since it might come as a surprise that the flexibility gain is more than offset by the distortionary effect, a numerical example shall illustrate the argument. In 2004, the mineral oil tax per liter of gasoline was 0.65 € (BMF, 2009). Combustion of this liter gasoline causes 2.3 kg CO_2. Accordingly, the consumption of around 435 liter of gasoline results in one ton of CO_2. Therefore, the implicit pre-existing carbon tax on transport fuels is 283.61 €/t CO_2. Exempting road transport from carbon regulation leads a carbon price of around 10 €/t CO_2 and, therefore, the difference in effective carbon taxes is reduced. In contrast, in the FUEL TAX scenario the carbon price in the transport sector increases by around 54 €/t CO_2 while emission trading sectors pay a price 9.50 €/t CO_2. Thus, the gap in effective carbon taxes is even increased.

While the example is illustrative, it neglects taxes on transport fuels that do not solely relate to carbon emissions. Other externalities such as local pollution and associated health damages, congestion, noise, and accidents are also addressed. However, congestion as the main externality of road transport is included in the model. Regardless, the exemption of transport shows a positive effect.

Due to the higher marginal abatement cost in road transport, reduction mainly takes place in the emission trading sectors especially in electricity generation. Consequently, the generation mix is only slightly affected by an increase of hard coal fired generation in the mid load segment.

Concerning private transport, the ETS FUEL scenarios mirrors the results of the FUEL TAX scenario in an attenuated form. The composition of the new car purchases is influenced towards more fuel efficient diesel cars and total trips are slightly reduced. Own private road transport, bus, and metro and tram trips incline and are partly substituted by the use of private trains, the slow mode, and airplanes.

5.3.5 Increasing subsidies on public transport

Like the ETS scenario, the ETS SUB introduces emission trading between electricity generation, energy intensive industries, and refined oil production. However, in contrast to the ETS scenario the revenues of carbon regulation are not to recycled lump-sum but used to uniformly increase subsidies on public transport, i.e. busses, private trains trips, and metro and trams.

Revenue recycling using increased public transport subsidies shows a clear positive welfare effect compared to emission trading under lump-sum recycling. Total and marginal abatement costs slightly reduce. Remarkably, the average costs of carbon regulation strongly decline resulting in a ratio of marginal to average abatement costs of 0.2. The subsidy on private trains becomes 52 % and busses and metro and tram trips are subsidized at a rate of 21 %.

Increased public transport subsidies yield substitution away from private road transport towards the subsidized modes bus, metro and tram, and trains. Accordingly, emissions of private cars are decreasing by 1.3 %. This decrease is even larger than in scenarios where road transport emissions are addressed by fuel based regulation approaches. The fuel based approaches implement economy wide regulation, i.e. also include transport emissions of industrial sectors. In consequence, the abatement burden is shifted to industries showing only small effects on private transport. In contrast, public transport subsidies solely affect the households’ decision of private transport modes and offer incentives substituting away from cars.

The increased reduction effort of private road transport spills over to the emission trading system since the overall reduction of 179.2 Mt CO_2 is fixed. While energy intensive production and refineries increase emissions, the electricity sector further reduces its emissions. Despite reduced emissions, electricity generation is expanding compared to the ETS by expanding the use of the CCS technology in the base load.

Private transport subsidies induce a switch to public transport modes simultaneously increasing the total number of kilometers traveled. Trips using cars are decreasing by 1 %, while trips on busses, metros and trams, and trains increase by 4.8, 6.9, and 32.9 %, respectively. The excessive use of trains is explained by the assumption that revenues are recycled uniformly increasing subsidies. Since the subsidy on trains are already higher in the benchmark, a uniform multiplier on subsidies results in larger absolute effects on the subsidies for private train trips.

The clear cut positive welfare effect is explained by the reduction of the congestion externality. Table 31 shows the impact of the scenarios on speed on different road types differentiated by travel periods. While all other scenarios show negligible impacts on speed, the ETS PUB scenario results in a 2 % (1.5 %) increase of travel speed on urban (non-urban) roads in the peak period.

Table 31: Impacts on road speed [% vs. benchmark]

		ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB
Urban	peak	0.00	0.00	0.02	0.13	0.52
	off-peak	-0.02	-0.03	0.02	0.19	1.99
Non-Urban	peak	0.00	0.00	0.01	0.07	0.16
	off-peak	-0.01	-0.02	0.02	0.20	1.46

5.4 Sensitivity analysis

5.4.1 Malleability of technology specific capital

The malleability of generation capacities is controlled by the transformation elasticity of the activity which converts malleable capital into technology specific capital (ε_{KE}). The sensitivity of the results to a change of the transformation elasticity is examined by halving and doubling the benchmark value of unity. A lower value of the elasticity implies a higher degree of irreversibility in electricity generation. Table 32 shows the impact of varying the transformation elasticity on the gross cost of regulation and total and marginal abatement cost for the ETS and ETS FUEL scenarios. A lower value of the elasticity implies a higher degree of irreversibility in electricity generation, i.e. the reallocation of technology specific capital is limited. Accordingly, welfare losses and abatement costs are decreasing in the value of the elasticity since the ability of responding to price changes is increased. Although the magnitude of the results is affected, the qualitative effect of including transport fuel into the emission trading scheme remains. Still the inclusion shows a negative welfare impact.

Table 32: Sensitivity to capacity malleability

	$\varepsilon_{KE} = 0.5$		$\varepsilon_{KE} = 1$		$\varepsilon_{KE} = 2$	
	ETS	**ETS FUEL**	**ETS**	**ETS FUEL**	**ETS**	**ETS FUEL**
Welfare change [‰ HEV]	-0.83	-1.23	-0.64	-0.92	-0.44	-0.69
Abatement cost [billion €]	2.27	2.25	1.76	1.75	1.46	1.46
CO_2 price emission trading [€/t CO_2]	12.68	12.55	9.86	9.79	8.17	8.14

5.4.2 Private transport

Following Harrison et al. (1992), the sensitivity of the result to a change of the elasticities in the utility function and private transport module is examined using unconditional, systematic sensitivity analysis. The values given in Table 14 are taken as expected values of the substitution elasticities which are assumed to be uniformly distributed in the interval from half to double the expected value. The model is repeatedly run 5000 times drawing elasticities from their respective distribution and solving the scenarios. Table 33 lists characteristics of the resulting distribution of the welfare results.

Table 33: Sensitivity to substitution elasticities in household transport [‰ HEV]

	ETS	**ETS AIR**	**ETS FUEL**	**FUEL TAX**	**ETS SUB**
Mean	-0.61	-0.60	-0.92	-2.30	-0.19
Standard deviation	0.01	0.01	0.03	0.16	0.53
Minimum	-0.65	-0.63	-0.98	-2.65	-1.68
Maximum	-0.59	-0.57	-0.86	-1.95	1.15

The mean of the welfare changes are close to the central model estimates. Policies which address household transport by separate instruments (FUEL TAX, ETS SUB) show a higher variability since the elasticities are more important than in economy wide regulation approaches. The FUEL TAX scenario always incurs the highest gross costs of carbon regulation. The ranking of welfare costs is independent of the parameter choice for all scenarios except the ETS SUB one. Beside ETS SUB, the ETS AIR scenario always has the lowest cost followed by ETS and ETS FUEL. The ETS SUB scenario shows a high standard deviation and range of results. However, in around 77 % of the simulation runs the conclusion of the central model estimate is valid: the recycling of revenues from carbon regulation increasing subsidies on public transport shows the lowest gross cost of carbon regulation.[55]

5.5 Conclusion

This chapter presented a small open economy model of Germany based on the year 2004. The model includes technological details of electricity generation incorporating different generation technologies

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[55] In 90 % of the runs, increasing subsidies show lower cost than the inclusion of public transport in the emission trading scheme.

differentiated by load segment. Furthermore, private transport decisions are taken into account by a detailed description of trips distinguished by purpose, distance, and travel period and the main important transport modes. Moreover, the model integrates congestion as the main externality of road transport affecting the time needed to drive one kilometer and consequently the utility of the representative agent.

The results show that exempting transport from carbon regulation is beneficial shifting the reduction burden to electricity generation and energy intensive production. Optimal taxation of carbon requires a carbon price which is equal for all sectors. The pre-existing tax on transport fuels already implies a price on carbon in road transport. Consequently, exempting road transport lowers the difference in carbon prices. Due to the magnitude of the pre-existing tax, the beneficial effect of lowering the difference in carbon prices outweighs the loss of decreasing flexibility of carbon mitigation. However, even if the model accounts for congestion as the main externality of road transport, other external effects such as accidents and noise are not accounted for. Therfore, the model still overestimates the beneficial effect of excluding transport from carbon regulation. Nevertheless, the systematic bias is smaller than in the previous chapter due to the inclusion of congestion.

The introduction of an emission trading system including refineries induces a shift to more fuel efficient diesel cars. Although diesel has a higher carbon content than gasoline, diesel cars are more carbon efficient since the effect of the higher fuel efficiency exceeds the one of higher carbon content. Accordingly, refineries under emission trading imply a switch to more carbon efficient diesel cars. Since the input costs of refineries are increasing, the price of transport fuels also rises implying incentives switching to diesel cars. The lower tax on diesel fuels amplifies this effect.

Using the revenues obtained by the introduction of emission trading increasing subsidies on public transport clearly leads to positive effects. Increased public subsidies result in a mode switch from private cars towards public transport. On the one hand, carbon emissions of private transport are decreasing even more than in fuel based regulation approaches where reduction mainly occurs in industrial road transport. On the other, decreasing car use also reduces the congestion externality raising speed mainly in the peak travel period.

6 Conclusion

6.1 Summary and conclusion

This thesis posed the question whether including road transport into the EU ETS will lower the cost of carbon regulation. Two different CGE models are employed: an international and a small-open economy model.

The multi-region model shows that a European-wide increase of transport fuel taxes is not a promising option regulating the carbon emissions of transport. Including road transport into the EU ETS indeed can lower the gross cost of carbon regulation. However, the most preferable approach is exempting transport from regulation.

The results are confirmed by the small-open economy model which offers a far more detailed representation of electricity generation and private transport but abstracts from term-of-trade changes. Including transport in emission trading lowers the cost compared to an increase in fuel taxes but the exemption is the most favorable approach.

Thus, the answer to the main question depends on the basic approach of policy makers. If governments decide to use pricing strategies for transport fuels, then the inclusion into emission trading is the best approach. However, generally, no carbon regulation in the road transport sector is the best strategy. Due to already high excise taxes, the exemption of transport moves the after-regulation tax scheme closer to the optimal one. Put differently, the exemption leads to effective carbon tax rates that are closer to uniform across the economy. The small-open economy model shows that the result is stable concerning congestion as a justification for high fuel tax rates. However, both models exclude further external effects such as accidents and noise and, therefore, the results overestimate the beneficial effext of not further increasing transport fuel prices. It is an interesting topic for future research to include these effects in a detailed and concise manner.

The detailed model shows that including aviation in the trading scheme further lowers the cost of regulation. Furthermore, the results indicate that subsidies on public transport may play a significant role in addressing the carbon emission of private transport. Subsidies have two positive effects. First, the costs of carbon regulation decrease by the induced switch to environmentally friendly public transport. Second, the congestion externality inclines due to fewer vehicles on roads. Further welfare gains not included in the model can be expected since the decrease in the traffic-flow also reduces other externalities of transport such as accidents, noise, and local pollution. However, this claim has not been tested against other revenue recycling schemes, in particular the cut of labor taxes. Whether or not the result will prove stable is subject to future research.

6.2 Future research

This thesis neglects the spatial and network aspects of the transport problem as well as of electricity transmission. The inclusion of the spatial dimension of transport is an important topic for future research since it determines the substitution possibilities available for private cars, e.g. rural households have less access to public transport modes and, accordingly, less substitution possibilities. Such differences can be captured in modeling different household types with different locations of living and utility functions (e.g. Mayeres, 1999; Kalinowska et al., 2007). However, such models are not well suited to model households' modes decisions or mode switches in freight transport. An approach of explicitly including transport networks into the general equilibrium model would be preferable. Furthermore, such models allow a better assessment of transport infrastructure improvement. It has to be decided whether the CGE and network models are designed in an integrated formulation or whether they are separately designed and linked in some algorithm.

Roson (1996) describes the MITER model which iteratively links three different sub-models. Ferris et al. (1999) show a Wardop equilibrium problems can be represented in a mixed-complementarity problem. Such a representation allows including detailed network representations into the general equilibrium framework. A first application of integrating public and freight transport networks into a CGE model is given by Ivanova (2003). The discussion about the mitigation of greenhouse gas emissions of transport would benefit from such a modeling approach in order to assess interesting topics such as improved public transport networks and freight network intermodality.

Electricity networks play a substantial role in the penetration of renewable electricity generation. Leuthold et al. (2009) show the impact of additional wind power on the European transmission grid. While the amount of additional grid investments in their study is modest, the integration of solar power from the Middle East and northern Africa into the European grid imposes real challenges (DLR, 2006). In order to assess such scenarios in a general equilibrium framework, it would be useful to integrate grid requirements. This can also be done using the MCP framework.

However, for both, transport and electricity networks, the detailed modeling implies an increase in data requirements. For every node in the network, data on production and demand need to be collected. Furthermore, an increased number of modeled power plants increases the number of installed capacities in the consumers' endowments. Accordingly, income effects become larger and models become computably less tractable. This points into the direction of falling back to decomposition methods and building detailed transport and energy system models. Efficient decomposition methods for CGE models in MCP models have been demonstrated by Rausch and Rutherford (2007) and Rutherford and Tarr (2007) a large number of consumers as well as Böhringer and Rutherford (2009) for large scale energy system models. A combination of these approaches would allow for the implementation of the spatial dimension into the energy system model and using the aggregation approach for households to upscale data from the detailed geographical dimension to a representative agent in the CGE model. A similar approach is implementable for transport system models.

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Appendix A Additional results for Chapter 4

Table 34: Correspondence of GTAP6 and model commodities

GTAP Label	Description	GTAP Label	Description
Agriculture (AGR)			
b_t	Beverages and tobacco products	omt	Meat products nec
c_b	Sugar cane sugar beet	osd	Oil seeds
cmt	Meat: cattle, sheep, goats, horse	pcr	Processed rice
ctl	Cattle, sheep, goats, horses	pdr	Paddy rice
frs	Forestry	pfb	Plant-based fibers
fsh	Fishing	rmk	Raw milk
gro	Cereal grains nec	sgr	Sugar
lea	Leather products	tex	Textiles
lum	Wood products	v_f	Vegetables fruit nuts
mil	Dairy products	vol	Vegetable oils and fats
oap	Animal products nec	wap	Wearing apparel
ocr	Crops nec	wht	Wheat
ofd	Food products nec	wol	Wool silk-worm cocoons
Energy intensive production (EINT)			
fmp	Metal products	nmm	Mineral products nec
i_s	Ferrous metals	ppp	Paper products publishing
nfm	Metals nec		
Industrial transport (TRN)			
atp	Air transport	wtp	Sea transport
otp	Other transport (road, rail, pipeline)		
Industries and services (MAC)			
cgds	Aggregate investment	ome	Machinery and equipment nec
cmn	Communication	omf	Manufactures nec
cns	Construction	omn	Minerals nec
crp	Chemical, rubber, plastic products	osg	Public administration, defense, health, and education
dwe	Dwellings	otn	Transport equipment nec
ele	Electronic equipment	ros	Recreation and other services
isr	Insurance	trd	Trade
obs	Business services nec	wtr	Water
ofi	Financial services nec		
Natural gas (gas)			
gas	Natural gas	gdt	Natural gas manufacture & distribution
Not aggregated			
coa	Coal	oil	Crude oil
ely	Electricity	p_c	Petroleum coal products
mvh*	Motor vehicles and parts		

* Relabeled as CAR sector; nec: not elsewhere classified

Table 35: Correspondence of GTAP6 and model regions

GTAP Label	Description	GTAP Label	Description
		Annex I	
aus	Australia	tur	Turkey
can	Canada	usa	United States
che	Switzerland	xef	Rest of EFTA
jpn	Japan	xer	Rest of Europe
nzl	New Zealand	xsu	Rest of Former Soviet Union
rus	Russian Federation		
		Benelux	
bel	Belgium	nld	Netherlands
lux	Luxembourg		
		Remaining east European countries	
bgr	Bulgaria	ltu	Lithuania
cyp	Cyprus	mlt	Malta
cze	Czech Republic	rom	Romania
est	Estonia	svk	Slovakia
hun	Hungary	svn	Slovenia
lva	Latvia		
		Rest of the world	
alb	Albania	twn	Taiwan
arg	Argentina	tza	Tanzania
bgd	Bangladesh	uga	Uganda
bra	Brazil	ury	Uruguay
bwa	Botswana	ven	Venezuela
chl	Chile	vnm	Vietnam
chn	China	xap	Rest of Andean Pact
col	Colombia	xca	Central America
hkg	HongKong	xcb	Rest of the Caribbean
hrv	Croatia	xea	Rest of EastAsia
idn	Indonesia	xfa.	Rest of FTAA
ind	India	xme	Rest of Middle East
kor	Korea	xna	Rest of North America
lka	SriLanka	xnf.	Rest of North Africa
mar	Morocco	xoc	Rest of Oceania
mdg	Madagascar	xsa	Rest of South Asia
mex	Mexico	xsc	Rest of South African CU
moz	Mozambique	xsd	RestofSADC
mwi	Malawi	xse	Rest of Southeast Asia
mys	Malaysia	xsm	Rest of South America
per	Peru	xss	Rest of Sub-Saharan Africa
phl	Philippines	zaf.	SouthAfrica
sgp	Singapore	zmb	Zambia
tha	Thailand	zwe	Zimbabwe
tun	Tunisia		
		Remaining west European countries	
aut	Austria	grc	Greece
irl	Ireland	prt	Portugal

Non-aggregated European regions are not listed.

Table 36: Selected carbon prices in the SECTORAL scenario [\$/t CO_2]

	Manufacture and services	Electricity	Energy intensives	Refined oils	Industrial transport	Household transport
Benelux	26.28	10.85	19.98	33.89	71.17	200.88
Denmark	33.08	9.03	14.64	156.35	47.44	232.90
Finland	30.63	9.74	30.66	36.14	63.06	159.36
France	19.76	8.23	19.64	60.82	50.62	231.52
Germany	16.46	6.83	15.38	55.09	54.06	152.17
Italy	20.92	8.80	18.42	45.02	56.39	178.02
Poland	0	0	0	0	0	0
Spain	11.53	3.94	13.79	40.80	27.69	93.74
Sweden	40.11	7.79	74.82	47.92	44.15	156.90
United Kingdom	16.08	8.35	18.01	58.45	71.81	232.12
Western EU	15.19	4.68	10.89	49.17	23.96	90.83
Eastern EU	0	0	0	0	0	0

Table 37: National carbon prices [\$/t CO_2]

	NATIONAL	ETS	ETS CLOSED TRN	ETS TRN	ETS EXEMPT TRN
Benelux	27.31	31.10	29.20	29.46	29.34
Denmark	21.21	23.70	24.49	25.29	25.01
Finland	19.84	23.00	22.80	23.42	23.15
France	32.79	34.47	34.06	34.21	34.23
Germany	14.70	16.03	15.40	15.70	15.59
Italy	21.74	25.03	24.40	25.01	24.84
Poland	0.00	1.30	0.00	1.35	1.36
Spain	10.23	10.73	10.19	10.70	10.56
Sweden	43.24	46.73	46.57	46.73	46.54
United Kingdom	18.32	19.81	19.37	19.77	19.73
Western EU	10.35	10.81	10.38	10.69	10.49
Eastern EU	0.00	0.57	0.00	0.27	0.25
Annex I	4.36	4.25	4.31	4.24	4.24
Rest of the World	0.00	0.00	0.00	0.00	0.00

Table 38: European carbon prices [\$/t CO_2]

	FULL	ETS	ETS CLOSED TRN	ETS TRN	ETS EXEMPT TRN
Electricity	8.77	6.16	9.81	7.27	8.10
Transport	8.77		17.71	7.27	0.00

Table 39: Export of carbon permits [Mt CO_2]

	Full	ETS	ETS CLOSED TRN	ETS TRN	ETS EXEMPT TRN
Benelux	-32.329	-18.412	-14.641	-21.733	-22.074
Denmark	-5.419	-4.967	-3.477	-5.184	-5.218
Finland	-5.270	-5.297	-3.734	-5.318	-5.207
France	-38.474	-10.779	-8.955	-20.658	-23.052
Germany	-44.083	-47.199	-25.252	-44.520	-43.011
Italy	-32.366	-26.304	-19.136	-28.856	-29.239
Poland	92.992	71.684	57.802	77.399	79.780
Spain	-3.203	-7.721	-0.379	-6.288	-7.368
Sweden	-6.832	-2.871	-2.505	-5.693	-6.230
United Kingdom	-41.055	-34.207	-22.157	-33.899	-33.322
Western EU	-3.539	-8.042	-0.850	-6.461	-7.200
Eastern EU	119.580	94.114	43.283	101.209	102.140

Table 40: Compliance cost [billion $]

	SECTORAL	NATIONAL	FULL	ETS	ETS CLOSED TRN	ETS TRN	ETS EXEMPT TRN
Benelux	2.599	1.374	0.158	0.776	0.698	0.609	0.615
Denmark	0.613	0.221	0.044	0.074	0.092	0.062	0.065
Finland	0.412	0.191	0.038	0.054	0.073	0.047	0.051
France	3.711	1.824	0.150	1.405	1.111	0.997	0.990
Germany	4.935	1.790	0.681	0.766	1.147	0.769	0.827
Italy	3.280	1.264	0.226	0.507	0.551	0.396	0.409
Poland	0.000	0.000	0.449	0.184	0.477	0.259	0.309
Spain	0.783	0.317	0.244	0.181	0.374	0.197	0.207
Sweden	0.641	0.393	0.020	0.248	0.120	0.093	0.091
United Kingdom	0.679	0.289	0.213	0.150	0.329	0.167	0.178
Western EU	4.382	1.621	0.416	0.743	0.919	0.708	0.738
Eastern EU	0.000	0.000	0.501	0.195	0.553	0.282	0.324
EU 27	22.034	9.284	3.140	5.283	6.444	4.586	4.803

Table 41: Emission reduction of selected sectors [%]

	NATIONAL			FULL			ETS			ETS CLOSED TRN			ETS TRN			ETS EXEMPT TRN		
	ELE	**HTRN**	**TRN**	**ELE**	**HTRN**	**TRN**	**ELE**	**HTRN**	**TRN**	**ELE**	**HTRN**	**TRN**	**ELE**	**HTRN**	**TRN**	**ELE**	**HTRN**	**TRN**
Benelux	29.5	3.3	7.8	11.4	0.9	2.2	9.8	3.0	6.6	14.0	1.8	4.0	11.0	0.6	1.5	11.9	-0.1	-0.3
Denmark	33.4	2.1	9.7	16.6	0.7	3.9	12.9	2.4	10.4	19.0	1.7	7.8	14.9	0.6	3.2	16.2	-0.2	-0.3
Finland	26.4	2.4	5.8	12.4	0.9	2.2	9.2	2.7	5.9	14.4	2.0	4.6	10.7	0.7	1.7	11.9	-0.3	-0.2
France	35.3	2.6	9.7	13.2	0.4	2.2	11.9	2.4	9.5	16.4	1.1	4.8	13.0	0.3	1.8	14.0	-0.3	-0.4
Germany	26.1	1.4	4.1	16.8	0.7	2.2	12.6	1.4	3.9	18.9	1.6	4.4	14.5	0.5	1.7	15.9	-0.3	-0.3
Italy	25.4	1.9	5.9	12.1	0.6	2.1	9.7	2.0	5.9	14.0	1.4	4.3	10.9	0.4	1.7	11.9	-0.3	-0.2
Poland	-2.2	-0.5	-1.1	22.9	0.0	5.1	16.6	-0.9	0.4	25.0	2.0	9.8	19.3	0.1	4.1	21.1	-1.3	0.1
Spain	21.2	0.9	3.7	18.9	0.8	3.3	14.1	1.0	3.7	20.8	1.9	6.7	16.2	0.6	2.7	17.6	-0.3	-0.3
Sweden	43.7	5.8	16.4	14.9	0.9	3.4	12.6	5.6	16.5	17.6	2.1	6.9	14.0	0.7	2.8	15.2	-0.2	-0.3
United Kingdom	28.8	1.4	4.4	15.8	0.6	1.9	12.1	1.4	4.3	18.0	1.3	3.9	13.9	0.4	1.5	15.2	-0.2	-0.2
Western EU	19.0	0.9	4.1	16.4	0.8	3.9	12.1	1.0	4.2	18.2	1.9	7.8	14.0	0.6	3.1	15.3	-0.4	-0.4
Eastern EU	-2.8	-0.7	-1.3	19.9	0.5	5.3	14.3	-1.1	-0.1	21.3	3.0	9.6	16.6	0.4	4.1	18.0	-1.4	0.1

Legend: ELE: Electricity; HTRN: Household own provided transport; TRN: Industrial transport

Table 42: Sensitivity results substitution elasticity between own transport and consumption [% HEV vs. BAU]

	NATIONAL	ETS	ETS CLOSED TRN	ETS TRN	ETS EXEMPT TRN
0	-0.413	-0.328	-0.311	-0.179	-0.11
0.1	-0.413	-0.328	-0.311	-0.179	-0.11
0.2	-0.413	-0.329	-0.311	-0.179	-0.11
0.3	-0.413	-0.329	-0.311	-0.179	-0.11
0.4	-0.413	-0.329	-0.311	-0.179	-0.11
0.5	-0.414	-0.329	-0.311	-0.179	-0.11
0.6	-0.414	-0.329	-0.312	-0.179	-0.11
0.7	-0.414	-0.329	-0.312	-0.179	-0.11
0.8	-0.414	-0.329	-0.312	-0.179	-0.11
0.9	-0.414	-0.329	-0.312	-0.179	-0.11
1	-0.414	-0.329	-0.312	-0.179	-0.11

Default value is marked in grey.

Table 43: Sensitivity results fuel price demand elasticity [% HEV vs. BAU]

	NATIONAL	ETS	ETS CLOSED TRN	ETS TRN	ETS EXEMPT TRN
0	-0.39	-0.31	-0.30	-0.18	-0.12
0.1	-0.40	-0.32	-0.30	-0.18	-0.12
0.2	-0.41	-0.32	-0.31	-0.18	-0.11
0.3	-0.41	-0.33	-0.31	-0.18	-0.11
0.4	-0.42	-0.34	-0.32	-0.18	-0.11
0.5	-0.43	-0.34	-0.32	-0.18	-0.11
0.6	-0.43	-0.35	-0.33	-0.18	-0.10
0.7	-0.44	-0.36	-0.33	-0.18	-0.10
0.8	-0.45	-0.36	-0.34	-0.19	-0.10
0.9	-0.45	-0.37	-0.34	-0.19	-0.10
1	-0.46	-0.38	-0.34	-0.19	-0.09

Default value is marked in grey.

Table 44: Sensitivity results substitution elasticity other transport cost [% HEV vs. BAU]

	NATIONAL	ETS	ETS CLOSED TRN	ETS TRN	ETS EXEMPT TRN
0	-0.414	-0.329	-0.311	-0.179	-0.11
0.1	-0.414	-0.329	-0.311	-0.179	-0.11
0.2	-0.414	-0.329	-0.311	-0.179	-0.11
0.3	-0.414	-0.329	-0.311	-0.179	-0.11
0.4	-0.414	-0.329	-0.311	-0.179	-0.11
0.5	-0.414	-0.329	-0.311	-0.179	-0.11
0.6	-0.414	-0.329	-0.312	-0.179	-0.11
0.7	-0.414	-0.329	-0.312	-0.179	-0.11
0.8	-0.414	-0.329	-0.312	-0.179	-0.11
0.9	-0.414	-0.329	-0.312	-0.179	-0.11
1	-0.414	-0.329	-0.312	-0.179	-0.11

Default value is marked in grey.

Table 45: Sensitivity results substitution elasticity own and purchased transport [% HEV vs. BAU]

	NATIONAL	ETS	ETS CLOSED TRN	ETS TRN	ETS EXEMPT TRN
0	-0.414	-0.329	-0.311	-0.179	-0.11
0.1	-0.414	-0.329	-0.311	-0.179	-0.11
0.2	-0.414	-0.329	-0.311	-0.179	-0.11
0.3	-0.414	-0.329	-0.311	-0.179	-0.11
0.4	-0.414	-0.329	-0.311	-0.179	-0.11
0.5	-0.414	-0.329	-0.311	-0.179	-0.11
0.6	-0.414	-0.329	-0.311	-0.179	-0.11
0.7	-0.414	-0.329	-0.311	-0.179	-0.11
0.8	-0.414	-0.329	-0.311	-0.179	-0.11
0.9	-0.414	-0.329	-0.311	-0.179	-0.11
1	-0.414	-0.329	-0.311	-0.179	-0.11

Default value is marked in grey.

Appendix B GAMS codes for the international model

GAMS code to calibrate household transport

```
$title Calibration of the International Transport Emission Trading Model

$ontext
***** STRUCTURE
         (1) LOAD AND RENAME GTAP DATA
         (2) SEPARATE HOUSHOLD TRANSPORT SECTOR
         (3) CREATE HOUSEHOLD TRANSPORT SECTOR HTRN
         (4) CALIBRATE EMISSIONS
         (5) SAVE DATA TO GDX

***** OPTIONS
         ds:             name of GTAP6 source file
         datadir:        name of data directory
         out:            name of output file
         trn:            label of transport sector
         xls:            name of xls file containing additional data


***** Additional files
         gtap6data.gms   rutherford tool to load GTAP6 data
         http://www.mpsge.org/gtap6/

REFERNECES:
Paltsev et al. (2004): "Dissaggregating Household Transport in the MIT-EPPA Model".
         MIT Joint Program on the Science and Policy of Global Change.
         Technical Note No 5
$offtext

* GTAP 6 input file
$set ds ET_TRN
$set out ET_TRN_htrn

* Assign default values
$if not set datadir $set datadir "..\data\"
$if not set trn $set trn "trn"
$if not set xls $set xls trn_shares

* Check inputs
$if not set ds $abort "###### Specify Data Source ######"
$if not exist "%datadir%%ds%.gdx"  $abort "###### Source File Missing ######"
$if not exist "%datadir%%xls%.xls"  $abort "###### Additional Data File Missing ######"

*###############################################################################
*                         (1) LOAD AND RENAME GTAP DATA
*###############################################################################
* Load data using GTAP6 tools
$include gtap6data

parameter
         y0      total output 10^9$
         d0      output to domestic market 10^9$
         e0      exports 10^9$
         to      output tax
         id0     intermediate inputs  10^9$
         pi0     intermediate input price
         ti      intermediate input tax
         fd0     factor demand 10^9$
         pf0     factor purchase price
         tf      factor tax

         c0      total private consumption (incl tax) 10^9$
         cd0     private consumtion 10^9$
         pc0     private consumption purchase price
         tc      tax on private consumption
         fs0     factor supply 10^9$
         inv0    investment

         g0      total public consumption (incl tax) 10^9$
         gd0     public consumption 10^9$
         pg0     public consumption purchase price
         tg      tac on public consumption
         bop     balance of payment 10^9$
```

```
         ctax    direct consumer tax 10^9$

         a0      armington output 10^9$
         m0      aggregated imports 10^9$
         mad0    transport margin demand fo imports 10^9$
         md0     import by countries 10^9$
         tm      tax on imports
         te      tax on exports
         pm0     bilateral import price
         ma0     trnsport margin 10^9$
         mae0    transport margin exports by country 10^9$
         pma0    margin price 10^9$

         check   check of equilibrium conditions should be zero
;

scalar
         rounding        rounding factor for data        /8/
;

*----------------------------- FIRM PARAMETER ----------------------------------
e0(i,r)          = round(sum(s, vxmd(i,r,s)) + vst(i,r), rounding);
d0(i,r)          = round(vdpm(i,r) + vdgm(i,r) + sum(j, vdfm(i,j,r)) + vdim(i,r), rounding);
y0(i,r)          = e0(i,r) + d0(i,r);
to(i,r)          = rto(i,r);
id0(i,j,r)       = round(vdfm(i,j,r) + vifm(i,j,r), rounding);
ti(i,j,r)$id0(i,j,r) = (rtfd(i,j,r)*vdfm(i,j,r) + rtfi(i,j,r)*vifm(i,j,r))/(id0(i,j,r));
pi0(i,j,r)       = 1 + ti(i,j,r);
fd0(f,i,r)       = round(vfm(f,i,r), rounding);
tf(f,i,r)        = rtf(f,i,r);
pf0(f,i,r)       = 1 + tf(f,i,r);

check("zpf",i,r) = round(y0(i,r)*(1-to(i,r)) - (
                         sum(j, pi0(j,i,r)*id0(j,i,r))
                         + sum(f, fd0(f,i,r)*pf0(f,i,r))
                         ),8);

*----------------------------- PRIVATE PARAMETER -------------------------------
cd0(i,r)              = round(vdpm(i,r) + vipm(i,r),rounding);
tc(i,r)$cd0(i,r)      = (vdpm(i,r)*rtpd(i,r) + vipm(i,r)*rtpi(i,r))/cd0(i,r);
pc0(i,r)              = 1 + tc(i,r);
c0(r)                 = sum(i, cd0(i,r)*pc0(i,r));
fs0(f,r)              = round(evom(f,r),rounding);
inv0(i,r)             = round(vdim(i,r),rounding);
ctax(r)               = sum(f, evom(f,r)) - c0(r) - sum(i, inv0(i,r));
check("inc","x",r)    = round(c0(r) + sum(i, inv0(i,r)) + ctax(r)
                      - sum(f, fs0(f,r)) ,8);

*----------------------------- TRADE PARAMETER ---------------------------------
md0(i,r,s)       = round(vxmd(i,r,s),rounding);
* If no imports from the region exist set exports of region to zero
e0(i,r)$(not sum(s, md0(i,r,s))) = 0;
tm(i,r,s)        = rtms(i,r,s);
te(i,r,s)        = -rtxs(i,r,s);
pm0(i,r,s)       = (1+te(i,r,s))*(1+tm(i,r,s));
mad0(i,j,r,s)    = round(vtwr(i,j,r,s),rounding);
m0(i,r)          = round(vigm(i,r) + vipm(i,r) + sum(j, vifm(i,j,r)),rounding);
mae0(i,r)        = round(vst(i,r),rounding);
ma0(i)           = round(vtw(i),rounding);
pma0(i,r,s)      = 1 + tm(i,r,s);
a0(i,r)          = m0(i,r) + d0(i,r);

check("imports",i,r) = round(m0(i,r) - (
                         sum(s, md0(i,s,r)*pm0(i,s,r))
                         + sum((s,j), mad0(j,i,s,r)*pma0(i,s,r))),8);

check("margin",i,"x") = round(ma0(i) - sum(r, mae0(i,r)),8);

*---------------------------- PUBLIC PARAMETER ---------------------------------
gd0(i,r)         = round(vdgm(i,r) + vigm(i,r),rounding);
tg(i,r)$gd0(i,r) = (vdgm(i,r)*rtgd(i,r) + vigm(i,r)*rtgi(i,r))/gd0(i,r);
pg0(i,r)         = 1 + tg(i,r);
g0(r)            = sum(i, gd0(i,r)*pg0(i,r));
bop(r)           = round(vb(r),rounding);

check("gov","x",r) = round(g0(r) - (
                         ctax(r)
                         + sum(i, gd0(i,r)*tg(i,r))
                         + sum(i, cd0(i,r)*tc(i,r))
                         + sum((i,j), id0(i,j,r)*ti(i,j,r))
```

```
                         + sum((i,f), fd0(f,i,r)*tf(f,i,r))
                         + sum(i, y0(i,r)*to(i,r))
                         + sum((i,s), tm(i,s,r)*md0(i,s,r)*(1+te(i,s,r)))
                         + sum((i,j,s), tm(i,s,r)*mad0(j,i,s,r))
                         + sum((i,s),te(i,r,s)*md0(i,r,s))
                         )
                     - bop(r),8);
display "Initial equilibrium condition check: ", check;

*################################################################################
*                (2) SEPARATE HOUSHOLD TRANSPORT SECTOR
*################################################################################
parameter
         es(r)           share of own transportation in total expenditure
         os(r)           share of gasoline in refined oil consumption
         own             own transport spendings
         gaso            gasoline spendings
         otc             other transport costs
         car             car purchases
         emi             empirical total emissions by region
         sharesHH        data parameter
;

* Load data from xls
execute "gdxxrw %datadir%%xls%.xls o=%datadir%%xls% par=sharesHH rng=GAMS!A1"

$gdxin "%datadir%%xls%"
$load sharesHH

es(r)    = sharesHH(r,"ES");
os(r)    = sharesHH(r,"OS");
emi(r)   = sharesHH(r,"emi")/1000;
own(r)   = es(r)*c0(r);
gaso(r)  = cd0("p_c",r)*os(r);
car(r)   = cd0("car",r);
otc(r)   = (own(r) - gaso(r)*pc0("p_c",r) - car(r)*pc0("car",r))/pc0("mac",r);

*################################################################################
*                (3) CREATE HOUSEHOLD TRANSPORT SECTOR HTRN
*################################################################################
i("htrn") = yes;
set
         trn(*)     set of transport modes
         /%trn%/
;
display trn;

* CARS
id0("car","htrn",r)       = car(r);
ti("car","htrn",r)        = tc("car",r);
pi0("car","htrn",r)       = 1 + ti("car","htrn",r);

* FUELS
id0("p_c","htrn",r)       = gaso(r);
ti("p_c","htrn",r)        = tc("p_c",r);
pi0("p_c","htrn",r)       = 1 + ti("p_c","htrn",r);

* OTHER TRANSPORT COST
id0("mac","htrn",r)       = otc(r);
ti("mac","htrn",r)        = tc("mac",r);
pi0("mac","htrn",r)       = 1 + ti("mac","htrn",r);

* TRANSPORT
id0(trn,"htrn",r)         = cd0(trn,r);
ti(trn,"htrn",r)          = tc(trn,r);
pi0(trn,"htrn",r)         = 1 + ti(trn,"htrn",r);

* OUTPUT
y0("htrn",r)              = own(r) + sum(i$trn(i), cd0(i,r)*pc0(i,r));
d0("htrn",r)              = y0("htrn",r);
a0("htrn",r)              = d0("htrn",r);


* Correct household sector
cd0("car",r)              = 0;
cd0("p_c",r)              = cd0("p_c",r) - gaso(r);
cd0("mac",r)              = cd0("mac",r) - otc(r);
cd0("htrn",r)             = y0("htrn",r);
cd0(trn,r)                = 0;
tc("htrn",r)              = 0;
```

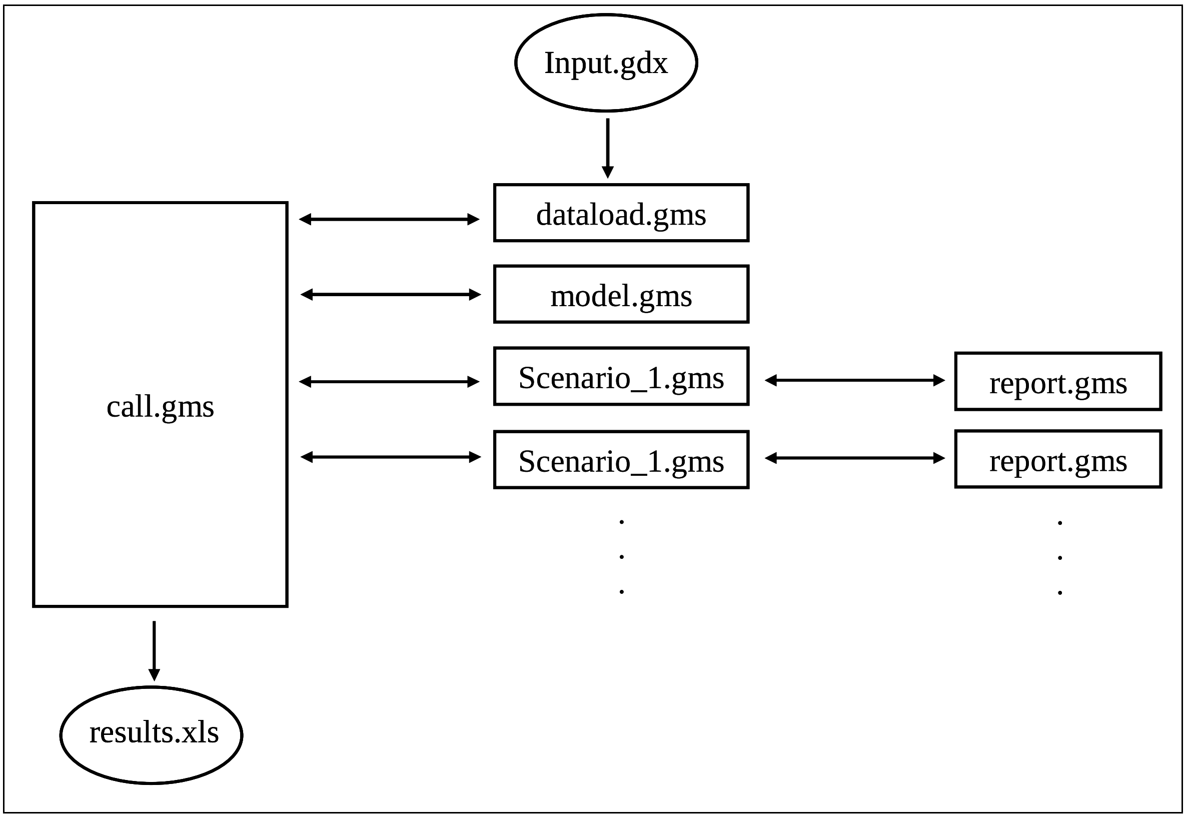
```
pc0("htrn",r)            = 1 + tc("htrn",r);

c0(r)          = sum(i, pc0(i,r)*cd0(i,r));
a0(i,r)        = m0(i,r) + d0(i,r);

* Again check of zero profit and income conditions:
check("zpf",i,r) = round(y0(i,r)*(1-to(i,r)) - (
                         sum(j, pi0(j,i,r)*id0(j,i,r))
                         + sum(f, fd0(f,i,r)*pf0(f,i,r))
                         ),8);

check("inc","x",r) = round(c0(r) + sum(i, inv0(i,r)) + ctax(r)
                     - sum(f, evom(f,r)) ,8);

check("gov","x",r) = round(g0(r) - (
                         ctax(r)
                         + sum(i, gd0(i,r)*tg(i,r))
                         + sum(i, cd0(i,r)*tc(i,r))
                         + sum((i,j), id0(i,j,r)*ti(i,j,r))
                         + sum((i,f), fd0(f,i,r)*tf(f,i,r))
                         + sum(i, y0(i,r)*to(i,r))
                         + sum((i,s), tm(i,s,r)*md0(i,s,r)*(1+te(i,s,r)))
                         + sum((i,j,s), tm(i,s,r)*vtwr(j,i,s,r))
                         + sum((i,s),te(i,r,s)*md0(i,r,s))
                         )
                     - bop(r),8);
display "Final equilibrium condition check: ", check;

* Split energy data
evf("p_c","htrn",r) = evh("p_c",r)*os(r);
evh("p_c",r) = (1-os(r))*evh("p_c",r);


*###############################################################################
*                          (4) CALIBRATE EMISSIONS
*###############################################################################
scalar   convert conversion factor Mtoe -> EJ   /0.04186798/;

evf(i,j,r) = convert*evf(i,j,r);
evh(i,r)   = convert*evh(i,r);

parameter
         emic    emission coefficient Source:IPCC Guidelines
         co20    benchmark carbon emissions in Gt
;
emic("coa",i,r)          = 0.101;
emic("gas",i,r)          = 0.0583;
emic("p_c",i,r)          = 0.0792;
emic("coa","htrn",r)       = 0.101;
emic("gas","hh",r)       = 0.0583;
emic("p_c","hh",r)       = 0.0792;

* Assign special factor for household transport
emic("p_c","htrn",r)     = 0.0675;
emic("p_c",i,r)$trn(i)   = 0.0675;

* Carbon emission below 1 Million t are neglected
co20(i,j,r)$id0(i,j,r)   = round(emic(i,j,r)*evf(i,j,r),3);

* Account for transformation input in refineries (~7% are combustion input, Eurostat energy
* tables)
co20(i,"p_c",r)          = co20(i,"p_c",r)*0.07;
co20(i,"hh",r)$cd0(i,r) = round(emic(i,"hh",r)*evh(i,r),3);
co20("total",i,r)        = sum(j, co20(j,i,r));
co20("total","hh",r)     = sum(i, co20(i,"hh",r));
co20("total","region",r) = sum(i, co20("total",i,r)) + co20("total","hh",r);

display co20;

*------------------- SCALE EMISSIONS TO EMPIRICAL DATA -------------------------
* If no empirical emission data are provided take calibrated data:
emi(r)$(not emi(r)) = co20("total","region",r);

parameter
         checkemi        check of calibrated emission deviation from empirical emissions
;

checkemi("predicted",r) = co20("total","region",r);
checkemi("empirical",r) = emi(r);
checkemi("abs dev",r)   = co20("total","region",r) -  emi(r);
```

```
checkemi("rel dev",r)   = (co20("total","region",r) -  emi(r))/co20("total","region",r);

parameter
         correct(r)      correction factor to meet empirical emissions
;

correct(r)               = 1 - checkemi("rel dev",r);
co20(i,j,r)              = round(correct(r)*emic(i,j,r)*evf(i,j,r),3);
co20(i,"p_c",r)          = co20(i,"p_c",r)*0.07;
co20(i,"hh",r)$cd0(i,r)  = round(correct(r)*emic(i,"hh",r)*evh(i,r),3);
co20("total",i,r)        = sum(j, co20(j,i,r));
co20("total","hh",r)     = sum(i, co20(i,"hh",r));
co20("total","region",r) = sum(i, co20("total",i,r)) + co20("total","hh",r);

checkemi("predicted2",r) = co20("total","region",r);
checkemi("abs dev2",r)   = co20("total","region",r) -  emi(r);
checkemi("rel dev2",r)   = (co20("total","region",r) -  emi(r))/emi(r);
display checkemi;

parameter
         co20shares       share of sectors in emissions
;

co20shares(i,r) = co20("total",i,r)/co20("total","region",r);
co20shares("hh",r) = co20("total","hh",r)/co20("total","region",r);
display co20shares, co20;

*###############################################################################
*                           (5) SAVE DATA TO GDX
*###############################################################################
$if not set out $exit
execute_unload "%datadir%%out%.gdx" co20, i, f, r, rnum, mf, sf,
         y0, d0, e0, to, id0, pi0, ti, fd0, pf0, tf,
         c0, cd0, pc0, tc, fs0, inv0,
         g0, gd0, pg0, tg, bop, ctax,
         a0, m0, mad0, md0, tm, te, pm0, ma0, mae0, pma0,
         etrae, esubva, esubm, esubd, eta, epsilon
;
```

GAMS model codes

The model is written in a modular form. *call.gms* is the main file. In this file the data source and the scenarios are defined. It calls *dataload.gms* which loads the data and performs additional data manipulation. Afterwards the file *model.gms* is included which generates the MPSGE model. The selected scenarios are computed and the results are stored. Finally, the results are exported to Excel in a pivot table friendly format.

Figure 12: Programming flow chart



call.gms

```
$title Call File for European Transport Emission Trading Model
$ontext
STRUCTURE:
         (1)     ASSIGN INPUTS FILES AND LOAD DATA
         (2)     DEFINE POLICY PARAMETER
         (3)     GENERATE MODEL
         (4)     INVOKE SCENARIOS
         (5)     CREATE RESULTS FILE

***** OPTIONS
         ds:             name of data source gdx
         results:        name of result file
         model:          model file name
         datadir:        name of data directory
         resultsdir:     directory for results
         scenariodir:    directory with scenario files
         scale:          scaling value for monetary data; orginal unit is 19**9 $
         sensi:          yes if sensitivity analysis is performed

***** ELASTICITIES
         PEtrn:          price elasticity of demand of transport fuels
                         default: 0.3
         esub_htop:      substitution between consumption and transport
                         default: 0.3
         esub_htrn:      substitution purchased vs own transport
                         default: 0.2
         esub_hotc:      substitution other transport costs
                         default: 0.5
$offtext

*###############################################################################
*                   (1)     ASSIGN INPUTS FILES AND LOAD DATA
*###############################################################################
* Set Inputs
$set ds ET_TRN_HTRN
$set model model
$set results results_tax

* Assign default values
$if not set datadir $set datadir "..\data\"
$if not set debug $set debug no
$if not set resultsdir $set resultsdir "..\results\"
$if not set scenariodir $set scenariodir "..\scenarios\"
$if not set PEtrn $set PEtrn 0.3
$if not set scale $set scale 1
$if not set sensi $set sensi no

* Check inputs
$if not set ds $abort "###### Specify Data Soource ######"
$if not set model $abort "##### Specify model file #####"
$if not exist "%datadir%%ds%.gdx"  $abort "###### Source File Missing ######"

* Install default elasticities
$if not set PEtrn $set PEtrn 0.3
$if not set esub_htop $set esub_htop 0.5
$if not set esub_htrn $set esub_htrn 0.2
$if not set esub_hotc $set esub_hotc 0.5
$if not set etagas $set etagas 1
$if not set etaoil $set etaoil 1
$if not set etacoa $set etacoa 0.5

* Load data
$include dataload

*###############################################################################
*                   (2)     DEFINE POLICY PARAMETER
*###############################################################################
parameter
         carblimI(r)     endowment for first trading system
         carblimII(r)    endowment for second trading system
         carblimIII(r)   endoement for third trading system
         carblimS(*,r)   endowment for sectoral policy
         keynes          one if keynesian closure is used     /0/
;

carblimI(r)      = 0;
carblimII(r)     = 0;
carblimIII(r)    = 0;
```

```
carblimS(i,r)    = 0;
carblimS("hh",r) = 0;

set
         etsI(*,r)       sectors under emission trading system I
         etsII(*,r)      sectors under emission trading system II
         etsIII(*,r)     sector under emission trading system III
         intI(r)         countries which participate in international trade with system I
         intII(r)        countries which participate in international trade with system II
         intIII(r)       countries which participate in international trade with system III
         exempted(*,r)   sector exempted from carbon policy
         euets(*)        sectors under European emissions trading
         euetsII(*)      sector under European emission trading II
;

etsI(i,r) = no; etsI("hh",r) = no; etsII(i,r) = no; etsII("hh",r) = no; etsIII(i,r) = no;
etsIII("hh",r) = no; intI(r) = no; intII(r) = no; intIII(r) = no; exempted(i,r) = no;
euets(i) = no; euetsII(i)= no;

parameter        redu    reduction requirements by countries (effort sharing)
         /
         dnk     0.20
         fin     0.16
         fra     0.14
         deu     0.14
         gbr     0.16
         ita     0.13
         esp     0.10
         swe     0.17
         pol     -0.14
         ben     0.16
         weu     0.10
         eeu     -0.15
         ani     0.05
         /
;

*###############################################################################
*                   (3)     DEFINE POLICY PARAMETER
*###############################################################################
$include "model"

*###############################################################################
*                   (4)     INVOKE SCENARIOS
*###############################################################################
$include "%scenariodir%benchmark"
$include "%scenariodir%Sectoral"
$include "%scenariodir%National"
$include "%scenariodir%Full"
$include "%scenariodir%ETS"
$include "%scenariodir%ETS_closed_trn"
$include "%scenariodir%ETS_trn"
$include "%scenariodir%ETS_exempt_trn"

*###############################################################################
*                   (5)     CREATE RESULTS FILE
*###############################################################################
$if not set results $exit
$if exist "%resultsdir%%results%.xls" $call "rm %resultsdir%%results%.xls"
$set workbook "%resultsdir%%results%"
$set pivotids pivotids.txt
$batinclude pivotdata activity scenario type from to region
$batinclude pivotdata price Scenario Variable From To Region
$batinclude pivotdata abatement Scenario Sector Region
$batinclude pivotdata carbon Scenario Sector Region
$batinclude pivotdata reduction Scenario Sector Region
$batinclude pivotdata carbonlim Scenario Sector Region
$batinclude pivotdata carbontrade Scenario System Region
$batinclude pivotdata reduction Scenario Sector Region
$batinclude pivotdata report Scenario Stat Region
$batinclude pivotdata trntax Scenario Type Sector Region
$batinclude pivotdata htrnshares Type Input Region
$batinclude pivotdata tot scenario type Region
$batinclude pivotdata eint input sector region
$batinclude pivotdata cint region
$batinclude pivotdata expo scenario type level commodity region
$batinclude pivotdata fueltax sector region
```

dataload.gms

```
$title Data load for EU transport Emission Trade Model
$ontext
STRUCTURE:
         (1)     LOAD ALL RELEVANT DATA FROM GDX
         (2)     DEFINE NESTING SETS
         (3)     DEFINE AND ASSIGN ELASTICITIES
         (4)     ADDITIONAL CALIBRATION OF SECTO SPECIFIC RESOURCES
         (5)     DEFINE REPORT PARAMETER
$offtext

*###############################################################################
*                 (1)     LOAD ALL RELEVANT DATA FROM GDX
*###############################################################################
set
         i       set of commodities
         f       set of factors
         r       set of regions
         rnum(r) numeraire region
         mf(f)   mobile factors
         sf(f)   sluggish factors
;
$load i f r rnum mf sf
alias (i,j), (r,s);

set
         eu(r)           EU 27 countries
         /dnk, fin, fra, deu, gbr, ita, esp, swe, pol, ben, weu, eeu/
         annexI(r)       remaining annex I countries
         /ani/
         nonannexI       non-annex I countries
;
nonannexI(r)$(not eu(r) and not annexI(r)) = yes;

parameter
         y0      total output 10^9$
         d0      output to domestic market 10^9$
         e0      exports 10^9$
         to      output tax
         id0     intermediate inputs  10^9$
         pi0     intermediate input price
         ti      intermediate input tax
         fd0     factor demand 10^9$
         pf0     factor purchase price
         tf      factor tax
         c0      total private consumption (incl tax) 10^9$
         cd0     private consumption 10^9$
         pc0     private consumption purchase price
         tc      tax on private consumption
         fs0     factor supply 10^9$
         inv0    investment
         g0      total public consumption (incl tax) 10^9$
         gd0     public consumption 10^9$
         pg0     public consumption purchase price
         tg      tax on public consumption
         bop     balance of payment 10^9$
         ctax    direct consumer tax 10^9$
         a0      Armington output 10^9$
         m0      aggregated imports 10^9$
         mad0    transport margin demand for imports 10^9$
         md0     import by countries 10^9$
         tm      tax on imports
         te      tax on exports
         pm0     bilateral import price
         ma0     transport margin 10^9$
         mae0    transport margin exports by country 10^9$
         pma0    margin price 10^9$
         co20    carbon dioxide emission Gt
         ra0     benchmark consumers income
         gov0    benchmark government income
         check   check of equilibrium conditions should be zero
;
$load co20 y0 d0 e0 to id0 pi0 ti fd0 pf0 tf
$load c0 cd0 pc0 tc fs0 inv0 g0 gd0 pg0 tg bop ctax
$load a0 m0 mad0 md0 tm te pm0 ma0 mae0 pma0

*------------------------------ Scale Values -----------------------------------
scalar   scale   scaling coefficient for values  /%scale%/;
y0(i,r)       = y0(i,r)*scale;
```

```
d0(i,r)       = d0(i,r)*scale;
e0(i,r)       = e0(i,r)*scale;
id0(i,j,r)    = id0(i,j,r)*scale;
fd0(f,i,r)    = fd0(f,i,r)*scale;
c0(r)         = c0(r)*scale;
cd0(i,r)      = cd0(i,r)*scale;
fs0(f,r)      = fs0(f,r)*scale;
inv0(i,r)     = inv0(i,r)*scale;
g0(r)         = g0(r)*scale;
gd0(i,r)      = gd0(i,r)*scale;
bop(r)        = bop(r)*scale;
ctax(r)       = ctax(r)*scale;
a0(i,r)       = a0(i,r)*scale;
m0(i,r)       = m0(i,r)*scale;
mad0(i,j,r,s) = mad0(i,j,r,s)*scale;
md0(i,r,s)    = md0(i,r,s)*scale;
ma0(i)        = ma0(i)*scale;
mae0(i,r)     = mae0(i,r)*scale;

*################################################################################
*                        (2)     DEFINE NESTING SETS
*################################################################################
set
         nhtrn(i)        only household transport
         /htrn/
         ntrn(i)         transport sectors
         /trn/
         next(i)         extraction industries
         /coa, gas, oil/
         nene(i)         all energy commodities
         /coa, gas, p_c, ely/
         nfof(i)         nesting set fossil fuels
         /coa, gas, p_c/
         nely(i)         nesting set electricity
         /ely/
         ncoa(i)         nesting set only coal
         /coa/
         nlqd(i)         nesting set liquid fossil fuels
         /gas, p_c/
         nc(i)           nesting set normal = non-energy consumption commodities
;
nc(i)$(not nene(i) and not nhtrn(i)) = yes;

*################################################################################
*                 (3)     DEFINE AND ASSIGN ELASTICITIES
*################################################################################
parameter
         ysub_top(i,r)   substitution elasticity top level production
         ysub_vae(i,r)   substitution elasticity value added and energy aggregate
         ysub_va(i,r)    substitution elasticity value added
         ysub_ene(i,r)   substitution elasticity electricity and fossil fuel aggregate
         ysub_fof(i,r)   substitution elasticity coal and liquid fossil fuels
         ysub_lqd(i,r)   substitution elasticity liquid fossil fuels
         ysub_out(i,r)   output transformation elasticity
         ysub_pur(i,r)   substitution elasticity purchased transport in household transport
         ysub_otc(i,r)   substitution elasticity other transport cost in household transport
         ysub_own(i,r)   substitution elasticity cars and other cost in household transport
         csub_top(r)     substitution elasticity top level private consumption
         csub_ce(r)      substitution elasticity top level "normal" and energy commodities
         csub_c(r)       substitution elasticity top level "normal" commodities
         csub_e(r)       substitution elasticity top level energy commodities
         gsub_top(r)     top level elasticity public consumption
         msub(i,r)       elasticity for imports from different countries
         dmsub(i,r)      Armington elasticity
         tsub(i)         elasticity for transport margins from different countries
         sfsub(f,r)      sector specific resource transformation elasticity
;

scalar
         PEtrn           price elasticity for private fuel demand                /%PEtrn%/
         sub_htop        substitution elasticity consumption transport           /%esub_htop%/
         sub_htrn        substitution elasticity purchased own transport         /%esub_htrn%/
         sub_hotc        substitution elasticity other transport cost            /%esub_hotc%/
;

* Production
ysub_top(i,r)    = 0;
ysub_vae(i,r)    = 0.8;
ysub_va(i,r)     = 1;
ysub_ene(i,r)    = 0.3;
```

```
ysub_fof(i,r)    = 0.5;
ysub_lqd(i,r)    = 1;
ysub_out(i,r)    = 2;
ysub_vae(next,r) = 0;
ysub_va(next,r)  = 1;

* Household transport
ysub_top(nhtrn,r)    = sub_htop;
ysub_pur(nhtrn,r)    = sub_htrn;
ysub_otc(nhtrn,r)    = sub_hotc;
ysub_own(nhtrn,r)    = PEtrn/(1-(id0("p_c","htrn",r)/sum(i$(not ntrn(i)), id0(i,"htrn",r))));

* Consumption
csub_top(r)      = 0.5;
csub_ce(r)       = 0.25;
csub_c(r)        = 0.5;
csub_e(r)        = 0.4;

* Other
gsub_top(r)      = 0;
msub(i,r)        = 5;
msub(nfof,r)     = 4;
msub("p_c",r)    = 6;
msub("ely",r)    = 0.5;
dmsub(i,r)       = 2.5;
dmsub("ely",r)   = 0.3;
tsub(i)          = 1;
sfsub(f,r)       = 0.0001;

*###############################################################################
*        (4)     ADDITIONAL CALIBRATION OF SECTOR SPECIFIC RESOURCES
*###############################################################################
* Define sector Specific Resource
mf(f) = yes; sf(f) = no;
mf("res") = no; sf("res") = yes;

parameter      temptax         temporary tax parameter;

scalar         moveLR  share moved to resources        /0.5/;

loop((next,r)$(not fd0("res",next,r) and y0(next,r)),
         tf("res",next,r)  = 0;
         fd0("res",next,r) = fd0("lab",next,r)*moveLR;
         tf("lab",next,r)  = fd0("lab",next,r)*tf("lab",next,r)/((1-moveLR)
                             *fd0("lab",next,r));
         pf0("lab",next,r) = 1 + tf("lab",next,r);
         fs0("lab",r)      = fs0("lab",r) - fd0("lab",next,r)*moveLR;
         fs0("res",r)      = fs0("res",r) + fd0("lab",next,r)*moveLR;
         fd0("lab",next,r)       = fd0("lab",next,r) - fd0("lab",next,r)*moveLR;
);

loop(i$(not next(i)),
         temptax(r)      = tf("cap",i,r)*fd0("cap",i,r)  + tf("res",i,r)*fd0("res",i,r);
         fd0("cap",i,r)  = fd0("cap",i,r) + fd0("res",i,r);
         tf("cap",i,r)$fd0("cap",i,r)   = (temptax(r))/fd0("cap",i,r);
         pf0("cap",i,r)  = 1 + tf("cap",i,r);
         fd0("res",i,r)  = 0;
);
fs0(f,r) = sum(i, fd0(f,i,r));

* Calibrate extractive industries first level elasticity to supply elasticity
parameter
         eta             supply elasticity of fossil fuel supply
         extshare        share of sector specific resources in extractive industries
;

eta("gas") = %etagas%;
eta("oil") = %etaoil%;
eta("coa") = %etacoa%;

extshare(next,r)$y0(next,r) = sum(sf, fd0(sf,next,r)*pf0(sf,next,r))/y0(next,r);
ysub_top(next,r)$y0(next,r) = eta(next) * sum(sf, fd0(sf,next,r)*pf0(sf,next,r))/y0(next,r);
```

```
*################################################################################
*                        (5)     DEFINE REPORT PARAMETER
*################################################################################
parameter
         activity        report parameter for activities
         price           report variable for prices
         carbon          report variable for carbon
         carbonlim       report of carbon limit
         reduction       report of carbon reduction
         report          other reports
         abatement       report of abatement costs
         carbontrade     report carbon trade
         intermediates   report on intermediate demand
         trntax          report on tax income from transport sectors
         tot             report on terms of trade changes
         expo            exports
         impo            imports
;
```

MPSGE code

```
$title International GTAP Model Including Household Transport
option solprint=off, limrow=0, limcol=0;
$ontext
$model:trnet

*################################################################################
*                                ECONOMY DEFINITION
*################################################################################
$sectors:
         Y(i,r)$y0(i,r)                                   ! Production activity
         C(r)                                             ! Private consumption
         G(r)                                             ! Government consumption
         M(i,r)$m0(i,r)                                   ! Imports
         A(i,r)$a0(i,r)                                   ! Armington aggregations
         YT(i)$ma0(i)                                     ! International transport services
         E(i,j,r)$(a0(i,r) and id0(i,j,r) and nfof(i))    ! Energy commodity with carbon
         EC(i,r)$(cd0(i,r) and nfof(i))                   ! Household energy commodities
         FT(f,r)$(sf(f) and fs0(f,r))                     ! Sluggish factor transformation
         INV(r)$keynes                                    ! Investment sector
         EMIT(i,r)$co20("total",i,r)                      ! Emission in industries
         EMITH(r)                                         ! Household emissions
         EXEMPT(i,r)$(exempted(i,r) and co20("total",i,r))! Carbon exemption
         EXEMPTH(r)$exempted("hh",r)                      ! Household carbon exemption

$commodities:
         PY(i,r)$y0(i,r)                                  ! Domestic commodity price
         PX(i,r)$e0(i,r)                                  ! Export price
         PC(r)                                            ! Private consumption price
         PG(r)                                            ! Public consumption price
         PM(i,r)$m0(i,r)                                  ! Import price
         PA(i,r)$a0(i,r)                                  ! Armington price
         PT(i)$ma0(i)                                     ! Transport margin price
         PF(f,r)$fs0(f,r)                                 ! Factor supply
         PFT(f,i,r)$(fd0(f,i,r) and sf(f))                ! Price of sector specific factors
         PE(i,j,r)$(a0(i,r) and id0(i,j,r) and nfof(i))   ! Price energy commodity with carbon
         PEC(i,r)$(cd0(i,r) and nfof(i))                  ! Price household energy goods
         PINV(r)$keynes                                   ! Price aggregated investments

         Pcarbon(i,r)$co20("total",i,r)                     ! emission price in sectors
         Ecarbon(i,r)$(co20("total",i,r) and exempted(i,r)) ! Carbon Price exempted sectors
         EcarbonH(r)$exempted("hh",r)                       ! Carbon Price exempted household
         PcarbonH(r)                                        ! Emission price for household
         PcarbI(r)$(carblimI(r) and not intI(r))            ! Permit price trading system I
         PcarbII(r)$(carblimII(r) and not intII(r))         ! Permit price trading system II
         PcarbIII(r)$(carblimIII(r) and not intIII(r))      ! Permit price trading system III
         WcarbI$(sum(r, carblimI(r)) and card(intI))        ! International permit price I
         WcarbII$(sum(r, carblimII(r)) and card(intII))     ! International permit price II
         WcarbIII$(sum(r, carblimIII(r)) and card(intIII))  ! International permit price III
         PcarbS(i,r)$carblimS(i,r)                          ! Sectoral carbon price
         PcarbH(r)$carblimS("hh",r)                         ! Household carbon price

$consumers:
         RA(r)     ! Representative Agent
         GOV(r)    ! Government

$auxiliary:
         LS(r)     ! Multiplier constraint for lumpsum revenue recycling

*################################################################################
*                                EMISSION SYSTEM
*################################################################################
$prod:exempt(i,r)$(exempted(i,r) and co20("total",i,r))
         O:Ecarbon(i,r)          Q:1
         I:Pcarbon(i,r)          Q:1
+                                A:GOV(r)        T:(-0.99999999)

$prod:exemptH(r)$exempted("hh",r)
         O:EcarbonH(r)          Q:1
         I:PcarbonH(r)          Q:1
+                                A:GOV(r)        T:(-0.99999999)

$prod:emit(i,r)$co20("total",i,r)
         O:Pcarbon(i,r)                                                  Q:1
         I:PcarbI(r)$(etsI(i,r) and carblimI(r) and not intI(r))         Q:1
         I:PcarbII(r)$(etsII(i,r) and carblimII(r) and not intII(r))     Q:1
         I:PcarbIII(r)$(etsIII(i,r) and carblimIII(r) and not intIII(r)) Q:1
         I:WcarbI$(etsI(i,r) and carblimI(r) and intI(r))                Q:1
         I:WcarbII$(etsII(i,r) and carblimII(r) and intII(r))            Q:1
```

```
         I:WcarbIII$(etsIII(i,r) and carblimIII(r) and intIII(r))        Q:1
         I:PcarbS(i,r)$carblimS(i,r)                                     Q:1

$prod:emitH(r)
         O:PcarbonH(r)                                                      Q:1
         I:PcarbI(r)$(etsI("hh",r) and carblimI(r) and not intI(r))         Q:1
         I:PcarbII(r)$(etsII("hh",r) and carblimII(r) and not intII(r))     Q:1
         I:PcarbIII(r)$(etsIII("hh",r) and carblimIII(r) and not intIII(r)) Q:1
         I:WcarbI$(etsI("hh",r) and carblimI(r) and intI(r))                Q:1
         I:WcarbII$(etsII("hh",r) and carblimII(r) and intII(r))            Q:1
         I:WcarbIII$(etsIII("hh",r) and carblimIII(r) and intIII(r))        Q:1
         I:PcarbH(r)$carblimS("hh",r)                                       Q:1

$prod:E(nfof,i,r)$(a0(nfof,r) and id0(nfof,i,r))    s:0
         O:PE(nfof,i,r)                   Q:(id0(nfof,i,r)*pi0(nfof,i,r))
         I:PA(nfof,r)                     Q:id0(nfof,i,r)         P:pi0(nfof,i,r)
+                                         A:GOV(r)                T:ti(nfof,i,r)
         I:Pcarbon(i,r)$(co20("total",i,r) and not exempted(i,r))
+                                         Q:co20(nfof,i,r)        P:1e-6
         I:Ecarbon(i,r)$(co20("total",i,r) and exempted(i,r))
+                                         Q:co20(nfof,i,r)        P:1e-6

$prod:EC(nfof,r)$cd0(nfof,r)     s:0
         O:PEC(nfof,r)                    Q:(cd0(nfof,r)*pc0(nfof,r))
         I:PA(nfof,r)                     Q:cd0(nfof,r)           P:pc0(nfof,r)
+                                         A:GOV(r)                T:tc(nfof,r)
         I:PcarbonH(r)$(not exempted("hh",r))
+                                         Q:co20(nfof,"hh",r)     P:1e-6
         I:EcarbonH(r)$exempted("hh",r)
+                                         Q:co20(nfof,"hh",r)     P:1e-6

*###############################################################################
*                                PRODUCTION
*###############################################################################
$prod:Y(i,r)$(y0(i,r) and not next(i) and not nhtrn(i))     s:ysub_top(i,r)    t:ysub_out(i,r)
+                        vae(s):ysub_vae(i,r)
+                        va(vae):ysub_va(i,r)    ene(vae):ysub_ene(i,r)
+                        fof(ene):ysub_fof(i,r)
+                        lqd(fof):ysub_lqd(i,r)
         O:PY(i,r)               Q:d0(i,r)
+                                A:GOV(r)        T:to(i,r)
         O:PX(i,r)               Q:e0(i,r)
+                                A:GOV(r)        T:to(i,r)
         I:PF(mf,r)              Q:fd0(mf,i,r)   P:pf0(mf,i,r)    va:
+                                A:GOV(r)        T:tf(mf,i,r)
         I:PFT(sf,i,r)           Q:fd0(sf,i,r)   P:pf0(sf,i,r)    va:
+                                A:GOV(r)        T:tf(sf,i,r)
         I:PA(j,r)$(not nfof(j)) Q:id0(j,i,r)    P:pi0(j,i,r)    ene:$nely(j)
+                                A:GOV(r)        T:ti(j,i,r)
         I:PE(nfof,i,r)          Q:(id0(nfof,i,r)*pi0(nfof,i,r)) fof:$ncoa(nfof)
+                                                                lqd:$nlqd(nfof)

$prod:Y(nhtrn,r)$y0(nhtrn,r)     s:ysub_top(nhtrn,r)
+                                pur(s):ysub_pur(nhtrn,r) own(s):ysub_own(nhtrn,r)
+                                otc(own):ysub_otc(nhtrn,r)
         O:PY(nhtrn,r)           Q:y0(nhtrn,r)
         I:PA(i,r)$(not nfof(i)) Q:id0(i,nhtrn,r) P:pi0(i,nhtrn,r)       pur:$ntrn(i)
+                                                                        otc:$(not ntrn(i))
+                                A:GOV(r)         T:ti(i,nhtrn,r)
         I:PE(nfof,nhtrn,r)      Q:(id0(nfof,nhtrn,r)*pi0(nfof,nhtrn,r)) own:


$prod:Y(next,r)$y0(next,r)       s:ysub_top(next,r)      t:ysub_out(next,r)
+                        vae(s):ysub_vae(next,r)
+                        va(vae):ysub_va(next,r)
         O:PY(next,r)            Q:d0(next,r)
+                                A:GOV(r)                T:to(next,r)
         O:PX(next,r)            Q:e0(next,r)
+                                A:GOV(r)                T:to(next,r)
         I:PF(mf,r)              Q:fd0(mf,next,r)        P:pf0(mf,next,r) va:
+                                A:GOV(r)                T:tf(mf,next,r)
         I:PFT(sf,next,r)        Q:fd0(sf,next,r)        P:pf0(sf,next,r)
+                                A:GOV(r)                T:tf(sf,next,r)
         I:PA(j,r)$(not nfof(j)) Q:id0(j,next,r)         P:pi0(j,next,r) vae:
+                                A:GOV(r)                T:ti(j,next,r)
         I:PE(nfof,next,r)       Q:(id0(nfof,next,r)*pi0(nfof,next,r))   vae:


$prod:FT(sf,r)$(fs0(sf,r))    t:sfsub(sf,r)
         O:PFT(sf,i,r)           Q:fd0(sf,i,r)
```

```
         I:PF(sf,r)              Q:fs0(sf,r)

$report:
         V:exports(i,r)                  O:PX(i,r)       Prod:Y(i,r)
         V:intdem(i,j,r)$(not nfof(i))   I:PA(i,r)       Prod:Y(j,r)
         V:intdem(i,j,r)$nfof(i)         I:PA(i,r)       Prod:E(i,j,r)

*###############################################################################
*                                  TRADE
*###############################################################################
$prod:YT(i)$ma0(i)       s:tsub(i)
         O:PT(i)         Q:ma0(i)
         I:PX(i,r)       Q:mae0(i,r)

$prod:M(i,r)$m0(i,r)     s:msub(i,r)      s.tl:0
         O:PM(i,r)               Q:m0(i,r)
         I:PX(i,s)               Q:md0(i,s,r)    P:pm0(i,s,r)    s.tl:
+                                A:GOV(r)        T:(tm(i,s,r)*(1+te(i,s,r)))
+                                A:GOV(s)        T:te(i,s,r)
         I:PT(j)#(s)             Q:mad0(j,i,s,r) P:pma0(i,s,r)
+                                A:GOV(r)        T:tm(i,s,r)

$prod:A(i,r)$a0(i,r)     s:dmsub(i,r)
         O:PA(i,r)               Q:a0(i,r)
         I:PY(i,r)               Q:d0(i,r)
         I:PM(i,r)               Q:m0(i,r)

$report:
         V:Imports(i,s,r)        I:PX(i,s)       PROD:M(i,r)

*###############################################################################
*                                 FINAL DEMAND
*###############################################################################
$prod:C(r)               s:csub_top(r)
+                        ce:csub_ce(r)
+                        c(ce):csub_c(r)         e(ce):csub_e(r)
         O:PC(r)                 Q:c0(r)
         I:PA(i,r)$(not nfof(i)) Q:cd0(i,r)      P:pc0(i,r)      c:$nc(i)
+                                                                e:$nene(i)
+                                A:GOV(r)        T:tc(i,r)
         I:PEC(nfof,r)           Q:(cd0(nfof,r)*pc0(nfof,r))     e:


$prod:G(r)               s:gsub_top(r)
         O:PG(r)                 Q:g0(r)
         I:PA(i,r)               Q:gd0(i,r)      P:pg0(i,r)
+                                A:GOV(r)        T:tg(i,r)

$prod:INV(r)$keynes     s:0
         O:PINV(r)               Q:(sum(i, inv0(i,r)))
         I:PA(i,r)               Q:inv0(i,r)

*###############################################################################
*                                 ENDOWMENTS
*###############################################################################
$demand:RA(r)    s:1
         D:PC(r)                 Q:c0(r)
         E:PF(f,r)               Q:fs0(f,r)
         E:PC(r)                 Q:(-ctax(r))            R:LS(r)
         D:PINV(r)$keynes        Q:(sum(i, inv0(i,r)))
         E:PA(i,r)$(not keynes)  Q:(-inv0(i,r))

$demand:GOV(r)
         D:PG(r)                         Q:g0(r)
         E:PC(r)                         Q:(ctax(r))             R:LS(r)
         E:PC(rnum)                      Q:bop(r)
         E:PcarbI(r)$(not intI(r))       Q:carblimI(r)
         E:PcarbII(r)$(not intII(r))     Q:carblimII(r)
         E:PcarbIII(r)$(not intIII(r))   Q:carblimIII(r)
         E:WcarbI$intI(r)                Q:carblimI(r)
         E:WcarbII$intII(r)              Q:carblimII(r)
         E:WcarbIII$intIII(r)            Q:carblimIII(r)
         E:PcarbS(i,r)                   Q:carblimS(i,r)
         E:PcarbH(r)                     Q:carblimS("hh",r)

*###############################################################################
*                              ADDITIONAL CONSTRAINTS
*###############################################################################
$constraint:LS(r)
         G(r)            =E=     1;
```

```
$offtext
$sysinclude mpsgeset trnet
trnet.workspace = 15;
trnet.reslim    = 8000;
PC.FX(rnum)      = 1;

*##############################################################################
*                                REPLICATION CHECK
*##############################################################################
LS.L(r)          = 1;
LS.LO(r)         = - inf;
Pcarbon.L(i,r)   = 0;
PcarbonH.L(r)    = 0;
PcarbI.L(r)      = 0;
PcarbII.L(r)     = 0;
PcarbIII.L(r)    = 0;
WcarbI.L         = 0;
WcarbII.L        = 0;
WcarbIII.L       = 0;
PcarbS.L(i,r)    = 0;
PcarbH.L(r)      = 0;
emit.L(i,r)      = co20("total",i,r);
emitH.L(r)       = co20("total","hh",r);

trnet.iterlim = 0;
$include trnet.gen
solve trnet using MCP;
trnet.iterlim = 100000;

display "precision of benchmark: ", trnet.objval;
abort$(trnet.objval ge 1e-4) "Model does not replicate";

* Save benchmark income values
ra0(r) = RA.L(r);
gov0(r)= GOV.L(r);
```

Appendix C Additional tables for Chapter 5

Table 46: Private transport by trip purpose [billion pkm]

	Leisure						Work					
	Bench-mark	**ETS**	**ETS AIR**	**ETS FUEL**	**FUEL TAX**	**ETS SUB**	**Bench-mark**	**ETS**	**ETS AIR**	**ETS FUEL**	**FUEL TAX**	**ETS SUB**
Bus	80.309	80.367	80.370	80.237	79.688	84.463	11.347	11.361	11.361	11.352	11.319	11.554
Car	596.620	596.495	596.516	595.997	593.758	596.233	327.229	327.344	327.352	327.279	326.979	318.421
Metro/tram	8.759	8.767	8.768	8.741	8.626	9.437	3.342	3.347	3.348	3.339	3.305	3.496
Plane	41.091	41.094	40.966	41.126	41.271	40.942	2.830	2.832	2.820	2.838	2.863	2.737
Slow	38.495	38.278	38.281	38.336	38.598	51.880	28.834	28.691	28.693	28.751	29.021	37.586
Train	46.931	46.944	46.942	47.006	47.286	46.992	8.397	8.404	8.404	8.420	8.491	8.184
Total	812.205	811.944	811.843	811.442	809.228	829.945	381.979	381.979	381.979	381.979	381.979	381.979

Table 47: Private transport by trip distance [billion pkm]

	Short						Long					
	Bench-mark	**ETS**	**ETS AIR**	**ETS FUEL**	**FUEL TAX**	**ETS SUB**	**Bench-mark**	**ETS**	**ETS AIR**	**ETS FUEL**	**FUEL TAX**	**ETS SUB**
Bus	90.495	90.566	90.569	90.428	89.845	94.837	1.161	1.161	1.162	1.161	1.161	1.180
Car	892.322	892.315	892.314	891.788	889.410	883.303	31.528	31.524	31.555	31.488	31.327	31.350
Metro/tram	12.101	12.115	12.115	12.080	11.931	12.933	0	0	0	0	0	0
Plane	0.111	0.111	0.110	0.111	0.112	0.108	43.811	43.815	43.676	43.853	44.023	43.571
Slow	65.760	65.409	65.413	65.525	66.049	87.369	0	0	0	0	0	0
Train	55.328	55.348	55.346	55.426	55.777	55.175	1.568	1.560	1.561	1.562	1.571	2.097
Total	1116.117	1115.864	1115.868	1115.358	1113.124	1133.726	78.067	78.059	77.954	78.064	78.083	78.198

Table 48: Private transport by travel period [billion pkm]

	Peak						Off-Peak					
	Bench-mark	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB	Bench-mark	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB
Bus	18.072	18.085	18.086	18.061	17.959	18.762	73.584	73.642	73.646	73.528	73.048	77.255
Car	165.283	165.303	165.307	165.230	164.902	162.680	758.566	758.537	758.562	758.046	755.836	751.974
Metro/tram	2.802	2.805	2.805	2.798	2.767	2.951	9.300	9.310	9.311	9.282	9.164	9.982
Plane	5.643	5.643	5.628	5.647	5.662	5.612	38.279	38.283	38.158	38.317	38.473	38.067
Slow	14.912	14.843	14.844	14.867	14.974	19.077	52.416	52.125	52.130	52.220	52.645	70.389
Train	9.257	9.260	9.260	9.272	9.324	9.182	46.072	46.087	46.086	46.154	46.453	45.993
Total	215.968	215.938	215.929	215.874	215.589	218.264	978.216	977.985	977.893	977.548	975.618	993.660

Table 49: Effects on domestic production [% vs benchmark]

	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB		ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB
Agriculture	-0.02	-0.02	-0.11	-0.51	-0.05	**Mining**	-0.12	-0.12	-0.28	-0.97	-1.19
Air transport	0.09	-0.37	0.58	2.70	-0.20	**Motor vehicles**	-0.12	-0.12	-0.14	-0.19	-0.19
Coal	-33.29	-33.30	-33.08	-31.81	-33.08	**Other transport**	-2.00	-2.00	-2.01	-2.04	-2.00
Energy intensives	-0.13	-0.11	-1.24	-5.40	-0.18	**Refined oils**	0.50	0.51	0.44	0.18	-1.23
Electricity	-3.04	-3.03	-3.06	-3.13	-3.11	**Rail transport**	-0.03	-0.01	0.40	2.16	0.99
Natural gas	-4.60	-4.60	-4.60	-4.59	-4.42	**Services**	-0.86	-0.91	-1.18	-2.41	-1.20
Manufacture	-4.26	-4.27	-4.18	-3.77	-4.11	**Water transport**	-0.67	-0.67	-0.55	-0.02	21.75

Table 50: Trade effects [% vs benchmark]

	Exports					Imports				
	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB	ETS	ETS AIR	ETS FUEL	FUEL TAX	ETS SUB
Agriculture	0.23	0.24	-0.03	-1.18	0.29	-0.31	-0.31	-0.20	0.28	-0.43
Air transport	0.32	-0.51	0.82	3.01	0.08	-0.30	-0.13	0.17	2.19	-0.69
Coal	-33.79	-33.79	-33.56	-32.22	-33.56	-32.75	-32.75	-32.55	-31.35	-32.55
Crude oil	0.00	0.00	0.00	0.00	0.00	-0.85	-0.90	-1.18	-2.40	-1.19
Energy intensives	-4.69	-4.69	-4.72	-4.80	-4.70	0.45	0.45	0.44	0.39	0.25
Electricity	-17.27	-17.26	-17.22	-17.01	-17.04	-0.93	-0.93	-0.95	-1.00	-0.76
Natural gas	-4.04	-4.06	-3.94	-3.40	-3.81	-4.74	-4.74	-4.72	-4.58	-4.79
Nuclear fuel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manufacture	-0.05	-0.05	-0.07	-0.14	-0.07	-0.28	-0.28	-0.29	-0.32	-0.47
Mining	-2.40	-2.40	-2.40	-2.37	-2.33	-1.48	-1.48	-1.51	-1.61	-1.56
Motor vehicles	0.65	0.66	0.59	0.33	-1.02	0.06	0.07	0.00	-0.26	-1.84
Other transport	0.32	0.35	0.31	0.14	1.38	-0.46	-0.44	0.50	4.70	0.52
Refined oils	-1.75	-1.80	-2.07	-3.28	-2.06	0.53	0.48	0.19	-1.08	0.15
Rail transport	-0.95	-0.94	-0.81	-0.19	21.45	-0.33	-0.33	-0.23	0.20	22.11
Services	0.46	0.47	0.45	0.41	0.53	-0.59	-0.59	-0.58	-0.55	-0.68
Water transport	7.18	7.25	8.02	11.75	8.51	-1.03	-1.02	-0.55	1.50	-1.30

Appendix D GAMS codes for the Small Open Economy model

Calibration procedure

The codes for the calibration are run in the order as they are stated.

Extract the social accounting matrix from the German input-output table

```
$title Extract IO table from XLS and save as GDX
$ontext
(1)      EXTRACT BASE DATA
(2)      EXTRACT PARAMETER
(3)      LOAD ENERGY DATA
(4)      SPLIT CRUDE OIL SECTOR
(5)      ENERGY AND EMISSION FLOWS
(6)      SAVE PARAMETERS

Options:
         - iot           name of excel sheet containing data
         - pio:          name of excel sheet containing physical energy data
         - datadir       name of directory containing data
         - resdir        name of directory for dumping results
$offtext


$if not set iot $set iot IO_2004_simple
$if not set piot $set piot PIOT_2004
$if not set result $set result "%iot%_extracted"

$if not set datadir $set datadir "..\data\"
$if not set resdir $set resdir "%datadir%"
$if not set iot $abort "########## IO TABLE NOT SPECIFIED ###########"

*###############################################################################
*                        (1) EXTRACT BASE DATA
*###############################################################################

*--------------------------- EXTRACT DATA TO GDX -------------------------------
$onecho >temp.tmp
o=%datadir%%iot%.gdx
par=domIO        rng=IO_domestic!D13     rdim=1  cdim=1
par=impIO        rng=IO_import!D13       rdim=1  cdim=1
par=Ouse         rng=Use!D13             rdim=1  cdim=1
par=Omake        rng=Make!D13            rdim=1  cdim=1
par=consumption  rng=Consumption!D6      rdim=1  cdim=1
par=labor        rng=Labor!D8            rdim=1  cdim=1
dset=i           rng=MAP!D2              rdim=1
set=mapCPA       rng=MAP!C2              rdim=2
set=c            rng=MAP!H2              rdim=1
set=mapc         rng=MAP!G2              rdim=2
$offecho
$call "gdxxrw %datadir%\%iot%.xls @temp.tmp"

*---------------------------- LOAD DATA TO GAMS --------------------------------
set
         n       numbers
         /1*200/
         i       set of commodities
         c       set of consumption classes
         mapCPA  map for commodities in CPA
         mapC    mapping for consumption transition matrix
         adjK    sectors for which capital payments are negative and  are adjusted
;
alias(i,j,k), (n,nn);
parameter
         domIO           domestic IO table (basic prices)
         impIO           import IO table (basic prices)
         Ouse            original use matrix (market prices)
         Omake           original make matrix (basic plus transition to market prices)
         consumption     consumption transition matrix
         labor           employment per sector
;

$gdxin %datadir%\%iot%.gdx
```

```
$load i c mapCPA mapC
$load domIO impIO Ouse Omake consumption labor
$gdxin

*###############################################################################
*                       (2) EXTRACT PARAMETER
*###############################################################################
parameter
         y0              benchmark total [million €]
         d0              benchmark output to domestic market [million €]
         e0              benchmark exports [million €]
         id0             benchmark intermediate input [million €]
         kd0             benchmark capital demand
         ld0             benchmark labor demand
         otax            benchmark output tax [million €]
         utax            benchmark tax for commodity use [million €]
         a0              benchmark Armington demand [million €]
         m0              benchmark imports [million €]
         cd0             benchmark private consumption demand [million €]
         c0              benchmark total consumption [million €]
         ks0             benchmark capital supply [million €]
         ls0             benchmark labor supply [million €]
         gd0             benchmark public consumption demand [million €]
         g0              benchmark total public consumption [million €]
         inv0            benchmark investment demand [million €]
         bop             balance of payment
         cons            consumption matrix
         lab             labor force
;

id0(i,j)         = sum((n,nn)$(mapCPA(n,i) and mapCPA(nn,j)), domIO(n,nn) + impIO(n,nn));
cd0(i)           = sum(mapCPA(n,i), domIO(n,"73") + domIO(n,"78") + impIO(n,"73") +
                   impIO(n,"78"));
c0               = sum(i, cd0(i));
gd0(i)           = sum(mapCPA(n,i), domIO(n,"74") + domIO(n,"75")
                                  + impIO(n,"74") + impIO(n,"75"));
g0               = sum(i, gd0(i));
inv0(i)          = sum(mapCPA(n,i), domIO(n,"76") + domIO(n,"77")
                                  + impIO(n,"76") + impIO(n,"77") );
e0(i)            = sum(mapCPA(n,i), domIO(n,"79"));
m0(i)            = sum(mapCPA(n,i), impIO(n,"82") - impIO(n,"79"));
kd0(i)           = sum(mapCPA(n,i), domIO("78",n) + domIO("79",n));
ld0(i)           = sum(mapCPA(n,i), domIO("76",n));
adjK(i)$(kd0(i) lt 0)    = yes;
ld0(i)           = ld0(i) + min(kd0(i),0);
kd0(i)           = max(kd0(i),0);
ks0              = sum(i, kd0(i));
ls0              = sum(i, ld0(i));
utax(i)          = sum(mapCPA(n,i), domIO("74",n));
otax(i)          = sum(mapCPA(n,i), domIO("77",n));
y0(i)            = sum(j, id0(j,i)) + ld0(i) + kd0(i) + otax(i) + utax(i);
d0(i)            = y0(i) - e0(i);
a0(i)            = m0(i) + d0(i);
bop              = sum(i, m0(i) - e0(i));
cons(i,c)        = sum((n,nn)$(mapCPA(n,i) and mapc(nn,c)), consumption(n,nn));
lab(i,"total")   = sum(mapCPA(n,i), labor(n,"1"));
lab(i,"employed")= sum(mapCPA(n,i), labor(n,"2"));

*###############################################################################
*                     (3) LOAD ENERGY DATA
*###############################################################################
$onecho >temp1.tmp
o=%datadir%%piot%.gdx
set=e            rng=MAP!B2               rdim=1
set=mape         rng=MAP!A2               rdim=2
par=eiot         rng=energy!C3            rdim=1  cdim=1
par=eriot        rng=eenergy!C3           rdim=1  cdim=1
par=emissions    rng=emissions!C1         rdim=1  cdim=0
par=prices       rng=prices!A1            rdim=1  cdim=0
$offecho
$call "gdxxrw %datadir%%piot%.xls @temp1.tmp"

set
         e               energy commodities
         mape            map numerical accounts to energy commodities
;

parameter
         eiot            original energy flows in TJ
         eriot           original emission relevant energy flows in TJ
```

```
         emissions       original emission in 1000 t
         prices          price of energy carriers
;

$gdxin "%datadir%%piot%"
$load e mape
$load eiot eriot emissions prices

*###############################################################################
*                     (4) SPLIT CRUDE OIL SECTOR
*###############################################################################
parameter
         ene0            total energy flow (with double counting)
         shareC          crude oil share in total demand by sector
;

i("gas") = yes;
ene0(e,i)        = sum((n,nn)$(mapCPA(n,i) and mape(nn,e)), eiot(n,nn));
ene0(e,"HH")     = sum(mape(n,e), eiot("72",n));
ene0(e,"imp")    = sum(mape(n,e), eiot("73",n));
ene0(e,"exp")    = sum(mape(n,e), eiot("74",n));
ene0(e,"prod")   = sum(mape(n,e), eiot("75",n));
shareC(i)$(prices("cru")*ene0("cru",i) + prices("gas")*ene0("gas",i))
                 =  prices("cru")*ene0("cru",i)/(prices("cru")*ene0("cru",i)
                    + prices("gas")*ene0("gas",i));
id0("gas",i)     = id0("cru",i)*(1-shareC(i));
id0("cru",i)     = id0("cru",i)*shareC(i);
cd0("gas")       = cd0("cru");
cd0("cru")       = 0;
gd0("gas")       = gd0("cru");
gd0("cru")       = 0;
cons("gas",c)    = cons("cru",c);
cons("cru",c)    = 0;
y0("gas")        = y0("cru");
y0("cru")        = 0;
e0("gas")        = e0("cru");
e0("cru")        = 0;
id0(i,"gas")     = id0(i,"cru");
id0(i,"cru")     = 0;
kd0("gas")       = kd0("cru");
kd0("cru")       = 0;
ld0("gas")       = ld0("cru");
ld0("cru")       = 0;
m0("gas")        = m0("cru") - sum(i, id0("cru",i)) - inv0("cru");
m0("cru")        = sum(i, id0("cru",i)) + inv0("cru");
d0(i)            = y0(i) - e0(i);
a0(i)            = d0(i) + m0(i);
otax("gas")      = otax("cru");
otax("cru")      = 0;
utax("gas")      = utax("cru");
utax("cru")      = 0;

*###############################################################################
*                     (5) ENERGY AND EMISSION FLOWS
*###############################################################################
parameter
         evf             emission relevant energy from i used in sector j
         evh             emission relevant energy from i used in household consumption
         eevf            emission relevant energy from energy commodity e used in sector j
         eevh            emission relevant energy from energy commodity e used in consumption
         co20            benchmark co2 emission in 1000t
;

eevf(e,i)                = sum((n,nn)$(mapCPA(n,i) and mape(nn,e)), eriot(n,nn));
eevh(e)                  = sum(mape(n,e),eriot("72",n));
evf("coa",i)             = sum(mapCPA(n,i), eriot(n,"2") + eriot(n,"3"));
evh("coa")               = eriot("72","2") + eriot("72","3");
evf("coa","gas")         = evf("coa","cru");
evf("coa","cru")         = 0;
evf("gas",i)             = sum(mapCPA(n,i), eriot(n,"12"));
evh("gas")               = eriot("72","12");
evf("gas","gas")         = evf("gas","cru");
evf("gas","cru")         = 0;
evf("p_c",i)             = sum(mapCPA(n,i), eriot(n,"4"));
evh("p_c")               = eriot("72","4");
evf("p_c","gas")         = evf("p_c","cru");
evf("p_c","cru")         = 0;
co20("total",i)          = sum(mapCPA(n,i), emissions(n));
co20("total","gas")      = co20("total","cru");
co20("total","cru")      = 0;
```

```
co20("total","hh")       = emissions("72");

*###############################################################################
*                     (6)   SAVE DATA
*###############################################################################
execute_unload "%resdir%%result%" i, c, e,
                         y0, d0, e0, id0, kd0, ld0, otax, utax, m0, a0,
                         cd0, gd0, inv0, bop, c0, g0,
                         cons, lab
                         evf, eevf, evh, eevh, co20, ene0
                         mapCPA, mapC
;
```

Calibrate discrete electricity generation technologies

```
$title Calibrates Electricity Sector Generation Technologies
$ontext
(1)      LOAD DATA
(2)      CALIBRATION MODEL
(3)      CREATE NUCLEAR INPUT
(4)      ADJUST ELECTRICITY SECTOR
(5)      SAVE RESULTS

OPTIONS:
         -iot            name of gdx file containing basic sam
         -sam            name of file containing extracted sam
         -datadir        name of directory containing data
         -bu             name of xls file providing bottom up electricity generation data
         -ele            label of electricity sector
         -out            name of output gdx
$offtext

$set iot IO_2004_simple
$if not set sam $set sam "%iot%_extracted"
$set bu Technologies_DISS_v04_27042009
$if not set datadir $set datadir "..\data\"
$if not set out $set out "%iot%_Bottom_up"
$if not set iot $abort "####### SPECIFY DATA SOURCE ########"
$if not exist "%datadir%%iot%.gdx" $abort "######## DATA SOURCE MISSING ########"
$if not set bu $abort"####### SPECIFY BOTTOM UP DATA #######"
$if not exist "%datadir%%bu%.xls" $abort "BOTTOM UP DATA MISSING #######"

*###############################################################################
*                           (1) LOAD  DATA
*###############################################################################

*----------------------------- TOP DOWN DATA ----------------------------------
set
         i       commodity set
         e       energy commodity set
         c       consumption classes
         mapCPA  map for commodities in CPA
         mapC    mapping for consumption transition matrix
;
alias(i,j);
parameter
         d0      domestic output [million €]
         e0      exports [million €]
         y0      total output [million €]
         id0     intermediate inputs [million €]
         kd0     capital demand [million €]
         ld0     labor demand [million €]
         otax    output and production taxes [million €]
         utax    commodity use taxes [million €]
         c0      total private consumption [million €]
         cd0     private consumption demand [million €]
         inv0    investment demand [million €]
         g0      total public consumption [million €]
         gd0     public consumption demand [million €]
         bop     balance of payment [million €]
         m0      imports [million €]
         a0      armington supply [million €]
         cons    consumption transition matrix [million €]
         lab     labor force [1000 people]
         ene0    total energy flow (with double counting)[TJ]
         evf     emission relevant energy from commodity i used in sector j  [TJ]
         evh     emission relevant energy from commodity i used in household consumption [TJ]
         eevf    emission relevant energy from energy commodity e used in sector j [TJ]
         eevh    emission relevant energy from energy commodity e used in consumption [TJ]
         co20    emissions [1000 t]
;

$gdxin "%datadir%%sam%"
$load i e c
$load d0 e0 y0 id0 kd0 ld0 otax utax
$load c0 cd0 inv0 g0 gd0 bop
$load m0 a0 cons lab
$load ene0 evf evh eevf eevh co20
$load mapCPA mapC
$gdxin

parameter
```

```
         ekd            capital demand of electricity sector
         eld            labor demand of electricity sector
         eid            commodity demand electricity sector
         eout           output electricity sector
         etax           output tax electricity sector
         eene           energy flows to electricity sector
;

ekd      = kd0("ele");
eld      = ld0("ele");
eid(i)   = id0(i,"ele");
eout     = y0("ele");
etax     = otax("ele") + utax("ele");
eene(e)  = eevf(e,"ele");

*----------------------------- BOTTOM UP DATA ----------------------------------
set
         g              set of technologies
         ga(g)          set of active technologies
         gn(g)          set of non-active technologies
         l              set of load segments
         r              set of renewables
         mapL           mapping technology to load
         mapF           mapping technology to fuel
;
alias(ga,gaa);

parameter
         techn          technology data
         gener          generation by technology in TWh
         minmaxOI       minimum maximum share of other activity
;

$onecho >temp.tmp
set=g            rng=Cost_Shares_CGE!B2          rdim=1  cdim=0
dset=l           rng=Cost_Shares_CGE!A2          rdim=1  cdim=0
set=mapL         rng=Cost_Shares_CGE!A2          rdim=2  cdim=0
set=mapF         rng=Cost_Shares_CGE!I2          rdim=2  cdim=0
par=techn        rng=Cost_Shares_CGE!B1:H16      rdim=1  cdim=1
par=gener        rng=Generation!A2               rdim=1  cdim=0
par=minmaxOI     rng=Other!A1
$offecho
$call "gdxxrw %datadir%%bu%.xls @temp.tmp"
$gdxin "%bu%"
$load g l mapl mapf techn gener minmaxOI
$gdxin

parameter
         eff            plant efficiency
         pfuel          fuel prices
         pgen           generation prices
         share          cost shares in generation
;
eff(g)                  = techn(g,"efficiency");
pgen(g)                 = techn(g,"pgen");
pfuel(g)                = techn(g,"pfuel");
share("cap",g)          = techn(g,"capital");
share("lab",g)          = techn(g,"labor");
share("fuel",g)         = techn(g,"fuel");
share("gener","total")  = sum(g, gener(g)*pgen(g))/eout;
ga(g)$gener(g) = yes; gn(g)$(not gener(g)) = yes;
r(g)$(share("fuel",g) eq 0) = yes;
share("outVal",g)       = pgen(g)*gener(g)/sum(ga, pgen(ga)*gener(ga));
share("outPhy",g)       = gener(g)/sum(ga, gener(ga));



*###############################################################################
*                            (2) CALIBRATION MODEL
*###############################################################################
scalar
         wK             weight on capital share         /1/
         wL             weight on labor share           /1/
         wI             weight on fuel share            /1/
         wO             weight on output share          /1/
         wEFF           weight on efficiency            /1/
         wGEN           weight on total generation      /0/
;

Variable
```

```
         DEV             sum of fractional deviation
         devGK           deviation generation capital share
         devGL           deviation generation labor share
         devGI           deviation generation fuel share
         devEFF          deviation efficiency
         devOUT          deviation generation output share
         devG            deviation generation
;

Positive Variable
         OI              material input non-generation
         OK              capital input non-generation
         OL              labor input non-generation
         GI              fuel inputs to technologies
         GK              capital input to technologies
         GL              labor input to technologies
         GO              output technologies
         GEFF            efficiency of technologies
         SK              capital share
         SL              labor share
         SI              fuel share
         SO              output share
         SG              generation share
;

equation
         obj             objective function
         zpf             total zero profits
         mkt_i           market clearing material
         mkt_k           market clearing capital
         mkt_l           market clearing labor
         zpf_G           technology zero profits
         effiec          efficiency definition
         def_devGK       Definition deviation generation capital share
         def_devGL       Definition deviation generation labor share
         def_devGI       Definition deviation generation fuel share
         def_devEFF      Definition deviation efficiency
         def_devOUT      Definition deviation generation output share
         def_devG        Definition deviation generation share
         def_SK          Definition capital share
         def_SI          Definition fuel share
         def_SL          Definition labor share
         def_SO          Definition output share
         def_SG          Definition generation share
;

*------------------------------ OBJECTIVE -------------------------------------
obj..
         DEV             =E=     100*sum(ga, wK*sqr(devGK(ga))
                                         + wL*sqr(devGL(ga))
                                         + wI*sqr(devGI(ga))
                                         + wO*sqr(devOUT(ga))
                                         + wEFF*sqr(devEFF(ga))
                                         + wGEN*devG
                                 )
;

*-------------------------- DEFINTION OF DEVIATIONS ----------------------------
def_devGK(ga)..
         devGK(ga)       =E=     SK(ga)/share("cap",ga) - 1
;

def_devGL(ga)..
         devGL(ga)       =E=     SL(ga)/share("lab",ga) - 1
;


def_devGI(ga)$pfuel(ga)..
         devGI(ga)       =E=     SI(ga)/share("fuel",ga) - 1
;

def_devOUT(ga)..
         devOUT(ga)      =E=     SO(ga)/share("outVAL",ga) - 1
;

def_devEFF(ga)$pfuel(ga)..
         devEFF(ga)      =E=     GEFF(ga)/eff(ga) - 1
;

def_devG..
```

```
         devG            =E=     SG/share("gener","total") - 1
;

*------------------------------- OVERALL LEVEL ---------------------------------
zpf..
         eout            =E=    sum(ga, GK(ga)) + OK + sum(i, sum(ga, GI(i,ga)) + OI(i))
                                + sum(ga, GL(ga)) + OL + etax
;

mkt_i(i)..
         eid(i)          =E=     sum(ga, GI(i,ga)) + OI(i)
;

mkt_k..
         ekd             =E=     sum(ga, GK(ga)) + OK
;

mkt_l..
         eld             =E=     sum(ga, GL(ga)) + OL
;

*------------------------------- GENERATION LEVEL ------------------------------
zpf_G(ga)..
         GO(ga)          =E=     sum(i, GI(i,ga)) + GK(ga) + GL(ga)
;

effiec(ga)$pfuel(ga)..
         GEFF(ga)        =E=     GO(ga)*pfuel(ga)/(sum(i,GI(i,ga))*pgen(ga))
;

*------------------------ SHARE DEFINITIONS -----------------------------------
def_SK(ga)..
         SK(ga)          =E=     GK(ga)/GO(ga)
;

def_SL(ga)..
         SL(ga)          =E=     GL(ga)/GO(GA)
;

def_SI(ga)$pfuel(ga)..
         SI(ga)          =E=     sum(i, GI(i,ga))/GO(ga)
;

def_SO(ga)..
         SO(ga)          =E=     GO(ga)/sum(gaa, GO(gaa))
;

def_SG..
         SG              =E=     sum(ga, GO(ga))/eout
;

*----------------------- MODEL ASSIGNEMENT AND BOUNDS --------------------------
model calib /all/;

* Install lower bound to avoid domain errors
GK.LO(ga)                = 0.001;
GL.LO(ga)                = 0.00001;
GI.LO(i,ga)$(pfuel(ga) and mapF(i,ga)) = 0.00001;
GEFF.LO(ga)$pfuel(ga)    = 0.00001;
GO.LO(ga)                = 0.00001;
OK.LO                    = 0.00001;
OL.LO                    = 0.00001;

* Fix fuel share and efficiency for technologies with no fuel input
GI.FX(i,ga)$(not pfuel(ga)) = 0;
GEFF.FX(ga)$(not pfuel(ga)) = 0;
GI.FX(i,ga)$(not mapF(i,ga))= 0;

* Assing intital values
GK.L(ga)                 = share("cap",ga) * gener(ga) * pgen(ga);
GL.L(ga)                 = share("lab",ga) * gener(ga) * pgen(ga);
GI.L(i,ga)$mapF(i,ga)    = share("fuel",ga) * gener(ga) * pgen(ga);
GEFF.L(ga)               = eff(ga);
GO.L(ga)                 = gener(ga) * pgen(ga);

* Additional bounds on consumption of other activities
OI.UP(i)$minmaxOI(i,"max") = minmaxOI(i,"max")*eid(i);
OI.LO(i)$minmaxOI(i,"min") = minmaxOI(i,"min")*eid(i);

* Coal is only used in electricity generation
```

```
OI.FX("coa") = 0;

* Setting lower and upper bound for fractional deviation
scalar
         maxdev  maximum deviation       /1/
         mindev  maximum deviation       /-1/
;

devGK.UP(ga)         = maxdev;
devGL.UP(ga)         = maxdev;
devGI.UP(ga)         = maxdev;
devEFF.UP(ga)        = maxdev;
devOUT.UP(ga)        = maxdev;

devGK.LO(ga)         = mindev;
devGL.LO(ga)         = mindev;
devGI.LO(ga)         = mindev;
devEFF.LO(ga)        = mindev;
devOUT.LO(ga)        = mindev;

solve calib minimizing dev using NLP;

parameter
         quality         quality report
;

quality("K_share",ga,"predicted") = share("cap",ga)*100;
quality("K_share",ga,"actual")    = SK.L(ga)*100;
quality("K_share",ga,"deviation") = devGK.L(ga)*100;
quality("L_share",ga,"predicted") = share("lab",ga)*100;
quality("L_share",ga,"actual")    = SL.L(ga)*100;
quality("L_share",ga,"deviation") = devGL.L(ga)*100;
quality("F_share",ga,"predicted") = share("fuel",ga)*100;
quality("F_share",ga,"actual")    = SI.L(ga)*100;
quality("F_share",ga,"deviation") = devGI.L(ga)*100;
quality("eff",ga,"predicted")     = eff(ga)*100;
quality("eff",ga,"actual")        = GEFF.L(ga)*100;
quality("eff",ga,"deviation")     = devEFF.L(ga)*100;
quality("Pgen",ga,"predicted")    = pgen(ga);
quality("Pgen",ga,"actual")       = GO.L(ga)/gener(ga);
quality("Pgen",ga,"deviation")    = (quality("Pgen",ga,"actual")
                                     /quality("Pgen",ga,"predicted") - 1)*100;
quality("Value_Share",ga,"predicted") = share("outVAL",ga);
quality("Value_Share",ga,"actual")    = SO.L(ga);
quality("Value_Share",ga,"deviation") = devOUT.L(ga)*100;

*###############################################################################
*                         (3) ASSIGN TECHNOLOGY DATA
*###############################################################################
parameter
         unit    technology coefficients
;

*------------------------ active technologies ----------------------------------
unit("cap",ga)   = SK.L(ga);
unit("lab",ga)   = SL.L(ga);
unit(i,ga)$mapF(i,ga) = SI.L(ga);
unit("eff",ga)   = GEFF.L(ga);
unit("out",ga)   = GO.L(ga);
unit("TWh",ga)   = gener(ga);
unit("Pgen",ga)  = GO.L(ga)/gener(ga);

*------------------------ inactive technologies --------------------------------
unit("cap",gn)           = share("cap",gn);
unit("lab",gn)           = share("lab",gn);
unit(i,gn)$mapF(i,gn)    = share("fuel",gn);
unit("Pgen",gn)          = pgen(gn);

*###############################################################################
*                         (3) ADJUST ELECTRICITY SECOTR
*###############################################################################
parameter
         lod0    generation demand by load
;

id0(i,"ele")     = id0(i,"ele") - sum(ga, unit(i,ga)*unit("out",ga));
kd0("ele")       = kd0("ele") - sum(ga, unit("cap",ga)*unit("out",ga));
ld0("ele")       = ld0("ele") - sum(ga, unit("lab",ga)*unit("out",ga));
lod0(l,"ele")    = sum(ga$mapl(l,ga), unit("out",ga));
```

```
*###############################################################################
*                         (4) CREATE NUCLEAR INPUT
*###############################################################################
i("nuc") = yes;
y0("nuc") = 0; e0("nuc") = 0; id0(j,"nuc") = 0;
mapF("p_c","nuclear") = no; mapf("nuc","nuclear") = yes;
unit("nuc","nuclear")
          = unit("p_c","nuclear"); unit("p_c","nuclear") = 0;
m0("nuc") = unit("out","nuclear") * unit("nuc","nuclear");
a0("nuc") = m0("nuc");
a0("p_c") = a0("p_c") - a0("nuc");
m0("p_c") = m0("p_c") - m0("nuc");
d0(i)     = y0(i) - e0(i);
a0(i)     = d0(i) + m0(i);

*###############################################################################
*                         (5) SAVE RESULTS
*###############################################################################
execute_unload "%datadir%%out%" i, c, e, g, ga, gn, mapF, mapL, l,
                         y0, d0, e0, id0, kd0, ld0, otax, utax, m0, a0, lod0,
                         cd0, gd0, inv0, bop, c0, g0,
                         cons, lab
                         evf, eevf, evh, eevh, co20, ene0,
                         unit, quality,
                         mapCPA, mapC
;

*------------------ Dump quality results to XLS --------------------------------
$if exist "%datadir%Quality.xls" $call "rm %datadir%Quality.xls"
set
         labels
         /Variab, Technology, Status, Value/
;

execute_unload "temp.gdx" labels, quality;
$onecho >temp.tmp
o=%datadir%Quality.xls
set=labels       rng=Quality!A1          cdim=1
par=quality      rng=Quality!A2          cdim=0
$offecho
execute "gdxxrw temp.gdx @temp.tmp";
```

Impose private transport data

```
$title Calibration routine to calibrate transport sectors
$ontext
(1)      LOAD SAM DATA
(2)      LOAD BOTTOM UP DATA
(3)      SPECIFY CAR TECHNOLOGIES
(4)      LOAD AND AGGREGATE TREMOVE DATA
(5)      ASSING VALUES FOR TRANSPORT ACTIVITIES
(6)      SAVE DATA

options:
         -iot            name of gdx file containing basic sam
         -sam            nema of file containing exttracted sam
         -datadir        name of directory containing data
         -car            name of xls file providing bottom up electricity generation data
         -out            name of output gdx
         -tbu            name of xls file containing transport data
$offtext

$set iot IO_2004_simple
$set tbu transport_one
$set out "%iot%_transport_one"
$if not set sam $set sam "%iot%_Bottom_up"
$if not set datadir $set datadir "..\data\"
$if not set out $set out "%iot%_Bottom_up_Car"
$if not set iot $abort "####### SPECIFY DATA SOURCE ########"
$if not exist "%datadir%%iot%.gdx" $abort "######## DATA SOURCE MISSING ########"
$if not set tbu $abort"####### SPECIFY BOTTOM UP DATA #######"
$if not exist "%datadir%%tbu%.xls" $abort "BOTTOM UP DATA MISSING #######"

*###############################################################################
*                           (1) LOAD SAM DATA
*###############################################################################

*---------------------------- TOP DOWN DATA ------------------------------------
set
         i       commodity set
         e       energy commodity set
         c       consumption classes
         g       electricity technologies
         ga      active generation technologies
         gn      inactive technologies
         l       load segments
         mapF    mapping fuels to technologies
         mapL    mapping technology to load
         mapCPA  map for commodities in CPA
         mapC    mapping for consumption transition matrix
         ptrn    public transport modes in sam
         /otp, atp, rail/
;
alias(i,j);
parameter
         d0      domestic output [million €]
         e0      exports [million €]
         y0      total production [million €]
         id0     intermediate inputs [million €]
         kd0     capital demand [million €]
         ld0     labor demand [million €]
         otax    output and production taxes [million €]
         utax    commodity use taxes [million €]
         c0      total private consumption [million €]
         cd0     private consumption demand [million €]
         inv0    investment demand [million €]
         g0      total public consumption [million €]
         gd0     public consumption demand [million €]
         bop     balance of payment [million €]
         m0      imports [million €]
         a0      armington supply [million €]
         cons    consumption transition matrix [million €]
         lab     labor force [1000 people]
         ene0    total energy flow (with double counting)[TJ]
         evf     emission relevant energy from commodity i used in sector j  [TJ]
         evh     emission relevant energy from commodity i used in household consumption [TJ]
         eevf    emission relevant energy from energy commodity e used in sector j [TJ]
         eevh    emission relevant energy from energy commodity e used in consumption [TJ]
         co20    emissions [1000 t]
         unit    unit input vector of generation technologies
         lod0    electricity demand by load
```

```
         quality quality report of generation technology calibration
;
$gdxin "%datadir%%sam%"
$load i e c g ga gn l mapF mapL
$load y0 d0 e0 id0 kd0 ld0 otax utax
$load c0 cd0 inv0 g0 gd0 bop
$load m0 a0 cons lab
$load ene0 evf evh eevf eevh co20
$load unit lod0 quality
$load mapCPA mapC
$gdxin

*###############################################################################
*                           (2) LOAD BOTTOM UP DATA
*###############################################################################
set
         ct      car classes
         cf      car fuels
         sc      stock classes
         re      reference cars
         om      original transport modes
         m       aggregated transport modes
         oa      original transport aims
         a       aggregated transport aims
         maprt   mapping reference car to car class
         mapm    mode mapping
         mapa    aim mapping
         nn      aggregated TREMOVE networks
         nv      aggregated TREMOVE vehicle classes
         np      aggregated TREMOVE trip purposes
         nd      aggregated TREMOVE distance
         tp      travel period
         mapn    mapping TRREMOVE networks
         mapv    mapping TRREMOVE networks
         mapp    mapping TRREMOVE networks
         mapd    mapping TRREMOVE networks
         maptp   mapping TRREMOVE networks
;
alias(ct,cct), (cf,ccf), (sc, ssc);
alias(nn,nnn), (nnp,np), (nnv,nv), (nnd,nd), (ttp,tp);

parameter
         stockCT         car stock by car classes [million]
         stockCF         car stock by fuel [million]
         reference       reference cars
         addfuel         additional data on fuels
         opkm            original pkm data by
;

*------------------------ LOAD DATA FROM SPREADSHEET ---------------------------
$onecho >temp.tmp
set=ct           rng=stock!A3            cdim=0  rdim=1
set=cf           rng=stock!F3            cdim=0  rdim=1
set=sc           rng=stock!G2            cdim=1  rdim=0
set=re           rng=reference!B2        cdim=1  rdim=0
set=maprt        rng=reference!A30       cdim=0  rdim=2
set=om           rng=pkm!K3              cdim=0  rdim=1
dset=m           rng=pkm!L3              cdim=0  rdim=1
set=mapm         rng=pkm!K3              cdim=0  rdim=2
set=oa           rng=pkm!N3              cdim=0  rdim=1
dset=a           rng=pkm!O3              cdim=0  rdim=1
set=mapa         rng=pkm!N3              cdim=0  rdim=2
dset=nn          rng=map!L3              cdim=0  rdim=1
dset=nv          rng=map!G3              cdim=0  rdim=1
dset=np          rng=map!B3              cdim=0  rdim=1
dset=nd          rng=map!P3              cdim=0  rdim=1
dset=tp          rng=map!T3              cdim=0  rdim=1
set=mapn         rng=map!K3              cdim=0  rdim=2
set=mapv         rng=map!F3              cdim=0  rdim=2
set=mapp         rng=map!A3              cdim=0  rdim=2
set=mapd         rng=map!O3              cdim=0  rdim=2
set=maptp        rng=map!S3              cdim=0  rdim=2
par=stockCT      rng=stock!A2
par=stockCF      rng=stock!F2
par=reference    rng=reference!A2
par=addfuel      rng=fuel!A2
par=opkm         rng=pkm!A1
$offecho

$call "gdxxrw %datadir%%tbu%.xls @temp.tmp"
```

```
$gdxin "%tbu%"
$load ct, cf, re, maprt, om, m, mapm, oa, a, mapa, sc
$load stockCT, stockCF, reference, addfuel, opkm
$load nn nv np nd tp mapn maptp mapv mapd mapp

*--------------------------- ASSIGN PARAMETERS ---------------------------------
parameter
         refprice        reference car price by fuel and class [€]
         reffuel         reference fuel use by fuel and class [l per 100 km]
         refccm          reference cubic capacity by fuel and class [100 ccm]
         reflife         reference lifetime by fuel and class [years]
         refint          reference interest rate by fuel and technology
         refco2          reference co2 emissions by fuel and technology [g per km]
         refother        reference annual other cost by fuel and technology
;

refprice(cf,ct)    = sum(re$(maprt(re,ct) and reference(cf,re)), reference("price",re));
reffuel(cf,ct)     = sum(re$(maprt(re,ct) and reference(cf,re)), reference(cf,re));
refccm(cf,ct)      = sum(re$(maprt(re,ct) and reference(cf,re)), reference("ccm",re));
reflife(cf,ct)     = sum(re$(maprt(re,ct) and reference(cf,re)), reference("lifetime",re));
refint(cf,ct)      = sum(re$(maprt(re,ct) and reference(cf,re)), reference("interest",re));
refco2(cf,ct)      = sum(re$(maprt(re,ct) and reference(cf,re)), reference("co2",re));
refother(cf,ct)    = sum(re$(maprt(re,ct) and reference(cf,re)), reference("other",re));

*###############################################################################
*                       (3) SPECIFY CAR TECHNOLOGIES
*###############################################################################
parameter
         avl             average [liter per km]  from historical values
         avkm            average kilometer per car [km per car] from historical values
         accm            average cubic capacity per car implied by mvh tax fitting
         MUpcar          markup car prices to base car
         pfuel           implied fuel price
         cartax          car taxes
         os              implied share of transport fuel in total refined oil spendings
         carprice        average car price as implied by SAM
         mucar           markup of diesel car as implied by reference car
         muccm           markup of cubic capacity as implied by reference cars
         prefcar         price of reference gasoline car implied by SAM and markup
         vat             value added tax in final consumption    /0.16/
         rental          rental price of existing stock cars
         tc              consumption tax rate
         carshare        cost share of cars
;
tc(i) = vat;
parameter
         tfueld0         fuel demand by car technology [million €]
         tcard0          demand for car by technology [million €]
         totherd0        demand for other inputs [million €]
         tout0           output of car technologies
         cartax          motor vehicle tax per car [€ per car]
         fueltax         fuel taxes
         pvkm0           implied price per vehicle kilometer [€ per vkm]
         ecar0           energy consumption of cars
         snd0            stock demand for new cars [million €]
         ssd0            stock demand for existing stock [million €]
         sy0             stock activity output [million €]
         Pstock0         existing car stock [#]
         stock0          household endowment of cars
         ts              stock tax for new car purchases
;


avl(cf)                  = addfuel("liter",cf)/addfuel(„km“,cf);
avkm(cf,ct)              = addfuel(„km“,cf)/sum(sc, stockCF(cf,sc));
fueltax(cf)              = (addfuel("mwst",cf) + addfuel("oiltax",cf))
                           /(addfuel(„fuel“,cf) - addfuel("mwst",cf)
                           - addfuel("oiltax",cf));
pfuel(cf)                = addfuel(„fuel“,cf)/addfuel("liter",cf);
rental(cf)               = addfuel(“rental”,cf)
*--------------------------------- STOCK ACTIVITY ------------------------------
carprice("average","all")= cd0("mvh")/sum(cf, stockCF(cf,"new"));
mucar(cf,ct)             = refprice(cf,ct)/refprice(„gasoline“,“standard“);
carprice(cf,ct)          = mucar(cf,ct)*carprice("average","all");
snd0("mvh",cf,“standard“)= mucar(cf,“standard“)*stockCF(cf,"new")*cd0("mvh")
                           /sum(ccf, mucar(ccf,“standard“)*stockCF(cf,"new"));
cd0("mvh")               = 0;
ssd0(cf,ct)              = rental(cf)*stockCF(cf,"stock");
ts                       = vat;
sy0(cf,ct)               = (1+vat)*snd0("mvh",cf,ct) + ssd0(cf,ct);
```

```
tcard0(cf,ct)            = sy0(cf,ct);
Pstock0("stock",cf,ct)   = stockCF(cf,"stock");
Pstock0("new",cf,ct)     = stockCF(cf,"new");
Pstock0(„total“,cf,ct)   = stockCF(cf,"stock") + stockCF(cf,"new");
stock0(cf,ct)            = ssd0(cf,ct);
tfueld0(„p_c“,cf,ct)     = addfuel(„fuel“,cf) - addfuel("mwst",cf) - addfuel("oiltax",cf);
cd0(„p_c“)               = cd0(„p_c“) - sum((cf,ct), tfueld0(„p_c“,cf,ct));
os                       = sum((cf,ct), (1+fueltax(cf))*tfueld0(„p_c“,cf,ct))
                           /(sum((cf,ct), (1+fueltax(cf))*tfueld0(„p_c“,cf,ct))
                           + 1.418*cd0(„p_c“));
muccm(cf,ct)             = refccm(cf,ct)/refccm(„gasoline“,“standard“);
accm(cf,ct)              = refccm(„gasoline“,“standard“)*muccm(cf,ct);
cartax(cf,ct)            = Pstock0(„total“,cf,ct)*muccm(cf,ct)
                           *(refccm(„gasoline“,“standard“)/100)
                           *addfuel(„cartax“,cf);
accm(cf,ct)              = 100*(cartax(cf,ct)/Pstock0(„total“,cf,ct))/addfuel(„cartax“,cf);
cartax(cf,ct)            = cartax(cf,ct)*(addfuel(„cartaxtotal“,“gasoline“)
                           /sum((ccf,cct), cartax(ccf,cct)));
accm(cf,ct)              = (cartax(cf,ct)/Pstock0(„total“,cf,ct))/addfuel(„cartax“,cf)*100;
cartax(cf,ct)            = cartax(cf,ct)/Pstock0(„total“,cf,ct);
totherd0(i,cf,ct)$(cons(i,“total“) and not sameas(i,“p_c“))
                         = cons(i,"wkfz")/cons(i,“total“)*cd0(i)
                           *Pstock0(„total“,cf,ct)
                           /sum( (ccf,cct), Pstock0(„total“,ccf,cct));
cd0(i)$(not sameas(i,“p_c“)) = cd0(i) - sum((cf,ct), totherd0(i,cf,ct));
*------------------------------ COMPUTE TOTAL OUTPUT ---------------------------
tout0(cf,ct)             = sum(i, totherd0(i,cf,ct)*(1+vat)
                           + tfueld0(i,cf,ct)*(1+fueltax(cf)))
                           + tcard0(cf,ct) + Pstock0(„total“,cf,ct)*cartax(cf,ct);
pvkm0(cf,ct)             = tout0(cf,ct)/addfuel(„km“,cf);
carshare("car",cf,ct)    = (tcard0(cf,ct) + Pstock0(„total“,cf,ct)*cartax(cf,ct))
                           /tout0(cf,ct);
carshare("other",cf,ct)  = sum(i, totherd0(i,cf,ct)*(1+vat))/tout0(cf,ct);
carshare(„fuel“,cf,ct)   = sum(i,tfueld0(i,cf,ct)*(1+fueltax(cf)))/tout0(cf,ct);
*--------------------------- ASSIGN ENERGY VALUES ------------------------------
ecar0(„p_c“,“gasoline“,ct) = eevh(„gasoline“);
ecar0(„p_c“,“diesel“,ct)   = eevh(„diesel“);
evh(i)                     = evh(i) - sum((cf,ct), ecar0(i,cf,ct));

*###############################################################################
*                     (4) LOAD AND AGGREGATE TREMOVE DATA
*###############################################################################
$include"%datadir%tremove.inc"
parameter
         pkm             person and tonne km [million]
         vkm             vehicle kilometer [million]
         vot             value of time  [€ per hour]
         pce             passenger car equivalents [million]
         speed           speed on networks [km per hour]
         duration        length of travel period [hours]
;

pkm(np,nd,tp,nv,nn) = sum((p,d,tper,v,n)$(mapn(n,nn) and mapd(d,nd) and mapv(v,nv)
                                 and mapp(p,np) and maptp(tper,tp)), Tpkm(p,d,tper,v,n));
vkm(np,nd,tp,nv,nn) = sum((p,d,tper,v,n)$(mapn(n,nn) and mapd(d,nd) and mapv(v,nv)
                                 and mapp(p,np) and maptp(tper,tp)), Tvkm(p,d,tper,v,n));
pce(np,nd,tp,nv,nn) = sum((p,d,tper,v,n)$(mapn(n,nn) and mapd(d,nd) and mapv(v,nv)
                              and mapp(p,np) and maptp(tper,tp)), Tvkm(p,d,tper,v,n)*Tpcu(v));
alias(v,vv), (p,pp), (d,dd);
speed(nv,tp,nn)$sum((np,nd),vkm(np,nd,tp,nv,nn))
                    = sum((v,tper,n)$(mapv(v,nv) and maptp(tper,tp) and mapn(n,nn)),
                          Tspeed(v,tper,n)*sum((pp,dd), Tvkm(pp,dd,tper,v,n)))
                         /sum((np,nd),vkm(np,nd,tp,nv,nn));
speed(nv,tp,nn)$(not sum((np,nd),vkm(np,nd,tp,nv,nn)))
                   = sum((v,tper,n)$(mapv(v,nv) and maptp(tper,tp) and mapn(n,nn)),
                         Tspeed(v,tper,n));
vot(np,nd,tp,nv,nn)$pkm(np,nd,tp,nv,nn)
                   = sum((p,d,tper,v,n)$(mapn(n,nn) and mapd(d,nd) and mapv(v,nv)
                                 and mapp(p,np) and maptp(tper,tp)),
                                 Tvot(p,d,tper,v,n)*Tpkm(p,d,tper,v,n))
                                 /pkm(np,nd,tp,nv,nn);
duration(tp)      = sum(maptp(tper,tp), Tduration(tper));
```

```
*###############################################################################
*               (5) ASSING VALUES FOR TRANSPORT ACTIVITIES
*###############################################################################
*-------------------------------- PHYSICAL VALUES ------------------------------
parameter
         tact0   transport activity physical data
;

tact0(„pkm“,np,nd,tp,nv,nn)       = pkm(np,nd,tp,nv,nn);
tact0(„vkm“,np,nd,tp,nv,nn)       = vkm(np,nd,tp,nv,nn);
tact0("pce",np,nd,tp,nv,nn)       = pce(np,nd,tp,nv,nn);
tact0("speed",np,nd,tp,nv,nn)     = speed(nv,tp,nn);
tact0("vot",np,nd,tp,nv,nn)       = vot(np,nd,tp,nv,nn);
tact0("pcu",np,nd,tp,nv,nn)       = sum(mapv(v,nv), Tpcu(v));

*-------------------------- MONETARY VALUES: CARS ------------------------------
set
         allm(*,*,*,*,*)    set of all modes distances ...
         aallm(*,*,*,*,*)   set of all modes distances ...
;
allm(np,nd,tp,nv,nn) = yes; aallm(np,nd,tp,nv,nn) = yes;

parameter
         vkm0            scaled vehicle kilometers of cars
         share_pkm       share of pkm by trip class in total pkm of cars
         tactin0         input vectors to transport activities gross
         tactcarin0      input vectors to transport activities
         tay0            output of transport activities
         occup           occupancy rate
;
vkm0(cf,ct)                  = addfuel(„km“,cf)
                               *sum((nnp,nnd,ttp,nnn), tact0(„vkm“,nnp,nnd,ttp,"car",nnn))
                               /sum(ccf, addfuel(„km“,ccf));
pvkm0(cf,ct)                 = tout0(cf,ct)/vkm0(cf,ct);
occup(allm)$tact0(„vkm“,allm) = tact0(„pkm“,allm)/tact0(„vkm“,allm);
tactcarin0(cf,ct,np,nd,tp,"car",nn)
                             = pvkm0(cf,ct)*tact0(„vkm“,np,nd,tp,"car",nn)
                               *vkm0(cf,ct)/sum((ccf,cct),vkm0(ccf,cct));
parameter
         share_vkm      share of cars' vkm in total cars' vkm
;
*----------------------------- RAIL TRANSPORT ----------------------------------
tactin0("rail",np,nd,tp,"PTRAIN",nn)
                         = cd0("rail")*
                           tact0(„pkm“,np,nd,tp,"PTRAIN",nn)/
                           sum((nnp,nnd,ttp,nnn), tact0(„pkm“,nnp,nnd,ttp,"PTRAIN",nnn));
cd0("rail") = 0;
*----------------------------- BUS/METRO TRANSPORT -----------------------------
set
         public  sub set of modes which belong to public urban transport
         /METRAM, BUS/
;
alias(public,ppublic);
tactin0("otp",np,nd,tp,public,nn)
                         =  cd0("otp")*tact0(„pkm“,np,nd,tp,public,nn)/
                            sum((nnp,nnd,ttp,ppublic,nnn),
tact0(„pkm“,nnp,nnd,ttp,ppublic,nnn));
cd0("otp") = 0;
*----------------------------- AIR TRANSPORT ----------------------------------
tactin0("atp",np,nd,tp,"PLANE",nn)
                         =  cd0("atp")*tact0(„pkm“,np,nd,tp,"PLANE",nn)/
                            sum((nnp,nnd,ttp,nnn), tact0(„pkm“,nnp,nnd,ttp,"PLANE",nnn));
cd0("atp") = 0;
*----------------------------- CREATE MONETARY INPUTS --------------------------
tay0(np,nd,tp,nv,nn) = sum(i, tactin0(i,np,nd,tp,nv,nn))
                       + sum((cf,ct), tactcarin0(cf,ct,np,nd,tp,nv,nn));

*###############################################################################
*                            (6) SAVE DATA
*###############################################################################
execute_unload "%datadir%%out%" i, c, e, g, ga, gn, mapF, mapL, l,
                         y0, d0, e0, id0, kd0, ld0, otax, utax, m0, a0, lod0,
                         cd0, gd0, inv0, bop, c0, g0,
                         cons, lab
                         evf, eevf, evh, eevh, co20, ene0, ecar0
                         unit, quality,
                         mapCPA, mapC,
                         tactin0=taid0, tactcarin0=tacard0, tact0, tay0,
                         tout0=cy0, totherd0=cid0, tcard0=ccd0, tfueld0=cfd0
                         stock0, snd0, ssd0, sy0=sy0, Pstock0,
```

```
nn=n, nv=m, np=p, nd=d, tp
lavmohr, cf, ct
fueltax=tfuel cartax tc=tother
refco2 tnew ts pvkm0 vkm0;
```

Impose tax system

```
$title Program to impose tax system on the transport dataset

$set data IO_2004_simple_transport_one
$if not set datadir $set datadir "..\data\"
$if not set out $set out "%data%_tax"
$if not set data $abort "###### NO SOURCE FILE SPECIFIED ######"
$if not exist "%datadir%%data%.gdx" $abort "##### SOURCE FILE DOES NOT EXIST #####"

*##############################################################################
*                              (1) LOAD DATA
*##############################################################################
set
         i       set of commodities
         c       set of consumption account in transition matrix
         g       set of generation technologies
         e       energy commodities
         ga      set of active generation technologies
         gn      set of inactive generation technologies
         mapF    mapping fuels to technologies
         mapL    mapping technology to load
         l       load segments
         n       set of transport networks
         m       set of transport modes
         p       set of transport purposes
         d       set of transport distances
         tp      set of travel periods
         cf      set of car fuels
         ct      set of car technologies
;
allias(i,j);

parameter
         y0      total production [million €]
         d0      production for domestic market [million €]
         e0      production for exports [million €]
         id0     intermediate demand [million €]
         kd0     capital demand [million €]
         ld0     labor demand [million €]
         otax    output tax [million €]
         utax    use taxes [million €]
         lod0    demand by load [million €]
         m0      imports [million €]
         a0      armington supply [million €]
         unit    unit netput vector for generation technologies
         c0      total private consumption [million €]
         g0      total public consumption [million €]
         inv0    investment demand [million €]
         bop     balance of payment [million €]
         cd0     private demand [million €]
         gd0     public demand [million €]
         ls0     labor supply [million €]
         ks0     capital supply [million €]
         cons    consumption matrix
         taid0   intermediate inputs transport activities [million €]
         tacard0 car demand by transport activities [million €]
         tay0    output of transport activities [million €]
         tact0   physical data on transport activities [pkm vkm pce in million - km per hour]
         lavmohr average kilometer per trip for public transport [km]
         cy0     output of car technologies [million €]
         cid0    input of car technologies [million €]
         ccd0    car input of car technologies [million €]
         cfd0    fuel demand by car technology [million €]
         refco2  reference emissions [g c02 per km]
         vkm0    of cars by class [million vkm]
         stock0  stock of car technologies [million €]
         snd0    demand for new cars [million €]
         ssd0    demand for car stock [million €]
         sy0     output of stock activity
         Pstock0 stock of cars [million]
         ts      tax on new car purchases
         evh     energy demand household [TJ]
         eevh    enery demand household by energy commodities [TJ]
         evf     energy demand firms [TJ]
         eevf    energy demand firms by energy commodity [TJ]
         ecar0   energy demand by cars [TJ]
         co20    emissions [1000 t]
         tfuel   fuel tax payments [rate]
         cartax  car tax payments [million €]
```

```
         tother  tax on other inputs in car technologies [rate]
         pvkm0   price per vehicle kilometer
         kmpercat kilometers per car category [million]
;

$gdxin "%datadir%%data%"
$load i c g ga gn mapF mapL l n m p tp cf ct d e
$load y0 d0 e0 id0 kd0 ld0 otax utax lod0 m0 a0 unit
$load c0 g0 inv0 bop cd0 gd0
$load taid0 tay0 tacard0 tact0 lavmohr
$load cy0 cid0 ccd0 cfd0
$load stock0 snd0 ssd0 sy0 Pstock0
$load evh eevh evf eevf ecar0 co20
$load cartax tfuel tother cons refco2
$load pvkm0 ts vkm0

*################################################################################
*                       (2) TRANSPORT TECHNOLOGY TAXES
*################################################################################
parameter
         tcar    tax on cars
         pcar0   benchmark price of cars
         pfuel0  benchmark price on fuels
         pother0 benchmark price of other inputs
;
tcar(cf,ct)              = cartax(cf,ct)*Pstock0("total",cf,ct)/ccd0(cf,ct);
pcar0(cf,ct)             = 1 + tcar(cf,ct);
pfuel0(i,cf)             = 1 + tfuel(cf);
pother0(i)               = 1 + tother(i);

*################################################################################
*                       (3) TRANSPORT ACTIVITY TAXES
*################################################################################
parameter
         tta     tax on transport activity inputs
         pta0    benchmark price for transport activity inputs
;

parameter
         costcover       cost coverage of public transport [Source TREMOVE p. 39]
         /BUS            0.817
          METRAM         0.817
          PTRAIN         0.552
          FTRAIN         1
          PLANE          1
          SHIP           1
          SLOW           1
          CAR            1/;
tta(i,m)$(sum((p,d,tp,n), taid0(i,p,d,tp,m,n)))   = (costcover(m) - 1);
pta0(i,m) = 1 + tta(i,m);
tay0(p,d,tp,m,n) =  sum(i, pta0(i,m)*taid0(i,p,d,tp,m,n))
                    + sum((cf,ct), tacard0(cf,ct,p,d,tp,m,n));

*################################################################################
*                       (4) CONSUMPTION TAXES
*################################################################################
parameter
         tc      consumption taxes
         pc0     benchmark consumer prices
;
tc(i)$(cd0(i) and cons(i,"total")) = (cons(i,"total") - cd0(i))/cd0(i);
pc0(i) = 1 + tc(i);

*################################################################################
*                       (5) PRODUCTION TAXES
*################################################################################
parameter
         ty      ouput tax
         ti      input tax
         pi0     intermediat input price
;
set
         p_c     set to identify refined oils
         /p_c/
;
allias(i,jj);
ti(i,j)$utax(j)  = utax(j)/sum(jj, id0(jj,j));
ti(i,"otp")      = 0;
ti("p_c","otp")  = tfuel("diesel");
ti(i,"otp")$(not p_c(i)) = (utax("otp")- id0("p_c","otp")*ti("p_c","otp"))
```

```
                            /sum(jj$(not p_c(jj)), id0(jj,"otp"));
pi0(j,i) = 1+ ti(j,i);
ty(i)$y0(i) = otax(i)/y0(i);

*################################################################################
*                       (6) INCOME AND SOCIAL SECURITY
*################################################################################
scalar
*        Source: Source: OECD 2007 Revenue Statistic
         incometax       tax on household income                  /175558/
         hhsov           social insurance contribution household /135280/
         unsov           social insurance contribution firms     /152530/
;
parameter
         tl      tax on labor use
         pl0     benchmark labor price
         tw      tax on wage
         pw0     gross wage
         timeL0  time supplied to labor
;
tl(i)    = unsov/(sum(j, ld0(j)) - unsov);
pl0(i)   = 1 + tl(i);
ld0(i)   = ld0(i)/pl0(i);
ls0      = sum(i, ld0(i)) + sum(ga, unit("lab",ga)*unit("out",ga));
ks0      = sum(i, kd0(i)) + sum(ga, unit("cap",ga)*unit("out",ga));
tw       = (incometax + hhsov)/(ls0 - incometax - hhsov);
pw0      = 1 + tw;
timeL0   = ls0/pw0;

*################################################################################
*                       (7) DERIVE DIRECT TRANSFER
*################################################################################
parameter
         trans0          benchmark direct transfer [million €]
;
trans0   = - (ks0 + timeL0 - sum(i, pc0(i)*cd0(i) + inv0(i))
                   + sum((cf,ct), + stock0(cf,ct))
                   - sum((p,d,tp,m,n), tay0(p,d,tp,m,n))) ;
c0       = sum(i, cd0(i) + inv0(i)) + sum((p,d,tp,m,n), tay0(p,d,tp,m,n));
g0       = sum(i, gd0(i));

*################################################################################
*                          (8) SAVE DATA TO GDX
*################################################################################
execute_unload "%datadir%%out%" i, g, e, ga, gn, mapF, mapL, l, n, p, m, d, tp, cf, ct,
         y0, d0, e0, id0, kd0, ld0, lod0, m0, a0, unit, evf, eevf, tl, pl0, ty, ti, pi0,
         c0, g0, inv0, bop, cd0, gd0, ls0, ks0, evh, eevh, timeL0, trans0, tc, pc0, tw, pw0
         taid0, tay0, tacard0, tact0, lavmohr, tta, pta0
         cy0, cid0, ccd0, cfd0, ecar0, tfuel, tcar, tother, pcar0, pfuel0, pother0, refco2,
         stock0, snd0, ssd0, sy0, Pstock0,
         co20, otax, utax, ts, pvkm0, vkm0
;
```

Codes for the simulations

Files for the simulation are organized in the same manner as in the international model. Since the *call.gms* file is similar to the international model, it is not stated. In the *dataload.gms* file data are loaded, the congestion function is calibrated, and the tax system is additionally manipulated.

dataload.gms

```
$ontext
Programm to load all relevant benchmark data
Also serves as overview over all parameters, sets, and equilibrium conditions.

(1)      LOAD DATA
(2)      DATA SCALING
(3)      CALIBRATION ELECTRICITY TECHNOLOGIES
(4)      SEPARATING FUEL INPUTS
(5)      CALIBRATION TRANSPORT ACTIVITIES
(6)      CONGESTION FUNCTION
(6)      CARBON EMISSIONS
(7)      CONSUMPTION TAXES
(8)      INITALIZE POLICY PARAMETERS
OPTIONS:
------------------------ SCALING AND DATA LOAD ---------------------------------
         data            name of gdx file containing data
         datadir         name of data directory
         scalev          scalinf for monetary units
         scalet          scaling for emission
         scalee          scaling of energy values
         scalepkm        scaling of transport data

------------------------ MARKUPS INACTIVE TECHNOLOGIES ------------------------
         muCoalCCS       markup coal ccs technology
         muGASCCS        markup gas ccs technology
         muWindOff       markup offshore wind technology
         muPV            markup pV technology
         muBhcoaPC       markup hcoa in base
         muBCCGT         markup CCGT in base
         muhybrid        markup on hybrid cars
$offtext
$eolcom !
$if not set data $set data IO_2004_one
$if not set datadir $set datadir "..\data\"
$if not set scalev $set scalev 0.001
$if not set scalet $set scalet 0.000001
$if not set scalee $set scalee 0.001
$if not set scalepkm $set scalepkm 0.001
$if not set muCoalCCS $set muCoalCCS 0.25
$if not set muGASCCS $set muGASCCS 0.15
$if not set muWindOff $set muWindOff 0.1
$if not set muPV $set muPV 1.5
$if not set muBhcoaPC $set muBhcoaPC 0.19
$if not set muBCCGT $set muBCCGT 0.19
$if not set muhybrid $set muhybrid 0.03
$if not exist "%datadir%%data%.gdx" $abort "###### SOURCE DATA MISSING ######"
option solprint=silent;

*################################################################################
*                                 (1) LOAD DATA
*################################################################################
set
         i       set of commodities
         e       set of energy commodities
         l       set of load segments
         mapL    mapping technologies to load
         g       set of generation technologies
         ga      set of active generation technologies
         gn      set of in active generation technologies
         cf      set of transport fuels
         ct      set of transport technologies
         n       set of transport networks
         m       set of transport modes
         d       set of transport distances
         p       set of transport purposes
         tp      set of travel periods
         glo     global set
```

```
         gloe    global set of all energy and fuel inputs

;
alias(i,j,ii), (g,gg), (ga,gga), (gn,ggn), (n,nn), (d,dd), (p,pp), (m,mm), (tp,ttp),
         (cf,ccf), (ct,cct), (l,ll);

*------------------------------- NESTING SETS ----------------------------------
set
         ele     electricity sector
         /ele/
         fof     fossil fuels
         /coa, gas, p_c/
         p_c     refined oils
         /p_c/
         coa     only coal
         /coa/
         otp     other transport sector
         /otp/
         work    only work transport
         /work/
         leis    only leisure trips
         /cons/
         pub     set of public transport modes
         /bus, metram/
         ptrain  only private trains
         /ptrain/
         pur     purchased transportation modes
         /bus, metram, ptrain, plane/
         busm    busses and metro
         /bus, metram/
         trpl    train and plane
         /ptrain, plane/
         own     own transportation modes
         /car, slow/
         roadv   road vehicles
         /bus, car/
         busses  only busses
         /bus/
         cars    only car mode
         /car/
         lkws    only lkws
         /lkw/
         slow    only slow mode
         /slow/
         roads   set of road networks
         /URBAN, NURBAN/
         nroad   non road modes in production
         /atp, wtp/
         public  all public transport production sectors
         /bus, rail, metram/
         gaso    only gasoline cars
         /gasoline/
         prodtrn transport production sectors
         /otp, atp, wtp/
;

*----------------------------- SETS FOR POLICIES -------------------------------
set
         exempted       set to indicate if commodity i in j is exempted from carbon regulation
         tradeI         input i in sector j is part of trading scheme I
         tradeII        input i in sector j is part of trading scheme II
         tradeIII       input i in sector j is part of trading scheme III
         tradeIV        input i in sector j is part of trading scheme IV
         tradeS         input i in sector j is part of sectoral regulation
         ets            sector in emission trading scheme
;
*-------------------------- BENCHMARK PARAMETERS -------------------------------
parameter
         y0      total production [million €]
         d0      production for domestic market [million €]
         e0      production for exports [million €]
         id0     intermediate inputs [million €]
         kd0     capital inputs [million €]
         fd0     benchmark transport fuel demand
         tf      tax on transport fuel inputs
         pf0     benchmark price on fuel inputs
         ld0     labor inputs [million €]
         lod0    electricity demand by load [million €]
         ti      intermediate input tax
         pi0     intermediate inputs reference price
```

```
ty      output tax
tl      labor tax
pl0     reference labor price
unit    unit input vector generation technologies
phyld0  physical electricity demand by load
fuely0  transportation fuel output
fuelid0 transportation fuel input
a0      armington supply [million €]
m0      imports [million €]
g0      total government consumption [million €]
gd0     public commodity consumption [million €]
bop     balance of payments [million €]
trans0  direct transfers to household [million €]
c0      total private consumption [million €]
cd0     private commodity consumption [million €]
inv0    investments [million €]
ks0     capital endowment [million €]
ls0     labor supplied [million €]
timeL0  time supplied to labor [million €]
tw      tax on labor income
pw0     reference household wage
stock0  stock of cars [million €]
Pstock0 stock of cars [number]
tc      tax on private consumption
pc0     reference private consumption
ts0     supply of travel "speed"
timeT0  benchmark travel time budget
time0   total consumption and transport time endowment
leis0   benchmark leisure consumption
tay0    output of transport activity [million €]
taid0   intermediate demand transport activity [million €]
tacard0 car demand of transport activity [million €]
tta     tax on intermediate demand of transport activities
pta0    reference price intermediate demand transport activities
tat0    time input [million €]
tast0   time input for congestion link [million €]
speed0  speed of mode on network in travel period
duration        duration of travel periods [hours]
/opeak        7320
 peak         1440/
pce0    passenger car equivalents in benchmark [million]
pkm0    benchmark person or tone kilometer [million]
vkm0    vehicle kilometer in benchmark [million]
pcu     passenger car conversion factors
/car    1
 bus    2
 lkw    2/
occup   occupancy rates [persons per vehicle]
bpr     parameters in BRP function
shcom   committed value share in total mileage output
tacom0  demand committed mileage
tasup0  demand supplementary mileage
tcirc0  circulation tax in benchmark
tcirc   circulation tax in scenario
vot0    value of time of trips
costcov cost coverage rates for public transport [TREMOVE p. 39]
/bus    0.817
 metram 0.817/
cy0             output of car technologies [million €]
cid0            intermediate demand car technologies [million €]
cfd0            fuel demand by car technologies [million €]
ccd0            car demand [million €]
tfuel           transport fuel tax
tcar            car tax
pfuel0          reference fuel price
pcar0           reference car rental price
tother          tax on intermediate inputs
pother0         reference price car intermediate inputs
refco2          reference specific emissions [g per km]
kmpercat        kilometer per car category
pvkm            price of vehicle km
shcomitted      percentage of committed mileage
/diesel         0.65
 gasoline       0.65/
totalvkmcar     total pkm by cars
comy0           output of committed millage activity
comid0          maintenance input of committed mileage
comcar0         car input to committed mileage
comfd0          committed fuel input
supy0           output of supplementary millage activity
```

```
         supid0          maintenance input of supplementary inputs
         supfd0          supplementary fuel input
         carvkm0         vkm by car class [Million]
         pvkm0           price per vehicle kilometer by car class [€ per vkm]
         snd0            demand for new cars [million €]
         ssd0            demand for car stock [million €]
         sy0             output of stock activity [million €]
         stax            tax on new car purchases
         ps0             reference price new car purchases
         co20            carbon emission [1000 t]
         evh             household emission relevant energy [TJ]
         eevh            household emission relevant energy by energy commodity [TJ]
         evf             firms emission relevant energy [TJ]
         eevf            firms emission relevant energy by energy commodity [TJ]
         ecar            energy demand by cars [TJ]
         tact0           transport activity data [pkm vkm pce in million - speed:km per hour]
         carblim0        initial carbon emissions
;

$gdxin "%datadir%%data%"
$load i l mapl g ga gn cf ct n m d p tp e
$load y0 d0 e0 id0 kd0 ld0 lod0 ti pi0 ty tl pl0 unit
$load a0 m0
$load g0 gd0 bop trans0
$load c0 cd0 ks0 ls0 timeL0 tw pw0 stock0 Pstock0 inv0 tc pc0
$load tay0 taid0 tacard0 tta pta0
$load cy0 cfd0 cid0 tfuel tcar pfuel0 tother pother0 pcar0 refco2 ccd0 carvkm0 pvkm0
$load snd0 ssd0 sy0 ps0 stax=ts
$load co20 evh eevh evf eevf ecar tact0
*$load pvkm0
$gdxin
glo(i) = yes; glo(pub) = yes; glo("hh") = yes; glo(ct) = yes;
gloe(fof) = yes; gloe(cf) = yes;

*---------------------------- ELECTRICITY PARAMETER ----------------------------
parameter
         markupG      markup of inactive generation technologies
         /gasCCS         %muGasCCS%
          windOff        %muWindOff%
          PV             %muPV%
          coalCCS        %muCoalCCS%
          BhcoaPC        %muBhcoaPC%
          BCCGT          %muBCCGT%/
         capacities      estimated capacities in TWh
*        0       : no capacity expansion possible
*        +inf    : unlimited capacity possible
*        Source: BMU erneuraber energien in zahlen p. 44
         /CCGT           +inf
          BCCGT          +inf
          OCOT           +inf
          OCGT           +inf
          windOn         68
          windOff        135
          PV             105
          nuclear        0
          hcoaPC         +inf
          BhcoaPC        +inf
          ligniteST      +inf
          hydro          0
          other          0
          gasCCS         +inf
          coalCCS        +inf/
         relgen0         relative generation in %
         cap             capacity limit for technology g
         relcap          capacity relative to benchmark output
         convTWhTJ       conversion factor from TWH to TJ        /3599.99712/
         co2gen0         benchmark emission of generation technologies
         cpr             capture rate for ccs technologies
         /gasCCS         0.9
          coalCCS        0.9/
;

*---------------------------- TRANSPORT PARAMETER ------------------------------
parameter
         trn_p           total transport by purpose
         trn_pd          transport by purpose and distance
         trn_pdtp        transport by period purpose and distance
         trn_pdtpm       transport by mode period purpose and distance
         py0             output of public transport modes
         pid0            intermediate inputs public transport modes
```

```
         pkd0           capital demand public transport modes
         pld0           labor demand public transport modes
         pti            intermediate input tax public transport
         ppi0           intermediate input reference price public transport
         ptl            public transport labor tax
         ppl0           public transport labor price
         pty            public transport output tax
         tapubd0        transport activities public transport demand
         ttapub         tax on public transport inputs
         ptapub0        reference price public transport inputs
         co2pub0        carbon emissions public transport
         ptf            tax on transportation fuel inputs
         ppf0           reference price transportation fuel inputs
         pfd0           public transport fuel demand
         ra0            supply of available road capacity in benchmark
         tad0(p,d,tp,m,n)       demand for road time aggregate
         tara0(p,d,tp,m,n)      demand for road availability
         congpce        million pce per hour of travel period [million pcu]
         occup          occupancy rates [persons per vehicle]
         co2car0        carbon emissions by cars
;

*----------------------------- CARBON EMISSIONS --------------------------------
parameter        emicoef emission coefficient in [kg per TJ] [Source IPCC 2006]
                 /coa           101000
                  p_c           74100
                  gas           56100
                  diesel        74100
                  gasoline      69300
                  CCGT          56100
                  hcoaPC        98300   !Anthracite value
                  OCGT          56100
                  OCOT          74100   !gas diesel oil
                  ligniteST     101000/
;

*---------------------------- POLICY PARAMETERS --------------------------------
parameter
         carblimI       carbon limit trading scheme I
         carblimII      carbon limit trading scheme II
         carblimIII     carbon limit trading scheme III
         carblimIV      carbon limit trading scheme IV
         carblimS       carbon limit sectoral regulation
         carblimTRN     carbon limit private transportation in circulation tax case
         redu           reduction level of economy’s emissions                         /0/
;


* FLAGS
scalar
         congestion     one if congestion is used                       /1/
         endogL         endogenous labor                                /0/
         circulation    endogenous circulation tax on cars              /0/
         lump           one if lumpsum recycling                        /1/
         keynes         one if marginal propensity to save is one       /0/
         pubsub         one if revenues are recycled using public transport subsidy /0/
;

*###############################################################################
*                            (2) DATA SCALING
*###############################################################################
scalar
         scalev         scaling factor monetary units   /%scalev%/
         scalet         scaling factor emission units   /%scalet%/
         scalee         scaling factor energy units     /%scalee%/
         scalepkm       scaling factor pkm units        /%scalepkm%/
         rounding       rounding factor                 /8/
;

*-------------------------- SCALE MONETARY UNITS -------------------------------
y0(i)            = round(y0(i)*scalev, rounding);
d0(i)            = round(d0(i)*scalev, rounding);
e0(i)            = round(e0(i)*scalev, rounding);
m0(i)            = round(m0(i)*scalev, rounding);
a0(i)            = round(a0(i)*scalev, rounding);
kd0(i)           = round(kd0(i)*scalev, rounding);
ld0(i)           = round(ld0(i)*scalev, rounding);
id0(j,i)         = round(id0(j,i)*scalev, rounding);
lod0(l,i)        = round(lod0(l,i)*scalev, rounding);
cd0(i)           = round(cd0(i)*scalev, rounding);
```

```
inv0(i)          = round(inv0(i)*scalev, rounding);
trans0           = round(trans0*scalev, rounding);
ks0              = round(ks0*scalev, rounding);
timeL0           = round(timeL0*scalev, rounding);
ls0              = round(ls0*scalev, rounding);
stock0(cf,ct)    = round(stock0(cf,ct)*scalev, rounding);
tay0(p,d,tp,m,n)         = round(tay0(p,d,tp,m,n)*scalev, rounding);
taid0(i,p,d,tp,m,n)      = round(taid0(i,p,d,tp,m,n)*scalev, rounding);
tacard0(cf,ct,p,d,tp,m,n)= round(tacard0(cf,ct,p,d,tp,m,n)*scalev, rounding);
cy0(cf,ct)       = round(cy0(cf,ct)*scalev, rounding);
cid0(i,cf,ct)    = round(cid0(i,cf,ct)*scalev, rounding);
cfd0(i,cf,ct)    = round(cfd0(i,cf,ct)*scalev, rounding);
ccd0(cf,ct)      = round(ccd0(cf,ct)*scalev, rounding);
ssd0(cf,ct)      = round(ssd0(cf,ct)*scalev, rounding);
snd0(i,cf,ct)    = round(snd0(i,cf,ct)*scalev, rounding);
sy0(cf,ct)       = round(sy0(cf,ct)*scalev, rounding);
unit("out",g)    = round(unit("out",g)*scalev, rounding);
unit("pgen",g)   = round(unit("pgen",g)*scalev, rounding);
gd0(i)           = round(gd0(i)*scalev, rounding);
g0               = round(g0*scalev, rounding);
bop              = round(bop*scalev, rounding);
c0               = sum(i,cd0(i)*pc0(i)) + sum((p,d,tp,m,n), tay0(p,d,tp,m,n));

*--------------------------- SCALE PHYSICAL UNITS ------------------------------
co20("total",i)          = round(co20("total",i)*scalet, 3);
co20("total","hh")       = round(co20("total","hh")*scalet, 3);
evh(i)                   = round(evh(i)*scalee, 3);
eevh(e)                  = round(eevh(e)*scalee, 3);
evf(j,i)                 = round(evf(j,i)*scalee, 3);
eevf(e,i)                = round(eevf(e,i)*scalee, 3);
ecar(i,cf,ct)            = round(ecar(i,cf,ct)*scalee, 8);
tact0("pkm",p,d,tp,m,n)  = round(tact0("pkm",p,d,tp,m,n)*scalepkm, 8);
tact0("vkm",p,d,tp,m,n)  = round(tact0("vkm",p,d,tp,m,n)*scalepkm, 8);
tact0("pce",p,d,tp,m,n)  = round(tact0("pce",p,d,tp,m,n)*scalepkm, 8);
carvkm0(cf,ct)           = round(carvkm0(cf,ct)*scalepkm,8);
pvkm0(cf,ct)             = round(pvkm0(cf,ct)*scalev/scalepkm, 8);
unit("TJ",g)             = round(unit("TWh",g)*convTWhTJ*scalee, 8);

*################################################################################
*                  (3) CALIBRATION ELECTRICITY TECHNOLOGIES
*################################################################################
markupG(gn) = 1 + markupG(gn);
cap(g)$(capacities(g)  and capacities(g) lt +inf) = unit("pgen",g)*capacities(g);
cap(g)$(not capacities(g))                        = unit("out",g);
cap(g)$(capacities(g) eq +inf)                    = +inf;
cap("nuclear")  = unit("pgen","nuclear")*unit("TWh","nuclear");
phyld0("TWh",l) = sum(g$mapl(l,g), unit("TWh",g));
phyld0("out",l) = sum(g$mapl(l,g), unit("out",g));

*################################################################################
*                            (4) SEPARATING FUEL INPUTS
*################################################################################
* Fuel inputs are separated using the emission relevant energy flows
* which identify diesel and gasoline consumption in total refined oil consumption
* In order to convert energy flows to monetary units prices of transportation
* fuels and the light fuel oil are used which are given in oecd energy prices
* and taxes

parameter
         oilprice        prices of refined oils [$ per toe in 2004]
         /gasoline        1748.7
          diesel          1155
          lfo             483.2/
         temptax         temporary tax parameter
         lkwtax          total taxes paid by freight transport [Mio € - DIW p. 274] /37231/
;

temptax("old",i)         = sum(j, ti(j,i)*id0(j,i));
temptax("out",i)         = ty(i)*y0(i);
fd0(cf,j)$id0("p_c",j)   = id0("p_c",j)*oilprice(cf)*eevf(cf,j)
                           /(sum(ccf, oilprice(ccf)*eevf(ccf,j))
                           + (eevf("toil",j) - sum(ccf, eevf(ccf,j)))*oilprice("lfo"));
fd0(cf,"gas")            = id0("p_c","gas")*oilprice(cf)*eevf(cf,"cru")
                           /(sum(ccf, oilprice(ccf)*eevf(ccf,"cru"))
                           + (eevf("toil","cru") - sum(ccf, eevf(ccf,"cru")))
                           *oilprice("lfo"));
* Industries does not pay the value added tax (16%) on top of eco and mineral
* oil tax
tf(cf,i)                 = tfuel(cf)/(1.16);
* Ships do not pay taxes on diesel
```

```
tf("diesel","wtp")       = 0;
temptax("fuel",i)        = sum(cf, tf(cf,i)*fd0(cf,i));
* Correct intermediate demands
id0("p_c",i)             = round(id0("p_c",i) - sum(cf, fd0(cf,i)), rounding);

*--------------------------------- Tax system for production -------------------
ti(i,j) = 0;
* according to IEA 2008 tax on refined oil inputs is around 20%
ti("p_c",i) = 0.2;
ti("p_c","p_c") = 0;
ti("p_c","atp") = 0;
temptax("fuel",i) = temptax("fuel",i) + ti("p_c",i)*id0("p_c",i);
ti(j,i)$(sum(ii, id0(ii,i)) and not ti(j,i))
                 = (temptax("old",i) - temptax("fuel",i))
                   /sum(ii$(not ti(ii,i)), id0(ii,i));
temptax("new",i)  = sum(j, ti(j,i)*id0(j,i)) + sum(cf, tf(cf,i)*fd0(cf,i));
temptax("test",i) = temptax("new",i) - temptax("old",i);
pf0(cf,i)         = 1 + tf(cf,i);
pi0(i,j)          = 1 + ti(i,j);

*------------------------ Create transportation fuel activity ------------------
fuely0(cf)       = sum(i, fd0(cf,i)) +  sum(ct, cfd0("p_c",cf,ct));
fuelid0("p_c",cf)= fuely0(cf);

* Adjust energy flows to faciliate carbon calibration
evf(cf,i)        = eevf(cf,i);
evf("p_c",i)     = round(evf("p_c",i) - sum(cf, eevf(cf,i)), 8);
evf(i,"cru")     = 0;
evf(cf,"cru")    = 0;
evf(cf,"gas")    = eevf(cf,"cru");
evf("p_c","gas") = max(evf("p_c","gas") - sum(cf, eevf(cf,"cru")), 0);

*###############################################################################
*                 (5) CALIBRATION TRANSPORT ACTIVITIES
*###############################################################################
trn_p(p)                 = sum((d,tp,m,n), tay0(p,d,tp,m,n));
trn_pd(p,d)              = sum((tp,m,n), tay0(p,d,tp,m,n));
trn_pdtp(p,d,tp)         = sum((m,n), tay0(p,d,tp,m,n));
trn_pdtpm(p,d,tp,m)      = sum((n), tay0(p,d,tp,m,n));

* Adjust total final consumption since work trips are implemented using rationing
c0 = c0 - trn_p("work");

*###############################################################################
*                           (6)   CONGESTION FUNCTION
*###############################################################################

*--------------------- CALIBRATION CONGESTION FUNCTION (BPR) -------------------
speed0(m,n,tp)                            = tact0("speed","cons","short",tp,m,n);
speed0("METRAM",n,tp)                     = 30.78253; !TREMOVE
occup(p,d,tp,m,n)$tact0("vkm",p,d,tp,m,n) = tact0("pkm",p,d,tp,m,n)/tact0("vkm",p,d,tp,m,n);
pkm0(p,d,tp,m,n)                          = tact0("pkm",p,d,tp,m,n);
vkm0(p,d,tp,m,n)$occup(p,d,tp,m,n)        = pkm0(p,d,tp,m,n)/occup(p,d,tp,m,n);
pce0(p,d,tp,m,n)                          = vkm0(p,d,tp,m,n)*pcu(m);
congpce(tp,n)                             = sum((p,d,m), pce0(p,d,tp,m,n))
                                            /duration(tp);

Positive Variable
         freeflow        calibrated free flow speed
         capacity        calibrated capacity of road net work
;
Variable
         dummy           dummy objective
;
Eqaution
         objII           dummy objective
         eq_bpr          BPR function to be calibrated
;

objII..
         dummy                   =E=     0
;

eq_bpr(tp,n)$(roads(n))..
         1/speed0("car",n,tp)    =E=     freeflow(n) *
                                         (1 + 0.15*(congpce(tp,n)/capacity(n))**4)
;

capacity.LO(n) = 0.0001;
freeflow.LO(n) = 0.0001;
capacity.FX(n)$(not sum(tp, congpce(tp,n))) = 0;
```

```
freeflow.LO(n)$(not sum(tp, congpce(tp,n))) = 0;
freeflow.L(n)  = sum(tp$(ord(tp) eq card(tp)), speed0("car",tp,n));
capacity.L(n)  = sum(tp$(ord(tp) eq card(tp)), congpce(tp,n));
model calibcong /objII, eq_bpr/;
solve calibcong using NLP maximizing dummy;

bpr("free_time",n)       = freeflow.L(n);
bpr("free_speed",n)$freeflow.L(n) = 1/freeflow.L(n);
bpr("capacity",n)        = capacity.L(n);
bpr(tp,n)                = bpr("free_time",n)*(1+0.15*
                           ((sum((pp,dd,m),pce0(pp,dd,tp,m,n))
                           /duration(tp))/bpr("capacity",n))**4);

*--------------------- CALIBRATION CONGESTION FUNCTION (EXP) --------------------
*        time = a1*[a2 + a3*exp(a4*Flow/hours)]
variable
         A1, A2, A3, A4
;

eqaution
         exp1, exp2
;

exp1(tp,n)$roads(n)..
         60*(1/speed0("car",n,tp))    =E=     A1(n)*(A2(n) + A3(n)*exp(A4(n)
                                              *congpce(tp,n)))
;

exp2(n)$roads(n)..
         freeflow.L(n)*60           =E=     A1(n)*(A2(n) + A3(n))
;

model calibcongIII /objII, exp1,exp2/;

A1.FX(n) = 1;
A2.L(n) = 1; A3.L(n) = 1; A4.L(n) = 1;

solve calibcongIII maximizing dummy using NLP;

parameter a1bus(n);
parameter
         tempt    temporary parameter to store time per km
         a1bus(n) a1 parameter for busses
;
tempt(m,tp,n)$(roadv(m) and speed0(m,n,tp)) = 1/speed0(m,n,tp);
a1bus(n)$tempt("car","opeak",n) =  tempt("bus","opeak",n)/tempt("car","opeak",n);
speed0("bus",n,tp)$a1bus(n) = speed0("car",n,tp)/a1bus(n);

*----------------------------- CREATE INPUTS ------------------------------------
parameter
         tempocc         occupancy rates for non-road trips
         /slow           1
          ptrain         200
          plane          100/
;

vot0(p,d,tp,m,n) = tact0("vot", p,d,tp,m,n);
ra0(tp,"car",n)$roads(n) = (1 - 1/speed0("car",n,tp))
                           *sum((p,d), vkm0(p,d,tp,"car",n));
ra0(tp,"bus",n)$roads(n) = (1 - 1/speed0("bus",n,tp))
                           *sum((p,d), vkm0(p,d,tp,"bus",n));
tat0(p,d,tp,m,n)$(speed0(m,n,tp) and tempocc(m))
                         = tact0("pkm",p,d,tp,m,n)/speed0(m,n,tp);
tat0(p,d,tp,m,n)$(speed0(m,n,tp) and tempocc(m))
                         = tact0("pkm",p,d,tp,m,n)/(tempocc(m)*speed0(m,n,tp));
tat0(p,d,tp,m,n)$(speed0(m,n,tp) and vkm0(p,d,tp,m,n))
                         = vkm0(p,d,tp,m,n)/speed0(m,n,tp);
tara0(p,d,tp,"car",n)$speed0("car",n,tp)
                         = (1 - 1/speed0("car",n,tp))*vkm0(p,d,tp,"car",n);
tara0(p,d,tp,"bus",n)$speed0("bus",n,tp)
                         = (1 - 1/speed0("bus",n,tp))*vkm0(p,d,tp,"bus",n);
timeT0("total")          = sum((p,d,tp,m,n), tat0(p,d,tp,m,n));
timeT0("share_L")         = timeT0("total")/(timeL0+timeT0("total"));

* Set total time endowment for consumption and transport (labor is inelastically
* supplied). Destatis 2006: Verkehr in Deutschland p. 28 reports 81 minutes of
* transportation per day. Assuming 8 hours of work and recreation time (both
* consistent with DESTATIS time survey) leaves 8 hours for consumption and transport
* Thus, transportation is around 17% of total available time.
time0 = timeT0("total")/0.17;
```

```
leis0 = time0 - timeT0("total");

*------------------------- CORRECT OUTPUTS AND DEMANDS -------------------------
* Correct outputs of transport activities
tay0(p,d,tp,m,n)$(work(p) or leis(p)) =  tay0(p,d,tp,m,n) + tat0(p,d,tp,m,n)
                                         + tara0(p,d,tp,m,n);
trn_p(p)                 = sum((d,tp,m,n), tay0(p,d,tp,m,n));
trn_pd(p,d)              = sum((tp,m,n), tay0(p,d,tp,m,n));
trn_pdtp(p,d,tp)         = sum((m,n), tay0(p,d,tp,m,n));
trn_pdtpm(p,d,tp,m)      = sum((n), tay0(p,d,tp,m,n));
* Recompute total consumption
c0 = sum(i,cd0(i)*pc0(i)) + sum((d,tp,m,n), tay0("cons",d,tp,m,n)) + leis0;

*---------------------- SPECIFY COMITIED AND SUPLEMENTARY MILAGES --------------
totalvkmcar       = sum((p,d,tp,n), vkm0(p,d,tp,"car",n));
comid0(i,cf,ct)   = shcomitted(cf)*cid0(i,cf,ct);
supid0(i,cf,ct)   = (1-shcomitted(cf))*cid0(i,cf,ct);
comfd0(cf,ct)     = shcomitted(cf)*cfd0("p_c",cf,ct);
supfd0(cf,ct)     = (1-shcomitted(cf))*cfd0("p_c",cf,ct);
comcar0(cf,ct)    = ccd0(cf,ct)*pcar0(cf,ct);
comy0(cf,ct)      = sum(i, pother0(i,cf,ct)*comid0(i,cf,ct))
                    + comfd0(cf,ct)*pfuel0("p_c",cf) + comcar0(cf,ct);
supy0(cf,ct)      = sum(i, pother0(i,cf,ct)*supid0(i,cf,ct))
                    + supfd0(cf,ct)*pfuel0("p_c",cf);
shcom(cf,ct)      = comy0(cf,ct)/(supy0(cf,ct)+comy0(cf,ct));
tacom0(cf,ct,p,d,tp,m,n) = shcom(cf,ct)*tacard0(cf,ct,p,d,tp,m,n);
tasup0(cf,ct,p,d,tp,m,n) = (1-shcom(cf,ct))*tacard0(cf,ct,p,d,tp,m,n);
tcirc0(cf,ct)     = (pcar0(cf,ct)*sy0(cf,ct) -sy0(cf,ct))/(sy0(cf,ct)*pcar0(cf,ct));
tcirc(cf,ct)      = tcirc0(cf,ct);

*-------------------------- DETERMINE UNIT INPUT VECTOR FOR CARS ---------------
parameter
         cunit   committed mileage unit input vector
         sunit   supplementary mileage unit input vector
         carunit total car unit vector
         newunit new car unit vector
;
cunit("out",cf,ct)       = comy0(cf,ct);
cunit("car",cf,ct)       = comcar0(cf,ct)/cunit("out",cf,ct);
cunit("fuel",cf,ct)      = (comfd0(cf,ct)*pfuel0("p_c",cf))/cunit("out",cf,ct);
cunit(i,cf,ct)           = comid0(i,cf,ct)/cunit("out",cf,ct);
sunit("out",cf,ct)       = supy0(cf,ct);
sunit("fuel",cf,ct)      = supfd0(cf,ct)*pfuel0("p_c",cf)/sunit("out",cf,ct);
sunit(i,cf,ct)           = supid0(i,cf,ct)/sunit("out",cf,ct);
carunit("out",cf,ct)     = comy0(cf,ct) + supy0(cf,ct);
carunit("vkm",cf,ct)     = carvkm0(cf,ct) ;
carunit("price",cf,ct)   = carunit("out",cf,ct)/carvkm0(cf,ct);
carunit("car",cf,ct)     = comcar0(cf,ct)/carunit("out",cf,ct);
carunit("fuel",cf,ct)    = cfd0("p_c",cf,ct)*pfuel0("p_c",cf)/carunit("out",cf,ct);
carunit(i,cf,ct)         = cid0(i,cf,ct)*pother0(i,cf,ct)/carunit("out",cf,ct);

*###############################################################################
*                            (6)      CARBON EMISSIONS
*###############################################################################
parameter
         adjemicoef      adjustment of emission coefficients
         roundco2        rounding factor for emissions           /3/
         tempco2         temporary parameter to adjust emissions
;
evf(i,"ele") = 0;
co20(i,j)$id0(i,j)       = round((evf(i,j)/scalee)*(emicoef(i)/10**6)*scalet,
                           roundco2);
co20(cf,j)$fd0(cf,j)     = round((evf(cf,j)/scalee)*(emicoef(cf)/10**6)*scalet,
                           roundco2);
co20(i,"hh")$cd0(i)      = round((evh(i)/scalee) * (emicoef(i)/10**6)*scalet,roundco2);
co2pub0(i,pub)           = round((evf(i,pub)/scalee)*(emicoef(i)/10**6)*scalet, roundco2);
co2pub0(cf,pub)          = round((evf(cf,pub)/scalee)*(emicoef(cf)/10**6)*scalet, roundco2);
co2car0(cf,ct)           = (ecar("p_c",cf,ct)/scalee)*(emicoef(cf)/10**6)*scalet;
co2car0(cf,"total")      = sum(ct, co2car0(cf,ct));
co2car0("total",ct)      = sum(cf, co2car0(cf,ct));
co2car0("total","total") = sum((cf,ct), co2car0(cf,ct));
co2gen0(g)$unit("eff",g) = sum(i$unit(i,g), (unit("TJ",g)/unit("eff",g))
                           /scalee*(emicoef(g)/10**6)*scalet);
co2gen0("total")         = sum(g, co2gen0(g));
tempco2(i)               = sum(j, co20(j,i)) + sum(cf, co20(cf,i));
tempco2(pub)             = sum(j, co2pub0(j,pub)) + sum(cf, co2pub0(cf,pub));
tempco2("hh")            = sum(i, co20(i,"hh")) + co2car0("total","total");
tempco2("ele")           = tempco2("ele") + co2gen0("total");
tempco2("total")         = sum(i, tempco2(i)) + sum(pub, tempco2(pub)) + tempco2("hh");
co20("total","total")    = sum(i, co20("total",i)) + co20("total","hh");
```

```
* Adjust emissions to meet totals
adjemicoef(i)$(not ele(i) and not otp(i) and co20("total",i))
                         = co20("total",i)/(sum(j, co20(j,i)) + sum(cf, co20(cf,i)));
adjemicoef("otp")        = co20("total","otp")/(sum(i,sum(pub, co2pub0(i,pub))+co20(i,"otp"))
                           + sum(cf, sum(pub, co2pub0(cf,pub)) + co20(cf,"otp")));
adjemicoef("ele")        = co20("total","ele")/(co2gen0("total") + sum(cf, co20(cf,"ele"))
                           + sum(i, co20(i,"ele")));
adjemicoef("hh")         = ((co20("total","hh")-co2car0("total","total"))1
                           /sum(i,co20(i,"hh")));
co20(i,j)                = co20(i,j)*adjemicoef(j);
co20(cf,j)               = co20(cf,j)*adjemicoef(j);
co20(i,"hh")             = co20(i,"hh")*adjemicoef("hh");
co20(cf,"hh")            = co20(cf,"hh")*adjemicoef("hh");
co2pub0(i,pub)           = co2pub0(i,pub)*adjemicoef("otp");
co2pub0(cf,pub)          = co2pub0(cf,pub)*adjemicoef("otp");
co2pub0("total",pub)     = sum(i, co2pub0(i,pub)) + sum(cf,co2pub0(cf,pub));
co2gen0(g)               = co2gen0(g)*adjemicoef("ele");
co2gen0("total")         = sum(g, co2gen0(g));
tempco2(i)               = sum(j, co20(j,i)) + sum(cf, co20(cf,i));
tempco2("otp")           = tempco2("otp") + sum(pub, sum(i, co2pub0(i,pub))
                           + sum(cf, co2pub0(cf,pub)));
tempco2(pub)             = sum(j, co2pub0(j,pub)) + sum(cf, co2pub0(cf,pub));
tempco2("hh")            = sum(i, co20(i,"hh")) + co2car0("total","total");
tempco2("ele")           = tempco2("ele") + co2gen0("total");
tempco2("total")         = sum(i, tempco2(i)) + sum(pub, tempco2(pub)) + tempco2("hh");
co20(i,"total")          = sum(j, co20(i,j)) + sum(g$unit(i,g),co2gen0(g))
                           + sum(pub, co2pub0(i,pub)) + co20(i,"hh");
co20(cf,"total")         = sum(j, co20(cf,j)) + sum(ct, co2car0(cf,ct))
                           + sum(pub, co2pub0(cf,pub)) + co20(cf,"hh");
unit("co2",g)$unit("out",g)      = co2gen0(g)/unit("out",g);
unit("co2","coalCCS")            = unit("co2","ligniteST")*(1-cpr("coalCCS"));
unit("co2","gasCCS")             = unit("co2","CCGT")*(1-cpr("gasCCS"));
unit("co2","BCCGT")              = unit("co2","CCGT");
unit("co2","BhcoaPC")            = unit("co2","hcoaPC");
co20("total","total")            = sum(i, co20(i,"total"))
                                    + sum(cf, co20(cf,"total"));
co20("total",i)$(not ele(i))     = sum(j, co20(j,i)) + sum(cf, co20(cf,i));
carblim0 = co20("total","total");


*###############################################################################
*                          (7) CONSUMPTION TAXES
*###############################################################################
* generally impose VAT of 16 %
tc(i) = 0.16;
* For refined oils IEA 2008 tax rate is taken
tc("p_c") = 0.418;
pc0(i) = 1 + tc(i);
* Correct transfers and final demand values
trans0 = trans0 + sum(i, tc(i)*cd0(i));
c0 = sum(i, pc0(i)*cd0(i)) + sum(p$leis(p),trn_p(p)) + leis0;
trans0 = c0 + sum(i, inv0(i)) +  sum(p$(not leis(p)),trn_p(p))
         - (ks0 + timeL0 + time0 + sum((cf,ct), stock0(cf,ct)) + sum((tp,n,m), ra0(tp,m,n)));

*###############################################################################
*                     (8) INITALIZE POLICY PARAMETERS
*###############################################################################
carblimI = 0; carblimII = 0; carblimIII = 0; carblimIV = 0;
tradeI(i,j) = no; tradeI(cf,j) = no; tradeI(i,"hh") = no; tradeI(i,pub) = no;
tradeI(cf,pub) = no; tradeI(cf,ct) = no; tradeI(g,"ele") = no;
tradeII(i,j) = no; tradeII(cf,j) = no; tradeII(i,"hh") = no; tradeII(i,pub) = no;
tradeII(cf,pub) = no; tradeII(cf,ct) = no; tradeI(g,"ele") = no;
tradeIII(i,j) = no; tradeIII(cf,j) = no; tradeIII(i,"hh") = no; tradeIII(i,pub) = no;
tradeIII(cf,pub) = no; tradeIII(cf,ct) = no; tradeI(g,"ele") = no;
tradeIV(i,j) = no; tradeIV(cf,j) = no; tradeIV(i,"hh") = no; tradeIV(i,pub) = no;
tradeIV(cf,pub) = no; tradeIV(cf,ct) = no; tradeI(g,"ele") = no;
tradeS(i,j) = no; tradeS(cf,j) = no; tradeS(i,"hh") = no; tradeS(i,pub) = no;
tradeS(cf,pub) = no; tradeS(cf,ct) = no; tradeS(g,"ele") = no;
carblimS(i) = 0; carblimS("hh") = 0; carblimS(pub) = 0;
exempted(i,j) = no;
```

MPSGE code for the small open economy model

```
$stitle small open economy model with transport

$ontext
$model:ger_cong

$sectors:
        Y(i)$y0(i)                          ! Production
        A(i)$a0(i)                          ! Armington aggregation
        GEN(g)                              ! Generation
        TKG                                 ! Capital transformation active generation
        ELEC                                ! Electricity generation
        TA(p)$trn_p(p)                      ! Transport activities
        TA_D(p,d)$trn_pd(p,d)               ! Transport activity distance and purpose
        TA_DTP(p,d,tp)$trn_pdtp(p,d,tp)     ! Transport distance purpose and travel period
        TA_DTPM(p,d,tp,m)$trn_pdtpm(p,d,tp,m)  ! Transport by mode distance purpose period
        TA_DTPMN(p,d,tp,m,n)$tay0(p,d,tp,m,n)  ! Transport all
        CAR(cf,ct)                          ! Combines committed and supplementary mileage
        COMCAR(cf,ct)                       ! Committed mileage
        SUPCAR(cf,ct)                       ! Supplementary mileage
        STOCK(cf,ct)                        ! Car stock activity
        YTF(cf)                             ! Transportation fuels
        GC                                  ! Public consumption
        C                                   ! Private consumption
        LT                                  ! Labor transformation
        INV$keynes                          ! Investments
        EY(i,j)$(fof(i) and a0(i) and id0(i,j))    ! Energy carbon aggregation
        EC(i)$(fof(i) and cd0(i))                  ! Energy carbon aggregation household
        YF(cf,i)$fd0(cf,i)                         ! Fuel carbon aggregate
        FCAR(cf,ct)$cfd0("p_c",cf,ct)              ! Fuel carbon aggregation for cars
        CARBON(i,j)$co20(i,j)                      ! Carbon emission from i in j
        FCARBON(cf,j)$co20(cf,j)                   ! Carbon emission from fuel cf in j
        CARBONH(i)$co20(i,"hh")                    ! Carbon emission from in household
        CARBONCAR(cf,ct)$co2car0(cf,ct)            ! Carbon emission cars

        EXCARBON(i,j)$(co20(i,j) and exempted(i,j))       ! Exempted carbon emission i in j
        EXFCARBON(cf,j)$(co20(cf,j) and exempted(cf,j))   ! Exempted carbon emission cf in j
        EXCARBONH(i)$(co20(i,"hh") and exempted(i,"hh"))  ! Exempted carbon emission in hh
        EXCARBONCAR(cf,ct)$(co2car0(cf,ct)  and exempted(cf,ct)) ! Exempted emission cars

$commodity:
        PY(i)$y0(i)                                ! Commodity price
        PA(i)$a0(i)                                ! Armington composite price
        PFX                                        ! Foreign currency
        PLOAD(l)                                   ! Electricity price by load segment
        PKG(g)$ga(g)                               ! Capital inputs active generation
        PCAP(g)$(cap(g) lt +inf)                   ! Scarcity price potential
        PELEC                                      ! Production price electricity
        PTA(p)$trn_p(p)                            ! Transport activity price by purpose
        PTA_D(p,d)$trn_pd(p,d)                     ! Transport price by distance and purpose
        PTA_DTP(p,d,tp)$trn_pdtp(p,d,tp)           ! Transport price by dis pur period
        PTA_DTPM(p,d,tp,m)$trn_pdtpm(p,d,tp,m)     ! Transport price by mode dis pur per
        PTA_DTPMN(p,d,tp,m,n)$tay0(p,d,tp,m,n)     ! Transport price by mode dis pur per netw
        PRENT(cf,ct)                               ! Car rental price
        PSTOCK(cf,ct)                              ! Car stock price
        PCAR(cf,ct)                                ! Car resource cost
        PCOM(cf,ct)                                ! Price committed mileage
        PSUP(cf,ct)                                ! Price supplementary mileage
        PYTF(cf)                                   ! Price transportation fuels
        PG                                         ! Public consumption expenditure
        PC                                         ! Private consumption expenditure
        PK                                         ! Capital price
        PL                                         ! Firm wage
        PLS                                        ! Labor supply price
        PT$timeT0("total")                         ! Time price
        PRA(tp,m,n)$ra0(tp,m,n)                    ! Price for road availability
        PINV$keynes                                ! Investment price
        PE(i,j)$(fof(i) and a0(i) and id0(i,j))    ! Price energy carbon aggregate
        PEC(i)$(fof(i) and cd0(i))                 ! Price energy carbon aggregate household
        PYF(cf,i)$fd0(cf,i)                        ! Price fuel carbon aggregate
        PFCAR(cf,ct)$cfd0("p_c",cf,ct)             ! Price carbon aggregation for cars
        PCARBI$carblimI                            ! Carbon price scheme I
        PCARBII$carblimII                          ! Carbon price scheme I
        PCARBIII$carblimIII                        ! Carbon price scheme I
        PCARBIV$carblimIV                          ! Carbon price scheme I
        PCARBS(i)$carblimS(i)                      ! Sectoral carbon price
        PCARBH$carblimS("hh")                      ! Sectoral carbon price household
        PCARBON(i,j)$co20(i,j)                     ! Carbon price for input i in j
        PFCARBON(cf,j)$co20(cf,j)                  ! Price carbon from fuel cf in j
```

```
         PCARBONH(i)$co20(i,"hh")                   ! Carbon price for input i in household
         PCARBONCAR(cf,ct)$co2car0(cf,ct)           ! Price carbon emission cars

         PEXCARBON(i,j)$(co20(i,j) and exempted(i,j))      ! Price exempted emissions i in j
         PEXFCARBON(cf,j)$(co20(cf,j) and exempted(cf,j))  ! Price exempted emission cf in j
         PEXCARBONH(i)$(co20(i,"hh") and exempted(i,"hh")) ! Price exempted emission in hh
         PEXCARBONCAR(cf,ct)$(co2car0(cf,ct)  and exempted(cf,ct)) ! Price exempted  cars

$consumers:
         RA                                              ! Representative agent
         GOV                                             ! Government

$auxiliary:
         ADJWT                                           ! Adjustment of work trips
         LSREC                                           ! Lumpsum revenue recycling multpl
         ROADAV(tp,m,n)$(ra0(tp,m,n))                    ! road availability
         VKM(p,d,tp,m,n)$(occup(p,d,tp,m,n) and roads(n)) ! vehicle kiliometers
         LStta                                           ! multpl for public transport subsi

*-------------------------------------------------------------------------------
*                           CARBON ENERGY AGGREGATION
*-------------------------------------------------------------------------------
$prod:EY(fof,i)$(a0(fof) and id0(fof,i))
         O:PE(fof,i)             Q:(id0(fof,i)*pi0(fof,i))
         I:PA(fof)               Q:id0(fof,i)            P:pi0(fof,i)
+                                A:GOV                   T:ti(fof,i)
         I:PCARBON(fof,i)$(not exempted(fof,i))          Q:co20(fof,i)           P:1e-6
         I:PEXCARBON(fof,i)$exempted(fof,i)              Q:co20(fof,i)           P:1e-6

$prod:YF(cf,i)$(fd0(cf,i))
         O:PYF(cf,i)             Q:(pf0(cf,i)*fd0(cf,i))
         I:PYTF(cf)              Q:fd0(cf,i)             P:pf0(cf,i)
+                                A:GOV                   T:tf(cf,i)
         I:PFCARBON(cf,i)$(not exempted(cf,i))           Q:co20(cf,i)            P:1e-6
         I:PEXFCARBON(cf,i)$exempted(cf,i)               Q:co20(cf,i)            P:1e-6

$report:
         V:demYE(fof,i)          I:PA(fof)               Prod:EY(fof,i)
         V:demYF(cf,i)           I:PYTF(cf)              Prod:YF(cf,i)

$prod:EC(fof)$cd0(fof)
         O:PEC(fof)              Q:(pc0(fof)*cd0(fof))
         I:PA(fof)               Q:cd0(fof)              P:pc0(fof)
+                                A:GOV                   T:tc(fof)
         I:PCARBONH(fof)$(not exempted(fof,"hh"))        Q:co20(fof,"hh")        P:1e-6
         I:PEXCARBONH(fof)$exempted(fof,"HH")            Q:co20(fof,"hh")        P:1e-6


$prod:FCAR(cf,ct)$cfd0("p_c",cf,ct)
         O:PFCAR(cf,ct)          Q:(pfuel0("p_c",cf)*cfd0("p_c",cf,ct))
         I:PYTF(cf)              Q:cfd0("p_c",cf,ct)     P:pfuel0("p_c",cf)
+                                A:GOV                   T:tfuel(cf)
         I:PCARBONCAR(cf,ct)$(not exempted(cf,ct))       Q:co2car0(cf,ct)        P:1e-6
         I:PEXCARBONCAR(cf,ct)$(exempted(cf,ct))         Q:co2car0(cf,ct)        P:1e-6

$report:
         V:demCE(fof)            I:PA(fof)               Prod:EC(fof)
         V:demCF(cf,ct)          I:PYTF(cf)              Prod:FCAR(cf,ct)
*-------------------------------------------------------------------------------
*                                CARBON SYSTEMS
*-------------------------------------------------------------------------------
$prod:CARBON(i,j)$co20(i,j)
         O:PCARBON(i,j)                  Q:1
         I:PCARBI$tradeI(i,j)            Q:1
         I:PCARBII$tradeII(i,j)          Q:1
         I:PCARBIII$tradeIII(i,j)        Q:1
         I:PCARBIV$tradeIV(i,j)          Q:1
         I:PCARBS(j)$tradeS(i,j)         Q:1

$Prod:EXCARBON(i,j)$(co20(i,j) and exempted(i,j))
         O:PEXCARBON(i,j)        Q:1
         I:PCARBON(i,j)          Q:1
+                                A:GOV           T:(-0.99999)

$prod:FCARBON(cf,j)$co20(cf,j)
         O:PFCARBON(cf,j)                Q:1
         I:PCARBI$tradeI(cf,j)           Q:1
         I:PCARBII$tradeII(cf,j)         Q:1
         I:PCARBIII$tradeIII(cf,j)       Q:1
         I:PCARBIV$tradeIV(cf,j)         Q:1
```

```
         I:PCARBS(j)$tradeS(cf,j)        Q:1

$prod:EXFCARBON(cf,j)$(co20(cf,j) and exempted(cf,j))
         O:PEXFCARBON(cf,j)      Q:1
         I:PFCARBON(cf,j)        Q:1
+                                A:gov           T:(-0.99999)

$prod:CARBONH(i)$co20(i,"hh")
         O:PCARBONH(i)                   Q:1
         I:PCARBI$tradeI(i,"hh")         Q:1
         I:PCARBII$tradeII(i,"hh")       Q:1
         I:PCARBIII$tradeIII(i,"hh")     Q:1
         I:PCARBIV$tradeIV(i,"hh")       Q:1
         I:PCARBH$tradeS(i,"hh")         Q:1

$prod:EXCARBONH(i)$(co20(i,"hh") and exempted(i,"hh"))
         O:PEXCARBONH(i)                 Q:1
         I:PCARBONH(i)                   Q:1
+                                        A:GOV           T:(-0.999999)

$prod:CARBONCAR(cf,ct)$co2car0(cf,ct)
         O:PCARBONCAR(cf,ct)             Q:1
         I:PCARBI$tradeI(cf,ct)          Q:1
         I:PCARBII$tradeII(cf,ct)        Q:1
         I:PCARBIII$tradeIII(cf,ct)      Q:1
         I:PCARBIV$tradeIV(cf,ct)        Q:1
         I:PCARBH$tradeS(cf,"hh")        Q:1

$prod:EXCARBONCAR(cf,ct)$(co2car0(cf,ct)  and exempted(cf,ct))
         O:PEXCARBONCAR(cf,ct)           Q:1
         I:PCARBONCAR(cf,ct)             Q:1
+                                        A:GOV           T:(-0.999999)

*-------------------------------------------------------------------------------
*                                PRODUCTION
*-------------------------------------------------------------------------------
$prod:Y(i)$(y0(i) and not ele(i))        s:0     t:esub_out(i)
+                                vae:esub_vae(i)         trn:esub_trn(i)
+                                road(trn):esub_road(i)  fuel(road):esub_fuel(i)
+                                va(vae):esub_va(i)      ele(vae):esub_ele(i)
+                                coa(ele):esub_coa(i)    lqd(coa):esub_lqd(i)
         O:PY(i)                 Q:d0(i)
+                                A:GOV                   T:ty(i)
         O:PFX                   Q:e0(i)
+                                A:GOV                   T:ty(i)
         I:PA(j)$(not fof(j))    Q:id0(j,i)              P:pi0(j,i)       ele:$ele(j)
+                                                                         trn:$nroad(j)
+                                A:GOV                   T:ti(j,i)        road:$otp(j)
         I:PE(fof,i)             Q:(id0(fof,i)*pi0(fof,i))                coa:$coa(fof)
+                                                                         lqd:$(not coa(fof))
         I:PK                    Q:kd0(i)                                 va:
         I:PL                    Q:ld0(i)                P:pl0(i)         va:
+                                A:GOV                   T:tl(i)
         I:PYF(cf,i)             Q:(pf0(cf,i)*fd0(cf,i))                 fuel:

$prod:A(i)$a0(i)         s:esub_dm(i)
         O:PA(i)         Q:a0(i)
         I:PFX           Q:m0(i)
         I:PY(i)         Q:d0(i)

$report:
         V:Imports(i)            I:PFX           PROD:A(i)
         V:Exports(i)            O:PFX           PROD:Y(i)
         V:demY(i,j)             I:PA(i)         PROD:Y(j)

*-------------------------------------------------------------------------------
*                          ELECTRICITY GENERATION
*-------------------------------------------------------------------------------
$prod:Y(i)$ele(i)        s:0     t:esub_out(i)
+                        va(s):esub_va(i)    load(s):esub_load
+                        fuel(s):esub_fuel(i)
         O:PY(i)                 Q:d0(i)
+                                A:GOV                   T:ty(i)
         O:PFX                   Q:e0(i)
+                                A:GOV                   T:ty(i)
         I:PA(j)$(not fof(j))    Q:id0(j,i)              P:pi0(j,i)
+                                A:GOV                   T:ti(j,i)
         I:PE(fof,i)             Q:(id0(fof,i)*pi0(fof,i))
         I:PK                    Q:kd0(i)                                va:
         I:PL                    Q:ld0(i)                P:pl0(i)        va:
```

```
+                                A:GOV                  T:tl(i)
         I:PYF(cf,i)             Q:(pf0(cf,i)*fd0(cf,i))                fuel:
         I:PELEC                 Q:(sum(l, lod0(l,i)))

$prod:ELEC       s:esub_load
         O:PELEC                 Q:(sum((i,l),lod0(l,i)))
         I:PLOAD(l)              Q:(sum(i, lod0(l,i)))

$prod:GEN(ga)
         O:PLOAD(l)$mapL(l,ga)                   Q:1
         I:PKG(ga)                               Q:unit("cap",ga)
         I:PL                                    Q:unit("lab",ga)
         I:PA(i)                                 Q:unit(i,ga)
         I:PCAP(ga)$(cap(ga) lt + inf)           Q:1                    P:1e-6
         I:PCARBI$tradeI(ga,"ele")               Q:unit("co2",ga)       P:1e-6
         I:PCARBII$tradeII(ga,"ele")             Q:unit("co2",ga)       P:1e-6
         I:PCARBIII$tradeIII(ga,"ele")           Q:unit("co2",ga)       P:1e-6
         I:PCARBIV$tradeIV(ga,"ele")             Q:unit("co2",ga)       P:1e-6
         I:PCARBS("ele")$tradeS(ga,"ele")        Q:unit("co2",ga)       P:1e-6

$prod:GEN(gn)
         O:PLOAD(l)$mapL(l,gn)                   Q:1
         I:PK                                    Q:(unit("cap",gn)*markupG(gn))
         I:PL                                    Q:(unit("lab",gn)*markupG(gn))
         I:PA(i)                                 Q:(unit(i,gn)*markupG(gn))
         I:PCAP(gn)$(cap(gn) lt + inf)           Q:1                    P:1e-6
         I:PCARBI$tradeI(gn,"ele")               Q:unit("co2",gn)       P:1e-6
         I:PCARBII$tradeII(gn,"ele")             Q:unit("co2",gn)       P:1e-6
         I:PCARBIII$tradeIII(gn,"ele")           Q:unit("co2",gn)       P:1e-6
         I:PCARBIV$tradeIV(gn,"ele")             Q:unit("co2",gn)       P:1e-6
         I:PCARBS("ele")$tradeS(gn,"ele")        Q:unit("co2",gn)       P:1e-6

$prod:TKG        t:esub_kele
         O:PKG(ga)               Q:(unit("cap",ga)*unit("out",ga))
         I:PK                    Q:(sum(ga, unit("cap",ga)*unit("out",ga)))

$report:
         V:DEMANDLOAD(l)         I:PLOAD(l)      PROD:ELEC
*-------------------------------------------------------------------------------
*                             TRANSPORT ACTIVITIES
*-------------------------------------------------------------------------------
$prod:TA(p)$trn_p(p)                     s:tsub_d(p)
         O:PTA(p)                Q:trn_p(p)
         I:PTA_D(p,d)            Q:trn_pd(p,d)

$prod:TA_D(p,d)$trn_pd(p,d)              s:tsub_tp(p,d)
         O:PTA_D(p,d)            Q:trn_pd(p,d)
         I:PTA_DTP(p,d,tp)       Q:trn_pdtp(p,d,tp)

$prod:TA_DTP(p,d,tp)$trn_pdtp(p,d,tp)    s:tsub_m(p,d,tp)
         O:PTA_DTP(p,d,tp)       Q:trn_pdtp(p,d,tp)
         I:PTA_DTPM(p,d,tp,m)    Q:trn_pdtpm(p,d,tp,m)

$prod:TA_DTPM(p,d,tp,m)$trn_pdtpm(p,d,tp,m)      s:tsub_n(p,d,tp,m)
         O:PTA_DTPM(p,d,tp,m)    Q:trn_pdtpm(p,d,tp,m)
         I:PTA_DTPMN(p,d,tp,m,n) Q:tay0(p,d,tp,m,n)

$prod:TA_DTPMN(p,d,tp,m,n)$(tay0(p,d,tp,m,n) and not cars(m))    time:sigmaF
         O:PTA_DTPMN(p,d,tp,m,n)         Q:1
         I:PA(i)                         Q:(taid0(i,p,d,tp,m,n)/tay0(p,d,tp,m,n))
+                                        P:pta0(i,m)
+                                        A:GOV           N:LSstta
+                                                        M:tta(i,m)
         I:PT                            Q:(tat0(p,d,tp,m,n)/tay0(p,d,tp,m,n))
+                                                                       time:
         I:PRA(tp,m,n)$ra0(tp,m,n)       Q:(tara0(p,d,tp,m,n)/tay0(p,d,tp,m,n))
+                                                                       time:

$prod:TA_DTPMN(p,d,tp,m,n)$(tay0(p,d,tp,m,n) and cars(m))       time:sigmaF     cars:tsub_car
        O:PTA_DTPMN(p,d,tp,m,n)         Q:1
        I:PA(i)                         Q:(taid0(i,p,d,tp,m,n)/tay0(p,d,tp,m,n))
        I:PCAR(cf,ct)
+                     Q:((tacom0(cf,ct,p,d,tp,m,n)+tasup0(cf,ct,p,d,tp,m,n))/tay0(p,d,tp,m,n))
+                                                                       cars:
        I:PT                            Q:(tat0(p,d,tp,m,n)/tay0(p,d,tp,m,n))
+                                                                       time:
        I:PRA(tp,m,n)$ra0(tp,m,n)       Q:(tara0(p,d,tp,m,n)/tay0(p,d,tp,m,n))
+                                                                       time:

$report:
```

```
         V:TTIME(p,d,tp,m,n)             I:PT            PROD:TA_DTPMN(p,d,tp,m,n)
         V:demCT(i,p,d,tp,m,n)           I:PA(i)         PROD:TA_DTPMN(p,d,tp,m,n)
         V:demRA(p,d,tp,m,n)             I:PRA(tp,m,n)   PROD:TA_DTPMN(p,d,tp,m,n)

*-------------------------------------------------------------------------------
*                               CAR TECHNOLOGIES
*-------------------------------------------------------------------------------
$prod:CAR(cf,ct)                 coms(cars):tsub_coms
         O:PCAR(cf,ct)           Q:(comy0(cf,ct)+supy0(cf,ct))
         I:PCOM(cf,ct)           Q:comy0(cf,ct)
         I:PSUP(cf,ct)           Q:supy0(cf,ct)

$prod:COMCAR(cf,ct)
         O:PCOM(cf,ct)           Q:1
         I:PA(i)                 Q:cunit(i,cf,ct)        P:pother0(i,cf,ct)
+                                A:GOV                   T:tother(i,cf,ct)
         I:PFCAR(cf,ct)          Q:cunit("fuel",cf,ct)
         I:PRENT(cf,ct)          Q:cunit("car",cf,ct)

$prod:SUPCAR(cf,ct)
         O:PSUP(cf,ct)           Q:1
         I:PA(i)                 Q:sunit(i,cf,ct)        P:pother0(i,cf,ct)
+                                A:GOV                   T:tother(i,cf,ct)
         I:PFCAR(cf,ct)          Q:sunit("fuel",cf,ct)
+                                A:GOV

$prod:STOCK(cf,ct)           s:1000
         O:PRENT(cf,ct)          Q:(sy0(cf,ct)*pcar0(cf,ct))
+                                A:GOV                   T:tcirc(cf,ct)
         I:PA(i)                 Q:snd0(i,cf,ct)         P:ps0(i,cf,ct)
+                                A:GOV                   T:stax(i,cf,ct)
         I:PSTOCK(cf,ct)         Q:ssd0(cf,ct)

$report:
         V:NEWCARS(i,cf,ct)      I:PA(i)                 PROD:STOCK(cf,ct)

*-------------------------------------------------------------------------------
*                             TRANSPORTATION FUELS
*-------------------------------------------------------------------------------
$prod:YTF(cf)
         O:PYTF(cf)              Q:fuely0(cf)
         I:PA(i)                 Q:fuelid0(i,cf)

*-------------------------------------------------------------------------------
*                                GOVERNMENT
*-------------------------------------------------------------------------------
$prod:GC
         O:PG            Q:g0
         I:PA(i)         Q:gd0(i)

$demand:GOV
         D:PG            Q:g0
         E:PC            Q:(-trans0)             R:LSREC
         E:PFX           Q:(bop)
         E:PCARBI        Q:carblimI
         E:PCARBII       Q:carblimII
         E:PCARBIII      Q:carblimIII
         E:PCARBIV       Q:carblimIV
         E:PCARBS(i)     Q:carblimS(i)
         E:PCARBH        Q:carblimS("hh")

$report:
         V:demG(i)       I:PA(i)                 PROD:GC
*-------------------------------------------------------------------------------
*                             REPRESENTATIVE AGENT
*-------------------------------------------------------------------------------
$prod:LT
         O:PL                            Q:ls0
         I:PLS                           Q:timeL0        P:pw0
+                                        A:GOV           T:tw

$prod:INV$keynes
         O:PINV                          Q:(sum(i, inv0(i)))
         I:PA(i)                         Q:inv0(i)

$prod:C  s:csub_l                ct:csub_l    ce(ct):csub_ce
+        ene(ce):csub_ce         con(ce):csub_c
         O:PC                            Q:c0
         I:PT                            Q:leis0
         I:PA(i)$(not fof(i))            Q:cd0(i)                P:pc0(i)
```

```
+                                                                con:$(not ele(i))
+                                        A:GOV                   T:tc(i)         ene:$ele(i)
         I:PEC(fof)                      Q:(cd0(fof)*pc0(fof))                   ene:
         I:PTA(p)$leis(p)                Q:trn_p(p)                              ct:

$demand:RA       s:1
         D:PC                                    Q:c0
         D:PINV$keynes                           Q:(sum(i, inv0(i)))
         E:PA(i)$(not keynes)                    Q:(-inv0(i))
         E:PK                                    Q:ks0
         E:PLS                                   Q:timeL0
         E:PSTOCK(cf,ct)                         Q:stock0(cf,ct)
         E:PCAP(g)$(cap(g) lt + inf)             Q:cap(g)
         E:PTA(p)$work(p)                        Q:(-trn_p(p))           R:ADJWT
         E:PC                                    Q:trans0                R:LSREC
         E:PT                                    Q:time0
         E:PRA(tp,m,n)$ra0(tp,m,n)               Q:1                     R:ROADAV(tp,m,n)

$report:
         V:LEISURE       I:PT                    PROD:C
         V:demC(i)       I:PA(i)                 PROD:C

*-------------------------------------------------------------------------------
*                             CONSTRAINTS
*-------------------------------------------------------------------------------
$constraint:ADJWT
       sum((d,tp,m,n)$tay0("work",d,tp,m,n),
       TA_DTPMN("work",d,tp,m,n)*(pkm0("work",d,tp,m,n)/tay0("work",d,tp,m,n)))
                         =E=     sum((d,tp,m,n),pkm0("work",d,tp,m,n))*LT;

$constraint:LSREC$lump
         GC              =E=     1;

$constraint:LSREC$(not lump)
         LSREC           =E=     1;

$constraint:LStta$pubsub
         GC              =E=     1;

$constraint:LStta$(not pubsub)
         LStta           =E=     1;

$constraint:VKM(p,d,tp,m,n)$(occup(p,d,tp,m,n) and roads(n) and not lkws(m))
         VKM(p,d,tp,m,n) =E=
(pkm0(p,d,tp,m,n)/tay0(p,d,tp,m,n))*TA_DTPMN(p,d,tp,m,n)/occup(p,d,tp,m,n);

$constraint:VKM(p,d,tp,m,n)$(occup(p,d,tp,m,n) and roads(n) and lkws(m))
         VKM(p,d,tp,m,n) =E=     vkm0(p,d,tp,m,n);

$constraint:ROADAV(tp,m,n)$(ra0(tp,m,n) and congestion and cars(m))
    ROADAV(tp,m,n)  =E=    (1- (A2.L(n) +
                            A3.L(n)*exp(A4.L(n)*sum((p,d,mm)$(occup(p,d,tp,mm,n)),
                            VKM(p,d,tp,mm,n)*pcu(mm)/duration(tp))))/60)
                            *sum((p,d,mm)$(occup(p,d,tp,mm,n) and cars(mm)),
                            VKM(p,d,tp,mm,n));

$constraint:ROADAV(tp,m,n)$(ra0(tp,m,n) and congestion and busses(m))
    ROADAV(tp,m,n)  =E=    (1- (a1bus(n)*(A2.L(n) +
                            A3.L(n)*exp(A4.L(n)*sum((p,d,mm)$(occup(p,d,tp,mm,n)),
                            VKM(p,d,tp,mm,n)*pcu(mm)/duration(tp))))/60))
                            *sum((p,d,mm)$(occup(p,d,tp,mm,n) and busses(mm)),
                            VKM(p,d,tp,mm,n));

$constraint:ROADAV(tp,m,n)$(ra0(tp,m,n) and not congestion and cars(m))
         ROADAV(tp,m,n)  =E=    ra0(tp,m,n)*sum((p,d,mm)$(occup(p,d,tp,mm,n) and cars(mm)),
                                 VKM(p,d,tp,mm,n))
                                /sum((p,d,mm)$(occup(p,d,tp,mm,n) and cars(mm)),
                                vkm0(p,d,tp,mm,n));


$constraint:ROADAV(tp,m,n)$(ra0(tp,m,n) and not congestion and busses(m))
         ROADAV(tp,m,n)  =E=    ra0(tp,m,n)*sum((p,d,mm)$(occup(p,d,tp,mm,n) and busses(mm)),
                                 VKM(p,d,tp,mm,n))
                                  /sum((p,d,mm)$(occup(p,d,tp,mm,n) and busses(mm)),
                                 vkm0(p,d,tp,mm,n));
$offtext
$sysinclude mpsgeset ger_cong
```