A CO₂ Emission Trading Scheme for German Road Transport

assessing the impacts using a meso economic model with multi-agent attributes

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Cutting CO\textsubscript{2} emissions requires world-wide agreements on policy instruments, which create enough incentives for the industry and for consumers to apply energy-efficient technologies and to adapt their behaviour. Cap-and-Trade systems seem to be acceptable instruments, which have a number of advantages: First, caps can be set according to the desired CO\textsubscript{2} emission reductions such that the target achievement can be controlled periodically. Secondly, it is left to the market forces to determine the intensity of mitigation efforts in the different sectors of the economy. Under ideal conditions a least-cost trajectory will be found. Thirdly, the developing and transition countries might be interested to join in, if the caps are set accordingly, e.g. in terms of CO\textsubscript{2} emissions per capita. Under such a regime these countries could continue to foster industrial development and nevertheless sell emission rights for a long period of time.

While the principle of emission trading looks simple it is quite a challenge to develop a workable scheme and design it for implementation in an imperfect environment. This is the starting point for the research study of Patrick Jochem. He focuses on a partial market, which is road freight transport, because this market shows a rapid growth of CO\textsubscript{2} emissions. Several trading schemes are possible, such as downstream, midstream and upstream trading systems, which can be open or closed. Strong arguments are given in favour of an upstream system, in which the distributors of fossil energy are the trading parties. The transaction costs for such a system are comparatively low because the number of trading agents is limited.

The main purpose of the study is to analyse the impacts of open and closed trading schemes on the road transport market and the economy. Patrick Jochem develops a multi-agent model, in which oil companies, freight transport companies, households and vehicle manufacturers interact. This model has a micro foundation, but it works with clusters of agents in the empirical application, i.e. on a meso level. The reaction patterns of the agent clusters can be described by econometrically tested functions, and a dynamic reaction mechanism can be modelled, which results in trading quantities and prices on the market for CO\textsubscript{2} emission allowances. Jochem shows by numerical analysis that the CO\textsubscript{2} prices in a closed trading scheme are substantially higher than in an open scheme. Reason is that in an open scheme other sectors show lower mitigation costs rather than the transport sector and contribute more to the reduction target. A closed scheme would more intensively exploit the potential of road transport, but the price paid to avoid a unit of emission might be higher.

Finally, the macro-economic impacts are investigated using the system dynamics model ASTRA. The short-term effects of rising fuel prices might be negative, but the long-term effects are widely positive and underline that strict environmental policy may lead to increased research and development activities to create new
products and processes, thus supporting long-term growth and employment in the economy.

This study combines sophisticated modelling, advanced econometric testing and numerical simulation to get more insight in the impacts of implementing different CO₂ emission trading schemes. It is highly probable that such schemes will gain political importance after the next world climate conference in Copenhagen, which will decide on the post-Kyoto arrangements. The modelling family developed and applied by Patrick Jochem prepares an excellent base to test the Copenhagen agreements on their impacts on the transport market and the aggregate economy.

Werner Rothengatter
Foreword of the author

To counter the possible impacts of global warming, the European Union decided to ratify the Kyoto Protocol and promised to reduce its carbon dioxide (CO₂) emissions by 8% until 2010 compared to 1990. One of the policies implemented to do so is the European Emission Trading Scheme for CO₂ certificates (EU-ETS). So far, the transport sector, which contributes around 28% of total European CO₂ emissions, has been exempted from the ETS, although a further increase of CO₂ emissions from the transport sector is expected in the future. Furthermore, this is the only sector in which emissions have increased in Europe (by about 32%) and in Germany since 1990. Road transport could be included in the EU-ETS post-2012.

In Germany, CO₂ emissions have increased over the last few decades, even though emissions have fallen slightly recently because the vehicle miles travelled (VMT) have stagnated and the specific fuel consumption of vehicles has been reduced. Despite this minor achievement, considerable CO₂ emission reduction potentials are still believed to exist, especially in road passenger transport. This belief is based on the idea that reversing the trend towards heavier vehicles and higher engine performance could lead to cheap and significant CO₂ emission reductions. Furthermore, a more critical and aware modal choice of households could make another contribution to CO₂ emission reduction. However, no total CO₂ emission reduction is expected in road freight transport.

This gave reason to me to develop a partial meso-economic model to assess the impacts of a CO₂ emission trading scheme in German road transport. It becomes apparent that, from the current perspective, the households’ willingness-to-pay for prestigious (but fuel-inefficient) cars is higher than the technical mitigation costs in other sectors. Thus, in an open emission trading scheme (extension of the existing EU-ETS) no major changes in transport demand are expected. The main effect of introducing an open emission trading scheme will be constant CO₂ emissions from road transport, but high payments to other sectors for mitigation.

The very first round of the thanks goes to my supervisor Prof. Dr. Werner Rothengatter, for his scientific advice, his mentorship and for always ensuring a creative working atmosphere at the institute. Many thanks to my co-referees Prof. Dr. Yoshitsugu Hayashi (Graduate School of Environmental Studies, Nagoya) for his insightful questions and discussions during conferences and Prof. Dr. Wolf Fichtner (Institute for Industrial Production (IIP), Karlsruhe) for his intelligent questions, showing his comprehensive knowledge in this issue.

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Continuing the three years of PhD work could not have been possible without the social life and emotional support offered by my friends and colleagues. I can not thank my wife enough for her comprehensive support. She my first son and the upcoming baby were the main motivating factor behind my submitting this dissertation in time. My gratitude also extends to my parents, my brothers, and all others who contributed to what I am.

Patrick Jochem
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List of Common Abbreviations

ASTRA  ASsessment of TRAnsport strategies (system dynamics macro model)
BaU  Business-as-Usual
bn  Billion
CARS21  Competitive Automotive Regulatory System for the 21st Century
c.p.  Ceteris paribus (other things being equal)
CO  Carbon monoxide
CO₂  Carbon dioxide
CO₂e  Carbon dioxide equivalents (describes the climate change potency of GHG referred to the reference value of CO₂ emissions)
CT  Combined Transport
et al.  Et alii (and others)
etc.  Etcetera
EC  European Commission
EU27  The European Union with 27 Member States
EU-ETS  European Emissions Trading Scheme
GDP  Gross Domestic Product
GHG  Green House Gases
GJ  Giga Joule
GMP  German Mobility Panel (Deutsches Mobilitäts Panel)
HGV  Heavy Goods Vehicle
i. e.  Id est (that is)
IPCC  Intergovernmental Panel on Climate Change
mill.  Million
Mt  Mega tons (1.000.000 t)
NOₓ  Nitrogen oxide
OECD  Organisation for Economic Co-operation and Development
p.a.  Per annum
pkm  Passenger kimometres
ppm  Parts per million (the share of the number of (CO₂) molecules to the total number of molecules in dry air)
RePAST  Recursive Porous Agent Simulation Toolkit (JAVA library for multi-agent modelling)
t  Tons
tkm  Ton kilometres
VMT  Vehicle miles travelled
VOC  Volatile Organic Compound
1 Introduction

The most recent IPCC (Intergovernmental Panel on Climate Change) assessment report indicates that the increase in the planet’s global average surface temperature is very likely caused by the observed increase in the concentration of anthropogenic greenhouse gases (GHG) (IPCC, 2007). As a result the current trend of rising GHG emissions will presumably trigger a greater probability of heavy rainfall events, heat waves, floods, storms, fires, droughts, acidification of the seas and a rise in ocean water temperature (IPCC, 2007). According to this report, the global emissions of GHG increased by 70% between 1970 and 2004. The major share of GHG emissions (78%, Ecofys, 2007) and the fastest growth are in carbon dioxide (CO$_2$) emissions. Global atmospheric CO$_2$ concentration rose from its pre-industrial value of about 280 ppm to 380 ppm in 2005 (IPCC, 2007). And as the degradation of CO$_2$ in the troposphere is very slow (Solomon et al., 2009), the long-term effects of this rise are impossible to calculate.

It is generally estimated that stabilising the GHG concentration in the atmosphere at 2000 levels will cause the average global temperature to rise by +0.1°C per decade (IPCC, 2007). Climate change is no longer avoidable. The currently targeted stabilisation of GHG concentration at 450 to 550 ppm carbon dioxide equivalents (CO$_2$e) will still lead to a temperature increase of about +2°C compared to the period before the industrial revolution (IPCC, 2007). Emissions should be reduced as early as possible and an emission reduction target of -60 to -80% for 2050 based on 2000 emissions has been proposed (Stern, 2006, and IPCC, 2007). The former Chief Economist of the World Bank, Sir Nicolas Stern, has advised against postponing action on global warming, warning of the huge costs which will be incurred towards the end of this century if countermeasures are delayed. He stated that investing 1% of world Gross Domestic Product (GDP) per year now in reducing CO$_2$ emissions may avoid adaptation and damage costs of more than 20% of GDP per year by 2050.

Some CO$_2$ abatement measures have already been implemented. The Kyoto Protocol is a key instrument in the battle against rising emissions. It was initiated by the member states of the United Nations Framework Convention on Climate Change (UNFCCC) in their third conference of the parties (COP3) in Kyoto. An emission target for five GHG$^1$ of 5.2% on average compared to emission levels in 1990 was set by international law for the so called Annex-I-States$^2$ to be met by 2012. In order

$^1$ The five gases covered by the Kyoto Protocol are carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (laughing gas, N$_2$O), sulphur hexafluoride (SF$_6$), and perfluorocarbons (PFC) as well as hydrofluorocarbons (HFC), which may destroy the ozone layer.

$^2$ There are 40 countries listed as Annex-I-States in the Kyoto Protocol including most of the industrialised nations.
to reach this target in Europe, a certificate³ trading scheme for CO₂ emissions (EU-ETS) was introduced for energy-intensive industries and electricity generation.

In addition to this, in a closed meeting in Meseberg in August 2007, the German federal cabinet decided on guidelines for a detailed energy and climate programme for Germany. They stipulated a national reduction target of 40 % GHG emissions by 2020 related to 1990 levels and recommended concrete measures for achieving this target (BMU, 2008). Of the 29 measures listed, eight⁴ relate to road transport. This high share is motivated by the huge quantity of CO₂ emissions generated by transport and by the only small emissions reductions achieved in this sector so far compared to the base year of 1990. The economic impacts are supposed to be positive (Schade et al., 2008). Even before this report, the relevance of reducing CO₂ emissions from road transport was very high and some policy instruments had already been discussed. Since there has been no major abatement of the CO₂ emissions from road transport despite the policy instruments already implemented, alternative measures are now attracting an increased level of attention. A certificate trading scheme is a convincing measure with regard to efficiency and target conformity. At present, the Kyoto Protocol will expire in 2012 and there are no fixed plans for continuing the EU-ETS, so that it would be possible to expand the current EU-ETS to include road transport (EC, 2007a:5). Therefore multiple possible attributes, designs and applications are being discussed (among others Raux, 2004).

In German road transport, which is taken as the standard scenario in this thesis, there have been the first indications of a reversal of the CO₂ emission trend of the last decades in road passenger transport unlike the situation in road freight transport. In Europe, the number of newly registered passenger cars emitting less than 120 g CO₂ per kilometre has increased exponentially in recent years (EEA, 2008:23). The specific fuel consumption of passenger cars had already begun to decrease in 1995. This development was driven by the voluntary commitment of the European Automobile Manufacturers’ Association (ACEA) in 1998 to achieve average specific emissions of less than 140 g CO₂ per kilometre by 2008 for the Association’s new cars sold in Europe (EC, 1998). As a result, the energy demand of road passenger transport has – at least in Germany – remained constant even though transport increased by about 27 % in the same period (German Transport Forum, 2006a).

Worldwide, however, the forecast is for a further considerable rise in vehicle miles travelled (VMT) and thus an associated increase in the CO₂ emissions from road passenger transport (EIA, 2008a). The same holds at the European level, where road passenger transport performance is expected to grow by 30 % until 2020 (EC,

³ Certificates analysed in this thesis are perceived as emission allowances.
⁴ These eight measures are: (1) A strategy to reduce the CO₂ emissions from new passenger cars by setting specific emission thresholds. (2) Modifying the motor vehicle tax based on CO₂ emissions. (3) Improved labelling of energy classes. (4) Increased support of battery-powered vehicles. (5) A rising biofuel quota strategy (14 % in 2020 and 18 % in 2030). (6) A more differentiated road charge for heavy goods vehicles. (7) Obligatory use of smooth running lubricant. (8) A CO₂-based tax on company cars.
Emission reductions are essential, not only for environmental reasons, but also because of the strong dependency of industrialised countries on the few oil producing countries.

From the viewpoint of economic theory, CO$_2$ emissions represent a market failure, or more precisely an external effect. They are emitted by traffic participants who do not pay for the damages caused by the emissions (Baumol and Oates, 1988). In doing so, they reduce the welfare of the economy. And according to economic theory, internalisation of these external effects leads to an increase in welfare. Different policy instruments like taxes, rules, bans, standards or certificates can be implemented to do so. The policy instruments differ particularly with respect to their economic efficiency, but also in their degree of target achievement.

According to Coase (1960), external effects can be efficiently internalised via property rights if transaction costs can be neglected. Montgomery (1972) improved this general illustration and applied it to the current comprehension of certificate trading schemes using the example of a company’s sulphur dioxide emissions.

To internalise external effects in economic theory, an equilibrium between the marginal emission abatement costs (MAC) and the marginal external costs (MEC) of emissions has to be established (see Figure 1). To do so, it is necessary to estimate the MAC of the polluter and the MEC of the persons concerned and to determine where they intersect. The MAC curve shows the marginal costs for polluters to
reduce one unit of emissions. The MEC consists of the marginal costs of the economic damage per unit of emissions. If no external effects are internalised, too many pollutants will be emitted \((e^0)\) as the polluter does not have to compensate for the damages caused. This reduces the level of economic welfare. When internalising external effects using a certificate trading scheme, the number of allocated certificates is restricted to the welfare optimum \(e^*\). If more emissions than \(e^*\) were emitted, the polluter would have a reduction in costs with an absolute value lower than the additional costs for the persons affected — hence welfare would decrease. If fewer emissions than \(e^*\) were emitted, the opposite would be true: the additional costs of the polluter would be more than the corresponding reduction in damage to the persons affected. Compared with the pure quantity limitation polluters with high marginal abatement costs have an advantage in the certificate trading solution when trading emission allowances with polluters with low marginal abatement costs; this imply an economic efficiency gain (Baumol and Oates, 1988, and Jochem and Schaffer, 2008). The second advantage compared to a pure price solution (e.g. taxes) is the exact achievement of the emission reduction target \(e^*\).

1.1 Objectives

This thesis aims to analyse the impact of introducing an upstream CO\(_2\) certificate trading scheme for German road transport by developing a micro-based, meso economic partial model of German road transport. Secondly, the general attributes of multi-agent models are presented and their suitability for simulating road transport is discussed. The developed model will incorporate some of these attributes and its results will give insights in impacts on traffic participants as households and freight forwarders. The examination of selected macroeconomic and environmental impacts completes the analysis.

1.2 Structure

The remainder of this thesis is organised as follows. First, an introduction is given to European and specifically to German road transport, focusing on the CO\(_2\) emissions caused (Chapter 2). The current and future policy instruments for reducing CO\(_2\) emissions from road transport are also discussed. Potential CO\(_2\) emission certificate trading schemes are developed for road transport and technical emission reduction possibilities at the level of vehicles are outlined (Chapter 3).

Chapter 4 describes the recent development of multi-agent modelling in the social sciences and identifies relevant attributes for modelling road transport which confirms the suitability of multi-agent models for road transport simulation. A brief look at other transport modelling approaches in economics supports this recommendation.
In Chapter 5, a micro-based, meso economic model of German road transport is developed to provide a realistic picture when simulating the impacts of introducing a CO\textsubscript{2} emission trading scheme. The model includes some attributes of multi-agent modelling. Possible certificate price developments and the impacts on traffic participants as well as the identification of especially affected traffic participants are discussed in the analysis of the results.

The results are then used in Chapter 6 for a further analysis using the system dynamics model ASTRA to identify the macroeconomic impacts on selected transport-relevant air pollutants of introducing the CO\textsubscript{2} emission trading scheme.

The thesis is completed by a summary of the results, conclusions, and an outlook.
When taking into account all the associated costs, individual passenger car traffic is the most expensive means of transport for most purposes. At present, however, transport cost calculations do not consider all these costs. This may change in the future if, as demanded by the European Commission (EC, 2006a), the external costs of transport are further internalized. This is a challenging task since many pollutants interact only on a local basis so that external costs vary considerably with the time of day and the location. On average, they amount to about 4 euro-cent per passenger kilometre for passenger transport and account for almost 20% of total costs. The external costs of all other transport modes are significantly lower. For freight transportation, road transport is in second place with 0.02 euro per tkm after air transport with 0.2 euro per tkm (CE Delft et al., 2007). And even though these external effects are being increasingly charged to those causing them (objective of the European Commission's revised White Paper (EC, 2006a) and Green Paper (EC, 2007b)) following the underlying ‘polluter-pays principle’, vehicle miles travelled (VMT) continues to rise in both German road passenger transport and in freight transport in particular.

In passenger transport, this development is accelerated by the demand for ever more powerful cars (Schallaböck et al., 2006). However, the most recent car registration figures for February 2009 reflect a decline in this trend regarding vehicle weight and cylinder capacity (KBA, 2009). This seems to be an effect of the German trade-in incentive\(^5\), but it might be supported by the continuing discussion of climate change in the media with one focus the CO\(_2\) emissions from passenger cars and a result of the uncertainty about how passenger cars will be taxed in the future. That the media focus especially on the specific fuel consumption of passenger cars is due to the failed voluntary agreement of the European Automobile Manufacturers Association (ACEA) from the year 1998, which guaranteed to reduce the specific CO\(_2\) emissions from newly registered passenger cars in Europe to 140 g CO\(_2\) per km by 2008. Further policy measures are presented in Chapter 3. However, reducing specific emissions will not lower overall emissions as long as the VMT continues to increase as it has done over the last few decades. It might even give an incentive for households to increase their VMT according the decrease in variable costs (“rebound effect”, see Frondel et al., 2007). The following paragraphs should give an outline of the current situation of German road transport.

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\(^5\) Due to the financial crisis the German government is offering for a limited time period motorists 2,500 euros towards a car up to 12 months old when trading-in a car more than nine years old.
2.1 Current situation and transport mode choice in German passenger transport

The first stagecoaches were introduced in the 17th century which then became the modal choice of transport for the broader population. Before this time, distances could only be covered by foot by the middle and lower classes. Not until the 19th century were stagecoaches supplemented by railways and later by bicycles. At the end of the 19th century, Bertha Benz heralded a new era with her first “long-distance” journey of more than 100 kilometres from Mannheim to Pforzheim.

Figure 2: Passenger car mileage travelled 2002 (Infas and DIW, 2002)

Today, there is a much wider range of transport modes available for short distances for nearly every household, at least in Europe. Besides passenger cars, public transport systems offer buses, trams or even underground electric railways and specially constructed bicycle lanes or pavements are available. For long distance travel, aviation is growing in importance. But decisions about transport modes are often made based on habits and are strongly dependent on the subjective characteristics of the decision-maker. It is not possible to generalize these decisions or observe the presence of an interpersonal and universal decision rule. Nor is economic optimization considered during the modal choice. Thus, e.g. every tenth car journey is less than one kilometre (see Figure 2) – which is not the most economic option for most trips.

Furthermore, the last KONTIV survey (Infas and DIW, 2002) shows that 45% of the journeys made by passenger cars are shorter than five kilometres (see Figure 6).

The KONTIV-Survey (continuous census of transport behaviour – Mobility in Germany) for Western Germany was made in the years 1976, 1982, and 1989. In 2002 the survey was done...
2). The average is about 15 kilometres. Zumkeller et al. (2005) show that the passenger car is only 4 minutes faster than an average pedestrian for a 1.1 km trip – neglecting time spent searching for parking in crowded cities. Referring this share to the mileage instead of the number of trips the share on journeys decreases to less than 10%.

Figure 3: Share of trip purposes in German passenger transport 2002 based on vehicle mileage travelled

Regarding the travel purpose, holiday and leisure trips have the main share in passenger transport volume at 38.4%. These are followed by commuter and education traffic with 23.8%, shopping traffic with 18% and business trips with 12.7%. Trips made to accompany somebody have a much lower share of about 6% (see Figure 3). Compared to 1982, the VMT for private purposes (leisure, shopping and accompanying) increased by 48%, slightly higher than the VMT for business purposes (business, commuting and education) which increased by 36%. A strong increase can also be seen in the share of shopping trips and trips to accompany someone else. Shopping trips are more often accomplished by car rather than on foot. The share of leisure trips decreased slightly.

In German passenger transport, VMT increased between 1991 and 2005 by 21.5% to about 870 billion passenger kilometres. Regarding the modal share in passenger transport based on VMT, motorized individual traffic plays the dominant and increasing role in this market with 80% (see Figure 4). Motorized individual

for the reunified Germany. The most recent survey for 2008 had not yet been published before the completion of this thesis.
traffic increased by 21.9% in the considered time period. Public transport (rail and local public transport) has a declining share of about 15%. The remaining share of about 5% can be allocated to the fast rising area of aviation, which has more than doubled its VMT over the last 14 years. If non-motorized passenger transport (pedestrians and bicycles) is also considered, their share is about 6% of VMT (Infas and DIW, 2002: 96). Regarding the CO₂ emissions, the share of road transport is about 90% and aviation and public transport each have a share of about 5%. Direct emissions of rail transport only have a share of about one percent.

Figure 4: Passenger transport performance in Germany (BMVBS, 2008a)

On the day the participants were surveyed, 86% of them were mobile and covered a distance of about 40 km in about 74 minutes on average (Infas and DIW, 2002). In the last few years the number of trips and the VMT has increased continuously.

A further finding of the KONTIV (Infas and DIW, 2002) survey was that modal choice is influenced, apart from by socioeconomic (e.g. profession or age) and geographic (distances and accessibility) factors, in particular by mobility styles (as “Seldom-Mobiles”, “Bicyclists”, “Public-Transport-Captives” etc.), which can be statistically demonstrated.
In the last decade, besides these factors concerning the traffic participants of German passenger transport, a strong trend to bigger and higher performance passenger cars could also be observed. This trend is highlighted by newly applied technologies (e.g. ESP, airbags, air conditioning, etc.) and the associated corresponding total weight of the car\(^7\), but also by an additional demand for more powerful vehicles with higher cylinder capacities and greater horsepower. The average vehicle weight increased in the last 25 years by between 15 and 30 %. Schallaböck et al. (2006) delivered a good paradigm: At the beginning of 2004, the share of passenger cars with a weight of more than 1.7 t in the current fleet was about 41 %. Looking at newly registered passenger cars in 2004, this share had already risen to about 70 % (see Figure 5).

2.1.1 Relevant data sources in German passenger transport

Besides the KONTIV survey, in which about 25,850 households with about 61,730 members participated in 2002 and reported on more than 190,000 trips, the German Mobility Panel (GMP) has also existed since 1994. A big advantage of this survey is that it is held on an annual basis. About 750 households\(^8\) or 1,800 persons are questioned. Besides the usual survey, the participants have to fill out a logbook on all the trips made over a period of more than one week. Around 25,000 trips are documented as a result in these logbooks (Zumkeller et al., 2004). A further advantage of the GMP is that this survey time period of more than a week is much better suited to reflect personal mobility behaviour than the survey of a (randomly chosen) single day, which is the usual survey period for most of the other transport surveys. Although the KONTIV survey asks which mode is usually used, the logbook record

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7 E.g. the total weight of a Volkswagen Golf increased by about 40 % from about 750 kg in 1975 (Golf I) to 1,050 kg in 1998 (Golf IV) (WBCSD, 2004).

8 These households can stay in the panel for a maximum of three years and are then substituted by others.
of more than one week should provide much more reliable data on what “usual mode” means than a single answer. This is even more valid as the subjects have much more time to fill in the questionnaires and a stronger familiarisation with the questionnaire takes place over one week of auditing. Furthermore, participants in a telephone survey of one day tend to distort or bias answers according to their subjective impressions (Zumkeller, 1999). A disadvantage of the long observation period is that a certain exhaustion of the survey participants can be observed (Fatigue-Effect).

Besides the advantages of the GMP, it is much easier to allocate households to the corresponding mobility types due to the longer survey period and the annual basis. Furthermore, the survey period of one week is much better suited to represent a meaningful planning horizon for simulated activity plans of traffic participants (Gringmuth, 2007). Thus a more accurate estimation of annual mileage is obtained from repeating an individual’s representative week 52 times than from repeating a representative day 365 times as hebdomadal activities are neglected. This is also true for estimating the modal choice of the considered household. In principle it is possible to compare the VMT of one household between two years. But as some important influences such as the milieu of the household (e.g. occupational changes) are not included in the survey, the result – in particular the modal choice – might be strongly biased (Wassmuth, 2000). The data of the GMP also allows estimations of the effective average fuel combustion of the passenger cars since tank contents, magnitudes of refuelling and VMT are given for the whole survey period. According to Zumkeller et al. (1998: 124), the GMP includes all the relevant core passenger transport indicators to simulate Germany’s motorized individual transport in a consistent way.

2.1.2 Demand segments in mode choice in motorized individual transport

Besides the socioeconomic and characteristic factors of the neighbourhood, other (mostly not measurable) parameters exist which have a strong influence on the mobility behaviour of individuals – especially on their choice of transport mode (Zinn et al., 2003, Infas and DIW, 2002 and 2004). For this reason, it might be useful to group traffic participants into mobility types before applying only socioeconomic characteristics. Götz and Schubert (2004) used seven mobility types, e.g. “Seldom-Mobiles”, “Bicyclists”, “Public-Transport-Captives”, “Public-Transport-Users”, “Mix-Users”, “Rural-Individual-Transport-Users”, and “Urban-Individual-Transport-Users”. These mobility types differ particularly in their “soft” factors such as emotions, subjective symbolic importance of car ownership and other aesthetic preferences of the individual (Götz and Schubert, 2004) as well as their mobility needs, mobility orientations, and mobility attitudes (City:mobil, 1999 as well as Hunecke and Wulfhorst, 2000). Therefore, apart from the socioeconomic and characteristic factors of the neighbourhood, these soft characteristics of traffic participants should also be considered in the description and explanation of mobility
behaviour (Hunecke et al., 2002, and Götz et al., 2003). In this context it can be observed that modal choice alternatives are subjectively valued and the corresponding choice is mainly based on a habitualised decision. Furthermore, Simma and Axhausen (2003) also noted the different initial equipment of households in the different mobility types concerning the different characteristics of their neighbourhood and vehicle availability. If a passenger car is easily available, it is much more likely to be used. The same is true for a commuter pass for public transport; if this is available, the probability of using public transport is much higher. Furthermore cross-elasticities are negative so that car ownership reduces the probability of using public transport.

A further influencing factor of mode choice is the trip purpose. This, however, holds mainly for intra personal comparisons: for the same trip purpose, people tend to use the same mode as a rule (Zumkeller et al., 1998). This is especially true for commuting, where the authors show a strong correlation between the used modes of two subsequent workdays. This is also true even if the working time differs. The corresponding correlation is highest for passenger car drivers at 95.3 which exceeds the correlation of 90.4 for pedestrians and for passenger car passengers (72.8). The correlation is even higher for two working days with the same working time.

As “Mobility is […] simultaneously both means and symbol of social integration” (Götz and Schubert, 2004: 224) as well as a precondition for lifestyle positioning (Jahn and Wehling, 1999), econometrically identified mobility types which consider social aspects are essential for simulating the modal choice of traffic participants. In recent years at least six cluster analyses have been performed to identify behaviour clusters among German traffic participants (Hunecke et al., 2002, Götz et al., 2003, Zinn et al., 2003, Hunecke et al., 2005, Götz and Schubert, 2004, and PTV, 2005).

2.2 The current state in freight transport and its mode choice

While passenger transport actors are very heterogeneous, freight transport is much more homogeneous. In contrast to motorized individual traffic, transport costs are mainly minimized. According to the German Commercial Code (HGB), three different main actors can be identified in road freight transport (German Transport Forum, 2001): the shipper, who sends the merchandise, the forwarder or haulier, who dispatches or organizes the transport, and the carrier, who simply ships the commodities. The paradigm of a transport schedule begins with the shipper’s need for transport. He might have his own means of transport and may consider accomplishing the transportation himself, or he may authorize a forwarder or carrier. If a forwarder is authorized, he may also decide to transport the goods himself or pass the order onto another carrier or a further forwarder. In the eyes of the legislator, the forwarder is an expert for organizing the dispatch of commodities, who helps the shipper find the most suitable transport alternative and who allocates different shipments. The carrier is located at the end of the transport chain. He actually carries out the transportation.
The total German freight transport volume equals the number of accomplished freight transports within the geographic borders of Germany over one year. A useful index for measuring transport volumes is the freight transport performance. This is defined as the sum of all the transport distances multiplied by the mass transported. It is measured in ton kilometres (tkm). Thus the index assigns the same value to two trucks each with a load of one ton as to one truck with a load of two tons transported over the same distance. Similarly, cubic contents are neglected. I.e. a truck carrying feathers are less weighted in the transport performance index as a truck with the maximum allowed vehicle payload. Hence a constant index does not guarantee a constant number of trucks on the road.

Figure 6: Development of freight transport performance in Germany (BMVBS, 2008a)

In recent years, German freight transport performance has been increasing (see Figure 6) and seems set to continue to increase in the next few decades (Progtrans, 2007). Between 1991 and 2005, freight transport performance (excluding pipelines) increased by 45.5 %. Freight transport is therefore growing faster than passenger transport (Bühler, 2006). The largest absolute increase within freight transport could be observed in road freight transport with 64.4 %. Relatively, aviation transport performance experienced the fastest development, starting from a relatively low level and more than doubling in the same period. The share of road freight transport increased from 61.4 % in 1991 to 69.5 % in 2005. This growth took place mainly at the expense of rail and inland waterways transport. In 1980 the share of rail and inland waterways transport together was almost at the same level as the share of
road freight transport but has now dropped to below 30%. Progtrans (2007) expects another doubling of freight transport performance in Germany by 2050. The majority of studies predict that transport performance will continue to increase (among others Progtrans, 2007, and UBA, 2003).

However the share of freight transport in the annual VMT on German roads measured in the number of transports is quite low. Private transport has a share of about 71.6%, passenger commercial transport about 14.2%, freight transport about 10% and other commercial transport about 4.2% (Wermuth, 2006).

When looking at the statistics of the last decades, a strong correlation between economic growth and freight transport volumes can be observed (Bühler, 2006). The White Book of the European Commission (EC, 2001) claimed to support “a marked break in the link between transport growth and economic growth, although without there being any need to restrict the mobility of people and goods” (EC, 2001:12). Improved logistics might be able to make a major contribution to achieving a decoupling of freight transport volumes from economic growth. Léonardi et al. (2004) estimates about 20% scope for improvement due to enhanced logistics in merchandise distribution. A decoupling of freight transport has not been observed so far (EC, 2006a:8). Besides improvements in logistics, a mode shift away from roads (in particular inland waterways) is promising, especially when regarding the bottlenecks in infrastructure (particularly in road and to some extent also for rail transport), but also when considering ecological aspects. However, political instruments to shift transport volumes from roads to other modes have largely been less effective than technological actions with regard to the CO₂ emission reduction potential in road freight transport (Bühler and Jochem, 2008).

2.2.1 Relevant freight transport data sources

There are considerably fewer comprehensive surveys of freight transport than there are of passenger transport. One of the available, recent surveys is the survey of “motor traffic in Germany” (KiD) from 2002. Its aim was to evaluate the utilisation of motor vehicles registered by German citizens. All types of vehicles were included. A random sample of the central vehicle register (ZFZR) was chosen from the German Federal Motor Transport Authority (KBA) which considered vehicle characteristics and geographical location. The survey is unique in that it covered all types of road transport vehicles, i.e. light duty vehicles (LDV) with loads below 3.5 t were considered for the first time. Thus the share of vehicles which are not used for private purposes (i.e. are used for commercial purposes) was able to be estimated based on this survey data as amounting to about 28.4% (Wermuth, 2006).

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9 This is measured in licensed motor vehicles registered by German citizens.
10 Despite this, freight traffic is still most responsible for road depletion (Rommerskirchen et al, 2009).
Besides the KiD survey, there is (among others) also a database at the Centre for European Economic Research (ZEW). Bühler (2006) generated this database from a survey of German forwarders to examine the modal choices in freight transport. According to Bühler (2006), forwarders do have the main influence on modal choice in freight transport. The database is not as comprehensive as the KiD survey regarding the vehicle fleet used, but it does have the advantage that it provides a much more detailed insight into company data with the focus on the modal choice decisions of forwarders.

The sample was stratified and drawn from a total population of 6,924 German forwarders. 716 telephone interviews were conducted, of which 498 were able to be used to analyse the modal choice of forwarders. In the survey, the forwarders were asked to describe in detail a typical shipment made by their company during the last week.

It is not as meaningful as in passenger transport to conduct a cluster analysis in freight transport because of the similar decision basis on the one hand (maximizing profits), and the different terms of references on the other (shipper, forwarder and carrier).

2.3 Conclusion I

This chapter aimed to give an overview of European and in particular German road transport. The focus, as in the remaining thesis, is on the directly generated CO₂ emissions of road transport. Over the last decades, the emissions from German passenger road transport have increased steadily, but recently this trend has been reversed and CO₂ emissions have declined due to a slightly decreasing VMT. Nevertheless huge emission reduction potentials remain within road passenger transport because of the recently observed trend towards heavier, more powerful passenger cars on the one hand, which are less efficient with regard to CO₂ emissions and because on the other hand the mode choice of households is mainly based on habits rather than on optimal decisions. The emission reduction potential is estimated to be much lower in road freight transport due to the competitive pressure here, the cost minimization, the already increased fuel prices in recent years, the introduced toll charges of the German "Lkw-Maut" and the corresponding optimization of logistics as well as the increasing freight transport demand. In the short run, significant efficiency gains might be possible in combined transport. However the realization of reduction potentials is strongly dependent on the implementation of policy instruments and changing price constellations. Therefore the following Chapter 3 is dealing with policy instruments and technical potentials of CO₂ emission reduction in road transport.
3 How to reduce CO₂ emissions from road transport

As described in the previous Chapter, the CO₂ emission reduction potentials in road transport and especially in road passenger transport are considerably. In road passenger transport, the increase of CO₂ emissions was determined by an increase in VMT, a higher car feet and an increase in the demand for ever more powerful cars (Schallaböck et al., 2006). However, the most recent car registration figures for the year 2008 reflect a first decline in this trend regarding specific fuel consumption and the absolute number of new cars sold (KBA, 2009). This might be an effect of the continuing discussion of the future taxation on passenger cars.

A highly discussed measure is the limitation of the specific fuel consumption of passenger cars. This focus arises due to the failed voluntary agreement of the European Automobile Manufacturers Association (ACEA) from the year 1998, which guaranteed to reduce the specific CO₂ emissions from newly registered passenger cars in Europe to 140 g CO₂ per km by 2008. This voluntary agreement represented one of the three pillars of the European Commission’s strategy to reduce CO₂ emissions in passenger road transport (EC, 1995). Furthermore it was the only really measurable target as the other two pillars do not deliver measurable effects of CO₂ emission reductions.

After the failure of their first strategy became foreseeable in 2005, the European Commission set up a new think tank (Competitive Automotive Regulatory System for the 21st Century – CARS21) to develop a revised strategy to reduce CO₂ emissions in passenger transport. Up to now 16 recommendations for protecting and improving the automotive industry in Europe have been presented (CARS21, 2008). With regard to the CO₂ emissions of motor vehicles CARS21 recommended an “Integrated Approach”, i. e. a comprehensive and holistic strategy which covers all the relevant actors and stakeholders such as car manufacturers, petroleum industry, consumers, drivers, public administration etc. This Integrated Approach consists of three areas: (1) The improvement of vehicle technology; (2) the development and increasing sale of bio-fuels; as well as (3) further accompanying measures. The latter two (bio-fuels and accompanying measures) can also grouped together under ‘complementary measures’. Accompanying measures include, for example, CO₂ based vehicle and fuel taxes, ecodriving training, gear recommendation displays, consumer information and measures to reduce traffic jams (EC, 2006a:27).

11 Similar agreements were made by two associations of Asian manufacturers (JAMA and KAMA) (EC, 2000).
12 140 g CO₂ per kilometre is based on a fuel consumption of about six litres petrol or 5.3 litres diesel respectively.
13 The other two pillars are: the obligation for all cars offered for sale to label their fuel consumption and the corresponding CO₂ emissions (pillar 2) and tax relief for newly registered cars with low specific fuel consumption (pillar 3).
According to the think tank CARS21, the new strategy should, in contrast to the former strategy of 1995, stipulate clear and measurable targets with suitable time schedules and clearly assigned responsibilities. During the implementation of the revised strategy, the media focussed particularly on the specific emission target for vehicle technology. It was decided to limit the average specific CO₂ emissions of newly registered passenger cars in Europe to max. 130 g CO₂ per kilometre by 2012. This is an ambitious target because, in October 2008, the average specific emissions were 163 g CO₂ per km. The automobile lobby has managed to push back the time horizon to 2015. Further reduction measures, e.g. an increased biofuel quota, should further reduce emissions to 120 g CO₂ per km (EC, 2007a:9). Overall, except for the extension of the period, all the suggestions made by CARS21 have been accepted.

However, reducing specific emissions will not compulsory lower overall emissions. Hence effective policy instruments are required to release the CO₂ emission reduction potentials within road transport. The following paragraphs present some possible policy instruments and outline technical CO₂ emission reduction possibilities for vehicles.

### 3.1 Policy instruments to lower CO₂ emissions from road transport

The transport sector is the only economic sector of the European Union (EU27) in which greenhouse gas emissions have risen significantly and are now clearly above the emission level of the Kyoto Protocol’s base year of 1990 (see Figure 7). In Germany, the transport sector is the only one which has not managed to reduce its CO₂ emissions compared to the base year. Furthermore, when considering shares in total CO₂ emissions, transport takes second place with 21.2 % after the energy sector with 45.3 %. Whereas, in 1990, the transport sector contributed considerably fewer CO₂ emissions than industry and less than 40 % of the emissions from the energy sector, today it has overtaken industry and increased its share compared with the energy sector to 47 % (EC, 2008). This is mainly caused by the fast growing demand for aviation and the rapidly rising volumes in road freight transport (EC, 2007a, and Jochem and Schaffer, 2008).

By signing the Kyoto Protocol, Germany is obliged to reduce its greenhouse gases by 21 % by 2010 compared to the base year 1990 as part of the European burden-sharing agreement. In 2007 Germany had already achieved a reduction of 18.2 % (EC, 2008). Every sector except the transport sector made a contribution to this overall reduction.

In economic theory, a tendency can only be termed efficient (and thus welfare optimal) if the considered market is not biased in the different sectors. This means that, with regard to climate change, the price for CO₂ emissions should be equal in all sectors of the market. Since only energy-intensive sectors such as the energy sector or some industry sectors fall under the European Emissions Trading Scheme (EU-ETS) so far, there is no uniform price for CO₂ emissions in all sectors of the economy.
Even within the transport sector the price for CO₂ emissions is very heterogeneous. In rail transport, operators pay the usual certificate price of the EU-ETS for each ton of CO₂ emitted by shipments made using electric locomotives. For diesel train rail shipments, the German energy tax is paid. Similar to road transport, this tax does not formally internalize the external effects of greenhouse gases but can be interpreted as doing so. A pure CO₂ tax at the same price level would be about 250 euros for petrol and around 180 euros for diesel per ton CO₂. However, it would then be very unclear how public roads are financed. In aviation, no consideration of the external effects of greenhouse gases has been introduced so far although the emission of a unit of CO₂ in the tropopause has two to four times the impact on climate change as emissions in the lower troposphere (IPCC, 1999). It has been decided to include aviation in the EU-ETS after 2012 (EC, 2007a).

Figure 7: Development of CO₂ emissions of sectors in the EU27 between 1990 and 2006 (EC, 2008)

Within the German transport sector, road transport is responsible for more than 90% of the overall CO₂ emissions in Germany (see Figure 8). The emissions of rail transport are on a stable level below 5%, whereas the emissions of aviation have risen sharply in recent years and now also make up 5% of German CO₂ emissions.
In summary, the transport sector is the only sector which does not contribute to meeting the Kyoto targets, neither on a European nor on a national level in Germany. Within the transport sector, road transport has the biggest share of greenhouse gas emissions. This trend cannot be reversed with technological measures alone. These technology measures may even have a smaller impact as behaviour changes (Frondel et al., 2008). These reasons lead to the conclusion that examining climate policy instruments for road transport should be done more precisely with regard to the behavioural changes of traffic participants. Some policies are already in force such as the motor vehicle tax considering the emissions standards of vehicles which was introduced in 1985, the eco tax (Ökosteuer), the German toll for heavy goods vehicles on motorways and selected by-pass roads which considers emissions standards and the effective axle load ("Lkw-Maut"), the Energy Tax Law (Energiesteuergesetz) and the Biofuel Quota Act (Biokraftstoffquotengesetz), a voluntary self obligation on the part of the automotive industry as well as other subsidies to improve the infrastructure of public transport and bicycle lanes or footpaths.

3.1.1 Overview of current policy instruments to reduce CO₂ emissions from German road transport

Since April 1999 another tax besides the petrol tax (now the energy tax) was introduced for all fuels in road transport, the so-called ecotax (Ökosteuer). In 1999 the
A surcharge was 3.07 euro-cents per litre petrol or diesel\textsuperscript{14}. This amount then increased every January between 2000 and 2003 by 3.07 euro-cents per year, so that in 2003, the surcharge had reached 15.35 euro-cents per litre fuel. This tax was also applied to other energy sources in parallel.

Another milestone was the Energy Tax Law passed by the German Parliament (Bundestag) on the 29\textsuperscript{th} of June, 2006. After being approved by the Federal Council (Bundesrat) on the 7\textsuperscript{th} of July, 2006 and published in the Federal Law Gazette (Bundesgesetzblatt) on the 15\textsuperscript{th} of July, 2006 it came into force on the 1\textsuperscript{st} of August of the same year. This law modified the German taxation system in line with the European Energy Tax Directive. For example, the previous petrol tax was completely revised and renamed the Energy Tax Law (Energiesteuergesetz) which is also applied to other energy sources. The tax rates for petrol (0.65 euro per litre) and diesel (0.47 euro per litre) already include the tax rate of the ecotax. Some extensions of the Energy Tax Law have already been implemented. In 2007, Germany finally translated into national law the biofuel directive of the European Parliament and European Council which had been passed in 2003 (EC, 2003). This directive stipulates a certain minimum addition of biofuels to conventional fuels for all European Member States. For 2005, this directive scheduled a 2 % share of biofuels\textsuperscript{15} in the total fuel consumption of national transport. This amount should be increased to 5.75 % until 2010. Since 2007 in Germany, the oil companies are obliged to add 4.4 % biofuels to diesel sales and 2 % to petrol. There are high penalties for any violations. To calculate the tax, the added common biofuels are considered conventional fuels. Pure vegetable oils, which were exempt from taxation until 2007, are now charged with an increasing tax rate from 0.10 (in 2008) to 0.45 (in 2012) euro per litre. In a similar way the tax rate for pure biodiesel will grow from 9 euro-cents per litre in 2007 to 45 euro-cents per litre in 2012. Nevertheless, both tax rates will remain below the tax rate for conventional diesel of 47.04 euro-cent per litre. Only “second generation” biofuels which use the whole crop are still untaxed so far.

Besides these taxes, in 1998 the European Automobile Manufacturers’ Association (ACEA) made a voluntary commitment to reduce specific CO\textsubscript{2} emissions of new vehicles by 25 % until 2008. Furthermore, since 2004, all new cars sold in Europe have to be labelled with their specific CO\textsubscript{2} emissions calculated based on their average fuel consumption (European Regulation on labelling of Energy Usage of Passenger Cars from 28\textsuperscript{th} of May 2004, BGBl. I S. 1037). However the reduction potential of technological changes in the vehicle accomplished by the car manufacturers alone is only estimated as 2.3 % (Kluge and Stromberger, 2007). A so-called Integrated Approach is seen as being much more effective. This approach would combine several coordinated cross-sector activities which may not be that effective

\textsuperscript{14} Properties (e.g. octane number or cetane number, respectively, density and sulphur content) for petrol or diesel sold in Europe are defined in the corresponding European standards EN228 or EN590 respectively.

\textsuperscript{15} The share is with regard to the energy content.
in isolation, but which together reach a much higher level of CO₂ emission reductions. Basically the Integrated Approach includes

- raising the proportion of alternative biofuels in conventional fuels,
- subsidizing the diffusion and further exploration of CO₂-efficient technologies and optimized rolling resistance tires,
- supporting the implementation of advanced driver assistance systems such as optimal gear choice displays or automatic tire pressure control systems,
- promoting ecodriving training courses and initiatives as well as
- optimising the transport infrastructure, modal use and modal choice.

A suitable division of the emission reduction potentials of these activities promises the maximum reduced CO₂ emissions (CARS21, 2008). All activities depend on acceptance by transport participants, the credo of the industry and the corresponding support by politics. The most attractive action for economic policy research is the last activity. On the one hand, civil engineers can optimize the infrastructure and its usage and, on the other hand, social scientists, especially economists, could develop policy instruments to accelerate the implementation of new technologies, or to change the behaviour of traffic participants.

The legal basis for increasing the share of alternative biofuels in conventional fuels has already been accomplished, as described above. So far, however, there are no European standards in place for the second activity of subsidizing diffusion technologies or the third activity of supporting advanced driver assistance systems. Thus neither the industry nor consumers have any clear ideas about which technology will penetrate the market. Technologies are already being developed and introduced to the market, but so far have not been widely accepted by consumers. This is also true for ecodriving training which is not popular as the political pressure and economic incentives for taking it are far too low. However, introducing an obligatory ecodriving training module during the acquisition of a driving licence is currently being discussed. Optimisation of the transport infrastructure is so far under the jurisdiction of the individual Member States. The optimisation of mode usage and mode choice has recently been one focus of the European Commission; the aim here is to harmonize the different regional approaches in a European policy.

The impacts of the implemented policy instruments to reduce CO₂ emissions in road transport are so far underachieved. This is especially true for the mode choice and usage optimisation. The share of road transport and aviation continues to increase as does the trend within motorised individual transport to increased engine performance. This is surprising when considering the monetary incentive systems explained above (Zinn et al., 2003, and Hunecke et al., 2005). This might be due to the fact that fuel prices have risen gradually. For abrupt fuel price increases a Shell study (Shell, 2001) attests much higher impacts and reactions. Schubert (2004) suggests taking the mobility types and lifestyles of the different population clusters into account when optimizing transport with respect to ecological efficiency as the impact is much higher if traffic participants are addressed individually and case specifically. Furthermore the author expects a huge CO₂ emission reduction
potential for transport related to leisure purposes.

In road freight transport, corresponding fiscal fuel regulations can be introduced. Also the vehicle tax is similar to the passenger car tax and is estimated mainly according to the gross vehicle weight and the emission category. Currently, the annual tax payment for a conventional 40-ton-semi-trailer of the emission category S2 (or a better category) is about 560 euros. For an older semi-trailer, which cannot be allocated to any emission category, 1,680 euros have to be paid. Besides this incentive to buy new trucks, the toll for older vehicles is much higher for every motorway kilometre driven. This toll („Lkw-Maut“) was finally introduced (after a lengthy delay) on German motorways and by-passes in January 2005. This was due to the European directive 1999/62/EC (charging of heavy goods vehicles). It is a performance-related toll for freight vehicles with a gross vehicle weight of more than 12 tons. The toll rate has been raised in January 2009 and now ranges between 0.14 euro per kilometre and 0.29 euro per kilometre. In principle two factors affect the tax paid: trucks with higher axle loads and worse emission categories pay more so that newer and lighter trucks pay on average much less than old trucks. The average toll rate in the beginning was about 0.13 euro per kilometre which was below the requirements of the European Commission. The new rates now comply with these requirements (Rommerskirchen et al., 2009). The next toll rate change is set for 2011. At the same time as the toll was introduced, the annual vehicle tax was lowered to be more in line with the polluter-pays principle.

A significant impact on mode choice was not expected due to the implementation of the Lkw-Maut on German highways (Rothengatter and Doll, 2001, and Bühler and Jochem, 2008) – and did not occur. For a significant improvement of workload, logistics and mode choice, the tolls should be much higher (BAG, 2008). Nevertheless a marginal change in the freight volume development could be observed due to the toll. Whereas the share of rail freight transport performance increased by 1.74 % between 2003 and 2007, the road freight transport performance increased by only 0.79 % to a share of 71.92 % of freight transport (BAG, 2008). In previous years this situation had been reversed – i.e. road freight transport performance had grown faster than rail freight transport performance. However during the same period the inland waterway freight transport performance also decreased by about 1 %. A much more significant impact of the toll can be seen in the fleet composition. The average age of the fleet has decreased significantly in recent years and the share of low-pollutant emission categories, S4 and S5, has increased dramatically: The emission category S4 (S5) increased its share in VMT from 0.9 % (0.2 %) in January 2005 to 7.2 % (27.9 %) in April 2008 (DIE WELT, 2008).

Even before the Lkw-Maut came into effect, more than half of the forwarders and carriers had already implemented at least one fuel-saving activity (e.g. optimized rolling resistance tires, wind spoilers, driver training etc.) for economic reasons (Léonardi et al., 2004). Thus further emission reduction potentials in road freight transport are seen especially in the improvement of workloads, which are currently around 50 to 70 % (Léonardi et al., 2004). However, despite these potentials, further increases in CO₂ emissions from freight transport will occur. Birnbaum et al. (2002)
forecast an emission increase compared to 1995 of 24 % until 2020. This is in line with other forecasts of freight transport volumes (Progtrans, 2007, EWI and Prognos, 1999, and BMVBS, 2001).

3.1.2 CO₂ certificate trading scheme in transport and the European Emission Trading Scheme (EU-ETS)

In general, the charm of emissions trading consists of exactly achieving the emission reduction target by using a market-conform instrument. Their scope and method of allocation should be carefully defined before implementation. On the one hand, it makes sense to limit the number of affected individuals in order to keep transaction costs as low as possible. On the other hand, a certain minimum number of participants are necessary to establish an efficient (polypoly) certificate trading scheme.

The CO₂ certificate trading scheme combines price incentives and conformity with the defined emission reduction target. On the one hand, high fuel prices might seem problematic for car-dependent households with lower incomes or small forwarding businesses; on the other hand, there is a large potential for emissions reduction here: The Federal Ministry of Transport, Building and Urban Affairs estimated in 2000 that the CO₂ emission reduction potential in road transport due to energy-conscious and ecological behaviour is more than 15 %. Furthermore, the Ministry stated that CO₂ emissions of road transport will progressively decrease after 2010 at the latest due to new alternative fuels (BMVBW, 2000: 45).

Besides economic instruments, such as the certificate trading scheme, voluntary, informational, and classical regulative instruments are all effective measures to reduce CO₂ emissions in road transport. Economic instruments include certificate trading schemes, taxes, and subventions. All of these give traffic participants financial incentives to reduce their emissions. But in contrast to the first alternative, the other two are purely price solutions whereas the certificate trading scheme is a volume solution. A price solution sets a price and the volume solution sets the volumes. Unlike economic instruments, voluntary instruments mainly concern agreements made between companies and the state. Penalties are usually not included in the contract. The most common application of informational instruments is consumer information used to guarantee an adequate level of knowledge for the customer. The classical regulative instruments include requirements, bans, and rules. They have advantages in avoiding major risks in the short term; especially those which are not recognised by the broader population.

Besides explicit bans, rules also cover technical regulations (e.g. standards), which represent the most popular instrument in environmental politics within the European Union. With regard to stationary emission sources, regulations ensure that the technological standards of large combustion plants are oriented on the best tech-
nology available. In the case of the mobile emission sources found in the transport sector, the major part of regulations are in the emission standards for vehicles, aircrafts, and vessels. Although technological regulations guarantee an individual unit’s compliance with given limits, they neither ensure an overall emission reduction, nor do they offer any incentive for companies to reduce their emissions below the level required by the regulation. Such an incentive could be given through a differentiated energy tax which charge used energy. If at the same time tax recycling is introduced to neutralise the additional burden by lowering income taxes, then welfare would increase due to the marginal deadweight loss of the energy tax (Nordhaus, 1994: 120).

Voluntary agreements with industry, as they are handled now on a national level as well as a European level allow a more flexible (and therefore more efficient) realisation of environmental targets compared to technological regulations. However, penalties are missing if industry does not meet the promised targets of the voluntary agreement. Thus, to start with, the voluntary agreement between the European Commission and the European Automobile Manufacturers Association was evaluated positively (EC, 2000), because an increase in the fuel efficiency of new passenger cars was observed. Later, once it became clear that the target of 140 g CO₂ per kilometre would not be reached, the positive evaluation declined quickly.

In the past, European environmental politics has certainly achieved a series of remarkable successes from applying these instruments. However, it should be noted that not all the regulations concerned the reduction of greenhouse gases (alone). Furthermore, most voluntary agreements, as well as regulatory and tax policy instruments, focus on specific emission reductions rather than on absolute emission reduction targets. Indeed this concentration on more efficient cars and large combustion plants improves their efficiency, but it cannot stop overall emissions increasing if new participants enter the market, or production levels or VMT increase. In these cases, specific reduction targets can decelerate emission increases via improved efficiency, but they cannot halt or reverse the trend. Additionally, due to the long diffusion time, a big time lag between the efficiency of new cars and the average efficiency of the whole car fleet can be observed. In some cases, more efficient production possibilities might even make higher production levels more profitable (“rebound effect”). Within the European Union, continuous growth in the economy and trade is expected and desired so that any efficiency improvement within the transport sector will have to exceed these growth rates and the rebound effect in order to reverse the upward trend of CO₂ emissions.

An essential advantage of the certificate trading scheme is the explicit and strong limitation of the overall CO₂ emission reduction target (target conformance). This

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16 See in particular the EC Directive on limiting the emissions of certain pollutants into the atmosphere from large combustion plants (2001/80/EC) as well as the EC Directive concerning integrated pollution prevention and control (2008/1/EC).
17 There is for example the EU Directive 2006/38/EC of the European Parliament and Council from the 17th of May 2006.
can be accomplished without restricting entrepreneurial rights (system conformance). Only variable prices of the certificates is undesirable from an entrepreneurial point of view, as these are then associated with major strategical uncertainties. This is why it might make sense to introduce an upper bound for CO₂ certificate prices. This can be done by guaranteeing a purchase of more certificates on other CO₂ emission markets, or by direct subsidising the traded certificates.

A further significant advantage compared to classical regulative instruments is the incentive for companies to reduce each profitable amount of emissions. Emission reduction is profitable as long as the marginal abatement costs are lower than the current certificate price.¹⁸ For this reason, it is expected that households and companies will be motivated to take up innovations more rapidly. This is especially true for companies with low marginal abatement costs. This results in cost-effective emission reduction (cost efficiency).

Theoretically, the CO₂ emission certificate trading scheme meets three of the four criteria presented by Rennings et al. (1997). The certificate trading scheme conforms to the target and system and is cost efficient. Only the last criterion, institutional controllability, is still unclear because there had been no experience with such huge certificate trading schemes in Europe before 2005.

Even if the arguments presented justify the introduction of a certificate trading scheme, it should be stated that this is not a universal solution to all the European environmental problems. From an economic point of view, it is much more important that different instruments are properly coordinated to generate synergies. For instance regulations are very suited to setting certain minimum standards in the short term, e.g. for regionally effective pollutants as in the European Directive limiting values for particulate matter (1999/30/EC). It is also conceivable that, besides the EU-ETS, an additional energy tax could cover small emission sources as it is too costly to include them in a certificate trading scheme. These emission sources could be private households, services as well as smaller, less energy-intensive industrial sectors.

The certificate solution seems to be advantageous for transport if the point at which leverage is applied is not the multitude of end users, but rather the more manageable number of fuel suppliers. This is possible because there is a linear correlation between the CO₂ emissions caused and fuel combustion and because the price surplus from the fuel suppliers due to the certificate trading scheme will also have a (minor) effect on traffic participants. How companies are issued with certificates in the first place can be done either according to the grandfathering principle, or according a government auction. In the grandfathering case, the certificates are allocated for free to companies based on their historical emissions. For this a business-as-usual scenario for every company is developed. These emission values are multiplied by a factor lower than unity so that all the companies have fewer certificates

¹⁸ This incentive is also given by the energy tax. However, if certificates are allocated for free, it is possible that companies make direct profits by reducing emissions. Within the tax solution "only" cost reductions are feasible.
than they would need. A disadvantage is that no revenue arises for the government. In the case of auctioning, companies have to purchase their certificates in an auction held by the government. Furthermore all possible compositions of both approaches are conceivable.

3.1.2.1 Different levels for certificate trading in road transport – up-, mid- vs. downstream approach

The different actors in road transport can be classified according to the energy flow chain into fuel producers (refineries or importers), petrol stations and traffic participants. Other actors are car manufacturers, who contribute to the CO₂ emissions of the transport sector in an indirect way. As the fuel producers and petrol stations are strongly linked in Germany, these two markets are only distinguished by the number of participants, so the number of affected groups can be reduced to three. These can be distinguished by “allocation of fuel and energy” (upstream approach), “production of vehicles and transport systems” (midstream approach) as well as “usage of transport services” (downstream approach). All the approaches have in common that first of all an absolute CO₂ emission reduction aim is to be defined for a certain period (e.g. 2013 to 2023) for the transport sector.

Downstream approach: Certificate trading for traffic participants

The downstream approach in the transport sector affects the traffic participants directly as they have to hold a certain number of certificates for every refuelling at the petrol station. This seems to meet the polluter-pays principle as the last link of energy flow is affected. For its implementation, a CO₂ emission forecast has to be made for car passengers as well as freight road transport for a certain time period. The estimated amount of emissions for road passenger transport might be allocated to all natives by a per capita approach (IFEU, 2001). In road freight transport, the corresponding certificates might be allocated according their historical emissions or according to their transport volumes. In both cases, the initial allocation can be accomplished by grandfathering, by auctioning, or a combination of the two.

In order to achieve a reduction of CO₂ emissions, fewer certificates should be allocated than traffic participants would need for business-as-usual. Thus additional certificates have to be bought and consequently the certificate price will rise. As certificates are necessary to refuel at petrol stations, the certificate price is basically a surcharge on top of the current fuel price. Traffic participants who have already used up all their certificates have to buy new ones at the current certificate price at the petrol station counter. Other traffic participants who still have enough certificates might consider the opportunity costs which arise: “If I save a certain amount of fuel, I could save the corresponding number of certificates and could make money
by selling them". This is assumed to reduce the fuel demand of traffic participants. The impact on fuel demand might be stronger because the participants are more aware of their limit than the impact on demand through a solely fuel price increase (Harwatt, 2008). A certificate account would have to be created for every traffic participant on a central server for the system to operate smoothly. An EMV\(^{19}\) chip card could be introduced to identify each customer, similar to the German health insurance card. This card could be used for refuelling at petrol stations but also for certificate trading at certain trading stations so that frequent drivers might restock their certificate accounts in good time. If a customer at a petrol station does not have the required number of certificates, these are automatically purchased by the petrol station at the current certificate price and charged to the customer.

However the costs of this approach are not negligible. According to Debold and Lux (2006), the installation of a card reading machine costs about 1,300 euros for each petrol station. The costs for producing and distributing the corresponding number of chip cards would be at least 1.50 euro per German citizen.\(^{20}\) Thus the material costs alone of such a scheme add up to about 140 million euros.\(^{21}\) This is about 0.07 % of Germany’s Gross Domestic Product. Among others this approach was examined by Raux and Marlot (2005). They analysed the introduction for France and came to the conclusion that due to the high transaction costs such a downstream approach is not the optimal solution for the French transport sector.

A survey by Harwatt (2008) showed that traffic participants in Great Britain would actually prefer a downstream certificate trading scheme to a further increase in fuel prices. However this survey among 60 attendees was slightly biased as the educational level of respondents was higher than the national average.\(^{22}\)

Midstream approach: certificate trading for vehicle manufacturers

If vehicle manufacturers are forced to trade with certificates, this is a midstream approach. The aim here is to change the relative prices among the different vehicle types according to their CO\(_2\) emissions. This gives customers incentives to buy more efficient vehicles. Indirectly, vehicle manufacturers are then also influenced to produce more efficient cars: If competitors produce a similar car with a more efficient engine they will have an absolute price advantage in the price of the new car and additionally they can advertise a cost advantage in the flexible costs during the utilisation of the more efficient car. In this way, this approach focuses on reducing emis-

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19 EMV is a standard chip for international chip cards as e.g. used at credit cards. The term EMV comes from the initial letters of Europay, MasterCard and VISA.
20 Information about the costs for a chip card was obtained from the chip card producer Gemalto by phone, 02.11.2008.
21 This is calculated by multiplying 1,300 euro by 15,000 petrol stations plus 1.50 euro multiplied by 80 million citizens.
22 The share of respondent with high education was 44 %, whereas the share within the British population is 11 % (Harwatt, 2008:13).
sions of the new vehicle fleet and the efficiency impact on the whole fleet is delayed because it takes several years for new cars to diffuse.

One discussed taxonomy of a midstream certificate trading scheme for vehicle manufacturers is characterised by allocation based on grandfathering according to their market share and other vehicle-specific characteristics. A “gateway construction”\(^\text{23}\) could be used to ensure not only increased fuel efficiency, but also an overall CO\(_2\) emission reduction, and to allow certificate trading with other sectors. Such a construction consists of a government agency which sets specific efficiency targets for every vehicle producer and at the same time tries to ensure an overall CO\(_2\) emission reduction. To do so, the agency buys certificates from other sectors. This is done if the overall emissions exceed the absolute reduction target due to an increase in (high performance) vehicle demand by traffic participants, or if a vehicle manufacturer requests an increase of his respective target. In the latter case the vehicle manufacturer has to pay for the certificates purchased from other sectors. The data requirements are manageable since only the average fuel consumption for every sold car is needed. In principle, this is already being done today. At the end of the trading period, the average specific CO\(_2\) emissions of all purchased cars are calculated for every vehicle manufacturer. The resulting figure should comply with the CO\(_2\) reduction limit set in the emission trading scheme. If the current emissions are above the target, the manufacturer has to purchase extra certificates to cover the difference and if it is below the target he can sell the surplus certificates. It is assumed that the vehicle manufacturer will pass the costs of the emission trading scheme on to the prices of vehicles to about 100 % (among others IFEU, 2001). Furthermore it is assumed that the gateway approach, which allows certificate trading with other sectors, will have a strong impact on certificate prices as the willingness-to-pay for bigger cars is much higher than the mitigation costs in other sectors.

This midstream approach is being broadly discussed within the European context. However, German car manufacturers tend to produce more luxury cars for the upper end of the market, whereas French and Italian car makers have already achieved a much lower specific CO\(_2\) emission value in their fleet, so there is a national bias to this basic midstream approach. This resulted in the rejection of this approach and the discussion of including a reference value. This would remove some of the bias but it is still unclear which and how such a reference value should be used. During the discussion, two approaches emerged which found general consensus. Both approaches consider the specific emissions divided by a reference value. One consensus was reached on the reference value of the vehicle footprint\(^\text{24}\). The other consensus was reached on the vehicle weight. This means that heavier or bigger cars are allowed to emit more CO\(_2\). There are still plenty of ways to reach the specific target of the European Union of 130 grams CO\(_2\) per km until 2012. It was agreed that

\(^{23}\) A gateway construction within emission trading schemes means that a clearing agency generates or buys certificates from outside of the emission trading scheme to allow a controlled flow of certificates into and out of the emission trading scheme.

\(^{24}\) The vehicle footprint is calculated by multiplying its wheelbase with its track.
every car manufacturer should make an effort, even those who already had average specific fleet emissions below 130 grams CO₂ per km so that an upwards trend of the company-specific reduction targets should result (see Figure 9). But the slope and the position of the reduction curve were still unclear and a broad discussion took place among European vehicle manufacturers. It is clear that even a small change to the line has a significant impact on most car manufacturers’ budgets.

The average CO₂ emission per manufacturer as function of average mass is illustrated in Figure 9. The dashed line is the sales weight fit estimated by a linear OLS regression. This line is in the focus of the European policy. To reduce specific emissions to 130 grams of CO₂ the fit has to drop. But this might be due to a flat slope or by its parallel translation. Such a modified line is considered to represent the specific emission reduction target for each vehicle manufacturer. Thus the specific target depends on the average mass of the sold vehicle fleet. It is evident that the decision on the way how the fit is changed has strong impacts on the different vehicle manufacturer especially in the boundary areas of the figure. It is very difficult to set a specific and justified reduction curve. Steep curves represent more leniencies for heavy cars; flat lines represent lower impacts on lighter and smaller vehicles.
When considering the substantial costs of reducing specific CO\textsubscript{2} emissions of up to 7,000 euros for 50 grams of CO\textsubscript{2} per km (see Figure 10), it becomes clear that certificate prices would be very high in a midstream approach\textsuperscript{25}. This might result in vehicle manufacturers who are unable to meet the specific target facing a double penalty. First, they would have to pay for certificates; but instead of paying this sum to the government, they would have to pay it to their rivals. And the rival would enjoy a double dividend which he could use to lower vehicle prices and increase the number of sales.

Midstream approach: Certificate trading for transport service providers

The midstream approach concerning service providers is focused on the CO\textsubscript{2} emission reduction of public transport services and freight transport forwarders. To calculate their current CO\textsubscript{2} emissions, service providers were asked to report the number of vehicles and their specifications including their VMT and specific CO\textsubscript{2} emissions. If the grandfathering option were chosen, these values could be used to

\textsuperscript{25} The abatement costs of 7,000 Euros for 50 grams of CO\textsubscript{2} per kilometer equals an certificate price of about 700 Euro per ton when the optimistic assuumption is made that the car will drive 200,000 kilometres during its life time (50 grams per km * 200,000 km = 10 tons of CO\textsubscript{2}). Kluge and Stromberger (2007) estimated similar marginal abatement costs of about 540 Euro per ton CO\textsubscript{2}.
estimate the historical emissions of the service provider and provide the basis for allocation. In the years following the introduction of such an emission trading scheme, service providers’ emissions could be calculated based on the reported VMT multiplied by the corresponding specific emissions of the vehicles. Or, alternatively, they could be estimated based on the volume of consumed fuel reported. The reduction target can be formulated using an absolute or a specific value. The specific value is depicted in transport performance, i.e. in grams per tkm or pkm. However, it should be noted that the specific CO₂ emissions differ significantly for different commodities, volumes, modes or distances. Analogous to other certificate trading schemes, it is assumed that the surplus of the certificate trading scheme will be passed on to the customers. The trading of certificates might be restricted to the sector and to within national borders. However, two reasons limit the meaningfulness of this approach. On the one hand, the service providers are already quite CO₂ efficient and, on the other hand, the CO₂ emissions from transport service providers are relatively low compared to the overall emissions.

A third midstream certificate trading approach is discussed. This is connected to the energy flow chain similar to the up- and downstream approaches and affects the centre of the chain where petrol stations are located. As will be shown later, this approach is very similar to both the up- or downstream approach.

Upstream approach: Certificate trading at the fuel supply

In contrast to the downstream approach with many participants and high transaction costs, the upstream approach impacts the upper end of the energy flow chain at the fuel refineries and importers. This does not endanger the achievement of the reduction target because CO₂ emissions correlate exactly with fuel combustion. In this approach, all the actors who supply the transport sector with CO₂ relevant energy sources are affected and should hold the corresponding number of certificates for each unit of energy sold. Again, the certificates could be allocated by grandfathering, auctioning or a mixture of the two as in the other trading schemes.²⁶

The German energy flow of fuels usually starts with imports of crude oil or an already refined fuel (see Figure 11). Crude oil is then broken down into its components in refineries (these include diesel and heavy fuel oil, kerosene, and petrol among others). Most refineries belong to big oil companies such as Shell or BP or these are at least shareholders. Diesel and petrol are then forwarded to fuel traders or the oil companies concerned directly allocate fuel to their petrol stations or other industrial consumers. If petrol stations are owned by the oil companies they are known as “(oil company) dependent petrol stations”. Energy tax has to be paid when importers or refineries deliver fuel to the petrol station or other industrial consumer. Consequently, all the relevant data is carefully collected and saved. This link in the

²⁶ IFEU (2001:15) suggested a share of 80% of certificates by grandfathering and 20% by auctioning.
energy flow is therefore very suited to an upstream certificate trading scheme. FIFO et al. (2005) identified 61 tax payers of the energy tax on fuels in the German road transport sector. It was not possible to identify either a monopolistic or a strongly oligopolistic structure among these actors because the market shares are more evenly spread than in the German energy sector. This would mean a low but still sufficient number of certificate traders in a certificate trading scheme. Furthermore it is assumed that the refineries and importers or fuel traders will pass on the surcharge on the fuel price to the petrol stations, which will also act accordingly and pass it on to their customers, so that, ultimately, traffic participants will foot the bill.

Figure 11: Outline of an upstream certificate trading scheme in road transport (FIFO et al., 2005:88)

Today, the relevant fuel quantities and qualities as well as the sellers of all the relevant energy sources used in road transport are already known due to the energy tax. Thus this database would also be appropriate for the introduction of an upstream certificate trading scheme in road transport. Only the initial allocation and the evaluation of company balances would have to be introduced in order to monitor whether the budgets are kept. The companies are responsible for balancing their budgets. If the fuel sold emits more CO₂ emissions than covered by the certificates held by the company, the company will have to buy certificates on the certificate market. As already mentioned, any additional costs arising are assumed to be passed on to the traffic participants.

Similar to the other certificate trading schemes, an open or a closed trading scheme is conceivable. In an open trading scheme, certificates can be traded with other sectors and other countries in the EU-ETS. In a closed scheme, in contrast, trading is limited to the owners of refineries, importers or corresponding fuel traders within the road transport sector.
3.1.2.2 The European CO₂ emission trading scheme (EU-ETS)

As part of the Kyoto Protocol, the European Union has committed itself in the burden sharing agreement between its Member States to reduce greenhouse gases by 8 % compared to the base year 1990. One instrument introduced to reach this target is the European Certificate Trading Scheme (EU-ETS), besides the more general support for environmentally-compatible technologies and other policy instruments. Within the EU-ETS, country-specific reduction targets were specified for each Member State. The European Commission passed the emissions trading directive 2003/87/EC in October 2003, which obligates Member States to take all the necessary steps towards a system for trading greenhouse gas emission certificates within the European Union.

To start with, the EU-ETS was applied solely to the CO₂ emissions of a few industries and all certificates were allocated for free based on historical emissions (grandfathering principle). First of all the country-specific National Allocation Plans (NAP) were calculated using a micro (bottom-up) and macro (top-down) approach. In Germany, the plans were used to estimate the initial number of certificates (target quantity of the first trading phase), taking the 21 % reduction target for Germany and the expected reduction paths of all other sectors into account. Obviously, the reduction paths of other sectors are very uncertain and dependent on many other factors (e.g. winter temperatures). Thus it is hard to make reliable prognoses and at the same time to reach an acceptable consensus for all objects concerned. In principle, the macro plan applies the reduction target to all the installations covered by the EU-ETS. The micro plan then allocates a target to an individual industrial facility based on its historical emission path assuming an equal reduction percentage for every industrial facility affected by the EU-ETS.

As described above, as soon as a company can foresee that the allocated number of certificates will not be enough to cover its predicted production output, it should either attempt to reduce its CO₂ emissions, or buy the relevant number of additional certificates within the certificate trading scheme, or use the flexible mechanisms of the Kyoto Protocol to avoid being penalized by the government.

So far the EU-ETS is quite effective. The affected industries are responsible for about 45 % of the overall CO₂ emissions within the EU; the number of facilities is small enough to be monitored and surveyed and at the same time the number is large enough to permit a reasonable level of competition within the certificate trading scheme.

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27 In its first trading phase, the EU-ETS was introduced for stationary emitters with large combustion plants (with a combustion heat performance of more than 20 MW) in the industrial sectors of energy conversion, iron and steel production, mineral processing as well as pulp, paperboard, and paper production (2003/87/EC Annex I).

28 The initial allocation of certificates also considers prior emission reductions, i.e. reductions before the EU-ETS was introduced. These are called early actions (Fhg-ISI, 2004).

29 The flexible mechanisms of the Kyoto Protocol are Joint Implementation, Clean Development Mechanism and the International Emission Trading within the Kyoto Protocol member states.
An enlargement of the EU-ES to all sectors will enhance competition because the marginal abatement costs for CO₂ emissions differ substantially within vehicle manufacturer and sectors.

Within the EU, a unique procedure for the initial allocation of certificates was employed in order to avoid national bias among industries. According to the above mentioned emission trading directive, all Member States should allocate at least 95% of the certificates for free during the first phase of the EU-ETS. In the German NAP, which is regulated by the German Zuteilungsgesetz (ZuG – Allocation Law), it was decided to distribute the entire initial allocation of certificates for free. Furthermore the law states that the allocation of certificates in the first phase of the EU-ETS should be based on historical emissions between 2000 and 2002 including early actions. The decision to allocate gratis certificates within the European Union was made firstly to avoid additional distortion of national and inter-sectoral competition and secondly to protect final consumers from further energy price increases.

In retrospect, both arguments turned out to be incorrect. First, the accounting law allows companies to enter freely allocated emission allowances as costs in the balance sheet to satisfy the opportunity costs approach. Thus the corresponding costs are charged to the customers. This procedure was observed within the energy sector where energy companies were able to increase their profits (Vorholz, 2005). Second, the argument of competition neutrality is at least questionable since investments to improve efficiency have a double dividend for companies within the EU-ETS and might be seen as an additional source of revenue, which is not permitted to other companies outside the certificate scheme. A further problem is the handling of new market participants, which might increase the number of certificates.

However these disadvantages do not necessarily outweigh the advantages of a certificate trading scheme. Furthermore, these experiences with the EU-ETS can be used to improve the architecture of any trading scheme applied in other sectors.

According to the agreement made as part of the Kyoto Protocol, the burden sharing agreement between the former EU15 and the new EU Member States is not to be revised until 2012. Thus the underlying targets have to be achieved independently of each other but with the possibility to balance the national certificate accounts within the International Certificate Trading Scheme in the Kyoto Protocol. This is the reason why so far the EU-ETS has been limited to the EU15. However, the system was deliberately designed to include additional states – in principle even countries outside Europe.

In the first trading phase of the ETS, which ended in 2007, allowances covering about 499 million tons of CO₂ emissions were allocated in Germany. In the second phase, this amount decreased to 453 million tons. In 2005, the transport sector in

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30 For example, in Germany about 1,850 facilities are affected. Of these, 1,235 facilities can be allocated to the energy industry and the other 615 facilities to the remaining emission-intensive industries. This is a share of 67% for the energy industry (UBA and DEHST, 2004).
Germany emitted about 159.8 million tons of CO₂ of which 152.2 million tons came from road transport. If the EU-ETS were extended to cover road transport, the volume of emissions within the certificate trading scheme would increase by about 35 %.

Up to now, most of the EU-ETS allowance certificates (about 60 %) are traded on stock exchanges. This share is equivalent to 553 million tons of CO₂. More than three quarters of them are traded on the European Climate Exchange (ECX) by Carbon Finance Instruments (CFI) contracts in London. The remaining certificates (18 %) are traded on the other three European exchange markets which permit CO₂ emissions certificate trading. These include the Scandinavian Nord Pool in Oslo, Powernext in Paris and the smallest CO₂ emission certificate exchange, the European Energy Exchange (EEX) in Leipzig (IFSL, 2007).

3.1.3 Studies on CO₂ emissions trading schemes in German transport

Several studies examining the potential implementation of a CO₂ certificate trading scheme in the German transport sector have been published in recent years. Different characteristics of emission trading schemes are discussed. Some of these studies (IFEU, 2001, IFEU et al., 2003, FIFO et al., 2005, short study of PriceWaterhouse-Coopers, 2002, Deuber, 2002, as well as CE Delft et al., 2005, and CE Delft, 2002) are described in the following paragraphs.

The IFEU study 2001: The aim of this analysis was to establish concrete approaches for applying the flexible mechanisms of climate policies within the transport sector. All the approaches were evaluated on the basis of an ad hoc developed list of criteria with respect to their opportunities and risks. Conclusions were then drawn about the ecological and economic utility of flexible instruments to efficiently reduce greenhouse gases within the transport sector and options were suggested for further developments of policy instruments. It was recommended that more detailed analyses of the chosen applications should be made in a follow up study (see below).

The focus of the study was threefold. First, a list of criteria was to be developed, which could be used to judge future implementations of climate policy-relevant flexible instruments in the transport sector. Second, a list of their concrete applications was to be compiled. Third, a rough evaluation of the flexible instruments was to be accomplished. The authors arrived at the conclusion that approaches with...
absolute emission reduction targets are superior with regard to the criteria of aim conformance. Thus approaches with specific reduction targets are not convincing with regard to an ecological aim conformance as absolute emission reduction targets are no more guaranteed when for example transport volumes increase. This is also true for the midstream approach of the CARS21 think tank which is directed at vehicles. The specific emission target for vehicles has no effect on the lifetime of the vehicle, nor its VMT, nor the real average fuel combustion. Thus an overall emission reduction depends heavily on the specific, concrete driving behaviour (VMT, speed, acceleration, etc.) of the individual traffic participant. These influences might well outweigh the reduction efforts on the part of vehicle manufacturers.

Regarding system conformance\textsuperscript{33}, specific emission target approaches perform better within social, economic and legal boundaries than approaches featuring absolute emission targets because they allow greater degrees of freedom in the reactions of traffic participants. In times when certificates are scarce, an absolute emission target puts much more pressure on traffic participants than a specific one. Furthermore a certificate trading scheme restricted to only one economic sector (closed trading scheme) will probably run much greater risks of scarce certificates than the emission trading scheme of a whole economy (open trading scheme) where more reduction potentials are available. In the same way, increasing the number of participating countries should also lower the risk of running short of certificates.

To sum up, an open trading scheme was considered more efficient than a closed one, as it is assumed that emission reductions are accomplished where the lowest marginal abatement costs can be obtained. Furthermore, an optimisation of all parameters only takes place in an upstream or downstream approach which features an absolute reduction target, whereas midstream approaches neglect the behaviour of traffic participants.

Concerning the transport sector specifically, a closed emission trading scheme would limit certificate trading to within this sector, so that the emission reduction target would also have to be met within it. From an economic point of view, this restriction is inefficient, however, since the transport sector has higher marginal CO\textsubscript{2} emission abatement costs, or at least a higher willingness-to-pay for fuel than other sectors.\textsuperscript{34} This is why linking a transport sector-specific emission trading scheme with the already implemented EU-ETS would yield efficiency gains for the economy as a whole. However, at the same time, the demand for certificates would grow

\textsuperscript{33} The assessment of system conformance was made within a pilot study against the background of the status quo of the social, economic, and legal system in Germany in 2001.

\textsuperscript{34} However, if greater pressure to reduce CO\textsubscript{2} emissions within the transport sector is desired, sector-specific closed emission trading schemes seem more likely to stimulate innovations within the transport sector.
so that the pressure on companies in other sectors to reduce CO₂ emissions would be increased.

The administrative costs for the government as well as the transaction costs for the actors affected are estimated to be much lower in an upstream approach than in a downstream one. This is due to the significantly lower, but still sufficient, number of affected actors in the upstream certificate scheme. In the midstream approach, the number of participants depends heavily on the trader involved. Whereas the number of vehicle manufacturers is rather small, the number of petrol stations or transport service providers is much larger. Nevertheless the midstream approach still affects fewer participants than the downstream one.

Additionally, the IFEU study states that companies might be affected very differently by a certificate trading scheme depending on their market position within the sector. This estimation is based on an earlier IFEU study of models and policy instruments on a European level.35

The IFEU study appraised the lowest microeconomic implications for the open emissions trading scheme with a specific emission target as it is less restricted, provides more alternatives and thus greater leeway for its participants. As mentioned above, an emission trading scheme which only covers one sector is much more expensive because cheaper emission abatement may be possible in other sectors. In the case of an absolute reduction target, a further increase in transport volumes raises the pressure for emission reductions in an unpredictable way. This is also true for intersectoral approaches as there is a strong increase of CO₂ emissions within the transport market. Thus, according to the IFEU study, the overall costs of the trading schemes are lower in an open trading scheme and will probably decline from the most expensive downstream approach through the midstream approach to the cheaper upstream approach.

Concerning the midstream approach which affects vehicle manufacturers, the implications for the industry are dependent on the allocation method (grandfathering or auctioning) and the previously offered product portfolio (compact cars to premium cars). Furthermore, absolute emission reduction targets might affect some manufacturers more than an emission trading scheme based on relative reduction targets. Today’s agreed reference level of 120 grams of CO₂ per kilometre relative to the vehicle mass actually favours heavier vehicles. So even the definition of the reduction target can dramatically influence the impact on the manufacturer. The aim is to come up with a solution which does not adversely influence the competitive situation on the market.

The IFEU study came to the result that, of all the multiple flexible approaches developed to reduce CO₂ emissions in transport, an open, upstream certificate trading scheme with an absolute reduction target should be preferred as its only disadvantage concerns the system conformance.

35 Among others, a policy instrument to monitor the emission reduction efforts of vehicle manufacturers was discussed within the ACEA agreement.
However, a midstream approach with a specific emission reduction target also has specific advantages if its target conformance is guaranteed by a gateway construction of the government. With such a gateway construction, unforeseen shortages in certificates could also be managed which might disarm much of the industrial resistance to strong limits.

The midstream approach with an absolute emission target has drawbacks with its poor system conformance and higher economic burden of the trading participants. However, it has advantages in target achievement. Therefore the IFEU study concludes that the midstream approaches for vehicle manufacturers and for transport service providers should be merged into a united, midstream approach and that the focus should instead be on differences in the architecture of this approach. The IFEU therefore suggested a follow-up study to compare a midstream approach with an absolute reduction target and a midstream approach with a specific reduction target linked to a corresponding gateway construction. Thus together with the above mentioned recommendation for the upstream approach three approaches were suggested for the follow-up study.

**IFEU follow-up study 2003:** The IFEU follow-up study for the Environmental and Transport Ministry of the federal state Baden-Württemberg focused on the development and evaluation of concrete ways to integrate transport into the EU-ETS (IFEU et al., 2003). The three approaches suggested in the previous study were examined in greater depth. Based on the developed list of criteria, the different designs of the trading schemes were evaluated and their opportunities and risks assessed.

Within this study, the transport sector is split into different sub-sectors: energy supply, vehicle manufacturing and vehicle usage. Transport is further classified by mode (road, rail, waterways, and aviation) and by purpose (passenger and freight transport).

The sub-sector energy supply covers all the processes from crude oil production to fuel supply to the vehicles. The total energy used in the transport sector is processed in this sub-sector.

The sub-sector vehicle manufacturing includes all the process steps from vehicle production to vehicle retailing. To reflect the multiplicity of steps between these two extremes, the process can be broken down still further according to the different actors involved. After the vehicle manufacturer has produced the vehicle, it is transferred to the vehicle trader, who sells it to the vehicle owner, who might not be iden-

36 This list of criteria includes the aim conformance, the amount of emissions covered, the economic and legal system conformance, the burden for the companies and traffic participants as well as the controllability of the system.
tical with the vehicle user. Vehicle users are divided into owners/users and service companies such as forwarders, rail, taxis etc.

The IFEU 2003 follow-up study examined the potential CO₂ reduction options of several different transport emission trading approaches. This study favoured the midstream approach affecting vehicle manufacturers due to its ecological efficiency, low transaction costs and high innovation incentives for vehicle manufacturers. Its disadvantages, such as the lagged market diffusion (it takes more than a decade to renew the whole German car fleet (>95 %) (Deuber, 2002)), are accepted. The study does not take the individual characteristics of end-users into account.

**FIFO study 2005:** This study introduces the issue of carbon dioxide emissions in German transport and then presents previous strategies to combat this problem. The study suggests at its beginning an upstream approach. Thus the whole study is focused on mechanisms, potential architecture, regulation and allocation possibilities, introduction problems, possible transaction costs of the public administration and the affected companies of the upstream approach. Furthermore, the study also estimates emission reduction potentials and finishes with an excursus on petroleum taxes.

**Short study by PricewaterhouseCoopers 2002:** The study of PriceWaterhouseCooper (PWC, 2002) on behalf of the German Council for Sustainable Development focused on the analysis of an applied certificate trading scheme. It compared the profitability of different instruments and investigated whether an emission trading scheme is suited to steering trends towards sustainable transport.

The study suggests different policy approaches for the sub-markets. In the private car segment, an upstream certificate trading scheme with auctioned certificates is recommended; this permits a comprehensive coverage of all energy-induced CO₂ emissions within this segment. This approach also covers behaviour modifications, fuel developments and structural effects in all sub-markets of road transport and its administrative complexity is acceptable. However, it only influences the efficiency of engines and vehicles indirectly.

**Deuber study 2002:** Based on the question of which contribution a CO₂ emission trading scheme can make within a transport policy framework, the author (Deuber, 2002) examines how individual motorized transport could be integrated into an emission trading scheme.

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37 For private passenger cars, the vehicle user is usually also the vehicle owner, or at least both live in the same household. However, for rental cars and fleet cars (company cars), this is usually not the case.

38 The amount of fuel consumed differs strongly among vehicle users. These range from small owner/users such as moped drivers to service companies such as international airlines with CO₂ emissions of about 18 million tons per year.
The author states that an open upstream approach results in a failure to meet the emission reduction target in passenger transport as its price elasticities are low. If emission reductions are strictly enforced by this approach, the burden for vehicle-dependent private households would be unacceptable. For these reasons the author prefers a so-called “standard and credit system” which specifies individual emission standards for each company fleet according to their respective emissions and the corresponding sale volume of their vehicle models. A specific target was chosen because of the limited influence of the car manufacturers. It was stated that they only have indirect influence on the fuel combustion of the vehicles and the carbon intensity of the fuel. Furthermore, the standard and credit system is independent of demand changes. This means that in cap-and-trade certificate trading schemes, high increases in the demand for fuel inefficient cars – which is an exogenous factor for car manufacturers – significantly increase the pressure on the corresponding car manufacturer. By weighting the average emissions of a vehicle with its respective sales, vehicle manufacturers are given an incentive to build more efficient vehicles and sell smaller cars. Furthermore, through the focus on fleet fuel consumption, vehicle manufacturers have more scope to channel their own development and are able to make their own decisions about where emission reductions should be made than in a cap-and-trade scheme.

To reach the national CO₂ emission reduction target, the study assumes an average annual reduction in the fleet standard of 2.35% between 1995 and 2010. If vehicle manufacturers do not comply with this target, they have to buy certificates from other manufacturers in order to avoid penalties.

The advantages in this approach, according the author, are in the low administrative costs, efficient monitoring, realisation of technical emission reductions due to high incentives and good institutional controllability. The latter is given through the already proven regulations between the government and the vehicle manufacturers. However, since the price elasticities of end-consumers in the car market are relatively low, vehicle manufacturers may have difficulties moving the consumers in the right direction, so that a failure to meet the reduction target cannot be ruled out within the transport sector.

**CE Delft 2002 and 2005:** These studies (CE Delft, 2002, and CE Delft et al., 2005) focused potential certificate trading schemes in aviation. These studies are not considered here because of the (so far) small share in total CO₂ emissions and problems with the international equitable implementation (see Cames and Deuber, 2004, and Treber, 1991 and 2001), nor are studies of certificate trading schemes in waterway transport (see Michaelowa and Krause, 2000).

39 This assumption is higher than the voluntary agreement of the ACEA (EC, 1998), which defined the upper bound for CO₂ emissions of newly registered cars until 2008 as 140 grams CO₂ per kilometre. Until 2003, the specific CO₂ emissions from passenger cars decreased by 12.4% to 163 gram per kilometre compared to 1990 (VDA, 2005:130). This equals about 1% per annum.
German Transport Forum, 2006: The German Transport Forum (Deutsches Verkehrsforum) argued against an implementation of a certificate trading scheme in the transport sector (German Transport Forum, 2006b). The authors found several reasons for each mode. They stated that an implementation in the aviation sector would strongly discriminate European and especially German against foreign airlines. According to the authors, the road transport is already strongly financially charged; rail transport is already affected by a high share through the EU-ETS; and for waterways transport standards might be a better approach.

Wuppertal Institute for Climate, Environment and Energy, 2007: This study (2007) gives a good overview of the greenhouse gas problematic, technical reduction options as well as possible mitigation strategies in road passenger transport. However, the authors do not draw any specific conclusions concerning a certificate trading scheme in the transport sector.

Besides these studies, there are numerous other general studies which focus on emission trading schemes and the EU-ETS, as well as analyses for other sectors. For example, the OXERA (2004) study analyses the impact of the EU-ETS on British industry, focusing on the potential competition disadvantages for British industries due to the EU-ETS. The Carbon Trust (2004) study should also be mentioned, which also focused on British industry and was not able to perceive any considerable disadvantages. According to this study, there might be negative impacts only for very energy-intensive industries with a price elastic demand and, at the same time, strong foreign competitors (e.g. aluminium). Road transport was not considered in either study.

However, none of these studies featured a concrete simulation to estimate the impacts of a CO₂ emission trading scheme in road transport. There are, however, many simulation results available from multi-agent models concerning the implementation of CO₂ certificate trading schemes in the liberalized energy market (among others Scheidt, 2002, Scheidt and Sebastian, 2001, Genoese et al., 2005, Bower and Bunn, 2001, and Bower et al., 2001).

Experiences made with previous certificate trading schemes in transport are also known from the United States of America. Besides the lead-in-petrol scheme, which has already expired, two other trading schemes (LEVII and CAFE) are still in force and contributing to a reduction of CO₂ emissions from transport.

The first emission trading scheme lead-in-petrol supported the diffusion of unleaded petrol in the United States from a previous market share of close to 0 % up to a share of 100 % within 13 years. This was achieved by introducing an upstream certificate trading scheme. In 1974, the government allocated permits to refineries and importers using a grandfathering allocation scheme which allowed them to sell petrol with 1.1 gram lead per gallon (business-as-usual). In the following years, the
value of the certificates was continuously reduced until they reached zero gram lead per gallon in 1987 (Hansjürgens and Gangelmann, 2003: 7ff, and Tietenberg, 1998: 15ff). Thus one of the first upstream certificate trading schemes in transport can be considered a big success.

3.2 Technical options to reduce CO₂ emissions in road transport

Besides policy instruments concerning mode choice and reduction of VMT, technical efficiency improvements are also seen as being suitable to reduce CO₂ emissions in road transport. This is particularly true in the international context (Schafer, 2000). Some measures are already profitable today (BDI, 2007, TNO et al., 2006a, and IEEP et al., 2007, ZEW and B&D, 2006, INFRAS, 2006, and many other). These technical measures will become even more profitable as learning effects (economies of scale) are expected. In addition to this, further increases in the price for crude oil will also mean that more and more measures become profitable. The pressure to identify and implement these efficiency improvements grows with the trend towards heavier vehicles and higher engine performance. For Germany, the profitable technical saving possibilities until 2030 amount to about 15 Mt CO₂ (about 10 %) (BDI, 2007). According to the German Board of Academic Advisers to the Federal Minister of Transport, Building and Urban Affairs (BMVBS, 2008b), synthetic biofuels as well as a reversal of the trend towards larger vehicles could triple these saving potentials. The efficiency of instruments can be distinguished from a policy viewpoint as two different strategies: A strategy of efficiency which focuses on policy instruments to reduce emission reductions via technical means; and a strategy of sufficiency, which focuses on emission reductions through behavioural changes.

If the different technical ways to reduce emissions are classified based on their average costs per ton of CO₂ abated, a marginal abatement cost curve results. This is known from environmental economics. It is shown in Figure 12 for the German transport sector.
It becomes apparent from Figure 12, that numerous profitable emission reduction measures could already be realized, especially in passenger cars. These include reducing engine friction losses, improving thermal management, optimal gear choice and combustion displays, optimized engine operating maps and ancillary components, low-rolling-resistance tyres, automatic tyre pressure control systems, downsizing\textsuperscript{40} and optimized air conditioning. The following chapters deal with emission reduction technologies which have considerable potential. These can be split into two groups: alternative driving technologies and other technical measures.

3.2.1 Alternative driving technologies

Alternative driving technologies should substitute and displace the share of classical fossil energy sources in road transport. This is done either by (1) using renewable fuel substitutes but keeping the driving technology unchanged, or by (2) changing the driving technology within the vehicle.

\textsuperscript{40} The concept of downsizing is understood to increase performance and torque with a simultaneous reduction in fuel consumption. This is achieved by optimizing pumps, vehicle mass and interior engine friction loss.
Biofuels are one important group of renewable fuels which can act as substitutes for fossil fuels. Among these there are dozens of different hydrocarbons from biomass\textsuperscript{41} which are considered suitable to replace fossil fuels in road transport.

Biofuels have advantages when compared to fossil fuels with respect to the security of energy supply in transport and their greenhouse gas emissions and energy balance (Quirin et al., 2004). However, the use of new biofuels raises other questions besides these advantages which have to be answered before their success or otherwise can be forecasted. For example, for some alternative fuels, a significant reorganisation of the existing infrastructure (petrol station network, maintenance, refuelling and some other vehicle properties) would be necessary. Biofuels which can be handled within the existing infrastructure have a huge cost advantage in their implementation over other types of biofuels which necessitate reorganisation. It is also assumed that these alternative fuels will be favoured by traffic participants as they do not need to change their behaviour. This is especially the case if it is possible to continue to run the car on conventional fossil fuels if no biofuel is available, for example, when driving abroad. There are also disadvantages associated with biofuels, particularly the substantial land areas they require as well as the negative greenhouse gas balance, which is assigned to many first generation biofuels (Larivé et al., 2004). For greenhouse gas balances, the whole life cycle from the energy source (well) to the emissions from the vehicle (to move the wheel) is assessed. Therefore this kind of analysis is known as a Well-to-Wheel (WTW) analysis and can be distinguished from the analysis of emissions from the allocation of fuels (Well-to-Tank – WTT) and the analysis of emissions from the fuel combustion within the vehicle (Tank-to-Wheel – TTW). In fuel production, many biofuels are actually considerably more energy-intensive than fossil fuels, i.e. the WTT analysis of their CO\textsubscript{2} emissions is worse than the corresponding analysis for fossil fuels. Furthermore, concerning the land use problematic, it is still unclear to what extent biofuels will be able to replace fossil fuels due to the vast amount of land they require. Kavlov and Peteves (2004) suppose that even the 5.75 \% target of the European Union can not be achieved without considerable efforts within Europe and help from abroad. New biofuels of the second generation which use the whole plant and are called biomass-to-liquid (BtL) perform better in their greenhouse gas balances as well as in their land demand. The use of these biofuels cannot be predicted at present because their development status is not yet sufficient to forecast their potentials within a nation-wide introduction (Larivé et al., 2004).

Recently, the number of ways to produce biofuels has increased considerably (see, among others, Helfrich, 2005). Besides extraction and fermentation, gasification, ester interchange, synthesis, pyrolysis or Hydro-Thermal-Upgrading (HTU)

\textsuperscript{41} Particularly oil plants (among others rapeseed or sunflowers) as well as residual biogenic materials from fermentation processes (sugar beets, wheat, waste wood, short turnover crops such as cottonwoods or willows, used straw, etc.) are suitable for producing fuels for road transport.
can be used to produce biofuels (see Figure 13). An overview of different biofuels is given below.

Petrol (according to EEN 228) is a compound made up of about 100 different, mostly light hydrocarbons. Based on the WTW analysis, a petrol-fuelled Otto engine emits about 2.33 kg CO₂ per litre petrol,[42] which is about 170 grams CO₂ per km for the average German car (Larivé et al., 2004). Diesel (according to EN 590) is comprised basically of alkanes, cycloalkanes and aromatic hydrocarbons. The WTW analysis attests a slightly higher amount of CO₂ emitted per l diesel with about 2.63 kg CO₂[43]. However, due to its higher energy content, a slightly more efficient result for diesel can be observed from the WTW analysis with regard to the kilometres travelled. This is also reflected in the average German emissions of about 160 grams CO₂ per km from diesel vehicles (Larivé et al., 2004).

Natural gas is already a popular option in road transport today in the form of compressed natural gas (CNG). As an alternative to CNG, which is stored, distrib-

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42 According to the IPCC (2000), the corresponding CO₂ emissions can be calculated by multiplying fuel combustion by the corresponding calorific value and the corresponding emission factor, which for petrol is: 1 l * 0.0336 GJ / l * 69.25 kg CO₂ / GJ = 2.33 kg CO₂ per l petrol.

43 According to the IPCC (2000), the corresponding CO₂ emissions for diesel are: 1 l * 0.0356 GJ / l * 74.01 kg CO₂ / GJ = 2.63 kg CO₂ per l diesel.
uted and refuelled at a pressure of about 200 to 220 bar in order to compress its volume to about 1% of its volume at standard atmospheric pressure, liquefied natural gas (LNG) is also available, but is much less common. This might be due to the fact that LNG is much more energy-intensive to handle as the gas must be cooled to -162°C to remain a liquid. Therefore it has almost disappeared from the transport fuel market. Natural gas contains methane (CH$_4$), but its share varies widely depending on its origin. Hence, although combusting gas has lower CO$_2$ emissions, its CH$_4$ emissions are much higher because of the higher H/C ratio. The climate change impact of these CH$_4$ emissions is about 20 times higher than CO$_2$ emissions, so that more greenhouse gases are generated in comparison with many other fuels. Nevertheless, when looking at the WTW analysis, CNG has a slight advantage compared to standard fossil fuels with about 140 g CO$_2$e per km (Larivé et al., 2004). As already mentioned, this value is strongly dependent on the origin of the natural gas. Natural gas can also be produced from the fermentation of non fossil feedstocks such as waste or other organic materials. In principle, compressed organic gas could use the existing infrastructure and replace the fossil-based CNG without any quality reduction. Its WTW analysis depends strongly on which feedstocks are used for fermentation.

Besides CNG and LNG, another possibility is the gas to liquids (GtL) technology, in which natural gas is converted into longer-chain hydrocarbons such as petrol or diesel fuel by the Fischer Tropsch process, for example. However this has not yet been widely accepted in road transport.

Liquefied Petroleum Gas (LPG) is a similar fuel, which is better known as autogas and is especially popular in Italy. It contains mainly propane and butane (C$_3$H$_8$ and C$_4$H$_{10}$) and accrues as a by-product of refinery processes. Unlike natural gas, LPG is heavier than air and is therefore dangerous if it is accidentally discharged in underground car parks or elsewhere as it can linger and may be ignited which can result in serious explosions. Its WTW analysis is again strongly dependent on the manufacturing process and is around 145 grams of CO$_2$e per kilometre.

There are many other fuels based on alcohols which are produced by fermentation. Among these, especially methanol and ethanol have significant market shares in road transport. In the EU, 5 vol.% ethanol are already being added to conventional petrol. In Brazil, where more than 21 billion litres of ethanol are produced annually, its share is already higher than 20%. According to the WTW analysis, ethanol emits between 20 and 170 grams CO$_2$e per kilometre – dependent on the production technique and the feedstock used.

A recent development is the production of synthetic fuels. They have the advantage that they can be tailor-made – in principle every type of engine could have its own optimized fuel to improve its efficiency. The efficiency gains are considerable,

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44 The CNG provided by the fermentation of organic materials is called compressed biogas (CBG).
45 LPG is liquefied at an increased pressure of about 2.2 bars. German petrol stations provide LPG as “Flüssiggas” or Autogas.
but the costs of adjusting the infrastructure for the variety of fuels would be too high. If crops are used to produce synthetic fuels, they are called Biomass to Liquid (BtL) fuels or second generation biofuels.\(^46\) First the biomass (principally the whole plant) is gasified to produce a synthetic gas (by pyrolysis). Then the gas is converted into a liquid by synthesis based on the Fischer-Tropsch process. In the future they have the potential to replace many fuel applications where petrol or diesel is used today. Up to now, however, the process is not technically mature enough, but it is assumed that it has big advantages over classical biodiesel production, particularly with regard to the land use problem (Larivé et al., 2004). A WTW analysis of these fuels is not yet meaningful due to their early development status.

In recent years, a similar approach, but with a simpler production technique, the hydrothermal upgrading (HTU) process for diesel, has also made considerable progress. In this approach, bio-crude is obtained from biomass decomposed in water which is then used to produce the diesel substitute. High-moisture biomass substances (e.g. sugar beet pulp) are very suitable as the basic raw material for this process.

Again, the drawback is that the CO\(_2\) emission reduction potentials are rather small for HTU diesel. This is also true for adding biofuels to conventional fossil fuels. In the case of diesel, these include, for example, fatty-acid methyl ester (FAME), or dimethyl ether (DME), or for Otto fuels, e.g. ethyl tert-butyl ether (ETBE)\(^47\).

In the future, minor CO\(_2\) emission reductions may occur for hydrogen-fuelled conventional combustion engines. However this is very dependent on how the hydrogen is produced. Furthermore, the energy efficiency of hydrogen-powered conventional combustion engines is very low at present. Fuel cells are considered to have much better energy efficiency and a considerable CO\(_2\) emission reduction potential (see below). Thus, hydrogen-powered conventional combustion engines are only an interim solution.

Especially in the long term, besides the different fuels for conventional combustion engines, it is assumed that alternative drive technology will have considerable CO\(_2\) emission reduction potentials (see Figure 14).

\(^{46}\) Furthermore BtL is also called SunFuel or pyrolysis oil.
\(^{47}\) The ETBE is a good substitute for the fossil MTBE, which is added to petrol to improve its knock resistance.
Among these alternative drive technologies, the electric vehicle is a widespread one, which has recently also become available as a hybrid. However the batteries still generate weight, capacity and range problems for both electric vehicles and full hybrids\textsuperscript{48} (SRU, 2005). Today, electric vehicles make up a relevant share of passenger cars only in regions with strong political support (e.g. in London due to their exemption from the congestion charge). It is assumed that future developments in battery technology (current zebra batteries) and lithium-titanate batteries will expand the range of electric vehicles from about 100 kilometres to more than 400 kilometres (Gage, 2003).

Another solution to the battery problem is to replace them with fuel cells. These are lighter, can be recharged quicker and might guarantee longer ranges in future. Hydrogen can be refuelled using cryogenic liquid (LH\textsubscript{2}) or highly compressed gas (CGH\textsubscript{2}). As already stated, the CO\textsubscript{2} emission reduction potentials are strongly dependent on the hydrogen production technology. In the long run, it is assumed that

\textsuperscript{48} Besides full hybrids, micro hybrids and mild hybrids also exist. The micro hybrid includes only an automatic start-stop function. This means that the combustion engine stops when the car is stopped and that the electric engine is strong enough to drive away the vehicle for the first meters. For city short-distance driving, energy savings of about 10\% are expected. In a mild hybrid the electric engine is already strong enough to support the combustion engine during driving which enables considerable fuel savings (in particular without acceleration). A further distinction is made between serial and parallel hybrids. Whereas road vehicles are usually parallel hybrids, which can use the torque of both engines at the same time (or individually), in rail transport, the diesel locomotives are usually serial hybrids, where both engines are serially connected: the diesel combustion engine usually generates the electricity which is then used by the electric engine to move the train.
the emission reduction potential could be considerably increased by further expansion of regenerative energies. Another improvement is in the degree of efficiency of the hydrogen fuel cell vehicle itself, which is assumed to increase by a factor of 1.15 to 1.5 (Wurster, 2008). At present, the share of regenerative energy is far from sufficient to generate a relevant amount of hydrogen for the German road transport sector. Considerably more renewable energy sources and a significantly improved production and usage of hydrogen may result in a breakthrough of hydrogen fuel cell vehicles, but at the soonest, this process will take several decades (Wurster, 2008, and Keles et al., 2008). An important advantage of fuel cell vehicles (as well as of electric vehicles), which has not been mentioned so far, is their lack of on-site emissions (TTW) while driving the vehicle.

From Concave et al. (2007), it can be summarized that the CO₂ emission reduction potentials of alternative fuels as well as their economic incentives are far from being exhausted. Furthermore, biofuels suffer from the drawback of the large areas of land required for their cultivation. For the time being, therefore, it is assumed that no real change in fuel demand will appear until there is a massive breakthrough in the development of efficient and competitive BtL.

3.2.2 Other technical methods

Besides alternative drive technologies, there is a set of other measures to reduce the CO₂ emissions of passenger cars. However most of them change the features of the vehicles considerably and their CO₂ emission reduction potential is very limited. For passenger cars, these include downsizing, in particular, the reduction of interior engine friction loss, rolling resistance optimized tires, improving the cooling and heating circuit as well as the power assisted steering, automotive lightweight construction, improved combustion (in particular for petrol engines), aerodynamics and gear choice optimization. For an additional cost of 1,000 euros, a 20 % reduction of CO₂ emissions is realistic for a medium-sized vehicle – any further reduction is much more expensive (TNO et al., 2006a). Hence the emission reduction potentials based solely on technical improvements of the vehicles and without considering emission reduction potentials of biofuels are very limited.

In German freight transport, an articulated heavy good vehicle (HGV) emits about 850 grams of CO₂ per kilometre (VDA, 2006) on average and thus about 70 grams of CO₂ per shipped ton with a decreasing tendency. In 2005, the specific emissions for the entire duty vehicle fleet decreased to 557 grams CO₂ per kilometre (IEFU, 2005). This figure includes light duty vehicles (LDV), which are responsible for about 40 % of the domestic VMT (IEFU, 2005). The workload, the company and the truck size as well as the loading capacity-dead-weight ratio all play a decisive role in the amount of emissions (SRU, 2005, and Léonardi et al., 2004). In recent years, considerable efficiency gains have been accomplished, particularly due to the optimization of logistics. This was possible by introducing constantly improved complex computer-based disposition systems. Léonardi et al. (2004) estimated their
efficiency gain potential as about 2.3 million tons of CO₂ within German freight road transport, which equals about 5% of the overall emissions from road freight transport. Besides improved logistics, other authors suggest about 100 other measures to reduce CO₂ emissions from road freight transport (Léonardi et al., 2004). These include a decrease in shipping speed during transport, reduction of engine runtimes, driver training, improved vehicle aerodynamics, using single tyres instead of double tyres, automotive lightweight construction, using smooth running lubricant as well as automatic tire pressure control systems (Wildhage, 2007). Léonardi et al. (2004) give an overview of the different emission reduction potentials and distinguish in particular between the potentials of on-board units, the short-term optimization of logistics, and the driving behaviour of drivers.

To what extent these measures are able to diffuse throughout the market is strongly dependent on the political pressure from policy instruments as well as their impact on or acceptability in the market. Nevertheless, because of the high competition between forwarders and the resulting cost pressure as well as the ongoing discussion about climate change, an average fuel efficiency gain of about 0.2 litres per year in road freight transport is expected (EWI and Prognos, 1999). A further emission reduction of about 0.5% can be reckoned with due to optimized logistics of shippers, forwarders and carriers. Furthermore the mode choice has a considerable impact on the CO₂ emissions of road freight transport. Although some emissions may be shifted to the rail and waterways sector, the resulting emissions are lower in most cases (Oekoinstitut et al., 2007). The main potential concerning the modal shift in freight transport is expected for combined transport (Walter, 2006). In combined transport containers, swap bodies or whole trucks are loaded on trains or vessels. It is expected that for many shipments with a distance of more than 300 kilometres, a mode shift means an ecological improvement. The share of shipments with more than 300 kilometres is about 13.9% of the total freight traffic volume (Walter, 2006). And based on their corresponding mileage, their share in freight traffic performance can be estimated at about 30%. However, the ecological and economic profitability is strongly dependent on the intermodal hubs available. Thus the actual mode shift potential is dependent on these available hubs and on policy instruments or changing prices.

EWI and Prognos (1999) assume an increasing transport performance in road freight transport of about 0.9% p.a. until 2020. BVU et al. (2001) forecast an increase in road freight traffic performance of more than 1% p.a. until 2015 and Progrtrans (2007) predicts more than 2% p.a. until 2030. Overall, the studies estimate a constant or even decreasing amount of CO₂ emissions within the transport sector (Birnbaum et al., 2002). In road freight transport as well as in aviation, a rising CO₂ balance is assumed due to the increase in transport demand.
3.3 Conclusion II

Over the last decades, the CO₂ emissions from German passenger road transport have increased steadily, but recently this trend has been reversed and emissions have declined due to an improvement in vehicle fuel efficiency and a slower growth in VMT. Nevertheless emission reduction potentials within road passenger transport remain unused. However the realization of reduction potentials is strongly dependent on the implementation of policy instruments and changing price constellations. Therefore an overview was given of already implemented as well as future policy instruments for reducing CO₂ emissions within road transport. These instruments include the fuel tax, the energy tax, the European biofuel directive, the voluntary self agreement of European vehicle manufacturers, the labelling directive and the German road charge for heavy good vehicles (HGV) on highways. Possible future instruments include in particular the certificate trading scheme and further labelling. The emission trading scheme for road transport might affect traffic participants (downstream approach), the transport service providers or vehicle manufacturers, respectively (midstream approach) or the fuel companies (upstream approach). Many German studies recommend the upstream certificate trading scheme in transport. This has the advantage that (1) all the relevant data are already available from the application of the energy tax; (2) the certificate trading market is large enough so that no monopolistic or oligopolistic market positions are expected and (3) the reduction target can be achieved in an economically efficient way by a system conform instrument. However, the drawback of such a scheme is that the affected companies have no direct influence on CO₂ emission reductions, but rather an indirect influence through price increases. If the certificates are allocated by grandfathering, the companies might increase fuel prices due to the opportunity cost principle, i.e. the “cost” of the freely allocated certificates is passed on to the traffic participants even though nothing is actually paid by the company. This is said to have occurred within the German energy sector when the EU-ETS was introduced and the profits generated in this way are called windfall profits (Sensfuß, 2008).

Finally, technical ways to reduce CO₂ emissions were presented. These are divided into alternative drive technologies as well as other technical measures. There is indeed a considerable reduction potential of up to 80 %, but this can only be achieved in the long run. Other technical measures are more suitable in the short to medium term and have a reduction potential of up to 20 %. However, the majority of technical measures are only feasible for new cars so that a long diffusion time has to be taken into account here.

Summing up, particularly in road passenger transport, CO₂ emission reduction potentials can be identified which could be realized by implementing suitable policy instruments.

Model simulations might help to identify these suitable policy instruments. A new development within model simulation in the social sciences is the multi-agent simulation approach, which is presented in the following chapter. In the fourth chapter, a concrete micro-economic model is developed and applied.
Models within the social sciences represent a fragment of reality as an artificial and unrestricted environment. They can be used to examine the influencing parameter of the represented system and impacts on the system with regard to certain assumptions. In economics, they tend to focus on policy instruments and their possible impacts on the economy. For this purpose, various mathematical-theoretical and empirical-economic models were developed in the past. Due to the increasing application of computers, the models became more comprehensive and complex and allowed a more realistic consideration of complex systems. This step took place initially in the macroeconomic perspective with the development of system dynamics models. Recently, however, agent-based models have also been developed to represent complex systems on a microeconomic level. However, these agent-based models have not been applied within economic theory, but rather in the natural sciences, computer sciences, sciences of management and other social sciences – but in most cases without being based on a concrete scientific theory. This is why the literature is full of different agent-based models and definitions. Some of them define the concept of multi-agent models rather widely (e.g. Parunak, 1999); others specify multi-agent models in much more detail (e.g. Wooldrige, 2002). Other authors define multi-agent models for a certain context where other features are more important. In the following, the definition of Wooldridge with its four characteristics of multi-agent models serves as a basis to develop a definition for road transport in order to tackle the underlying question of this thesis.

The following chapter gives a general description of multi-agent models as they seem to have very appropriate characteristics for representing features of road transport – in particular of passenger road transport. To indicate the differences to conventional economic models, the chapter also provides an outline of classical economic models and their advantages and disadvantages. Then the history of multi-agent models in general and with respect to road transport is presented along with the reasons for their suitability for analysing road transport.

The subsequent Chapter 4 adopts some characteristics of the multi-agent model approach in the agent-based meso economic model developed within this thesis to simulate the introduction of a CO$_2$ emission trading scheme in German road transport.

4.1 Simulation within the social sciences

“Simulation is the process of designing a model of a real system and conducting experiments with this model for purposes either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a crite-
rion or set of criteria) for the operation in the system” (Shannon, 1975). Simulation is used in many contexts including simulation of technology for performance optimization, environmental systems for a better comprehension, etc. Simulation can be used to show ex ante the eventual real effects of alternative conditions and courses of actions. In economics the development over time is an important issue.

In many disciplines simulations became a central pillar in the scientific work. Due to the increasing application of computers more complex simulations became feasible. But also the critics on statical and intradisciplinar approaches accelerated an application of simulation models. According to Hendrikson and McKelvey (2002), natural scientists had begun to question Isaac Newton’s theorem of classical mechanics by the end of the 20th century. At the same time, similar activities were observed in the science of philosophy. In particular, Paul Karl Feyerabend (1924 – 1994) advocated multidisciplinary scientific research. Just before the turn of the millennium, this development took place in the social sciences. Especially through the scientific movement philosophy of science, the social sciences shifted their focus away from axioms and general theory to models and experiments (among others Suppe, 1977 and Mc Kelvey, 2002). In economics, the methodologically open complexity sciences was developed out of the Austrian school which tried to consider the heterogeneity of the subject matter and its environment. Furthermore, scientific analysis focused on collective behaviour as well as its decomposition into the corresponding decisions by single agents and how they can be influenced by their environment. In the process, economists began to criticise the classical assumption of the representative homo oeconomicus and instead increasingly focused on heterogeneous agents used to represent more reliably empirical agents. For example, within the social sciences, Donald T. Campbell (1916 – 1996) in particular contributed to developing the scientific-empirical analysis of business strategies (McKelvey and Baum, 1999).

Today, modelling artificial simulations is applied as one of the main three pillars in the theory of sciences besides pure scientific induction and deduction (Baumann, 2002). Induction is understood in this context as an experience of empiricism and should not be confused with the concept of induction in mathematics or physics. Deduction derives possible impacts from theoretical assumptions. Therefore a simulation model might be inductive (e.g. econometric models), deductive (e.g. abstract general equilibrium models), or a mix of both. Thus the models can be distinguished by their simulation purpose. According to Axelrod (2005:3ff), simulation models can help to

- accomplish certain actions (e.g. clinical operation) (Performance),
- calculate forecasts (e.g. oil price forecasts) (Prediction),
- practise certain skills (e.g. flight simulator) (Training),
- entertain people (e.g. computer games) (Entertainment),
- learn (e.g. serious computer games) (Education),
- prove scientific rules (e.g. Conaway’s Game of Life) (Proof), and
- discover new coherences (Discovery).
Usually all models begin with some assumptions about the representation of the system. In this way they serve rather deductive aims. For models which help to prove scientific rules (Proof), inductive intentions might be presumed. However all the results are strongly dependent on the underlying assumptions and should not be considered in isolation – consequently simulation is always a type of thought experiment (Axelrod, 2005).

4.2 Classical economic models

Economic models are roughly divided into micro- and macroeconomic models (see Figure 15). Both models try to explain the market. Microeconomic models look at individual economic units and their behaviour, whereas macroeconomic models only consider their aggregates. In practice, usually some form of hybrid is used. In micro-economics, individuals are often grouped into microeconomic clusters (representative individual). On the other hand, macroeconomic models are often calibrated using individual data. The new concept of the meso-model has not been applied very often so far, but it combines both approaches and focuses on how structural forces within the economy play out (see Peters, 1986, and Liedtke, 2006).

![Figure 15: Overview of economic models](image)

Macroeconomic models are applied especially to estimate decision-relevant data for future situations and include input-output, Computable General Equilibrium (CGE), macroeconometric as well as system dynamics models. The microeconomic models comprise optimisation, game theory, microeconometric as well as multi-agent models. These models are briefly outlined below.

**Input-Output-Models** date from Leontief (1951) and are based on the economic input-output-matrix. Thus they deal inter alia with relationships between commodity volumes and final demand, or primary inputs and final demand in specific sectors or the economy as a whole.
Macroeconometric models consist of statistically-estimated equations, which are then used for simulation purposes by feeding them with other data or changed parameters. Tinbergen (1936) was one of the first economists to present a completely specified and validated macroeconometric model. This model covers a whole economy (complete), all the applied mechanisms were written in mathematical equations (specified) and all the parameters were estimated by econometric estimations using data from the system of national accounts (validated). Usually, levels of significance are accounted only for the decision whether a certain equation or variable should be included in the model. However they are not used within the simulation so the simulation result is again one explicit value without any variation or confidence intervals. Furthermore, macroeconometric models are often shaped by neo-Keynesian assumptions (Boulanger and Bréchet, 2002) i.e. the macroeconometric model is demand-driven and supply effects as well as efficiency gains due to research and development are underestimated. However, Lucas (1976) pointed out that calibrated models with ex-post data could not be transferred to future decisions without severe implications. This is particularly true when the political framework within the model is changed. Recent macroeconometric models include, e.g. the HERMES model (Italianer et al., 1993) and the E3ME-Model (Barker, 1998a and 1998b).

Computable General Equilibrium (CGE) models are based on classical Walrasian general equilibrium theory and allow more and more exceptions regarding their restrictive assumptions. Basic CGE models were developed, e.g. by Johansen (1960) and Harberger (1962). An overview is given by Shoven and Whalley (1984). They are often based on data from the system of national accounts or the input-output matrix and can have a microeconomic foundation. In this way, the models optimise at the micro level but assume representative individuals, complete markets without external effects and public goods, complete information, perfect competition etc. Furthermore, these models often examine macroeconomic issues, which today typically have an empirical background (e.g. Böhringer and Löschel, 2004). By limiting the economic equilibrium, their simulation is straightforward in a scientific perspective, but their results are limited from an empirical. This is particularly true for non-Walrasian markets. However, recent CGE models do allow deviation from the equilibrium. A challenge is the calibration of the model. Usually the values are taken from the literature, or estimated by econometric approaches and confirmed by a sensitivity analysis (Boulanger and Bréchet, 2002). If correctly calibrated, CGE models are especially suited to determining long-term forecasts.

System dynamics models are neither based on classical economic theory, nor on statistics, but instead try to represent the empirical dynamics system as realistically as possible without forcing an exact outcome. They resemble the multi-agent approach with regard to the reproduction of complex systems, but do so from a macroeconomic perspective. The astonishing fact is that both simulation models have developed mostly separately over the last decade so that considerable development

49 The calibration is a mathematical method to define the values of the parameters within the model.
potential has been lost (Scholl, 2001). Due to the rapid development in suitable computer software, system dynamics models can already be developed with user-friendly software such as, e.g. Vensim®. One famous system dynamics model contributed to the sensation caused by the Club of Rome with their report “The Limits to Growth” (Meadows et al., 1972) which forecast the limits to economic growth. This established a new ideology in particular within economics. Another system dynamics model is presented in Chapter 6 of this thesis, which is used to calculate the macroeconomic impacts of implementing a CO2 emission trading scheme in German road transport.

**Microeconomic models** feature microeconomic optimisation models, game theory and microeconometric models as well as multi-agent models. The microeconomic optimisation model is often applied to business-management issues, e.g. in operations research. It is well suited to optimising production processes within companies. In game theory models, statements about certain relationships, reactions or cognitive phenomena are usually derived inductively from laboratory experiments (Berninghaus et al., 2006). The microeconometric models are based – like macroeconometric models – on statistically estimated equations; however, they are generated using individual data. The most frequently applied microeconometric models within transport are discrete choice models (McFadden, 1974). Multi-agent models offer due to their short evolutionary history and wide application a range of possible interpretations. Hence the model developer has much more freedom in the model design, calibration, etc. While multi-agent models are applied in the social sciences to analyse the behaviour of individuals, the inverse approach is taken in microeconomic models by analysing the economic impacts of individual’s behaviour.

### 4.3 Multi-agent models

Multi-agent models are a significant and rapidly spreading type of simulation model in the social sciences. They overcome some disadvantages of classical models but generate other shortcomings at the same time. In this respect they are not universally applicable, but are particularly suited to specific issues. For instance, they are valuable for analysing decisions which are made by non-optimising agents with bounded rationality, intelligence, biased cognition or insufficient information.

It is possible to obtain practicable results even with limited knowledge of the relations within the analysed market. Gigerenzer et al. (1999) show that nonspecific reasons do influence many everyday decisions so that a multi-agent model is better suited to representing these indefinable decisions since it incorporates heterogeneous individuals and the heuristics for these decisions better than other (optimisation) models. However, the results of these multi-agent models should be carefully interpreted due to the potential uncertainty concerning the real reasons behind the decisions. These uncertainties embody both the advantages and disadvantages of multi-agent models.
The evolution and epistemology of multi-agent models is outlined next. Then a
definition of multi-agent models is given in the context of implementing a CO2 cer-
tificate trading scheme in German road transport before economic models are dis-
cussed. An introduction of software for multi-agent modelling completes this sub-
chapter.

4.3.1 Evolution and epistemology of multi-agent models

According to Epstein (2005) multi-agent models are in line with many other econo-
mists who criticised the neoclassical equilibrium theory of Léon Walras. Among
these critics are, e.g. Friedrich August von Hayek (1899 – 1992), Joseph Alois
Schumpeter (1883 – 1950) and John Maynard Keynes (1883 – 1946). According to
Epstein, even Alfred Marshall (1842 – 1924), who was a co-founder of the neoclas-
sical theory as it is known today, paved the way for multi-agent models by saying
that the “economic biology is the Mecca of economists” (Marshall, 1920:xii). Did
Marshall know that multi-agent models would one day emerge from the biological
sciences?

The economic neo-classical theory, which dominated economic science for dec-
ades, simplifies the market by making restrictive assumptions in order to be able to
apply strictly mathematical methods. This allows a neat derivation of results at the
cost of a realistic representation of the market. For example, the neoclassical models
represent market participants as representative individuals; this assumption is not a
realistic representation of the market for heterogeneous markets (Epstein, 2005: 30).

As the criticism of classical models became stronger and as high performance
computers were developed, more and more multi-agent models were applied in the
last decade of the twentieth century. One of the first famous models was the cellular
automaton (Klägl, 2001). This describes the interaction of an agent and a fixed ref-
ence environment such as, e.g. the “mice looking for cheese” cellular automaton.
In this model, the agent (a mouse) can only perceive a certain radius of its environ-
ment. In this environment there could be other mice or cheese. According to this
cognition, the mouse has to decide whether to avoid a possible collision or eat the
cheese (see Figure 16).

Further developments of the cellular automata feature, among others, Conway’s
Game of Life from 1970, where an agent dies as soon as fewer than two other agents
are located in its immediate vicinity. Agents are born as soon as there are more than
three agents in its vicinity (Poundstone, 1985). Another famous example in the
transport sciences was the model developed by Nagel and Schreckenberg (1992)
(see below), or the Sugarscape model by Epstein and Axtell (1996). The latter mod-
els a sugar world which is a space covering 50 times 50 fields. In this world, virtual
agents are equipped with certain searching algorithms. At the beginning, the agents
are randomly distributed within the playing field and two sugar stocks are located on
two fields. Agents then start to search for the sugar according to their algorithms.
The agents resemble ants and biologists expect to obtain some insights into optimal searching algorithms.

Figure 16: Cellular automaton – mice searching for cheese


It is necessary to identify the most suitable model for all these applications and for other models and the model should be epistemologically valid. To check for the epistemological validity of multi-agent models, Epstein (2005) recommends clarifying the following five issues.

(1) Generative sufficiency vs. descriptive necessity: According to Epstein, a market situation cannot be simulated if it cannot be explained. The reverse is not valid however: Not every simulation is an explanation of a market. Thus generative sufficiency is a necessary, but not sufficient explanation.

(2) Generative agent-based model vs. explicit mathematical models: Mathematical models are limited to the interaction of mathematical equations which explain the represented system. Other influences do not have an impact. Multi-agent based models can also incorporate other influences – potentially via random terms.

(3) Generative vs. deductive explanation: Simulation models usually deliver generative explanations which can be interpreted as deductive explanations if the models have been calibrated with empirical data. However it is questionable whether it is in fact possible to calibrate a model such that it accurately represents an entire popu-
lation and its characteristics. A model is always a specific representation of a population so that the generative explanations are actually inductive and should be interpreted as such.

(4) Generative explanation vs. inductive examination: As mentioned above, simulation models usually deliver inductive explanations showing the results of the model’s specific perspective and scientists then try to generalise these results. However, this kind of explanation is precarious and relies heavily on the calibration of the model.

(5) Generality of multi-agent models: As recent multi-agent models tend to simulate sub-systems of markets, the generality of their results is rather limited. Furthermore, the results are usually more volatile because of their own dynamics. Nevertheless, the generality of multi-agent models has increased in recent years with improving complexity and empirical reliability (Epstein, 2005: 21).

Main criticisms on the results of multi-agent models are that they allow too much arbitrary model adjustments (i) thus their results are neither deductive derived (ii) nor guarantee a general validity (iii). Epstein (2005:6) disproved the first two counts (i and ii) and with regard to the latter he assigned a merely underpart. According to Epstein, in principle, most multi-agent based models could also be interpreted as a system of mathematical equations. For multi-agent models using random error terms the results might in fact deliver (slightly) arbitrary results for the same input parameters but when the model is applied hundreds of times an econometric analysis of the resulting distribution would be a better forecast as a solely value which do say little about stability and probability of occurrence.

To sum up and as stated above, multi-agent models are still at an early stage of development, but have already become a popular instrument in the social sciences. Regarding their epistemological significance, these models have adequate sufficiency, a certain precision and correspondence to reality as well as an incipient scientific steadfastness (Epstein, 2005). Due to their early stage of development and their multifunctional applications, their knowledge gains differ widely and their results should be carefully interpreted. This is especially true for generalisations of their results. Here, there is considerable scope for improvement in the future.

4.3.2 Properties of a behavioural multi-agent model in road transport

Different multi-agent models have been applied in different sciences without a common fundamental consensus (among others Klügl, 2001, and Ferber, 1999:29). In particular, there are considerable differences between the different disciplines. In biology, multi-agent models are widely conceptualised and cover various types (Klügl, 2001:198ff.). In business administration, multi-agent models are defined more narrowly and are able to manage particularly complex production line optimisations which permit partial breakdowns and allow agents to resolve these troubles
on their own\textsuperscript{50} (among others Kassel, 2008). In computer science, models which use several software agents (e.g. for gathering information from the internet) are already called multi-agent models (Gilbert and Troitzsch, 2005). Consensus in economics seems to be the amount of agents (many), the model subject (an economic market) and the market characteristics (complex system).

One often cited definition within economic multi-agent simulation is that of Wooldridge (2002). According to Wooldridge, agents in multi-agent models should have the following four core characteristics. (1) The agents are autonomous, i.e. they operate without the direct intervention of humans, they can cope with unforeseen events and have some kind of control over their actions and internal state (Castelfranchi, 1995). (2) Agents should have some kind of social ability, i.e. they interact with each other (or possibly humans) via some kind of agent-communication language (Genesereth and Ketchpel, 1994). (3) Agents show some kind of reactivity, i.e. they somehow perceive their (model) environment and respond in a timely fashion to changes that occur in it. (4) Agents should be somehow pro-active, i.e. they do not simply act in response to their environment, they are also able to exhibit goal-directed behaviour by taking the initiative (Epstein, 2005). These requirements are widely recognised by scientists and are mostly applied in multi-agent models (Epstein, 2006).

Besides these general requirements, other agent characteristics which have been discussed in the literature include knowledge, belief, intention, and obligation (Shoham, 1993), mobility within the represented network or market (White, 1994), veracity of information, which might not be realised by agents (Galliers, 1988:159-164), a biased perception of agents (Gigerenzer and Selten, 2001), benevolence, which precludes that agents have conflicting goals (Rosenschein and Genesereth, 1985:227), rationality to pursue a goal (Galliers, 1988:49-54), heterogeneity (Ferber, 1999), emotional and canonical arguments (Gilbert, 1994), and independent learning (Marks, 2005). With regard to the considered issue, the following three approaches seem to be convenient. A dynamic adaptation processes (Axtell, 2000) and emergence of the system (Walker and Wooldridge, 1995) as well as possible network effects between agents (Gilbert and Troitzsch, 2005).

Most of these characteristics are case- or discipline-specific. Thus partly contradictory requirements can be found in the literature. For example some authors assume (in contrary to the above assumed rationality to pursue a goal) a bounded rationality (Simon, 1955).

Another multi-agent literature survey was conducted by Franklin and Graesser (1996). They highlight the requirements of autonomous agents, their perception and influence of their environment, their acting according to self-interest, as well as their having individual perspectives of future developments.

The main characteristics and basic functionality of agents within multi-agent models are summarised in Figure 17. The agent resides in a model environment, which he perceives through sensors, but where this perceived state does not neces-\textsuperscript{50} These processes are also called self-organising production processes (SOPP).
sarily correspond to the real state. However the perceived state influences the behavioural rules and thus the agent’s (re)action. At the same time, the state of the agent can be also affected by the perceived state. The state of the agent might then influence the behavioural rule as well. Thus the behavioural rule is influenced by the perceived state of the environment, by the state of the agent and also by other internal actions within the agent (e.g. time limit, certain requirements, etc.). Furthermore some agents might be capable of learning if, for example, the action accomplished does not lead to the desired result. According to Gilbert and Troitzsch (2005), simulation models with more than one agent constitute multi-agent models.

![Outline of the behavioural pattern of an agent](image)

Within the context of implementing an emission trading scheme in road transport, the following characteristics of agents are needed to supplement conventional economic models.

- Agents should meet their decisions *autonomously* and should neither be forced nor be dependent on the decisions of other agents within the legal framework.
- Agents should be *heterogeneous* and reproduce the individuality of the underlying subjects.
- Agents should show some kind of *reactivity* to influences of their environment.
- Agents pursue their own goals with their *bounded abilities*. They might have bounded rationality or biased perception or cognition and do not possess complete information about the system.
• Agents “know” their estimated time horizon and behave accordingly in a forward-looking manner.
• Agents might act without being provoked by the environment. This assumes a certain proactivity of the agent. This characteristic together with the forward-looking attribute might result in a certain dynamic adaptation process.
• Agents should interact with each other and with the environment. Furthermore a certain social ability and network effects can be assumed.

The model developed in the next chapter try to capture some of these features in order to improve the meso economic model developed for road transport.

4.3.3 Discussion: classical microeconomic vs. multi-agent models

Many neoclassical models are restricted to a representative individual: the homo oeconomicus. He is an egoistic, utility-maximising agent who only cooperates when this is profitable as, for example, in an oligopoly. Tactical considerations are only considered within game theory. A neoclassical homo oeconomicus is a rational utility-maximiser, who is only concerned with profit maximisation and considers no other tactics. Elster (1989) argues in favour of a humanisation of the homo oeconomicus (based on Emilie Durkheim’s homo sociologicus) by upgrading his social competences, learning skills and allowing for other (sub-)targets besides utility maximisation. Furthermore Elster (1989) claims that models should better represent reasons other than self-interest in order to explain the development of social norms and interactions because these occur in reality. Sociological multi-agent models have been developed and applied in this context.

In the past few decades, the above mentioned neoclassical assumption of homo oeconomicus has become a main element of economic theory. It is very helpful for understanding economic interrelations as well as the outcomes of many economic issues. However, it can be shown within the empirical microeconomic issues of everyday life that the heterogeneity of individuals has a much stronger influence than has been assumed in neoclassical theory so far. Markets with a higher variety of products (e.g. the passenger car market) are more strongly affected by this than markets with homogeneous commodities (e.g. the electricity market). This can be illustrated by the example of the Veblen effect as shown by Janssen and Jager (2003 and 2001). The Veblen effect has a much stronger influence on passenger car purchases than on the electricity market: If a local car dealer offers a discount on the retail price for a highly recommended passenger car, the customer is likely to be heavily influenced by this discount (and not just by the price). In homogeneous markets, this effect is negligible; on the electricity market no difference in demand can be observed between a discount on the recommended retail price and the usual price.

In contrast to most of the neoclassical economics models, multi-agent models do not necessarily assume that market participants have access to complete information. This is especially valid for markets where complete information cannot be empir-
cally observed due to bounded rationality or biased perception (see Gigerenzer and Selten, 2001:4). On the one hand, humans try to act rationally. This is not always realisable however due to limited or partly biased information. On the other hand, decision makers might outline a complex issue adequately, but do not find an optimal solution due to their bounded rationality (Simon, 1955, 1959, and March, 1978). Hence, these markets do not obey the Walrasian equilibrium (Roth, 2002) and are consequently suitable for simulation using multi-agent models (among others, see Conlisk, 1996, Board, 1994, and Spear, 1989). Thus the assumption of complete information of all market participants has become increasingly unpopular. Renowned economists have also distanced themselves from the assumption of complete information. For example, McFadden (2000), who was awarded the Nobel Memorial Prize in Economic Sciences, argues for a consideration of individual valuations and refers to non-optimal decisions of individuals due to biased perception (e.g. the anchor problem in McFadden, 2000: 363). In empirical everyday decisions, inconsistent decisions are ubiquitous with regard to the underlying system because most agents do not fully know their environment (Wooldridge, 2002). Moreover, the assumption of purely profit-maximising agents does not adequately reflect most human decisions (Helbing, 2004). Thus neoclassical models are not able to convincingly represent and explain most situational decisions because of the bounded rationality and biased perception of the empirical market participant (Langlois, 1990, and Langlois and Csontos, 1993). Heuristics and comprehensive algorithms might mirroring more efficient the decisions actually made.

In general, multi-agent models are convincing when describing phenomena which consist of more than just the sum of their individual elements (emergence). This can be demonstrated using an example from the natural sciences, where the hardness of bronze cannot be explained by its elements: “The hardness of bronze lies neither in the copper, nor in the tin, nor in the lead which have been used to form it, which are all soft or malleable bodies. The hardness arises from the mixing of them” (Durkheim, 1982: 39-40).

In the same way, the success of an agent does not depend solely on its needs and its attractiveness, but also on the dimension and quality of its available network. Multi-agent models are very suitable for modelling these networks. These might be local networks where agents can perambulate their model environment (e.g. in a village), but also networks where agents can communicate with any other place in the model (e.g. via telephone or the Internet). The interesting question then is which of these possible connections arise and which do not (Gilbert and Troitzsch, 2005).

A further aspect which is integrated into many economic models even though it is not empirically circumstantiated in everyday life is the adherence to sound arguments. In everyday life, multi-layered discussions take place and besides hard facts, emotional, visceral, and kisceral arguments are also used and considered (Gilbert, 1994 and Wooldridge, 2002:149). These can be accounted for in multi-agent models by representing the sympathies and antipathies between agents using clusters (Wooldridge, 2002: 155). For cooperation, the artificial agents should be able to identify and contact each other, build teams (with respect to social norms and other
factors), elaborate plans and then interact. Empirically it can be observed that humans cooperate more than would be rationally necessary (Conte, 2002).

Another attribute which is often used in multi-agent models is the ability of agents to learn. Agents can learn from their own previous behaviour and adopt their behaviour accordingly. To capture this, there are multiplicities of learning algorithms from game theory or other social sciences backgrounds (see Marks, 2005:11ff.). These learning algorithms can be differentiated into social learning and individual learning (Vriend, 2000). Social learning concerns the behaviour toward other agents, i.e. at least two agents are always involved in social learning. Especially for the construction of social networks social learning is a central attribute for each successful agent. If the first contact to another agent fails, the second contact to this agent should be managed using a different strategy. Individual learning, in contrast, may only involve a single agent, if the agent learns from interaction with its environment.

For these reasons, a multi-agent model is not as strictly delimited as other models; it is always possible that new subsystems or unforeseeable developments may occur as a result of the learning algorithms. This is the reason why multi-agent models were initially used mainly by evolution biologists, which led to the description “Darwin in Silicon”. But this approach was and still is favoured in other sciences as well because of this attribute. Innovative solutions are permitted which would remain undetected by other models. This interface with other sciences, in particular with biologists and computer scientists, has a certain advantage which should not be neglected when developing models or software (Axelrod, 2005:11).

But the learning attribute also has a disadvantage: the inconstant system gives rise to uncertainty concerning the model results. In principle, dozens of model runs should be conducted, similar to Monte-Carlo simulations, in order to allocate probabilities to every solution. Although this procedure does not necessarily lead to a unique solution, it may provide more resilient results.

In economics, dynamic adaptation processes also occur. Dynamic learning algorithms within multi-agent models can cope with these adaptation processes. This is managed in the same way as in the system dynamic models, which model these effects at the macroeconomic level. In contrast to this, Computable General Equilibrium (CGE) models are not generally able to consider these dynamics. Thus classical CGE models have difficulties with situational start-ups during the model’s time horizon. Furthermore, equilibrium rarely occurs in these markets with numerous start-ups so that multi-agent models seem to be more appropriate here (Axtell, 2000).

Foster (2004: 1), like Hayek (1952) and Vanberg (2004), allocates the economic system and its sub-components to “complex adaptive systems”. Additionally he wonders whether it automatically follows from this that economic theory which neglects the complexity of the economy should be pursued at all. Between two equilibria, the dynamics of a market and its agents become more and more important for economic issues as the characteristics in asymptotical market equilibrium (Marks, 2005). However, there is great uncertainty among economists concerning behaviour
beyond equilibria (Arthur, 2005). If the market dynamics become self-organising characteristics, it is helpful if agents have some kind of forward-looking properties instead of purely myopic optimisation.

Despite their advantages, many disadvantages can be identified for multi-agent models as well. These mainly stem from their recent development. Cioffi-Revilla (2002) identifies seven typical teething problems of multi-agent models. These occur particularly during the determination of the system size, platform geometry, platform division, network typology, phenomenological calibration, structural stability as well as the determination of (potential) connections. But no generic recommendations to avoid these problems are given.

Another criticism is that many models are considered to be valid based on the reproduction of one single former event – even if this is only the necessary and not the sufficient condition (Gilbert, 2004: 6). This applies equally to other models in the social sciences, which also do not have any alternative strategy for validation like comparing the results of the model with different empirical events. The important role of statistical methods within the social sciences is very evident here.

Arifovic (2001) shows that more complicated agents do not necessarily lead to more accurate results. The same is true for the smallest defined time unit of the model (tick length), as shorter tick lengths do not necessarily lead to more efficient results (Bottazzi et al., 2003).

Furthermore, it is not essential that multi-agent models always represent the maximum realistic reproduction of the observed population; they can be applied to analyse hypothetical situations of the system. One example is the evacuation of the Zurich main train station (Gloor et al., 2004). Similarly, the evaluation of potential causes of stock market crashes might be an equally suitable subject of investigation for multi-agent models. The literature shows that they are very widely applied, e.g. even for looking at specialities such as the standing ovation phenomenon (Miller and Page, 2004), or the Game of Life (Schelling, 1978). Indeed, according to Axelrod and Tesfatsion (2006: 6), the latter is not a pure multi-agent model. However, it does clearly reveal how the artificial residents of a settlement relocate as soon as five of their eight direct neighbours belong to a different ethical group than they do. During the simulation, several relocations and patterns were able to be observed until an “optimal” distribution of agents resulted for this settlement.

In conclusion, multi-agent models are a convenient tool to evaluate socio-economic systems (Janssen and Ostrom, 2004). Due to their recent development, they are still being widely applied. The trend toward multi-agent simulation is an ongoing process. According to Squazzoni and Boero (2007), it is important that statistical methods should be applied to confirm that the model effectively represents the empirical system under investigation and that empirical evidence should validate the model results. This helps developers avoid misleading interrelations between economic parameters (Coleman, 1990). This is of particular relevance for multi-agent models being applied to new research questions as there are often no benchmarks available here. These new research questions include, for example, models of
customer behaviour, but also some models which are trying to overcome the gap between micro- and macroeconomic models (Saam and Harrer, 1999) such as the model by Nowak and Latané (1994).

4.3.4 Software for programming multi-agent models

According to Gilbert and Bankes (2002), the software used to program multi-agent models developed in a similar way to the statistical software developed a decade earlier. More than two decades ago, the breakthrough in statistical programs resulted in program packages such as STATA, SPSS or SAS. Before their implementation, deeper programming knowledge was required to apply a statistical regression. This is still true for the development of CGE or multi-agent models within economics. Thus programming knowledge is (still) required to develop multi-agent models. The SESAM program (Klügl, 2001) developed in Würzburg was one of the first attempts to construct a program package with less programming code for the development of multi-agent models. This allowed the construction of a multi-agent model without prior knowledge of a programming language. Similar approaches are STARLOGO (2009) or AGENTSHEETS (2009). However, their features are still strongly limited. This is the same pattern as found in the development of statistical software – the newest scientific findings take about six years to be included in the program packages. Other systems have been developed in Europe based on SMALLTALK such as SDML (2009), CORMAS (2009) or DESIRE (2009).

When developing a multi-agent model, it is important to validly reproduce the system via its core characteristics, to use a well-documented and clear programming code, to aim for user-friendliness and simple expandability in the case of further developments (Axelrod, 2005). The ECLIPSE compiler was used in combination with the program library REPAST to program the model developed below. REPAST was developed for multi-agent models and is widely used among scientists (see Axelrod, 2005, Sensfuß et al., 2007, and the box below). Currently, the object-oriented program language JAVA is often used by scientists to program multi-agent models. Due to its object-oriented program operation, it reasonably satisfies the multi-agent model assumptions (Ratz et al., 2006a and 2006b).

The following box outlines the fundamental features of the JAVA library REPAST J.

**RePAST**

RePAST (version 3.1) is an open-source tool kit for developing agent-based simulation models of many scientific disciplines (e.g. biology and social sciences). It is an extension of the tool kit SWARM (2009) and was originally developed by the University of Chicago in cooperation with the Argonne National Laboratory.
Characteristics of RePAST

RePASTJ consists of six modules (North et al., 2006; see Figure B-1). Four of them are so-called fixed modules which are mandatory if the tool kit is used. The other two modules (flexible modules) can be optionally activated. Besides the main module “engine”, the other fixed modules comprise an “interactive-run” module, a “batch-run” module and a “logging” module. The main module, the engine module, with its four components (the engine, controller, scheduler, action, and agent) is responsible for the simulation process and for the central control of all other modules. The interactive-run module is used for the visualisation of results and also as an interface to the model user. The batch-run module checks all internal parameters and controls their correct processing during the simulation. The logging module logs the relevant and desired results during the model run. Simple arrays are saved within the data-logger; more comprehensive arrays can be stored in a corresponding object-logger.

Figure B-1: RePAST module and packages illustrating the main interactions

When applying the developed model, RePAST can be integrated using the fixed modules and some of the flexible models by systematically referring to the corre-
sponding REPASt packages. Each package contains some JAVA classes. Thus if a specific feature of REPASt is required within the developed model, using these thematically classified packages saves the programmer a lot of work. The thematical names of the packages are the engine, analysis, Graphical User Interface (GUI), parameter, adaptation and other domain-related module packages. The packages systematically launch the corresponding elements of different modules. E.g. the Engine package (obviously) concerns classes within the Engine Module, and the Analysis package particularly concerns classes of the interactive-run as well as the logging modules. The applied classes are displayed in the appendix.

Another JAVA-based toolkit for developing multi-agent models is ASCAPE (ASCAPE, 2009, and Inchiosa and Parker, 2002).

### 4.4 Previous models used to analyse transport behaviour in Germany

The following section explains and illustrates the micro- and macroeconomic perspective within economic models of transport based on some practical examples.

#### 4.4.1 The idea behind microeconomic transport models

The idea behind microeconomic transport models is to reproduce the traffic participants’ behaviour in a model. This synthetic transport market should include all the relevant individuals and their characteristics in order to analyse the impact of policy measures.

According to PTV (2005), up to now multi-level, logit, structure-equation, or ordered probit models have all been applied to the analysis of German passenger transport.

Multi-level models can include data from different data hierarchies and are able to analyse changes and causal relations at a lower level without neglecting influences from higher levels (see, e.g. Engel, 1998 and Goldstein, 2009). Usually they are calibrated by statistical panel regressions. As well as multi-level models, they are also called random coefficient models, mixed models or hierarchical linear models. One of the first multi-level models for transport analysis was introduced by Goulias (2002). It focuses on the interrelations between individuals’ transport behaviour and the corresponding characteristics of traffic participants.

Discrete choice models are the most frequently applied microeconomic transport choice models (McFadden, 1974). The basis of these models is the utility maximising behaviour of the decision maker within the model. Discrete choice models include the multinomial logit models as well as nested logit models and are the most frequently applied models for transport mode choices. Multinomial probit models are also applied within discrete decision models besides logit models. How-
ever, their application requires the evaluation of multi-integrals which makes the corresponding computer programs necessary (Ortúzar and Willumsen, 2004).

With a structure equation model (SEM), it is generally possible to analyse different endogenous and latent (not observable) variables simultaneously. To do so, not the observations themselves, but rather their covariance and correlations are used for the calculations. This approach has a confirmatory character, i.e. it is a hypothesis-verifying method and it generalises regression results, e.g. from factor analysis (see Jost, 2005). A complete structural equation model consists of three sub-models – two measuring models and a structural model. The two measuring models analyse the relations between the latent and the directly observable; the structural model analyses the relations between the exogenous and the endogenous variables. However, in practice, these models are often incomplete. This is why, for example, Simma and Axhausen (2001) argue that structural equation models are not suited to simulating most decisions in passenger transport.

Ordered probit models are linear regression models with a discrete regressand and are also suitable for ordinal scales, such as the interpretation of stated preference surveys. They were already being applied in biology as early as the 1960s (see Gurland et al., 1960). Even if the applicability of these models is limited because of their discrete variable structure, many transport economic issues have been examined with their help.

Until a decade ago, behaviour- and activity-based approaches which neglected personal characteristics dominated the transport sciences (Hunecke et al., 2005:26). Some of these models did at least consider some socio-demographic parameters and followed the four step approach (see Figure 18). This approach, which separates the mobility decision into four steps, dominated the models of mobility decisions since the 1960s. Its first step is trip generation which determines who wants to go where for what purpose at what time. In the next step, trip distribution, locations for the trips are allocated. Then the modal split choice is made before the trip assignment and concrete route choice is determined. However, this chronology is seldom observed in empirical road transport and especially not in passenger transport.
In contrast, activity-based approaches try to consider the heterogeneity of traffic participants and do not blindly follow the four step approach. This means that in many recent models, decisions are made via much more complex structures and the four steps are not treated as distinct, but seen as closely linked. At the very least, feedback loops are included between the four steps and short- and long-term decisions are distinguished (Zumkeller, 2006).

In recent years, transport models have used diverse methods. Firstly, rational choice approaches were applied. These approaches still presume that decisions are based on rational behaviour of the agents aimed at optimising their time or budget constraints. A few years later, planned behaviour approaches received more attention. These consider the subjective attitudes of individuals as well as their environment and the degree of self-control of their actions. When focusing more on environmental aspects, the norm-activity models (Schwartz, 1977, and Schwartz and Howard, 1981) should be mentioned. These models can include the ecological awareness of individuals. They were often applied within the domain of environmental entrepreneurship (Klöckner, 2005). The approach was indeed accepted for different norms (Schlaffer et al., 2002), but not with regard to environmental awareness alone. The integrated approach tries to integrate additional factors such as the location and social structure of households, individual lifestyle as well as other behaviour-theoretical backgrounds. However, these models suffer from the fact that usually a sufficient database is not available and that the corresponding survey would be very comprehensive. One example of an application is the ZIMONA study (Hunecke et al., 2005), which was based theoretically on the norm-activity approach and the theory of planned behaviour according to Ajzen (1991). Both are theories of aware decisions and therefore suitable for reproducing the long-term decisions of traffic participants.
4.4.2 The idea of macroeconomic transport models

Besides these microeconomic models, macroeconomic approaches have also been applied within the transport sector. These try to explain macroeconomic key variables and interrelationships. They analyse macroeconomic impacts on the economy as well as the relationships to other sectors or foreign countries. Mainly three approaches are applied: the Computable General Equilibrium (CGE) model, the macroeconometric approach and the system dynamics modelling approach. In principle, all the models consist of mathematical equations and a database.

As mentioned before, CGE models are based on neoclassical theory. However, recent CGE models are much more open for other applications. This is why they are not only one of the most frequently applied standard models in economic theory, but are also now widely applied within empirical simulation economics (Bröcker, 2004). Recently, they have also been convincing when applied to environmental issues (among others Böhringer et al., 2004). Here, they are mainly used to analyse policy instruments for climate change, foreign trade and transport (among others Bröcker, 2004). In transport they are particularly applied if classical cost-benefit analysis is limited due to imperfect competition and inflexible prices and for examinations where equity aspects within the population are irrelevant for the analysis (Bröcker, 2004:270). However, even the most recent CGE models in the transport sector do not consider dynamic developments of the market and are consequently static (Bröcker, 2004:284). A well-known example of a global CGE model is the GTAP model by Hertel (1997). The CGEurope model is another example applied to European transport. This was developed in the project IASON (University of Kiel et al., 2004), which was part of the Sixth Framework Programme for Research and Development of the European Commission. This large European network CGE model was developed with the focus on future welfare effects in a comparatively static equilibrium. Furthermore, the model comprises the core of the European transport network model TRANS-TOOLS (TNO et al., 2006b).

In recent decades, the macroeconometric approach has also improved its reputation among macroeconomic models. However, its influence is much smaller and its popularity is falling again because other models have also started to include the advantages of statistically estimated equations and empirically calibrated models in their modelling approaches. This expansion of modelling approaches is especially apparent in CGE models. A popular model in environmental economics is the Panta Rhei model by Meyer et al. (1999). However, these macroeconometric models are virtually unknown in the transport sector.

Besides CGE models, mainly system dynamics models are applied to transport economics. System dynamics models were already developed in the 1950s and are well established in many areas. They are appropriate for modelling dynamic and, at the same time, complex systems from a macroeconomic perspective. Internal feedback loops both within and between parameters play a central role besides the dynamic time component. These two characteristics were often neglected in earlier CGE models. Furthermore, system dynamics models distinguish flow and stock
value parameters as well. However, due to their dynamic property, there may be unforeseeable non-linear system results.

Such a model is the ASTRA model (Schade, 2005), which is applied in Chapter 6 of this thesis to calculate the macroeconomic and environmental impacts of implementing a CO₂ emission trading scheme in road transport.

4.5 Previous multi-agent models in road transport

Probably the best known multi-agent model is the Nagel-Schreckenberg model (Nagel and Schreckenberg, 1992). To start with, this was introduced as a cellular automaton, which simulated a road section with vehicles which individually adjusted their speed according to certain rules. In the initial Nagel-Schreckenberg model, the data concerning the vehicle and its speed were stored in the corresponding cell of the road through which the vehicle passed at a certain moment. Later, Klügel (2001), among others, changed this storage location to the vehicle itself and thus modified the model to be more similar to the angle of a multi-agent model. The simulation results remained unchanged. If an agent sees there is no vehicle in front, he accelerates and then remains at his preferred travel speed. Agents brake if another vehicle appears ahead. The data storage within the vehicle has the advantage of reproducing the effective information flow more realistically and individually. This makes it possible to implement driver- and vehicle-specific characteristics more easily and allows a further expansion of the model with respect to a realistic reproduction of the system (among others, see Wahle and Schreckenberg, 2001). In principle, many net-based, multi-agent models are based on this model. One recent example is the MATSim-T model (among others, Balmer, 2007).

Although the individuality and heterogeneity of participants in (passenger) road transport could only be inaccurately represented by the classical models up to now, multi-agent models still remain widely neglected within the transport modelling community. Instead, macroeconomic trends tend to be simulated by CGE and system dynamics models and microeconomic behaviour to be evaluated statistically. The socio-scientific findings of recent years point to transport decisions in everyday life usually being made by individual rule-based and habitualised algorithms without an explicit utility maximisation of the specific trip (Hunecke et al., 2002 and Götz et al., 2003). Despite this, only a few multi-agent models have been developed in recent years.

In Central Europe, most projects contain net-based decision and execution models besides the simulation of the modal choice:

- mobiTopp was developed within the European research project EuroTopp and models the net-based development of transport demand based on the German Mobility Panel (MOP) (Schnitger and Wittowsky, 2002). It simulates the activity patterns of persons over the period of one week. Within the model learning processes can cause changes in activity. Each actor is described using socio-
economic attributes, weekly activity patterns and individual behaviour with reference to the use of traffic data (Gringmuth et al., 2005).

- The ILUMASS (Integrated Land-Use Modelling and Transport System Simulation) model is divided into three microscopic modules: land use, transport, and environment (Wagner and Wegener, 2007). The model microscopically considers land use and transport effects together for urban and long-distance passenger transport as well as for freight transport.

- The TRANSIMS (TRansportation ANalysis SIMulation System) model is based on a military model. It is net-based and simulates a virtual transport system including its emissions (Bonabeau, 2002). The simulation starts by allocating virtual activities to artificial households. Then the length, time and modes of the associated trips are defined. Subsequently the reaction of the households to changes in the net or new policy measures can be simulated. As the basic model was still being used for military purposes and could therefore only be used without limitations in the US, the MATSIM model became increasingly popular in other countries (Balmer et al., 2006).

- VISSIM developed by PTV (2009) demonstrates traffic flow and allows the generation of homogeneous groups with specific transport characteristics. The initial state of the traffic network including transit traffic is calculated using PTV’s assignment model VISUM. It provides alternative routes for every origin-destination-pair (o-d-pair) that plotted in the travel demand matrix. The model delivers realistic traffic loads and travel times of the network. VISUM is similar to the FAMOS (Florida’s Activity Mobility Simulator) model for Florida (Pendyla et al., 2004).

- MATSim (2009) is a toolbox used for large-scale, agent-based transport simulations. This toolbox consists of several modules which can be used either as stand-alone units or combined. Currently, MATSim offers demand-modelling, net-based, agent-based mobility simulation, re-planning and methods to analyse the output generated by the modules. It is based on the four step approach. Many applications are already being implemented in Switzerland and especially the Zurich area (among others, Balmer, 2007, and Charypar, et al., 2007).

- Other models are DynaMIT (Ben-Akiva et al., 1997), MITSIM (Yang and Koutsopoulos, 1996), and DynaSMART (Mahmassani et al., 1995).

An overview of 56 agent-based transport models is given by Davidsson et al. (2005).

### 4.6 Conclusions III

Multi-agent models in the social sciences are a relatively new development of the last two decades. They try to overcome the weaknesses of conventional economic models, but provoke new problems at the same time. Multi-agent models have the advantage that they can consider regularities within groups without neglecting the
peculiarities of individuals. In economic science, they have more in common with microeconomic models and differ from neoclassical models in particular through their ability to represent the dynamics within the considered system and to consider the heterogeneity and limitations of individuals. They recognise that individuals often do not make their decisions based on an optimisation approach, but on individual heuristics. Hence the multi-agent approach is especially suitable where the classical assumptions of rational decision makers, complete information, homogeneous individuals and profit maximisation do not apply and where system dynamics could have a significant influence on the considered system. These attributes can be observed within road transport and especially in passenger road transport.

Although a unique definition of multi-agent models does not yet exist, some characteristics of multi-agent models are already generally accepted. Wooldridge (2002) is often referred to for the defining characteristics of multi-agent models. He specified four central attributes of multi-agent models, although many models differ from these in practice and other models with only a few software agents may already be termed multi-agent models (Axelrod, 2005:11). According to Wooldridge (2002), a multi-agent model is characterised by having several autonomous, reactive, and proactive agents with a certain social ability. The deviation from this definition observed in practice might be due to the recent development of multi-agent models. At present, the development of an applicable multi-agent model is still more of an art than a science (Gilbert, 2004: 8).

In the following chapter, a partial meso economic model of German road transport is developed, which features some attributes from multi-agent models.
5 Impacts on German road transport through a CO₂ certificate trading scheme

After the second and third chapter introduced in the German road transport with the focus on its CO₂ emissions and after in the fourth chapter some characteristics of multi-agent models were discussed, this chapter will merge these two issues by developing an agent based meso economic model for German road transport. The model allows an analysis of impacts on the simulated German road transport due to an introduction of an upstream CO₂ certificate trading scheme. The results are presented in this chapter and are used in the following chapter for calculating environmental and macroeconomic impacts with the system dynamic model ASTRA.

The in the following developed meso economic model represent the reactions of households and freight forwarders on increasing fuel prices with respect to their VMT and fleet structure. The model uses data of the German Mobility Panel (MOP) for an empirical representation of households and data from a survey by Bühler (2006) for the modelling of empirical freight forwarders. For the determination of reactions of the traffic participants statistical equations were estimated. Suitable elements of the multi-agent model approach were integrated thus the model might be named as a partial agent based meso model. Herewith the model is pretty appropriate to represent the German road transport close to reality with regard to the above mentioned issue and is in principle extendable to other countries if the corresponding data is available.

Suitable attributes of multi-agent models within this issue are presented in the previous chapter. Core attributes are the autonomy, reactivity, proactivity, and social ability of agents (Wooldridge, 2002) which can be also found in road transport. Additionally some further attributes of applied multi-agent models are observed within road transport as bounded rationality, incomplete information, rule based decision-making (according simple algorithms), and the ability to learn. According Axelrod (2005:11) the following model is a multi-agent model because it contains multiple agents. However, the above mentioned attributes of multi-agent models are only partly implemented.

Hence, this chapter develops a partial agent based meso model of German road transport to allow an analysis of potential impacts due to an introduction of an upstream CO₂ emission trading scheme in road transport. For this, initially relevant characteristics of German road transport with regard to a convenient representation of the above mentioned issue is sketched. Subsequently, a general overview of the model architecture and an introduction in the model is given before the core modules of the developed model are presented. For the interested reader, details which go beyond the basic understanding of the model are presented only in the appendix. The explanations within this chapter suffice to understand the model and its results. Finally the chapter concludes with core results of the model.
5.1 World of simulation: artificial German road transport

The developed model to analyse potential impacts of an introduction of an upstream CO₂ emission trading scheme in road transport on households and freight carrier contains a uniform reaction structure of agents but considers their individual characters and abstracts within passenger from specific trips. Consequently, households can simply reduce their VMT or buy other cars to change their fuel demand. Whether the change in VMT ascribed to a changed route choice, a modified modal split or a revised number of trips is not considered in the model because these changes are with respect to the considered issue irrelevant and only the change in fuel demand concerns. However, regarding freight road transport solely freight contracts are considered. For this, each day empirical freight contracts are leaked to freight forwarders which are accomplished during the day. In doing so, freight forwarders can use the two in the database available transport options. On the one hand they can use the truck and on the other hand they can use some kind of combined transport. By far most of these transports are currently accomplished by truck. But during an increase of fuel prices the cost minimising freight forwarders might switch some transports from truck to combined transport. Besides this short-run change of fuel demand of modal split another possibility is given similar as for the households. Freight forwarders might invest in a more fuel efficient truck fleet.

To simulate the effects of an implemented CO₂ emission trading scheme into road transport four different core markets are relevant (Figure 19)\(^{51}\). These are represented as simply and clearly as possible in the developed model with its core characteristics of the represented reality. The market of fuel demand of the motorized individual passenger traffic (1) consists of the demand on private households (HH) on VMT and the thereof derived demand on fuel (\(c\)). The market of fuel demand in road freight transport (2) consists of the due to the freight contracts induced demand of freight forwarders (Forw.) on VMT and thus the likewise deduced demand on fuel (\(c\)). Both markets are confronted with the oil companies (Oil Comp.) which supply the corresponding fuel for a certain price (\(e\)). The investment market (3) consists on the one hand of the demand driven by the need of households and freight forwarder to renew their car fleet (\(d\)) and on the other hand the new cars supply of car companies (CC) and the supply of used cars by households (HH) (\(h\)). Additionally the new market of certificates (4) is introduced, which is used by oil companies to trade certificates among each other or with other sectors within an upstream certificate trading scheme in road transport (\(f\) and \(g\)).

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\(^{51}\) Due to its few objects Figure 19 does not use professional model visualising methods as e.g. Unified Modeling Language (UML) (among others Fowler and Scott, 2000), Case Diagrams, Sequence Diagrams, Distribution Diagrams or Design Patterns (Ratz et al., 2001: 244).
The market of fuel demand of the motorized individual passenger traffic reflects particularly the need of households on VMT. Their causes are manifold and range from simple cruising via holiday trips and shopping trips to urgent emergency transports to the next hospital. The demand on VMT is strongly dependent on individual attitudes, needs, and habits but also on the costs – in particular the fuel costs. Due to the variety of trip purposes and different needs and hence the individual price sensitivity of traffic participants, the model does not consider each single trip but rather the total monthly VMT of each household. These are price sensitive thus an increase in fuel price leads to a decrease in average VMT of the households. However, a conclusion which trip is effectively economised (cancelled) is hard to determine and might differ strongly between individuals (Wadud et al., 2007). Hence an aggregated analysis of VMT per household suffices with regard to the concrete issue. The same holds for the road freight transport. But in road freight transport the transfer orders are the incitement of the VMT demand instead of the personal needs. The resulting transport performance is accomplished by the artificial freight forwarders with certain transport costs. If road transport costs are increasing (e.g., due to higher fuel prices), the freight forwarders try to minimize their VMT. However, because the number and the distance of transfer orders will increase in mid- as well as long-term and because most efficiency gains at the vehicle and in logistics are already implemented, the efficiency potential within road freight transport is considerably lower than those in road passenger transport. Hence a further increasing transport demand.
and the resulting rise in transport performance have an antidromic effect to CO₂ emissions in road freight transport than the efficiency gains in vehicles.

A further popular method to reduce VMT of trucks on trips longer than 100 kilometres is the combined transport (see Bühler and Jochem, 2008). For these distances on some relations the change from the truck alone to combined transport might be more cost efficient. In Europe the main run within combined transport is accomplished by rail or waterways. For both alternatives in principle two options exist: the unaccompanied transport, where only swap-bodies or containers are loaded or the accompanied transport, where the whole truck is loaded and hence the driver follows its load.

On the investment market for vehicles operate on the one hand the vehicle manufacturer, which provide new cars for households and new trucks for freight forwarders. On the other hand implicitly also used cars were provided by households and freight forwarders. The model simplifies the supply of vehicles: Due to a statistical regression the artificial households know when and which car he prefers – this car is provided by the car market (without considering whether the car is provided by households or vehicle manufacturer). The truck market is even more simplified. It is assumed that due to the severe competition among freight forwarders the fleet composition is relatively similar, thus the model assumes that freight forwarders have a uniform fleet. Furthermore it is assumed that the fuel efficiency of this uniform fleet improve each year by a specific value.

The implemented upstream CO₂ certificate trading scheme affects the oil companies. They trade certificates via the certificate market and they have to hold a certain amount of certificates for each litre of sold fuel. The amount of certificates for a litre fuel can be defined because a litre fuel emits always the same amount of CO₂ – however the fuel is combusted. If oil companies hold at the end of a trading period a too little amount of certificates to balance their amount of sold fuel, they have to buy the missing necessary amount of certificates on the certificate market to avoid penalties by the government. If they sell less fuel than they are allowed according the certificates they might provide their dispensable amount of certificates to their competitors. Consequently a price for CO₂ will be generated, which is passed on to the traffic participant by the oil companies. I.e. a corresponding surplus on the fuel price will occur. This surplus compensates on the one hand companies which reduce their CO₂ emissions (encouragement) and on the other due to the higher fuel price it signals the traffic participants to reduce their CO₂ emissions (effects of regulation).

However a priori the individual effect of regulation is hard to foresee, which is in particular due to the fact that the daily mobility decisions of households (especially the mode choice) is not realised as a real decision but is rather included within the habitualised daily routine which is not any more questioned (Verplanken et al., 1997). According to Verplanken et al. (1997) this is also the reason of the price inelastic demand of fuel and the very individual ways of reaction of households. The authors support their thesis by three comprehensive studies.

52 In Germany this is also called „Rollende Landstraße“ – rolling road.
5.2 The developed model

The in the following presented partial agent based meso model for road transport operates with empirical calibrated traffic participants, which are confronted with a fictive upstream CO\textsubscript{2} certificate trading scheme. This trading scheme has in the model to possible patterns, which can be selected by the model user. On the one hand an open certificate trading scheme can be selected where the oil companies might trade certificates with the already existing European certificate trading scheme EU-ETS. On the other hand a closed certificate trading scheme for the transport sector can be selected, which do not allow certificate trading with other sectors. Thus in the second option the CO\textsubscript{2} emission reduction has to take place within road transport and oil companies can trade certificates only among each other. Both trading patterns have in common that during ten years the allocated amount of certificates is reduced by 1.5\% per year. For that the oil companies receive about 1.5\% more certificates for the first trading period as they would need to satisfy the fuel demand of traffic participants. A trading period is one year and banking of certificates is allowed – borrowing form future periods not. Hence to avoid penalties by the government the oil companies (obligated parties) can mainly buy certificates from other sectors (in the open trading scheme) or to raise the fuel prices accordingly to stimulate traffic participants to reduce their fuel demand (in the closed trading scheme).

As already mentioned in the previous chapter, due to its object oriented character and the possibility of simultaneous execution of actions JAVA is nowadays one of the main programming languages for multi-agent models. Hence the following model is programmed using JAVA within the software development platform ECLIPSE, which is the usual compendium of compilers, debuggers etc. in an integrated development environment (Cuber, 2005). Together with the also within this model used JAVA library RePAST it provides a clear platform to compile multi-agent models.

5.2.1 Model schedule

Inputs of the model are households, freight forwarders, transport contracts and strongly simplified oil companies. All agents are equipped with specific characters (see appendix). Households and carriers feature a certain VMT in the base year. From this (combined with the specific fuel combustion of their corresponding vehicles) the emitted amount of CO\textsubscript{2} per vehicle and for the whole sector is calculated. Wherefrom the initial provided amount of certificates can be calculated which is in the first trading period 1.5\% higher than the calculated need of traffic participants. As already mentioned the obligated parties are the oil companies (upstream), which receive in the following years annually 1.5\% less certificates by the government. To avoid penalties they should not exceed the amount of fuel which equals the annual
amount of allocated certificates – unless they still hold the required difference of certificates form the previous trading period (banking). Contrariwise it is not allowed to transfer certificates from future periods to the current (borrowing). Thus the hypothetical certificate trading scheme has, in contrary to the EU-ETS, a trading period of one year.

As noted above two emissions trading scheme patterns can be selected by the models user. Within the open trading scheme pattern oil companies can sell in spite of the introduction of the emission trading scheme more fuel as certificates are allocated – as missing certificates can be purchased from other EU-ETS sectors. However within the closed certificate trading scheme option this is not allowed, thus oil companies have to influence fuel demand of traffic participants by raising the fuel price accordingly. Consequently, the corresponding CO₂ certificate price is considerably rising. Contrary, in the open trading scheme option the CO₂ certificate price is mainly predetermined by the certificate price of the EU-ETS and the marginal abatement costs of all EU-ETS sectors, which are considerably lower. This certificate price is represented within the model by a (adjustable) certificate price trend53 as well as a daily deviation from this trend54. If the transport sector is demanding certificates on the EU-ETS, other sectors have to abate additional amounts of CO₂ emissions. Consequently the certificate price will increase also in the open certificate trading scheme option – but significantly fewer because marginal abatement costs in other sectors are lower (TNO et al., 2006a, and BDI, 2007). In road passenger transport the costs for improving (additionally) fuel efficiency of vehicles assuming a constant preference structure of households amounts to about 700 euros per ton CO₂ for new vehicles (TNO et al., 2006a). Furthermore, improving efficiency may even induce more VMT by households because of the fall in variable costs (rebound effect – see Frondel et al., 2007).

When valuating the external effects of transport and comparing them with the actual charges for passenger cars it became obvious that charges equals to a large extend the external effects when external costs of congestion are neglected (see Figure 20). These are neglected as a charging within cities leads to a “double rebound effect” and foster urban sprawl (Rothengatter, 2003). This principle is considered in the current charging system as a kilometre on the motorway is equally charged even though external costs are much lower than in metropolitan areas (CE Delft et al., 2007). When considering an internalisation of external costs of climate change in road passenger transport one might think about lowering other charges. This is realised in the meso economic model as the initial fuel price already includes

53 The certificate price trend can be adjusted via the model interface before running the model in changing the certificate price at the end of the model run (CertPrice). The default value is a certificate price of 24.80 Euro per ton CO₂.

54 The daily price deviations within the model are taken from real historic price deviations within the EU-ETS certificate exchanges of recent years.

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a base certificate price of 22.33 euros per ton of CO₂. Any further increase in the certificate price leads however to an increase in the fuel price.

Figure 20: External costs and charges for big passenger cars in Germany (CE Delft et al., 2007)

The core of the model consists of a daily routine, which is repeated 264 times per year and thus represents each business day within a year (see Figure 21). For example, freight forwarders and household members come to the petrol pumps during a business day to refill their vehicles. They recognize the fuel price of the day and might adjust their VMT for the next few days. Freight forwarders might shift some shipments to combined transport or improve their logistics to reduce their fuel demand. From time to time households will buy a new car. If a household decides to do so, first the desired characteristics of the new car are determined such as age, performance and average fuel combustion. These wishes are then promptly met by the vehicle manufacturers. The trucks are represented in a very simplified way.

55 The households refuel on business days (mondays to fridays without national holidays) if the tank is almost empty (see appendix). Freight forwarders fill up every day.
56 The question of whether a new car is needed is raised every year in a household. If the idea is rejected, then a new car cannot be bought until the following year at the soonest. Purchases due to accidents are neglected.
57 Household can buy new cars (age is zero) or used cars from other households or dealers (age is older than one year).
within the model. They are renewed automatically and their fuel efficiency increases by about 1.5% p.a. After all the vehicles have been refuelled on a particular day, the oil companies sum up their sales and compare the amount of fuel sold with the number of certificates required to cover this. On average the difference should be zero for each year; consequently, in the model, oil companies balance their certificate account each day in order to avoid the risk of an unbalanced account at the end of the trading period. Severe penalties have to be paid for not holding enough certificates at the end of the trading period which are much higher than the certificate prices. In principle, however, it is unimportant how the emission reduction targets are achieved.

![Figure 21: Daily routine of the model](image)

In the open certificate trading scheme, the certificate price is formed within the EU-ETS. In the closed trading option, the emission reduction has to be achieved within road transport alone. Oil companies can influence the demand for fuel only by changing fuel prices. They do so by updating the estimated price elasticity of the households on a daily basis. If there is a shortage of certificates within road transport, the oil companies will raise the fuel prices so that the available certificates will balance the fuel demand at this specific price the following day. The calculated surplus equals the certificate price which would allow the oil companies to change their market shares. At the end of the year, the certificate accounts of every oil company are checked.
Figure 22: Schedule diagram of the model

An outline of the model showing the information exchanges within agent classes is depicted in Figure 22. Initially, for road freight transport, contracts are taken from the freight forwarder database of Bühler (2006) and allocated to the corresponding modes. Bulk and similar goods are not included in the model. These commodities are mainly transported by rail or inland waterways (IWW), which are beyond the scope of this model. Smaller shipment volumes and distances under 50 km are allocated directly to road transport. For all other shipments, a bivariate modal choice is made between truck and combined transport. The fuel price is considered in this discrete decision besides other variables. If the fuel price is raised, freight forwarders might decide to use more frequently combined transport. If they switch to combined transport, the demand for fuel in the road transport sector declines.

A similar approach is taken for road passenger transport. Households own and use passenger cars which generate VMT which in turn drives the demand for fuel from the oil companies. If certificate prices increase, fuel prices increase too. Households
can respond to increased fuel prices either by reducing their VMT or by buying a more efficient car. This is provided by the vehicle manufacturer.

As mentioned above, some characteristics of multi-agent models are applied within the developed model. Although only selected characteristics are implemented, the model can still be called a multi-agent model in line with Axelrod (2005:11) since it features several independent agents. When looking at the characteristics of multi-agent models introduced by Wooldridge (2002), the following conclusion can be drawn. All the agents within the model have a reaction function and are consequently reactive. These reaction functions have a unique structure within agent classes, but as the agents have different characteristics, reactions differ from individual to individual. The proactivity attribute, however, is not represented. Even if car demand might look like a proactive action from outside the model, it is still governed by predetermined equations. All decisions are made by the individual agent, so that a certain autonomy of agents is given. The social ability of agents rests solely on the implicit exchange of information between oil companies when trading certificates, as well as the exchange between oil companies, on the one hand, and households and freight forwarders, on the other, resulting from the demand for fuel and the corresponding fuel price. There is no cooperation between agents on a deeper level.

Some other attributes of multi-agent models developed by different authors are also integrated into the model. This is especially true for heterogeneity, because all the agents do differ from the other agents in the same agent class by their individual characteristics. The attributes of bounded rationality, veracity of information, dynamic adaptation, emergence of the system, perception and influence of their environment, as well as their ability to foresee for future developments are mainly fulfilled. In contrast, the following attributes are not or only partly fulfilled: complete information, all the social abilities such as knowledge, belief, intention, obligation, benevolence, consideration of emotional and canonical arguments, possible network effects, pure self interest and pure rationality as well as agent learning. The simple, structured reaction functions of the agents within the model mainly consider the attributes of incomplete information, bounded rationality as well as the ability to make decisions based on rules. The model could be further developed by improving the social ability of the agents including social networks and the learning ability of agents.

5.2.2 Classes, parameters and data structure of the model

Even if not every detail is important, the program classes, parameters and the underlying data structure make up the core of each computer model. These are presented in the following chapter, but for the sake of readability, model details are reduced to the minimum in this chapter. The interested reader is referred to the appendix for
However, all the details relevant for understanding the model are explained below.

The data used for passenger transport taken from the German Mobility Panel (MOP) have already been described in Chapter 2. These data, which represent the accomplished trips of households, reflect empirical traffic behaviour more realistically than data generated by questionnaires where hypothetical decisions have to be made ("what would you do, if …?"). Whether the affected person would really act in this way is questionable, at least for passenger transport relevant decisions, and this should be taken into account when modelling transport behaviour (Ortúzar and Willumsen, 2004:22). Even with multiple choice questions, the answers can be influenced simply by the given set of alternatives (Green et al., 1998).

For the model developed here, all households were taken from the German Mobility Panel with their corresponding passenger cars. Households display a certain VMT or fuel demand, among other things, and differ to other households by residential area and household type. The related passenger cars differ mainly by cubic capacity, age, tank size, fuel type, VMT, and the specific combustion type.

For freight transport, the data are from a database compiled as the result of a survey by Bühler (2006). This database contains a representative sample of German transport contracts of freight hauliers, the content of which corresponds to the database “Mobility in Germany” of the German Federal Motor Transport Authority. The freight forwarders in the model differ mainly with respect to company location, number of employees as well as their share of commercial employees. For each of the five hundred transport contracts, two transport possibilities are available in the database: On the one hand, the pure road transport option by truck and, on the other, a combined transport option with all the relevant characteristics (distance, durance, costs, etc.).

With regard to the certificate trading scheme, no suitable database was found for the post-2012 period as neither the flexible mechanisms of the Kyoto Protocol nor the EU-ETS have been defined for this period (see Benz et al., 2008). Even for the current EU-ETS period, price forecasts are very vague although they are possible (see, e.g. Dannenberg and Ehrenfeld, 2008). However, since the transport sector could not be included before the third trading period at the earliest, only the post-2012 period is relevant for the analysis. In the same way, the trading strategies on the new certificate market of oil companies are also very hypothetical in nature as no experiences with such trading has been made. It is even hard to predict how companies under the current EU-ETS will act, as their strategies vary widely and are sometimes discontinuous and arbitrary (Nill and Heiner, 2008). Nevertheless, as mentioned above, the attempt is made to define a certificate price which is as empirical as possible by applying a price trend which can be adjusted by the model user and a daily disturbance term.

There is a description in the appendix of all program classes (Co2Model, Co2Market, Household, Car, Carrier, Trip, FuelCompany, Db und CSVReader).
The agents and their interactions are explained below. In order to do so, the oil companies and their certificate trading within the open and the closed emission trading schemes are described to start with and then the subsequent reactions of the households and freight forwarders are outlined.

5.2.3 Price policy of oil companies

The price policy of oil companies depends on its specific interests and individual strategies and on the possible architecture of the corresponding emission trading scheme. As already mentioned, the model considers two upstream emission trading options for road transport. In an open trading scheme, oil companies\(^{59}\) can trade certificates with other sectors and countries participating in the EU-ETS, while this is not permitted in the closed trading system.

5.2.3.1 Open emission trading scheme

For both the open and the closed emission trading schemes, at the start of the simulation, the initial amount of CO\(_2\) emitted as a result of fuel combustion in vehicles on an usual day (CO\(_2\) demand of traffic participants) is estimated. This is used to estimate the initial number of emission allowances (certificates) required. The initial CO\(_2\) demand of households (\(co2DemandH\)) is determined based on the total fuel demand (\(fuelDemand\)) of the individual households. This is calculated by multiplying their VMT by the corresponding specific fuel combustion of the vehicle used (\(mileage \cdot fuelCombustion/100\)). Multiplying this by the coefficient of the CO\(_2\) emissions from the corresponding fuel (\(co2Factor\)) results in the CO\(_2\) demand (\(co2DemandH\)) of the considered household (equation (1)).

\[
co2DemandH_{t,i} = fuelDemand_{t,i} \cdot co2Factor_j \tag{1}
\]

The individual VMT, the specific fuel combustion and the fuel type are taken from the database of the German Mobility Panel. The specific coefficient used to calculate the corresponding CO\(_2\) emissions per fuel type varies between diesel and petrol. One litre of diesel emits about 2.63 kg CO\(_2\) and one litre of petrol about 2.33 kg CO\(_2\). Obviously this factor can be modified by adding biofuels.\(^{60}\)

\(^{59}\) Up to now, the obligated party has been defined as an oil company. As mentioned in Chapter 3, this is more precisely the owner of imported fuel, or the owner of fuel produced by a German refinery for sale in Germany. This then complies with the energy tax scheme, for which all the required data is already available.

\(^{60}\) The biofuels currently being added do not modify the factor considerably because the WTW analysis reveals that most of them emit comparable amounts of CO\(_2\). Future biofuels might
In road freight transport, the overall VMT of freight forwarders is \((\text{mileage}_{Q})\) calculated from the individuals’ VMT. Then it is multiplied by the specific fuel combustion of HGV \((\text{mileage}_{Q}\cdot\text{fuelCombustion}/100)\) to obtain the total fuel demand of freight forwarders. To determine the related CO\(_2\) demand of freight transport \((\text{co2Demand}_{Q})\) within the model, the fuel demand calculated is then multiplied by the CO\(_2\) content of diesel \((\text{co2Factor})\).

The total CO\(_2\) demand in road transport of a simulated working day \(t\) is then determined by adding up the two resulting CO\(_2\) demands of households and of freight forwarders (see equation (2)).

\[
\text{co2Demand}_{t} = \sum_{i=1}^{I} \text{co2Demand}_{i,t} + \sum_{q=1}^{Q} \text{co2Demand}_{q,t}
\]  

(2)

The number of certificates required by each oil company is calculated analogously by multiplying their market share \((\text{saleShare}_{m})\) by the total CO\(_2\) demand (equation (3)).

\[
\text{co2Demand}_{t,m} = \text{saleShare}_{m} \cdot \text{co2Demand}_{t}
\]  

(3)

For the certificates supplied by the government \((\text{co2Supply})\) for the initial trading period, first, this daily total CO\(_2\) demand is multiplied by the number of working days in the trading period (264) to obtain the annual total CO\(_2\) demand. Second, this total annual CO\(_2\) demand is increased by 1.5 % to guarantee an excess supply of certificates in the first year \((n=1)\) (see equation (4)).

\[
\text{co2Supply}_{n=1,m} = 264 \cdot \text{co2Demand}_{t,m} \cdot 1.015
\]  

(4)

In the following years, the number of certificates issued by the government decreases by 1.5 % per annum (see equation (5)).

\[
\text{co2Supply}_{n+1,m} = 0.985 \cdot \text{co2Supply}_{n,m}
\]  

(5)

In order to determine the available daily emission allowances for the fuel sales of individual oil companies \((\text{co2Supply}_{t,m})\), the supplied number of certificates \((\text{co2Supply}_{n,m})\) has to be divided by the number of days within the trading period. The amount of fuel sold daily by an oil company multiplied by the corresponding CO\(_2\) emission factor should not constantly exceed this emission allowance value – unless the oil company has another source for the missing certificates.

After the initial demand for and supply of CO\(_2\) certificates has been determined, these values are entered into the trading period loop of the model. This loop equals a have a much greater effect. However, the high level of uncertainty associated with the use of biofuels means that these were not considered in the model.
trading period, i.e. one year. The number of reruns can be selected by the model user to be between one and 10.\textsuperscript{61} The trading period loop is necessary to define the trading period within the model and to control the certificate accounts of oil companies and the purchasing period of vehicles by households.\textsuperscript{62}

A second loop is conducted every simulated day and thus 264 times each year. Within this working day, the oil companies might acquire or sell certificates on the CO₂ certificate market; and the households as well as the freight forwarders are able to meet their variable fuel demand. This is explained below in more detail.

To begin with, households and freight forwarders refuelling their vehicles check whether they would like to change their fuel demand. This depends on the actual fuel price which contains a volatile basic fuel price (\textit{baseFuelPrice}) and the surcharge of the certificate trading scheme (see Chapter 3) which is determined by the certificate demand of the oil companies from the previous day. This is obviously not the case for the very first day of the scheme – the certificate price is not specified for this day.\textsuperscript{63} Households then drive their VMT in line with the German Mobility Panel, and freight forwarders accomplish shipments by truck which is cheaper\textsuperscript{64} than using combined transport with respect to the current fuel price. Later on (in the evening), the oil companies compare the amount of fuel sold with the amount permitted under the emission trading scheme (target quantity $- co2Supply_{t,m}$). If the oil company constantly exceeds or falls short with regard to the number of certificates, it can either sell or has to buy certificates in order to avoid government penalties at the end of the year. However, looking at any particular day in isolation, it is entirely up to the individual company whether to buy or sell certificates or do neither. This decision depends on its appraisal of both future certificate prices and fuel volumes sold within the considered trading period. In the model, the demand strategy is simplified and all the oil companies balance their certificate accounts on a daily basis. With regard to the certificate price, it is evident that additional demand for certificates from the transport sector will reduce the number certificates in the open trading market which in turn will result in an increased certificate price. However, as explained below, within the closed certificate trading scheme, the certificate price is dependent on the price elasticity of traffic participants.

Hence, at the end of the daily loop, the fuel demand of households and freight forwarders has changed and perhaps the certificate price has, too. Any change in the latter will be due either to a certificate price alteration in the ETS, or to the altered certificate demand of oil companies. After the daily loop has been rerun 264 times, the certificate accounts of oil companies are checked and a new trading period commences until the \textsuperscript{n}th year defined by the user is reached.

\textsuperscript{61} As a default value, the model reruns 10 times – thus 10 years.
\textsuperscript{62} The certificate account of an oil company has to be balanced and the households can only buy one car each year as a maximum.
\textsuperscript{63} The certificate price of the first day is set equivalent to the certificate price of the ETS.
\textsuperscript{64} Cheaper is not only measured in monetary units but also in other beneath explained aspects of shipments.
The modelled certificate prices consist of two elements. In the open trading scheme, the price is (as already depicted) influenced by the oil companies’ demand for certificates and the price development in the EU-ETS ($baseCo2Price_{EEX}$). The latter consists of a price trend dependent on the model user and a volatile element gained from former certificate prices in the EU-ETS. Extending the EU-ETS to include road transport would increase the number of certificates by about 25%.\textsuperscript{65} Hence an increasing certificate demand by oil companies has a moderate influence on the certificate price. Based on BDI (2007), it can be deduced that an additional certificate demand of about 10 mega tons of CO\textsubscript{2} will bring about an increase in the certificate price of about 20 euros per ton due to the marginal abatement costs within the existing EU-ETS energy and industry sectors (see equation (6)). Consequently, a factor $\lambda$ can be defined, which depends on the number of households and freight forwarders configured by the model user. For the default number of households (40,000,000) and freight forwarders (18,000), $\lambda$ equals 0.0002.\textsuperscript{66} To sum up, an increased demand for certificates ($zDemand$) raises the certificate price within the whole EU-ETS by a certain amount ($co2Price_{Transp}$) (see equation (6)).

\[
co2Price_{Transp} = zDemand \cdot \lambda
\]  

(6)

The EU-ETS certificate price within the open trading scheme ($co2Price$) including road transport follows from equation (7).

\[
co2Price_t = baseCo2Price_{EEX,t} + co2Price_{Transp,t-1}
\]  

(7)

As oil companies balance their virtual certificate accounts on a daily basis ($zDemand_{t,m} = co2Demand_{t,m} - co2Supply_{t,m}$), their accounts are obviously balanced at the end of the trading period, too. The daily demand for certificates by the oil companies follows from the sum of the individual demands (equation (8)).

\[
zDemand_t = \sum_{m=1}^{M} zDemand_{t,m} = \sum_{m=1}^{M} co2Demand_{t,m} - co2Supply_{t,m}
\]  

(8)

The oil companies are informed about the certificate supply curve at the beginning of the model run. The oil companies have an incentive to reduce their consumption of certificates even in the first year as banking is allowed for one period and the oil companies can foresee the shortage of certificates in the following periods. To avoid huge price jumps between trading periods they try to pursue a con-

\textsuperscript{65} Motorised individual passenger transport emitted 110 mega tons of CO\textsubscript{2} in 2004; road freight transport 48 mega tons. The German number of EU-ETS certificates within the first trading period was equivalent to about 495 mega tons CO\textsubscript{2}.

\textsuperscript{66} For smaller number of households or carriers the value is bigger. This allows simulation runs with fewer agents without missing the effect on the EU-ETS.
stant CO₂ emission reduction in line with the certificates supplied by the government and take this into account when balancing their certificate account on a daily basis. The following relation is applied to determine this steady CO₂ emission reduction target line of the oil companies (equation (9)).

\[
\begin{align*}
co2Supply_{i,m} = \begin{cases} 
\frac{co2Supply_{n,m}}{264}, & \text{for the first half year in } n = 1 \\
\frac{co2Supply_{m} - co2Supply_{m}(0.01)(day - 132)}{264}, & \text{else}
\end{cases}
\end{align*}
\tag{9}
\]

This line is considered by oil companies according to their market shares \(\text{saleShare} \) (equation (10)).

\[
co2Supply_{m} = saleShare_{m} \cdot co2Supply
\tag{10}
\]

Due to the free allocation of certificates, the only costs incurred by the oil companies are for any additionally purchased certificates. But the oil companies still pass on these marginal costs for all of their allocated and purchased certificates to the households. This complies with the principle of opportunity costs as certificates are objects of value within the accounts of the oil companies. This generates so-called “windfall profits” as was the case within the first EU-ETS trading period for German energy companies (Sensfuß, 2008). How these windfall profits are handled by the oil companies is neglected within the model.

5.2.3.2 Closed emission trading scheme

The closed emission trading scheme does not permit certificate trading with other sectors. The initial phase is the same as in the open trading scheme. The initial CO₂ demand and CO₂ certificate supply are determined according to equations (1) to (5) above. The reactions of households and freight forwarders also remain the same. During a working day they refuel their vehicles and oil companies trade certificates with each other. Each day, after the oil companies have supplied the traffic participants with fuel, they compare the certificates used with their corresponding implicit target for the day of allocated certificates as in the open trading scheme. Once again, there are penalties assumed for an unbalanced certificate account at the end of the trading period. Within the closed trading scheme, however, the oil companies are confronted with unfavourable market conditions. As the certificates are distributed according to the market shares of the oil companies, all of them are similarly affected by the reduction of certificates. All of them will have a shortage of the same percentage of certificates, which means that intrasectoral certificate trading is not profitable in this
model as only very few (if any) modelled traffic participants change their petrol station. No oil company has the incentive to sell low-priced certificates.

Simultaneously they cannot directly influence the amount of CO₂ emissions. They can only indirectly influence this by raising the fuel price to stimulate traffic participants to reduce their fuel demand accordingly. Otherwise they have to pay penalties to the government. As the penalties are much more expensive than the certificates, the oil companies will try to use the price elasticities of traffic participants to reduce the amount of purchased fuel.

These price elasticities of traffic participants are calculated on a daily basis and help the oil companies to determine the “correct” fuel prices needed to achieve the given reduction target. If, for example, the implicit number of disposable certificates is not enough to cover the fuel demand on a specific day, the oil companies use the price elasticity calculated for the previous day to determine a higher fuel price for the next day, which should reduce fuel demand making it possible for the oil companies to balance their certificate accounts. Consequently, if price elasticities are low, the necessary price variations by the oil companies have to be high.

As in the open certificate trading scheme, the allocated number of certificates is too high. As these redundant certificates lose their validity, oil companies do not buy certificates within the first trading period. Consequently, the corresponding certificate price should be zero. It is conceivable, however, that oil companies may be permitted unilateral certificate trading with the EU-ETS even within the closed trading scheme – which might cause a certificate price of about 20 to 25 euros per ton. This price is assumed in the following.

To sum up, the oil companies require the actual price elasticities of traffic participants to determine the fuel prices (\( fuelPrice \)). If fuel prices remain constant for a day, the corresponding price elasticity is not defined. In this case, the short-term price elasticity of Graham and Glaister (2002) is assumed. Applying this value to the CO₂ price elasticity results in a value of -0.007. If, however, the fuel price does change within the considered day, the oil companies calculate the price elasticity of the fuel demand based on a rolling average of the five previous days. Thus the following equations (11) and (12) hold.

\[
\eta_t' = \begin{cases} 
-0.007 \text{ for (co2 Price}_t - \text{co2 Price}_{t-1}) = 0 \\
\frac{\text{co2 Demand}_t - \text{co2 Demand}_{t-1}}{\text{co2 Demand}_{t-1}}, \text{ else} \\
\frac{\text{co2 Price}_t - \text{co2 Price}_{t-1}}{\text{co2 Price}_{t-1}}.
\end{cases}
\] (11)

The rolling average is calculated by equation (12).

\[ \text{In the British certificate trading scheme used to increase the share of biofuels, the penalties are relatively low but the corresponding revenues are distributed to competing companies. This has a similar effect to very high penalties (Sorrell, 2003).} \]
\[ \eta_t = \frac{1}{2} \sum_{j=1}^{n} \eta'_j \]  

(12)

To conclude, the oil companies adjust the certificate price of the following day according to equation (13).

\[
\text{co2Price}_{t+1} = \begin{cases} 
\text{co2Price}_t, & \text{for } \text{co2Demand} \leq \text{co2Supply}, \\
\text{co2Price}_t + (\text{co2Supply} - \text{co2Demand}) \times \text{co2Price}_t, & \text{for } \text{co2Demand} > \text{co2Supply}, 
\end{cases}
\]  

(13)

For model trials the maximum price change for CO2 certificates is limited to 50% more than the price of the previous day.\(^{68}\) This eliminates unrealistic price changes when introducing new policies in the model.

To obtain the corresponding fuel price (fuelPrice), the certificate price in euro per ton is multiplied by the corresponding fuel specific CO2 emission factor (CO2Factors) and then the base fuel price (baseFuelPrice) is added (see equation (14)).

\[ \text{fuelPrice}_{t+1, j, i} = \text{co2Price}_t \times \text{CO2Factors}_i + \text{baseFuelPrice}_j \]  

(14)

Within the closed emissions trading scheme, only directly competing oil companies buy and sell certificates on the CO2 certificate market. A reasonable assumption, therefore, is that only very few certificates (if any) will be traded. Within the developed model, the certificate price of the closed trading scheme depends heavily on the CO2 emission reduction target. The certificate price describes the difference between the “usual” fuel price and the fuel price required to meet the reduction target taking into account the price elasticities of traffic participants (see Figure 23).

\(^{68}\) Thus the minimum (maximum) certificate price is 50% (150%) of the price of the previous day. All irregularities are displayed in the program console.
If the amount of fuel on the market is reduced below the equilibrium \((p^e \text{ and } x^e)\) to \(x^c\), the oil companies can move the traffic participants to reduce their fuel demand by increasing the fuel price from \(p^e\) to \(p^c\). This price supplement equals the certificate price \((CP)\) measured in litres of fuel. With regard to welfare, the consumer surplus \((CS)\) is reduced, while the producer surplus \((PS)\) of oil companies is increased if certificates are allocated for free. An deadweight loss \((DL)\) apparently remains. But as the external effects of CO₂ are not internalised either in fuel demand \((D)\) or fuel supply \((S)\), the change in welfare in Figure 23 depends on the marginal abatement and marginal social cost curves and on the level of the reduction target. A welfare gain is guaranteed if the reduction target is determined by the intersection of the marginal abatement and the marginal social cost curve (Baumol and Oates, 1988).

Within the model, it is assumed that oil companies try to impose a unique price for certificates and fuels which is neither underbid nor overbid by any other company due to their oligopolistic to polipolistic market situation. No change in the market shares of oil companies is expected because of the homogeneous product and the habitualised fuel demand of households. If, however, there are very few customer changes, oil companies will have to trade certificates to avoid penalties. Consequently, in these cases, the certificate price within the transport sector will be equal to the supplement on fuel prices calculated above (see Figure 24). This

69 The option to further raise the fuel price (as the only company) does not exist in a polipolistic market as sales would drop steeply.
assumes constant and uniform costs of fuel commitment and a constant marginal supply cost curve (within the relevant amounts) for all oil companies. Furthermore, as in the open trading scheme, the oil companies try to balance their certificate accounts on a daily basis.

Figure 24: Change of fuel provider by a traffic participant within the closed emissions trading scheme

To explain how the certificate price comes about within the closed trading scheme, it is first assumed that c.p. customers change their fuel providers. As a result, on the one hand, one oil company (certificate seller) registers a fuel demand decrease with a corresponding certificate surplus and, on the other hand, another oil company (certificate buyer) registers a fuel demand increase with a corresponding certificate shortage (see Figure 24). The certificate buyer then has to purchase certificates and is willing to pay its marginal profit ($CP$) at the maximum. The certificate seller has sold one unit less of fuel and saved costs amounting to $C$. Thus he missed making a profit amounting to $CP$. He would like to be reimbursed by this amount; i.e. both agents agree to certificate trading at the above determined certificate price.

5.2.4 Reaction behaviour of freight forwarders

In an ideal shipment (see Ewers and Holzhey, 1998), the shipper issues a shipment contract with the freight forwarder or directly with a carrier. The freight forwarder (see German Commercial Code §§453 and 454) schedules the optimal transport which is finally accomplished by a carrier (see German Commercial Code §425). In this ideal theoretical shipment, therefore, the freight forwarder is responsible for the modal choice. In reality, this might be very different. Shippers and freight forwarders usually have access to their own transport vehicles and carriers also delegate shipments to other carriers (German Transport Forum, 2001). As a result, in
real life, there are many hybrid combinations of shippers, freight forwarders and carriers. Within the developed model, however, it is assumed that all of them have a similar cost structure and preferences with respect to the modal choice; the modal choice of freight forwarders is taken as representative for all (see Bühler, 2008)\(^\text{70}\) and only freight forwarders are therefore exemplarily considered in the model.\(^\text{71}\)

The modal choice of freight forwarders is an individual, case-specific decision. The decision might apply to a specific single shipment or to a repeated transport at periodic intervals. Freight forwarders consider the specifications of the shipper as well as their own preferences when making the choice, e.g. with regard to the loading capacity of their trucks, the logistic combination possibilities with other shipments, but also with regard to the state of knowledge about the possibilities of combined transport for the considered contract.

Freight forwarders have two main alternatives concerning modal choice: They can transport the shipment purely by road, or by combined transport. All the other potential transport chains (see Figure 25) have much smaller shares (Bühler, 2006:51). According to Bühler (2006) and Walter (2006), combined transport is a preferable alternative to unimodal road transport because, on the one hand, most companies no longer have direct access to other modes and, on the other, broken transport chains (where commodities are individually transhipped) generally has higher loading costs than combined transport. Unimodal transport may be conceivable for some smaller volume, long-distance shipments where goods are collected from the production location by small truck and then transported to the destination region where they are unloaded and then loaded for distribution by small trucks, again. However, this option has a much smaller CO\(_2\) emission reduction potential.

The analysis of modal choice and the possibilities to reduce CO\(_2\) emissions through an appropriate modal choice by freight forwarders has to consider empirical shipments in the ex post perspective. Numerous previous surveys only compared combined transport and unimodal road transport for selected relations such as, e.g. Frankfurt to Hamburg (UIRR et al., 2001). They concluded that there are considerable market potentials for combined transport with significant advantages for their customers. However, due to the geographical structure of urban development in Germany, many shipments are not restricted to the main transport corridors. Instead, shipments tend to be diffusely distributed throughout the country. As a result, the advantages are not as pronounced outside these main transport corridors. The regional stratified survey of German freight forwarders by Bühler (2006) actually provides a more realistic picture of their modal choice.

\(^{70}\) There are considerable differences concerning the modal choice of freight forwarders who are not able to load their trucks to capacity – combined transport is much more expensive than an idle truck (further differences in Bühler, 2006:36ff).

\(^{71}\) A correction factor in the model guarantees that the sum of modelled CO\(_2\) emissions of freight forwarders matches the emissions of road freight transport as a whole.
In the survey by Bühler (2006), 3,000 freight forwarders participated in telephone interviews. These freight forwarders were asked to describe a recent company-typical shipment in detail. The term ‘typical’ might apply to the transport origin-destination-relation, its frequency, its regularity or to other attributes.

Care was taken to obtain a representative sample of forwarders for Germany both with regard to geographical location and number of employees. The aim of the study was to find statistical-based evidence for the modal choice of German freight forwarders. Dividing the forwarders into West and East Germany was considered appropriate because of the different densities of combined transport terminals in each region. A classification into small and large companies was also made due to their different operational background. Large companies usually have greater knowledge of and experiences with combined transport supply. However, most of the freight forwarders are actually in the classes of small and very small companies.

716 freight forwarders completed the survey. Due to the different general conditions for the shipments (e.g. the distance should be longer than 150 km) or missing data, some freight forwarders were excluded from further analysis. In the end, 498 questionnaires were used for the regression.
Table 1: Population and relevant interviews from the freight forwarder survey by Bühler (2006)

<table>
<thead>
<tr>
<th>Employees</th>
<th>Population</th>
<th>Relevant interviews</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N = 6,924</td>
<td>N2 = 498</td>
</tr>
<tr>
<td>3-49</td>
<td>6,924</td>
<td>3-49</td>
</tr>
<tr>
<td>≥ 50</td>
<td>498</td>
<td>≥ 50</td>
</tr>
<tr>
<td>Sum</td>
<td>74.7%</td>
<td>74.7%</td>
</tr>
</tbody>
</table>

Table 1 presents the population of all German freight forwarders and the number of interviews used for the regression. It shows that the distribution with regard to the company location corresponds with the population. However, a slight difference can be observed concerning company size.

Usually freight forwarders, as the organisers of shipments, are considered to be mode neutral, i.e. they are supposed to make an objective decision about the most appropriate mode for each shipment. The decision is based on comparing the available transport modes’ utilities. The utility is determined by several variables, e.g. the modal choice is made according to the following determinants:

- the different requirements of the shipper and the combined transport operators concerning transport volume, the departure time or duration,
- the related costs of transport, and
- the respective quality standards.

Ultimately, freight forwarders will choose the transport mode which best matches the shipment’s requirements. The decision between the available transport modes can be determined by applying an econometrical method. Discrete choice models reproduce the correlation between the observed modal choice and its determinants by implicitly assigning utilities to the available options.

Within the given dataset, the surveyed freight forwarders use their own trucks for about 59% of all shipments. 26.3% of freight forwarders order a carrier to accomplish the shipment. 70% of these are German carriers, the other 30% are from other European countries. Only 14.5% of freight forwarders used combined transport as a typical transport. Of these, about 69% used the combination road-rail, 26% the combination truck-ship and 5% a trimodal transport. 32% of combined transports and 39.5% of road transports were done using the mode determined by the shipper’s requirements. All other modal decisions were autonomously made by the freight forwarder.

Within the survey the share of road transport and that of combined transport differ considerably depending on the origin-destination relation. While the share of combined transport in national transport is about 6%, it is in the main European combined transport corridors (especially southern Europe) up to 26% (UIRR et al., 2001). Foreign truckers are only employed in international transport in the survey – in particular in shipments to Eastern Europe (48% of all transports here). Furthermore, the survey results corroborate the hypothesis that the share of combined
transport increases with the distance involved. While its share is only 5.7% of all shipments falling into the distance class between 150 and 500 km, it accounts for 20.1% in the distance class of more than 500 km.

Table 2: Modal choice elasticities of freight forwarders (Bühler, 2006)

<table>
<thead>
<tr>
<th>Explanatory variables</th>
<th>All freight forwarders</th>
<th>Large freight forwarders</th>
<th>Small freight forwarders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport distance</td>
<td>0.84</td>
<td>1.06</td>
<td>1.23</td>
</tr>
<tr>
<td>Frequency of CT</td>
<td>0.23</td>
<td>0.25</td>
<td>0.28</td>
</tr>
<tr>
<td>CT direct link dummy</td>
<td>0.09</td>
<td>--</td>
<td>0.11</td>
</tr>
<tr>
<td>Transport duration of CT</td>
<td>-0.46</td>
<td>-1.06</td>
<td>-0.48</td>
</tr>
<tr>
<td>Costs per km in CT</td>
<td>-1.20</td>
<td>-0.89</td>
<td>-1.49</td>
</tr>
<tr>
<td>Costs per km in road trans-</td>
<td>0.74</td>
<td>0.78</td>
<td>0.80</td>
</tr>
</tbody>
</table>
metre increases the probability for using combined transport). Combined transport is much more sensitive to changes in costs than unimodal road transport.

The modal choice of freight transport in the model developed here is based on the data depicted above and the nested logit model (equation (16)) according to Bühler (2006). As already stated, it is assumed that shippers and carriers make their modal choice decision according to the results for the surveyed freight forwarders.

Within the model, the modal choice of road freight transport has the following structure. Each day the freight forwarders accomplish transports according to the freight contracts received. Every forwarder receives one (typical) freight contract which is duplicated depending on the number of employees. Freight forwarders with more than 15 employees carry out the freight contract twice, those with more than 25 employees three times, etc. (see equation (15)).

\[
\text{repetitions} = \begin{cases} 
1 & \text{for } 1 < \text{employee}_{i} < 14 \\
2 & \text{for } 15 < \text{employee}_{i} < 24 \\
3 & \text{for } 25 < \text{employee}_{i} < 34 \\
\text{etc.} & \end{cases} \tag{15}
\]

Initially, the contracts, which are taken from the survey by Bühler (2006), are split into three categories according to distance, weight and volume. The first category covers commodities which are usually shipped directly by rail or ship or at least by combined transport. These are heavy commodities with high densities (bulk goods) or certain commodity classes (IVS et al., 2003). These are neglected in the model. In contrast, the third category covers light and expensive goods with a fast turnover which require rapid delivery. About 80% of the shipments in this category are transported less than 50 km for which combined transport is not suitable. All other shipments are grouped in the second category where freight forwarders have (in principle) the possibility to choose combined transport. Again, this modal choice is made within the developed model according to the logit model by Bühler (2006) as explained below.

The artificial freight forwarders in the model are generated from the data set of real forwarders. Similar to households, the freight forwarders can reduce their fuel demand by reducing their trucks’ VMT, by changing transport mode, or by optimising the fuel efficiency of their vehicle fleet\(^{72}\). In the model, the trucks are represented in a simplified way by a truck pool. This pool can be used by each forwarder and consists of identical trucks with the same specific fuel combustion. Each truck accomplishes one shipment per day. The trucks are assumed to be updated continuously and automatically by improving the uniform energy efficiency of the specific fuel combustion by 1.5% per year. Initial fuel consumption is 32 litres per 100 km

\(^{72}\) As logistics improvements are not considered in this behavioural model, they could be implicitly assumed within the improvement of fuel efficiency of vehicles. A net-based model would be more convenient (Liedtke, 2006).
so that after a model run of 10 years, the specific fuel consumption decreases to 27.5 litres. This initial fuel consumption corresponds to the average value in the survey by Bühler (2006).

The modal choice decision between road and combined transport is made for each freight contract according to the logit model from Bühler (2006) (see equation (16)). In equation (16), a value of $CT_{\text{Truck}} > 0$ results in a shipment by combined transport and values below zero mean that road transport is chosen (see equation (20)).

$$CT_{\text{Truck}} = \begin{cases} 
-2.401 - 0.092 \text{ost} + 0.0000298 \text{employee} + 0.509 \text{clerkShare} + 0.003 \text{truckKmTruck} - 1.412 \text{trailer} + 0.049 \text{transpVolume} - 0.133 \text{dangGood} - 0.091 \text{perishGood} - 0.38 \text{fragGood} + 0.371 \text{stockLog} - 0.831 \text{tracking} - 0.193 \text{liability} + 0.4 \text{priceVolume} - 0.24 \text{pairing} + 0.046 \text{partnerAtDest} + 0.001 \text{numberOfTransports} + 0.005 \text{timeForScheduling} + 0.002 \text{justInTime} + 0.083 \text{pulsing} + 0.675 \text{directTransport} - 0.021 \text{durationCT} - 0.027 \text{durationTruck} - 2.081 \text{costsCTPerKm} + 1.473 \text{costsTruckPerKm} + 0.009 \text{delayCT} - 0.038 \text{delayTruck} & \text{for truckKmTruck} > 50 \\
-1, \text{for truckKmTruck} \leq 50 
\end{cases}$$

The modal choice decision is dependent on many variables. On the one hand there are determinants on the company side. These are primarily the geographical location dummy $\text{ost}$, the number of employees $\text{employee}$ as well as the share of office workers $\text{clerkShare}$. There are many more determinants referring to the shipment itself; there are the contractual requirements, the existence and quality of alternative modes, and the characteristics of the commodity to be transported. All the variables are shown in Table 3.

Within the model, all the shipment and freight forwarder characteristics remain the same during the simulation, only the combinations of assignments differ. The variable costs of road transport ($\text{costsTruckPerKm}$) is the decisive influencing parameter. This changes related to changes in the price of diesel and influences the modal choice of freight forwarders accordingly. If the price of diesel increases, the costs of road transport ($\text{costsTruckPerKm}$) increase, too (see equation (17)). As $\text{costsTruckPerKm}$ have a positive sign in equation (16), this also has a negative impact on the modal choice variable $CT_{\text{Truck}}$. This results in an increasing number of shipments being shifted to combined transport.

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73 In statistics, boolean variables are called dummy variables. Here, the variable is one if the headquarters of the freight forwarder is in former East Germany and zero if it is located in West Germany.
Table 3: Variables influencing the freight forwarder’s modal choice (Bühler, 2006)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ost_{i,j}</td>
<td>boolean</td>
<td>Dummy for headquarter in East Germany</td>
</tr>
<tr>
<td>employeet_{i,j}</td>
<td>integer</td>
<td>Number of employees</td>
</tr>
<tr>
<td>clerkShare_{j,i}</td>
<td>double</td>
<td>Share of office workers</td>
</tr>
<tr>
<td>truckKmCT_{r}</td>
<td>double [km]</td>
<td>VMT of trucks for pre- and post-haulage in CT</td>
</tr>
<tr>
<td>truckKmTruck_{r}</td>
<td>double [km]</td>
<td>VMT of trucks during road transport</td>
</tr>
<tr>
<td>trailer_{r}</td>
<td>boolean</td>
<td>Dummy for trailer use</td>
</tr>
<tr>
<td>transpVolume_{r}</td>
<td>double [t]</td>
<td>Transport volume</td>
</tr>
<tr>
<td>dangGood_{r}</td>
<td>boolean</td>
<td>Dangerous commodity</td>
</tr>
<tr>
<td>perishGood_{r}</td>
<td>boolean</td>
<td>Perishable commodity</td>
</tr>
<tr>
<td>fragGood_{r}</td>
<td>boolean</td>
<td>Fragile commodity</td>
</tr>
<tr>
<td>stockLog_{r}</td>
<td>boolean</td>
<td>Storage and logistics is assigned to the freight forwarder</td>
</tr>
<tr>
<td>tracking_{r}</td>
<td>boolean</td>
<td>Package tracking is part of the contract</td>
</tr>
<tr>
<td>liability_{r}</td>
<td>boolean</td>
<td>Liability is part of the contract</td>
</tr>
<tr>
<td>priceVolume_{r}</td>
<td>boolean</td>
<td>Transport price and quantity included in contract</td>
</tr>
<tr>
<td>pairing_{r}</td>
<td>boolean</td>
<td>Dummy for symetric transport</td>
</tr>
<tr>
<td>partnerAtDest_{r}</td>
<td>boolean</td>
<td>Dummy for partner company at destination</td>
</tr>
<tr>
<td>numberOfTransports_{r}</td>
<td>integer</td>
<td>Number of transports on the relation involved</td>
</tr>
<tr>
<td>timeForScheduling_{r}</td>
<td>double [hours]</td>
<td>Period between assignment of forwarder and collection of goods by shipper</td>
</tr>
<tr>
<td>justInTime_{r}</td>
<td>boolean</td>
<td>Dummy for just-in-time transport</td>
</tr>
<tr>
<td>pulsing_{r}</td>
<td>integer</td>
<td>Frequency of CT connections per week</td>
</tr>
<tr>
<td>directTransport_{r}</td>
<td>boolean</td>
<td>Dummy for ramp-to-ramp transport with rail or IWW</td>
</tr>
<tr>
<td>durationCT_{r}</td>
<td>double [hours]</td>
<td>Transport duration of CT</td>
</tr>
<tr>
<td>durationTruck_{r}</td>
<td>double [hours]</td>
<td>Transport duration of road transport</td>
</tr>
<tr>
<td>costsCTPerKmTAB_{r}</td>
<td>double [euro/km]</td>
<td>Transport costs of CT per km</td>
</tr>
<tr>
<td>costsTruck-PerKmTAB_{r}</td>
<td>double [euro/km]</td>
<td>Transport costs of road transport per km</td>
</tr>
<tr>
<td>delayCT_{r}</td>
<td>double [%]</td>
<td>Length of delay of CT</td>
</tr>
<tr>
<td>delayTruck_{r}</td>
<td>double [%]</td>
<td>Length of delay of road transport</td>
</tr>
</tbody>
</table>
The variable of road transport costs (\(\text{costTruckPerKm}\)) from equation (16) consists of the value of the survey, \(\text{costsTruckPerKmTAB}\), and a model-specific summand. The latter depends on the actual fuel price and the specific fuel combustion of the truck fleet (see equation (17)).

\[
\text{costTruckPerKm}_{t,r} = \text{costsTruckPerKmTAB}_{t,r} + \left(\frac{\text{fuelCombustion}}{100}\right) \cdot \left(\frac{\text{fuelPrice} - 1.14}{100}\right)
\] (17)

The fuel price-dependent summand considers the fuel price supplement due to the certificate trading scheme. For instance, a certificate price of 40 euros per ton of CO\(_2\) would cause transport costs (\(\text{costTruckPerKm}\)) to increase from 1.11 euro to 1.14 euro per truck kilometre.

At the same time, combined transport is also affected by the increased certificate price both directly and indirectly: Indirectly because rail transport consumes either electricity, which is already included in the EU-ETS, or diesel which is now covered by the trading scheme implemented in the transport sector. And directly because the costs of pre- and post haulage by truck also have to be considered. This is included in the model by the following equation (18).

\[
\text{costCTPerKm}_{t,r} = \text{costsCTPerKmTAB}_{t,r} - 0.01 + \left(\frac{\text{co2Price}}{25}\right) \cdot 0.01
\] (18)

If the certificate price is 25 euros, the increase in the variable costs of combined transport (\(\text{costCTPerKm}_{t,r}\)) calculated by the model equals about one euro-cent per kilometre. Due to the linear function, a certificate price of 50 euros leads to a supplement of two euro-cents per kilometre.

As already mentioned, fleet modernization in the model is represented in a very simplified way. The fuel efficiency of the uniform truck fleet increases by 1.5 % per year (see equation (19)).

\[
\text{fuelCombustion}_{n,t,l} = \text{fuelCombustion}_{n-1,t,l} - \left(\text{fuelCombustion}_{n-1,t,l} \cdot 0.015 \cdot \frac{t}{264}\right)
\] (19)

To calculate the daily CO\(_2\) emissions of freight transport, firstly all the freight contracts of the considered day are allocated to their corresponding mode in line with equation (16) by using the mode dummy \(\text{CTTruckD}\) according to equation (20). This means that if the \(\text{CTTruck}\) value is below zero, the shipment is accomplished by truck and if the \(\text{CTTruck}\) value is equal to or greater than zero, combined transport is used.

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74 Besides technical improvements, further measures such as improved logistics could be applied.
The VMT of trucks (\(mileage_{eq}\)) can be calculated by adding up all the mileage of all the trucks (\(l = 1 \cdots L\)) used on that day (see equation (21)). This includes both the VMT of trucks used for pure road transport (\(truckKmTruck_{l,t}\)) as well as the VMT of trucks used for pre- or post-haulage in the combined transport chain (\(truckKmCT_{l,t}\)).

\[
mileage_{eq} = \sum_{l=1}^{L} truckKmCT_{l,t} \cdot kvTruckD_{l,t} + truckKmTruck_{l,t} \cdot (1 - kvTruckD_{l,t})
\]

All trucks are directly refuelled after use so that the diesel demand of freight forwarders on a particular day can be calculated by multiplying the VMT of trucks by their specific diesel combustion per kilometre (\(fuelCombustion_{l,n} / 100\)). The corresponding CO\(_2\) emissions can then be calculated by multiplying this value by the CO\(_2\) emission factor of diesel (\(co2Factors_5\)). This equals the CO\(_2\) demand of freight forwarders, i.e. the emissions due to the road freight transport of the day (\(co2Demand_{Q,t}\)) (see equation (22)).

\[
co2Demand_{Q,t} = co2Factors_5 \cdot (fuelCombustion_{l,n} / 100) \cdot mileage_{eq}
\]

The model assumes that the number of freight contracts increases by 1.5 % per year. This attempts to capture the growth in road freight transport forecasted by Progtrans (2007). As, at the same time, the specific fuel consumption decreases by 1.5 %, ceteris paribus,\(^\text{75}\) it is assumed that the CO\(_2\) demand of road freight transport remains more or less on the same level.

In conclusion, the price elasticity of freight forwarders’ fuel demand cannot be derived directly from equation (16), but has to be calculated from the sum of shipment-specific modal choices.

5.2.5 Reaction behaviour of households

The reaction of households to increased fuel prices is strongly influenced by several variables. Personal attitudes and the different possibilities and limitations of individuals play a large role here. Consequently traffic participants in road passenger

\(^{75}\) In particular assuming that fuel prices remain constant.
transport vary considerably in their reactions to changed fuel prices. Within the developed model, most of the behavioural rules governing traffic participants are based on statistical regressions which reflect the group-specific characteristics of the German mobility panel (GMP). This has the advantage that the model realistically represents the basic population with an appropriate model architecture and calibration.

The regression results support the hypothesis that traffic participants react individually to changed fuel prices and also show that other signals often outweigh price signals. For instance, job changes, a new hobby or moving house have a much stronger influence on fuel demand than a fuel price increase. It is therefore essential to consider individual socioeconomic variables in the regression in order to realistically depict road passenger transport.

Recently, there have frequently been macroeconomic assessments of fuel price elasticities but these have shortcomings due to the above mentioned heterogeneity of traffic participants. Furthermore the financial impacts on households differ considerably. Nevertheless, macroeconomic price elasticities may provide plausibility checks for microeconomic models.

The concept of elasticity goes back to the British economist, Alfred Marshall (1842 – 1924) and his publication of 1890 (Marshall, 1920). Elasticity indicates the ratio of the relative change in a variable to the relative change of another parameter (see equation (23)). Succinctly expressed, the determined price elasticity of transport demand is the percentage change in transport demand if fuel price increases by one percent. If the price elasticity of transport demand is -0.5, this means demand would fall by 0.5% if the fuel price increased by one percent.

\[
\varepsilon = \frac{N_2 - N_1}{U_2 - U_1} = \frac{N_2 - N_1}{U_2 - U_1} \cdot \frac{U_1}{N_1}
\]

(23)

There is a large body of literature pertaining to studies quantifying the price elasticity of road passenger transport. Blum et al. (1988), Drollas (1984) and Oum et al. (1992) represent older assessments of elasticities and distinguish between long- and short-term elasticities. Short-term elasticities are generally smaller and not statistically significant for many regressions. Another study is that by Kremers et al. (2002) who assess the different elasticities using an equilibrium model. In this respect, the paper by Sterner and Dahl (1992) is also worth mentioning. They estimated different fuel demand elasticities for 21 OECD states. Goodwin (1992) examines the different statistical approaches and highlights the differences in their results. Rouwendal and de Vries (1999a) estimated statistical random effects using a panel regression model for the Netherlands and differentiated trip purposes among other variables. They concentrated their analysis on the two years (1986 and 1991) when the national petroleum tax was increased. Commercial transport was excluded from the calcula-
tion as this is supposed to have a price elasticity of (close to) zero. This would only dilute the price elasticities of private households. This hypothesis was able to be corroborated by Rouwendal and de Vries (1999a) and they obtained price elasticities of private transport between -0.44 and -0.65 which are significantly above the average value of about -0.2. In addition, they applied a fixed effects panel regression model using the same data. Surprisingly, this did not support the hypothesis. One possible explanation is the short time axis of two years which makes the fixed effects panel model hard to apply (Frondel et al., 2007:14f). Furthermore some person-specific characteristics seem to differ between these two observations. Besides these elasticities, the authors also identified a dependency on the absolute price level: a low price level leads to inelastic fuel demand and a considerable price increase significantly boosts the elasticity of households. An exception to this is the study by the German Federal Ministry of Transport, Building and Urban Affairs (BMVBS, 2000), which identified an inelastic demand structure even for huge price changes. Assuming a simultaneous decrease in rail passenger transport costs of 30 % and a user cost increase of 70 % in road passenger transport resulted in a VMT decrease in individual road passenger transport of about 11.5 %. This equals a price elasticity of -0.16. In road freight transport, a user cost increase of 14 % led to a modal shift of 10 % if rail user costs were reduced simultaneously by 18 % and further policy measures were implemented.

Besides differences due to the fuel price level, price elasticities may also vary between different points in time. Espey (1998) shows that the short-term elasticities declined considerably with regard to the 1970s, while long-term elasticities have tended to increase. A comprehensive overview of the current literature on the fuel price elasticities of households is given by Graham and Glaister (2002). From their description, it becomes apparent that the values of elasticities differ considerably and that some studies even calculate positive price elasticities. Short-term fuel price elasticities lie between -2.13 and +0.59 with a mean of -0.25 and long-term price elasticities lie between -22.0 and +0.85 with a mean of -0.77. The huge variance in the results may be due to their different points in time, differences in their method of collecting data as well as differences in the applied statistical methods. Another explanation is that these different results reflect the heterogeneity of household reactions to increased fuel prices. It can be concluded that a very comprehensive database is required to estimate reliable fuel price elasticities. The calculated price elasticities of about zero are sometimes put forward as an argument for the strong car dependency of households. However, Zumkeller et al. (2005) argue that the ‘objective’ car dependency of German households is about 23 % in the trips accomplished. Instead, it can be argued that the small fuel price elasticities show that traffic partici-

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76 This can be partly confirmed for Germany (Wermuth, 2006) where the share of commercial transport in annual total transport involving cars registered in Germany is about 30 %. If this share is assigned to VMT, it is about 10 %.

77 Also assumed were a user cost increase of 18 % for aviation and a decrease of 25 % for inland waterways.
pants react to a price increase not by reducing VMT, but rather by increasing their mobility budget (Zumkeller et al., 2005: 31).

Figure 26: German average nominal consumer prices of fuels between 1970 and 200878 (MWV, 2001)

Another reason for varying results is the tiny price volatility of fuel prices over recent years. Although nominal fuel prices have tripled over the past three decades (see Figure 26), real prices have remained relatively constant, only interrupted by considerable price changes of more than 10% in 1974, 1981, 1986, 1989, and 2000 (see Figure 27).

78 Since 1990, fuel prices of reunified Germany are displayed, before then only prices for former West Germany.
As already highlighted, individual price elasticities might differ considerably from aggregated elasticities. Hence it is necessary to consider individual characteristics when estimating the impact of increasing fuel prices on individual households. Furthermore, the efficiency of the regression can be increased by using panel data (Hautzinger et al., 2004).

5.2.5.1 Regression of Hautzinger et al. (2004)

Hautzinger et al. (2004) analysed changes in individual mobility behaviour as a result of raised fuel prices. The focus was on VMT. The authors identified that German households are strongly individualistic and that there are very complex factors influencing their behaviour.

First, they estimated a classical linear regression model using data from the German Mobility Panel (GMP). The regression equation consists of the daily VMT per vehicle as the dependent variable and the fuel price, household size, number of children and vehicles in the household as well as the age of the vehicle and cylinder capacity of the engine as the explanatory variables (Hautzinger et al., 2004:109ff). With more than 2,000 observations, the corresponding coefficient of determination ($R^2$) is 0.11. But, although the variables forebode heteroscedasticity or

79 Since 1990, fuel prices of reunified Germany are displayed, before then only prices for former West Germany.
multicollinearity no corresponding test statistics was applied. However the regression results turn out as expected with regard to their significance and sign.

In order to take into account the individual-specific characteristics of households and vehicles, the authors applied a fixed effects panel regression. In doing so, they distinguished between households and vehicles and discovered that some vehicles react much more elastically than households (Hautzinger et al., 2004: 114).

Instead of using a Hausman test to determine the suitable regression method, the usual procedure in this context, the authors estimated also a random effects panel model. Furthermore they logarithmised the variables for this regression and added extra variables. This renders a comparison of both regression results impossible but the fixed effect regression seems to be more convenient here because there are so many unobservable individual-specific parameters influencing the decision. However, the short time axis suggests rather the random effects model (Frondel et al. 2007:14f).

The explanatory variables included the fuel price, number of household vehicles, vehicle age, four different household types\(^80\), number of holiday trips during the survey, fleet structure of the household\(^81\) and type of neighbourhood. Furthermore the authors again distinguished households and vehicles. Again, no statistical tests were run for multicollinearity or heteroscedasticity. Additionally no corresponding coefficient of determination is displayed.

All the regression results from Hautzinger et al. (2004) indicate a fuel price elasticity of German households ranging between -0.1 and -0.6. The hypothesis that households have increasing mobility budgets, which was originally suggested in Zumkeller et al. (2005), is supported by these results as an increase in fuel prices causes budget cuts in other areas of consumption. Another finding is that cross price elasticities with regard to public transport are very small and people do not use public transport instead of their own private vehicles (Hautzinger et al., 2004: 202).

The authors criticised that their applied database, the German Mobility Panel (GMP), was missing the variables of average fuel expenditures of the household and income which have since been integrated (from 2001). A similar regression was calculated by Vance and Buchheim (2004) but with a focus on gender differences.

5.2.5.2 Regression of Frondel et al. 2007

Frondel, Peters, and Vance (Frondel et al., 2007) also performed a regression using GMP data. They focused on the rebound effect, a phenomenon known from the

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\(^80\) The four household types distinguished are (1) 1 to 2 person households with employed person(s), (2) 1 to 2 person households without employed persons (in particular pensioners), (3) households with children under the age of 18, and (4) households without children and more than two adults (in particular shared accommodation).

\(^81\) The authors distinguish three vehicle fleets: One without powerful vehicles (cylinder capacity > 1,600 ccm), one with only powerful vehicles, and a mixed vehicle fleet.
electricity sector, which in transport describes the possible increase in VMT due to more fuel efficient vehicles (among others, see Khazzoom, 1980, and Binswanger, 2001). This effect is triggered by the reduction in variable costs per kilometre due to more efficient cars which results in households taking a more relaxed approach to VMT due to the cheaper mobility and squandering some of the fuel they could have saved due to the efficiency gain.

Frondel et al. applied three different models82 using GMP data. Fixed, between, and random effects estimators were calculated for all three models. For the issue of interest here, the fixed effects estimator seems to be the most appropriate as this accounts for unobservable parameters using an individual specific constant. Contrawise, the application of the fixed effects model is inappropriate because the households are only in the panel for a short time period of three years (Frondel et al., 2007:14f.).83 One of the three models uses the monthly VMT of households as the dependent variable and is therefore appropriate to be used in the developed meso economic model.

The model has the following regression equation (Frondel et al., 2007:13).

\[
\ln(kmit) = \alpha_0 + \alpha_\mu \cdot \ln(\mu_{it}) + \alpha_{pe} \cdot \ln(pe_{it}) + \alpha_x \cdot x_{it} + \xi_i + \upsilon_{it} \tag{24}
\]

The logarithmical monthly VMT of households \((kmit)\) depends on the logarithmised specific fuel consumption of the used vehicle \((\mu_{it})\) as well as the corresponding logarithmised fuel price \((pe_{it})\). The indices \(i\) and \(t\) stand for the included households and years, respectively. Eight other control variables are included in the model and represented in equation (24) by \(x_{it}\). These variables are the vehicle age, a premium-vehicle dummy84, a diesel dummy, household size85, the number of persons educated to secondary school standard (High-school diploma – \(HSD\)), the number of employed people, a dummy for a holiday trip by car during the survey period, and a dummy for children. Besides these control variables, two error terms are considered: one represents the unknown individual-specific characteristics of households \((\xi_i)\) and the other varies through time \((\upsilon_{it})\).

As in Hautzinger et al. (2004), the German Mobility Panel is used as the underlying database. However two older observations (1995 and 1996) were omitted and two new observations were added (2004 and 2005). Furthermore, only those households were considered which participated in the survey two or three times and which

82 Frondel et al (2007) try to overcome the three different types of the rebound effect applied in the literature (among others, Khazzoom, 1980, and Binswanger, 2001).
83 The data set contains 574 households which participated in the panel survey two or three times. The time axis does not refer to the nine survey periods, but to the three years considered.
84 In statistics, boolean variables are called dummy variables. The premium-vehicle dummy takes the value one if the vehicle is a premium car; otherwise it takes the value zero. It is a premium car if it is an Audi, BMW, Mercedes or Alfa Romeo, or has an engine performance of more than 120 PS for diesel vehicles, or more than 150 PS for petrol vehicles.
85 The household size is measured by the number of permanent household members.
own exactly one car. Unfortunately, a trend variable to consider other year-specific impacts or the trend was not considered even though Espey (1998) already depicted these different fuel price elasticities over time.

Table 4: Results of the fixed effects panel regression by Frondel et al. (2007)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln (specific fuel consumption)</td>
<td>**0.582</td>
<td>0.122</td>
</tr>
<tr>
<td>ln (fuel price)</td>
<td>**-0.615</td>
<td>0.164</td>
</tr>
<tr>
<td>Vehicle age</td>
<td>-0.01</td>
<td>0.006</td>
</tr>
<tr>
<td>Diesel dummy</td>
<td>-0.24</td>
<td>0.183</td>
</tr>
<tr>
<td>Premium-vehicle dummy</td>
<td>0.145</td>
<td>0.146</td>
</tr>
<tr>
<td>Household size</td>
<td>-0.019</td>
<td>0.05</td>
</tr>
<tr>
<td>Number of HSD</td>
<td>-0.013</td>
<td>0.056</td>
</tr>
<tr>
<td>Number of employed persons</td>
<td>**-0.133</td>
<td>0.046</td>
</tr>
<tr>
<td>Holiday dummy</td>
<td>**0.27</td>
<td>0.036</td>
</tr>
<tr>
<td>Children dummy</td>
<td>-0.087</td>
<td>0.116</td>
</tr>
<tr>
<td>Constant</td>
<td>**8.12</td>
<td>0.283</td>
</tr>
</tbody>
</table>

Note: * denotes significance at the 5 %-level and ** at the 1 % level, respectively. Source: Frondel et al. (2007:19)

The regression results of the fixed effects model display the expected signs and are significant regarding individual parameters and the regression equation ($\chi^2 = 0.00$). The specific fuel consumption of a passenger car has a significant, positive influence on the corresponding VMT and a negative influence on the fuel price as expected. The vehicle age, the diesel dummy, the premium-vehicle dummy, the household size, the number of persons educated to secondary school standard (HSD) and the children dummy are not significant in the fixed effects model. The number of employed household members has a significant negative influence on the VMT and the holiday dummy has a positive impact (see Table 4). The accomplished Hausman test (Hausman, 1978) shows that the estimators in the fixed effects model and the random effects model differ significantly.

This is supported by the results of the random effects model. They are similar to the results from the fixed effects model (see Table 5). Again, the specific fuel consumption has a significant, positive influence on the corresponding VMT and the fuel price a negative impact. Only vehicle age has a significant negative influence on VMT, all the other variables have a positive impact. The dummies for diesel and children are not significant.

A modified Hausman test for each variable only reveals a significant different impact on VMT between the fixed effects and the random effects models for the number of employed persons (see last column of Table 5). This means that the num-

86 In the between effects model applied, car age shows a negative impact and the premium vehicle dummy as well as the number of high-school diplomas have a positive impact.
ber of employed household members has a negative influence on VMT in the fixed effects model and a positive one in the random effects model. This is due to differences in time and differences among households. The fixed effects model considers differences of households – which is more relevant here. However, due to the short time axis, the results might be biased and must be interpreted with care. One possible interpretation is that if more household members become employed, VMT decreases (fixed effects model) and if two otherwise equal households differ only in the number of employed persons, the household with more employed members will drive more (random effect model). In this respect, the random effects model seems to be more appropriate.

Table 5: Results of the random effects panel regression of Frondel et al. (2007) and a modified variable-specific Hausman test

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>Hausman</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln (specific fuel consumption)</td>
<td><strong>0.58</strong></td>
<td>0.11</td>
<td>0.00</td>
</tr>
<tr>
<td>ln (fuel price)</td>
<td><strong>-0.59</strong></td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td>Vehicle age</td>
<td><strong>-0.02</strong></td>
<td>0.01</td>
<td>0.84</td>
</tr>
<tr>
<td>Diesel dummy</td>
<td>0.01</td>
<td>0.09</td>
<td>2.98</td>
</tr>
<tr>
<td>Premium-vehicle dummy</td>
<td><strong>0.22</strong></td>
<td>0.05</td>
<td>0.45</td>
</tr>
<tr>
<td>Household size</td>
<td>*0.04</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>Number of HSD</td>
<td>*0.07</td>
<td>0.03</td>
<td>2.64</td>
</tr>
<tr>
<td>Number of employed persons</td>
<td><strong>0.09</strong></td>
<td>0.03</td>
<td><strong>36.1</strong></td>
</tr>
<tr>
<td>Holiday dummy</td>
<td><strong>0.3</strong></td>
<td>0.03</td>
<td>3.25</td>
</tr>
<tr>
<td>Children dummy</td>
<td>0.36</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Constant</td>
<td><strong>7.86</strong></td>
<td>0.22</td>
<td>–</td>
</tr>
</tbody>
</table>

Note: * denotes significance at the 5 %-level and ** at the 1 % level, respectively.
Source: Frondel et al. (2007:19)

These regression results of the random effects model are used later in the developed meso economic model (see equation (25)).

As both dependent and explanatory variables are logarithmised, the corresponding parameter can be directly interpreted as elasticity. Hence the fuel price elasticity amounts to about -0.6, i.e. a fuel price increase of one percent leads to a decrease in VMT of about 0.6 %.

5.2.5.3 Own regression using GMP data

Finally, an own regression was applied which leans heavily on Frondel et al. (2007)’s regression with some minor changes. It uses recent GMP data from the surveys between 2001 and 2006 and includes all households which participated in
the survey two or three times and own at least one car. Two additional variables were included in the regression: The income class variable, which was introduced into the GMP in 2001 and a time variable which considers unobserved time-dependent influences.

As recommended by Klien (1962:100ff), auxiliary regressions were done to avoid biased parameters due to the multicollinearity of explanatory variables. Klien’s rule of thumb (1962:101) is that multicollinearity is only a problem if the $R^2$ obtained from an auxiliary regression is greater than the overall $R^2$, i.e. the $R^2$ from the original regression with all the explanatory variables. This was tested for all the explanatory variables and $R^2$ was found to be between 0 and 0.05 so that problematic multicollinearity can be excluded.

The panel regression was applied with STATA® using a random effects model estimated by the generalized last square (GLS) method which includes information on heteroscedasticity. This assures BLUE estimators.

The applied Hausman test (Hausman, 1978) rejected the null hypothesis — that the results of the fixed effects model equal the results of the random effects model — as in Frondel et al. (2007). For our model, therefore, the regression results of the random effects model are used as recommended in Frondel et al. (2007).

Table 6: Results of the random effects panel regression using recent GMP data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln (specific fuel consumption)</td>
<td>**0.539</td>
<td>0.075</td>
</tr>
<tr>
<td>ln (fuel price)</td>
<td>**-0.545</td>
<td>0.193</td>
</tr>
<tr>
<td>Vehicle age</td>
<td>**-0.015</td>
<td>0.004</td>
</tr>
<tr>
<td>Diesel-dummy</td>
<td>**0.206</td>
<td>0.045</td>
</tr>
<tr>
<td>Premium vehicle dummy</td>
<td>**0.235</td>
<td>0.057</td>
</tr>
<tr>
<td>Household size</td>
<td>-0.003</td>
<td>0.025</td>
</tr>
<tr>
<td>Number of HSD</td>
<td>*0.068</td>
<td>0.028</td>
</tr>
<tr>
<td>Number of employed persons</td>
<td>**0.103</td>
<td>0.031</td>
</tr>
<tr>
<td>Holiday dummy</td>
<td>**0.270</td>
<td>0.036</td>
</tr>
<tr>
<td>Children dummy</td>
<td>*0.108</td>
<td>0.061</td>
</tr>
<tr>
<td>Income class</td>
<td>0.011</td>
<td>0.015</td>
</tr>
<tr>
<td>Year trend</td>
<td>0.023</td>
<td>0.018</td>
</tr>
<tr>
<td>Constant</td>
<td>**7.658</td>
<td>0.174</td>
</tr>
</tbody>
</table>

Observations: 1409  Prob > chi² = 0.0000  $R^2_{within} = 0.14$

Note: * denotes significance at the 7 %-level and ** at the 1 % level, respectively.

87 The following income classes are distinguished 1(<500 €), 2 (500-1000 €), 3 (1000-1500 €), 4 (1500-2000 €), 5 (2000-2500 €), 6 (2500-3000 €), 7 (3000-3500 €), and 8 (>3500 €).
88 BLUE stands for best linear unbiased estimator.
As expected, the results display similar values as Frondel et al. (2007) (see Table 6). The model also delivers convincing results both with regard to the significance of individual parameters and with regard to the regression equation ($\chi^2 = 0.00$). Once again, specific fuel consumption has a significant positive influence on the corresponding VMT and the fuel price a negative one. Besides the fuel price VMT is only significantly negatively influenced by vehicle age, all other variables have a positive impact. The influence of the children dummy is only significant at the 7% level. Household size has a negative sign, but at an insignificant level. The two newly introduced variables of income and trend are not significant. This could be due to the premium vehicle dummy, which possibly reflects car affinity better than income class. The trend variable might change in the future as the increase in VMT in German passenger transport is expected to decline (BMVBS, 2008b). Including individual year variables (2002 to 2006) was also insignificant so that it is possible to rule out a relevant unobserved impact in one of the years considered.

5.2.5.4 Determined reaction behaviour of households

The households in the developed model refuel their passenger cars, as already mentioned, if their fuel tank content is less than half empty. Households check the fuel price every day (when passing the petrol stations) and adjust their VMT accordingly so that the frequency of refuelling might vary. Besides this direct effect, the households may replace a car. This decision is scheduled once a year. If they decide in favour of a new car, they identify the required features and purchase the corresponding vehicle second-hand or a new one on the car market. These two possibilities within the model are explained below.

Directly adjusting VMT to changed fuel prices plays a large role in the developed model. The certificate market determines the CO$_2$ certificate price which is added onto the fuel price which directly influences the VMT of households and thus the demand for certificates. The reaction function applied here therefore directly and substantially influences the results of the model and the effectiveness of the introduced certificate trading scheme.

As already described, the regression function by Frondel et al. (2007) (see equation (24)) and the results of the applied random effects panel model are used as the reaction function of households in the developed model. The variables of income, household size and trend are neglected as their impact is not significant. All the modelled households adjust their VMT in line with the following equation (25).

---

More exactly, if only one quarter fuel of the tank capacity is left the household refuels half of the tank capacity. If the tank content is below one quarter of the tank capacity the tank is filled entirely.
\[ \ln(m\text{ilege}_{n,i,k}) = 7.66 + 0.539 \cdot \ln(fuelCombustion_{n,i,k}/100) - 0.545 \]
\[ \cdot \ln(fuelPrice_{i,t}) - 0.02 \cdot (carAge_{n,i,k}) + 0.21 \cdot \text{diesel}_{i,k} \]
\[ + 0.24 \cdot \text{premium}_{i,k} + 0.07 \cdot nHSD_{i} + 0.10 \cdot nEP_{i} + 0.27 \]
\[ \cdot \text{holiday}_{i} + 0.11 \cdot \text{kid}_{D_{i}} - 0.0001 \cdot \ln(\text{co2Price}_{i,t})^2 \]  
\text{(25)}

The equation (25) shown here features the syntax of the developed meso economic model, but is based on the equation (24) by Frondel et al. (2007). Only a small adjustment to the regression model was made. The hypothesis of Rouwendal and de Vries (1999a) and Shell (2001:33) – that higher price levels and higher price variation cause stronger elasticities than the elasticities estimated with empirical data – is included in the model by taking logarithmised squared CO₂ certificate prices \((\text{co2Price})\) into account. This does not only consider a posteriori experiences but recent developments within the population such as the climate change debate and related changes in the awareness of traffic participants toward their own CO₂ emissions. These developments in the population’s attitude might have considerable effects on elasticity. In other words, the variable of CO₂ certificate price also reflects the awareness among the population of the climate change issue which might cause an increase in fuel price elasticity (see Kennedy and Wallis, 2007:57).

An example may help to clarify this relation of VMT and CO₂ certificate price according to equation (25). The passenger vehicle number 2,100,791 of the GMP is a BMW 118i in household 210,079 which replaced a Volkswagen Golf in 2005 and was included in the survey in 2005 and 2006. It has a specific petrol consumption of 8.6 litres per 100 kilometres and is two years old. The corresponding household is composed of one member with a high-school diploma, who is employed and accomplished a holiday trip during the survey period. In the first year of the model simulation, the petrol price is 1.41 euros per litre \((\text{fuelPrice})\) and the corresponding CO₂ certificate price is assumed to be 22.33 euros per ton CO₂. This results in the following calculation of this household’s VMT as depicted in equation (26).

\[ \ln(m\text{ilege}_{2,210079,1}) = 7.66 + 0.539 \cdot \ln(8.6/100) - 0.545 \cdot \ln(1.41) - 0.02 \]
\[ \cdot \ln(2) + 0.21 \cdot 0 + 0.24 \cdot 1 - 0.03 \cdot 1 + 0.07 \cdot 1 + 0.10 \cdot 1 \]
\[ + 0.27 \cdot 1 + 0.11 \cdot 0 - 0.0001 \cdot \ln(22.33) = 6.79 \]
\[ \cong 886 \text{ km per month} \]  
\text{(26)}

If, for example, the CO₂ certificate price increases within the first year to 30 euros per ton of CO₂, the fuel price will correspondingly increase to 1.43 euros per litre petrol. This leads to the following VMT adjustment by passenger car 2,100,791 (see equation (27)).

\[ \ln(m\text{ilege}_{2,210079,2}) = 7.66 + 0.539 \cdot \ln(8.6/100) - 0.545 \cdot \ln(1.43) - 0.02 \]
\[ \cdot \ln(2) + 0.21 \cdot 0 + 0.24 \cdot 1 + 0.03 \cdot 1 + 0.07 \cdot 1 + 0.10 \cdot 1 \]
\[ + 0.27 \cdot 1 + 0.11 \cdot 0 - 0.0001 \cdot \ln(30) = 6.78 \]
\[ \cong 878 \text{ km per month} \]  
\text{(27)}
Due to the increase in the CO₂ certificate price of about 30 %, the household reduced its VMT by less than one percent. For this household, this is equivalent to a price elasticity of about -0.6 with regard to changes in the petrol price.

In the initial phase of the model, this equation (25) is already used to determine the initial CO₂ demand of households. This, together with the initial CO₂ demand of the modelled freight forwarders, gives the total CO₂ demand of road traffic participants in the developed model. As stated above, the initial number of CO₂ certificates allocated to the oil companies by the government is geared to this overall CO₂ demand – and exceeds this by one percent.

Although this equation includes economic and sociographic aspects and implicitly also includes other unobservable influences, it still neglects (at least explicitly) mobility needs and attitudes.

5.2.6 Passenger car purchase of households

To estimate the demand of households for passenger cars seems a worthwhile but at the same time apparently impossible task from the perspective of car manufacturers. Nevertheless, numerous scientific papers have tackled this issue (among others Hocherman et al., 1983, Henscher and Le Plastrier, 1985, Hensher et al., 1992, Yamamoto et al., 1999, and Mohammadian and Miller, 2003). Most of these studies focused on the economic demand curve for passenger cars in a certain region or country (Train, 1986). But the demand for certain vehicle types or different years of construction have also been analysed. An overview by Train (1986) shows that most of the conducted studies consider similar influencing parameters for passenger car purchases. Eleven of 13 evaluated studies list household income, ten studies feature the number of household members, nine the vehicle age, seven the VMT and six include the level of education as well as the type of neighbourhood. All the other factors mentioned are considered in fewer than three studies. The main influencing factors of the demand curve for passenger cars in particular regions include the vehicle price, the average income of the household and other lag parameters (Train, 1986:130). An overview of the influencing factors of passenger car purchase by households can be found in Potoglou and Kanaroglou (2008a and 2008b).

Besides many country-specific studies, Johansson and Schipper (1997) analysed the elasticities in the passenger car stock for 12 OECD countries for the time period 1973 to 1992. The authors evaluate the elasticities with regard to fuel price, income and taxes and population density. According to their study, the passenger car stock is strongly dependent on the average national income per capita. The corresponding long-term elasticity is about 1.0. The value for long-term fuel price elasticity is rather low at -0.1. With regard to car tax, the price elasticity of passenger car ownership varies considerably from country to country as different tax rates and tax architectures apply. They range from about -0.01 in the US to about -0.13 in Denmark.

Today many studies assume that the passenger car fleet in Germany will remain relatively constant in the future. This is based on passenger car fleet growth in recent
years which declined from 1.2% in 2006 to 0.4% in 2008 (DeStatis, 2009). Major potentials for growth are seen in developing and emerging countries, in particular in China and India (see Hayashi, 2008, and Kasperk et al., 2006:44). Here, the income level in some cities is in certain (but still very visible) positions almost on a par with Western levels, but the passenger fleet of 20 cars per 1,000 inhabitants still lags far behind that in the West of about 600 cars per 1,000 inhabitants.

In the meso economic model, the vehicle transaction options by Mohammadian and Miller (2003) (see Figure 28) are reduced to replacing a vehicle or keeping the current car (“Do nothing”). The options of adding or (only) disposing a vehicle are neglected.

![Vehicle Transactions Model](image)

**Figure 28:** Vehicle transaction and type choice (Mohammadian and Miller, 2003)

Similar to the adjustment of VMT by households, their purchase of passenger vehicles within the developed model is estimated by an econometric regression function. It is derived from the regression model by Roorda et al. (2009) and transferred to the German context.

The decision about whether to replace a passenger car is activated on a particular day once a year for each household in the model. On this day, the household checks whether a replacement of its vehicle is necessary according to equation (29). The household $i$ replaces its car $k$ if the dependent variable $Car_{n,k}$ exceeds zero (see equation (30)). If a vehicle is replaced, the household purchases a new passenger car on a randomly chosen day ($t\{1-264\}$) within the corresponding year and disposes of the old car at the same time. Not until this stage does the household determine the parameters of its new car such as vehicle age ($carAge$) and specific fuel combustion ($fuelCombustion$) according to equations (31) and (32).
The applied regression is again based on the GMP data (surveys 1995 to 2006) and is a logit model like the modal choice of freight forwarders. The explanatory variables comprise VMT \((\text{mileage}_{n,i,k})\), vehicle age \((\text{carAge}_{n,i,k})\), specific fuel consumption \((\text{fuelCombustion}_{n,i,k})\), a premium vehicle dummy \((\text{premium}_{i,k})\)\(^90\), the type of neighbourhood \((\text{rt1}_i\text{ to rt3}_i)\)\(^91\), household type \((\text{hht1}_i\text{ to hht3}_i)\)\(^92\), and the total cylinder capacities of all the household’s car engines \((\text{cci})\)\(^93\). In addition, trend variables are included in the following equation (28) to account for unobserved year-specific influences or trends.

\[
\text{newCar}_{n,i,k} = \alpha_0 + \alpha_1 \ln(\text{mileage}_{n,i,k}) + \alpha_2 \cdot \text{rt1}_i + \alpha_3 \cdot \text{rt2}_i + \alpha_4 \cdot \text{rt3}_i \\
+ \alpha_5 \cdot \text{hht1}_i + \alpha_6 \cdot \text{hht2}_i + \alpha_7 \cdot \text{hht3}_i + \alpha_8 \cdot \ln(\text{carAge}_{n,i,k}) + \alpha_9 \\
+ \ln(\text{fuelCombustion}_{n,i,k}) + \alpha_{10} \cdot \text{premium}_{i,k} + \alpha_{11} \cdot \ln(\text{cci}) + \alpha_{12} \\
+ \text{trend95} + \ldots + \alpha_{21} \cdot \text{trend04} + \upsilon_{it} \tag{28}
\]

For the estimation, a total of 1,731 vehicle replacements were identified in the panel between the survey in 1995 and that in 2006 and the corresponding households entered the following regression. The results of the logit model convince to some extent with regard to the expected sign and significance of individual values and the regression equation \((\chi^2 = 0.00)\). The resulting coefficient of determination, the pseudo-R\(^2\) according to McFadden (1974), equals 0.06, which seems moderate at first, but as its explanatory power is highly controversial (among others, see Veall and Zimmermann, 2006), this does not prevent the regression equation being integrated into the meso economic model. Another reason for doing so is that so far there is no adequate alternative for the vehicle purchase decision. But, to account for this uncertainty and low R\(^2\), an error term is included in the reaction function to represent unobserved influences. This is an equally distributed term between -0.2 and 0.2.

---

90  The premium vehicle dummy was explained and used in Equation (24) and footnote 84.
91  The GMP distinguishes five different residential neighbourhoods with respect to the number of residents in the area. Neighbourhood type 1 is allocated to households in the centre of a major city with more than 100,000 inhabitants. Households classed as neighbourhood type 2 are located at the edge of these major cities and households of neighbourhood type 3 are in a city with about 20,000 to 100,000 inhabitants. Neighbourhood type 4 represents towns which range from 5,000 to 20,000 inhabitants and neighbourhood type 5 are villages with up to 5,000 inhabitants. However, in the following regression, the latter two types are combined as they do not differ significantly regarding their influence here.
92  Household types within the GMP are explained in footnote 80.
93  The total cylinder capacity of all the household’s vehicle engines is seen as a proxy for the vehicle affinity or dependency of the households and can also be interpreted as an income proxy (because the income variable was not completely included in the GMP data for the considered survey period from 1995 to 2006).
Table 7: Results of the logit model for vehicle purchase

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(mileage)</td>
<td>0.123</td>
<td>0.098</td>
</tr>
<tr>
<td>trend95</td>
<td>*0.877</td>
<td>0.381</td>
</tr>
<tr>
<td>trend96</td>
<td>*1.093</td>
<td>0.442</td>
</tr>
<tr>
<td>trend97</td>
<td>**0.893</td>
<td>0.276</td>
</tr>
<tr>
<td>trend98</td>
<td>*0.672</td>
<td>0.274</td>
</tr>
<tr>
<td>trend99</td>
<td>**0.983</td>
<td>0.306</td>
</tr>
<tr>
<td>trend00</td>
<td>*0.589</td>
<td>0.278</td>
</tr>
<tr>
<td>trend01</td>
<td>0.449</td>
<td>0.285</td>
</tr>
<tr>
<td>trend02</td>
<td>*0.493</td>
<td>0.281</td>
</tr>
<tr>
<td>trend03</td>
<td>0.404</td>
<td>0.272</td>
</tr>
<tr>
<td>trend04</td>
<td>-0.087</td>
<td>0.306</td>
</tr>
<tr>
<td>rtype1</td>
<td>*-0.373</td>
<td>0.157</td>
</tr>
<tr>
<td>rtype2</td>
<td>-0.212</td>
<td>0.188</td>
</tr>
<tr>
<td>rtype3</td>
<td>*-0.484</td>
<td>0.200</td>
</tr>
<tr>
<td>hhtype1</td>
<td>-0.106</td>
<td>0.209</td>
</tr>
<tr>
<td>hhtype2</td>
<td>*-0.521</td>
<td>0.238</td>
</tr>
<tr>
<td>hhtype3</td>
<td>*-0.358</td>
<td>0.204</td>
</tr>
<tr>
<td>ln(Age)</td>
<td>**0.493</td>
<td>0.083</td>
</tr>
<tr>
<td>ln(fuel combustion)</td>
<td>*-0.576</td>
<td>0.274</td>
</tr>
<tr>
<td>premium</td>
<td>*0.573</td>
<td>0.146</td>
</tr>
<tr>
<td>ln(cc)</td>
<td>-0.204</td>
<td>0.175</td>
</tr>
<tr>
<td>Constant</td>
<td>-0.476</td>
<td>1.739</td>
</tr>
</tbody>
</table>

Observations: 1731
Log likelihood LR chi2(21) Prob > chi² Pseudo-R²
807.84043 99.38 0.0000 0.0579

Note: * denotes significance at the 5 %-level and ** at the 1 % level, respectively.

According to the regression, households situated in major city centres as well as those in medium-sized cities replace vehicles less often than households in the countryside. Similarly, households with two unemployed members (in particular pensioners) (hhtype2) and households with children below the age of 18 (hhtype3) do not replace their vehicle as often as households with more than two adults and no children (in particular shared accommodation) (hhtype4). In addition, an older vehicle is more likely to be replaced. Car replacement is positively influenced by premium vehicles (premium) and negatively influenced by specific fuel combustion (fuel combustion). The variables VMT (ln(mileage)); households situated at the edges of major cities (rtype2), households with one or two employed members (hhtype1) and total cylinder capacity (cc) show no significant influence on the deci-
The high significance of many trend variables shows that other time-dependent variables play a large role in the vehicle replacement decision of households. These probably include many parameters which are difficult to measure such as emotional factors, but also strategic decisions regarding the needs of all household members.

If the regression results (see Table 7) are entered into equation (28), the following equation (29) is obtained for the car purchase decision of households.

\[
\text{newCar}_{n,i,k} = 0.123 \cdot \ln(\text{mileage}_{n,i,k}) - \text{rtConst}_i - \text{hhConst}_i + 0.493 \cdot \ln(\text{carAge}_{n,i,k}) - 0.576 \cdot \ln(\text{fuelCombustion}_{n,i,k}) + 0.573 \cdot \text{premium}_{n,i,k} + \varphi_{n,i,k}
\]  

(29)

The different neighbourhood types as well as the household type variables are simplified here by the constants (\text{rtConst}_i and \text{hhConst}_i). The corresponding values are displayed in Table 8.

Table 8: Estimated \text{hhConst} and \text{rtConst} parameters of equations (29) and (31)

<table>
<thead>
<tr>
<th>HH-Type/ RType</th>
<th>Equation (29)</th>
<th>Equation (31)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hhConst</td>
<td>rtConst</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.373</td>
</tr>
<tr>
<td>2</td>
<td>0.521</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0.358</td>
<td>0.484</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>0</td>
</tr>
</tbody>
</table>

Due to many and to some extend non-measurable influences on the car replacement decision of households as e.g. change of employment, relocation, heritage, accidents etc. a low coefficient of determination can be observed for the regression (see Appendix). To account for these various unconsidered influences an uniformly distributed error term between -0.1 and 0.1 (\(\varphi_{n,i,k}\)) is included in equation (29). It follows that the dummy variable \text{newCarD} equals 1 for values exceeding zero from equation ((29)) and 0 for values below zero (see equation (30)); i.e. if \text{newCarD} = 1, a vehicle is replaced.

94 Although the influence of the mileage variable is only significant on the 20% level, the variable is included in the following Equation 29. The constant and the \text{cc} variable are however excluded.
After the decision has been made to replace a vehicle, the new car’s features are determined. In the developed model, only two vehicle features are required: car age \((\text{carAge}_{i,k,n})\) and specific fuel consumption \((\text{fuelCombustion}_{n,i,k})\). It is assumed that the premium and the diesel attribute are not changed through the replacement. If the previous car was a premium diesel car the new car will also be a premium diesel car and so on.

As statistically determining the purchase date of vehicle replacement by households is already problematic, determining vehicle characteristics seems even more complicated (Hautzinger et al., 2004:97). The coefficient of determination is assumed to decline still further as so many unobservable parameters influence the concrete vehicle purchase decision, although further parameters could be integrated in multi-agent models using the appropriate heuristics.

The following two decision functions of households are again based on statistical estimations derived from GMP data on replaced vehicles from 1995 to 2006. The corresponding regression results are presented in the appendix.

The vehicle age of the purchased car is determined by the household using the following equation (31).

\[
\ln(\text{carAge}_{n+1,i,k}) = 2.916 + rtConst_i - hhConst_i + 0.526 \cdot \ln(\text{carAge}_{n,i,k}) - 0.419 \cdot \ln(\text{cci}) \quad \text{if newCarD} = 1
\]

The estimated value of \(\text{carAge}\) is rounded to a natural number between 0 and 100. If the value is higher than zero, a second-hand car is purchased, otherwise the household buys a new car. The vehicle age is therefore dependent on the neighbourhood \((rtype_i)\), the household type \((hhtype_i)\), the total cylinder capacity of all vehicle engines in the household \((cci)\) as well as the age of the previous vehicle \((\text{carAge}_{n-1,i,k})\). Thus from the regression with equation (31) it follows that households living in villages with 5,000 to 20,000 inhabitants tend to purchase younger vehicles, households with more adult members (in particular shared accommodation) prefer older, second-hand cars and the higher the total cylinder capacity \((cci)\), the higher the probability that a new car is preferred to a used one.

To determine the specific fuel combustion of the purchased vehicle, another regression was applied with the following variables: the specific fuel consumption of the previous vehicle \((\text{fuelConsumption}_{n+1})\), the current fuel price \((\text{fuelPrice}_i)\), the VMT \((\text{mileage}_{n,i})\) of the previous vehicle as well as the total cylinder capacity of all engines in the household \((cci)\). The regression (which is shown in the appendix) leads to the following equation (32).
\[
\begin{align*}
fuelCombustion_{t+1,i,k} &= 0.684 + 0.476 \cdot \ln(\text{fuelConsumption}_{t,i,k}) - 0.151 \cdot \text{fuelPrice}_{i,t} + 0.031 \cdot \ln(\text{mileage}_{t,i,k}) + 0.045 \cdot \ln(cc) \text{ if } newCarD = 1
\end{align*}
\]

According to this equation, fuel price has a negative influence on the specific fuel consumption of the purchased vehicle, whereas the VMT (\(\ln(\text{mileage})\)) of the previous vehicle as well as the total cylinder capacity have a positive impact. Hence, e.g. the passenger car fleet will increase its fuel efficiency if the CO\(_2\) certificate price increases.

A similar model was developed by Train (1986: 130ff). However, he provided a 120 prescribed passenger car classes for households to choose between. The 120 probabilities of choosing a vehicle of a certain passenger car class were estimated for every household by a multinomial logit model. The results show the influences of the different car characteristics on the vehicle purchase probability by households. Train (1986) was able to show that households tend to replace their cars with similar cars from the same vehicle class.

Roorda et al. (2009) introduced an integrated activity-based microeconomic model of vehicle transactions, activity scheduling and modal choice based on the Toronto area. The model is based on the concept of activity/travel stress which was developed by Miller (2005). The stress results from the two-way relationship between the long- and short-term decisions of households. Long-term decisions not only influence the constraints that restrict short-term decisions. If the day-to-day decisions of households are constrained by their spatial or mobility context, then there is an incentive to buy new vehicles. Miller (2005) called this feedback household ‘stress’. In the same way, Rouwendal and de Vries (1999b) developed a nested logit model for the fuel type choice of new cars by Dutch households.

### 5.3 Results of the meso economic model

The results of micro or meso based models are characterised by an outcome structure based on individuals. They can be applied to estimate the future impacts of policy instruments. They allow multifunctional reporting possibilities with regard to the different influences on separate population groups. This makes it possible to identify potential social hot spots, economic efficiency, the effectiveness or sufficiency of the policy instrument at an early stage. For example, within the transport sector, there have been numerous studies of the impacts of increasing the energy tax (e.g. Wadud, 2007), or of increasing the motorway toll for heavy goods vehicles (e.g. Doll and Schaffer, 2007). The aggregated results of the meso model are presented below and combined with the results of other models or empirical observations.
The results described here show the effects of introducing an upstream CO₂ certificate trading scheme to German road transport which aims to reduce the related direct CO₂ emissions by 10.5 % within ten years (2013 to 2023). The model user can select one of two scenarios for the scheme: First, a closed certificate trading scheme for road transport and, second, an open certificate trading scheme. The open trading scheme permits oil companies to trade certificates within the EU-ETS with companies from other sectors which leads to a fuel price increase of about 0.02 euro per litre fuel. The closed certificate trading scheme causes a more substantial price increase which has drawbacks for traffic participants.

The output of the meso economic model is applied in two different ways. During the simulation, traded certificates, certificate prices and the CO₂ emissions of freight forwarders and households as well as the number of CO₂ emission certificates supplied by the government are charted in real time as graphical output (Figure 29). In addition, the petrol price, the overall CO₂ demand of road transport, the CO₂ certificate price, the CO₂ supply as well as the number of traded CO₂ certificates by the oil companies is recorded for every simulated day in a separate text file. At the end of every simulation period, the VMT of every household as well as the characteristics of their passenger car fleet is saved in a csv file to allow car-specific evaluations. All other household-specific values remain constant during the simulation. The car-specific values stored in the csv file include the specific fuel combustion, the vehicle age and its VMT among others. This data allows changes in the vehicle fleet and household-specific changes of VMT to be analysed after the simulation.

Within an open CO₂ certificate trading scheme in transport, the traffic participants’ willingness-to-pay is, as expected, much higher than the marginal CO₂
abatement costs of industry in the EU-ETS. As a result, these cheap certificates are used to satisfy the fairly constant CO₂ demand of road transport. In other words, the CO₂ emission reductions in industry are funded by traffic participants. Despite this, the additional costs for the transport sector are still affordable. While the petrol price within the first simulation period equals 1.44 euros, which already includes a certificate price of 22.33 euros per ton of CO₂, after ten simulation periods it has only risen to about 1.46 euros per litre, which again includes the increased certificate price of 32 euros per ton CO₂. So far, other price influences are neglected. This marginal price increase is explained by the small increase in additional certificates demanded by the oil companies in the EU-ETS. Assuming a constant fuel demand by traffic participants, the 10.5 % reduction of CO₂ certificates in road transport is equivalent to an increase in the oil companies’ demand for certificates in the EU-ETS of 3.6 %.

Figure 30: CO₂ supply and demand within the closed emissions trading scheme

In contrast, the closed CO₂ emission trading scheme has to achieve the prescribed emission reductions solely within road transport (see Figure 30). The oil companies themselves do not have direct CO₂ emission reduction potentials but they can indirectly reduce the fuel demand of traffic participants by increasing the fuel price. They calculate the actual price elasticities of demand on a daily basis and

95 German road passenger transport emitted 110 million tons CO₂ in 2004 and German road freight transport 48 million tons. The German share of certificates in the EU-ETS amounts to about 459 million tons of CO₂. Thus the share of road transport would be about 25 %, 10.5 % of road transport emissions equal about 16.6 million tons of CO₂, i.e. about 3.6 % of the total emissions within the EU-ETS.
increase the fuel prices accordingly in order to reduce the fuel demand to a level such that the distributed number of certificates suffice to cover all the CO₂ emissions resulting from the fuel combustion of traffic participants. Hence, under this scheme, there is a substantial rise in fuel prices.

The certificate trading scheme in the model with an emission reduction goal of about 10.5 % over ten years leads to certificate prices of about 130 euros. This translates into a surcharge on the initial fuel price of about 0.28 euro per litre diesel and 0.25 euro per litre petrol.⁹⁶ Individual passenger road transport is responsible for about 17 million tons of CO₂ emissions reductions and road freight transport for about 2 million tons to reach the total required emissions reduction in road transport of about 19 million tons of CO₂. Hence, households cut their emissions by 15.7 % and freight forwarders by about 4.3 %. The corresponding fuel price elasticities amount to about -0.7 for individual passenger road transport and to -0.18 for road freight transport. The latter is based only on the modal shift in container transport. The fuel price elasticity of passenger transport is dependent on the VMT and the vehicle fuel combustion. If the fuel price remains constant the VMT stays constant but the specific fuel combustion of vehicles declines according the recent trend due to the econometric regression results. This means that for a small price raise the fuel price elasticity for households is positive. Compared to empirical elasticities the elasticity of the meso economic model neglects the trend to diesel cars, to longer trips, increase in vehicle population, and possible changes in reaction behaviour due to the rising awareness of climate change. But the meso economic model underestimates car replacements of households.

Due to the adding of biofuels into conventional fuels and due to alternative technologies it can be assumed that with regard to CO₂ emissions the corresponding price elasticity is much smaller. Hence a certificate price increase of about 90 to 100 euros is more probable in the analysed closed emission trading scheme.

If these figures are compared with other forecasts, most results can be confirmed. This is true for example when comparing these results with the price elasticities of individual passenger transport in Graham and Glaister (2002). They distinguish short-, medium- and long-term elasticities. Fuel demand changes because households either change VMT or buy more fuel-efficient cars. The first option dominates short-term price elasticities but both reasons might apply when estimating long-term price elasticities. Recently, there has been observed an increase in fuel efficiency in the German car market of almost 1 % per year for new registered passenger cars.⁹⁷ However, the effects of fleet modernization due to fuel-efficient vehicles only kick in after a considerable time-delay. According to the study by Graham and Glaister

⁹⁶ This surcharge seems quite small. Other authors postulated much higher fuel prices, e.g. the German Advisory Council on the Environment (SRU, 1994:295), which forecast a fuel price of 2.30 euros per litre.

⁹⁷ The decrease of average fuel consumption of passenger cars in Germany is accelerated through the shift from vehicles driven by petrol to diesel (BMVBS, 2008a).
the short-term demand change is marginal. A fuel price increase by 1 % leads to a fuel demand decrease of only 0.25 %. However, the long-term effects are much stronger. If the fuel price is increased by 1 % over a longer period, the fuel demand drops to about 0.77 %. However, some studies cite figures which deviate considerably from this value – some even estimate positive price elasticities, i.e. increasing fuel prices has the effect of boosting fuel demand (see Table 9). In countries with insufficient modal alternatives such as, e.g. the USA, Australia, Canada or New Zealand, the fuel price elasticity of households is about -0.2 which is lower than in most densely populated European countries with a well-developed public transport infrastructure (Kennedy and Wallis, 2007).

Table 9: Overview of international price elasticities according to Graham and Glaister (2002)

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
<th>Median</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short term</td>
<td>387</td>
<td>0.59</td>
<td>-2.13</td>
<td>-0.25</td>
<td>-0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>Medium term</td>
<td>52</td>
<td>0.28</td>
<td>-0.88</td>
<td>-0.35</td>
<td>-0.35</td>
<td>0.27</td>
</tr>
<tr>
<td>Long term</td>
<td>213</td>
<td>0.85</td>
<td>-22.00</td>
<td>-0.77</td>
<td>-0.55</td>
<td>1.65</td>
</tr>
</tbody>
</table>

According to Graham and Glaister (2002: 22), in Germany, the short-term fuel price elasticities are about -0.5 and the long-term elasticities are about -1.9. But a range of values are also determined here. For example, Sterner et al. (1992) estimated a short-term fuel price elasticity for Germany of -0.05 and a long-term elasticity of -0.56. However, neither value differs significantly from zero.

For German road freight transport, Rothengatter and Doll (2001) estimated fuel price elasticities depending on the level of the price increase in vehicle kilometres. These price increases can be converted into corresponding fuel price increases99. For a fuel price increase of about 0.34 %, they estimated a fuel price elasticity of about -0.015 and about -0.04 for a fuel price increase of about 0.53 %. When calculating recent macroeconomic fuel price elasticities100 for Germany the values diverge between -0.5 in 2003 and +0.8 in 2001 (BMVBS, 2008a).

Dargay (2002) estimated fuel and vehicle purchase price elasticities for rural regions and cities in Great Britain. He shows that for rural regions the demand is less elastic and at the same time less homogeneous. This makes it clear that the rural population is more dependent on private passenger cars than the urban population. According to Eck and Stark (2007:294), this will also be the case in the future, in

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98 These values are averages of the studies analysed by Graham and Glaister (2002).
99 The authors analysed an increase of vehicle kilometre charges of 13 and 20 cents per vehicle kilometre which equals an increase of about 0.39 euro and 0.60 euro per litre diesel, respectively.
100 Macro economic fuel price elasticities can be calculated by dividing the change of the macro economic fuel demand by the change of average fuel price.
other words, that an upstream certificate trading scheme in road transport will hit rural populations harder than urban dwellers.

Nevertheless, the additional financial burden even for rural households should not be over exaggerated as even in a closed emission trading scheme, the surcharge on diesel is only about 0.26 euro per litre and 0.23 euro per litre for petrol if a certificate price in the road transport sector of 100 euros is assumed. According to the simulation results of the meso economic model, the average additional burden for households amounts to about 20 euros per month, although this may exceed 150 euros per month for frequent drivers. As stated above, the rural population feel the effects more as their average VMT is higher and elasticities are smaller. Rural households will pay more than 22 euros per month and their counterparts in city centre about 20 euros on average (see Figure 31).

![Bar chart](image)

Figure 31: Average surplus financial burden of households due to the increased fuel price at a certificate price of 100 euros per ton CO₂

The model results indicate that the specific fuel combustion of passenger cars decreased only very moderately. Only 65 % of households replaced (at least once) a vehicle and their efficiency increased only by a 0.62 litre/100 kilometres in average. This is far below the recent observed tendency. If this were changed in the model,

101 This moderate improvement is especially due to the substantial underestimation of the vehicle replacement decision of households. According to Dudenhöffer (2008) the average car age in Germany is about 8 years. This implicates that (far!) more than 50 % of cars should be replaced during the simulation period of 10 years.
the fuel price elasticity of households would increase and long-term price elasticities of about -1 might result as forecasted by Graham and Glaister (2002: 22).

Concerning the development of the average fuel combustion of passenger cars in Germany, the following observations can be made. According to Dudenhöffer (2008), in recent years, the average age of the German passenger car fleet has increased from 6.7 years in 1999 to 8.1 years in 2006. 53 % of the fleet are younger than eight years (Dudenhöffer, 2008:86). Referring to the total market, one can assume that nearly every household replaces its vehicle at last once on average over a decade. At the same time, the average specific fuel combustion of passenger cars declined from 8.6 litres/100 kilometres in 1998 to 7.6 litres in 2007 (BMVBS, 2008a). This was however driven by the trend from petrol driven cars to diesel engines.102

However, if assuming a greater awareness of the population with regard to climate change and increasing fuel elasticity due to the higher fuel prices (see Frondel et al., 2007) the parameters in the model could change accordingly. I.e. households react more sensitive to raised fuel prices by clearly reducing their VMT and buying vehicles with lower specific fuel consumption. These effects could be expressed as follows.

First, in the reaction function regarding their VMT (equation (25)), the price elasticity parameter with the value of -0.545 is assumed to change to -0.9 so the following equation (33) holds:

\[
\ln(\text{mileage}_{n,i,k}) = 7.66 + 0.539 \cdot \ln(\text{fuelCombustion}_{n,i,k}/100) - 0.9 \\
\cdot \ln(\text{fuelPrice}_{n,i,t}) - 0.02 \cdot (\text{carAge}_{n,i,k}) + 0.21 \cdot \text{diesel}_{i,k} + 0.24 \\
\cdot \text{premium}_{i,k} - 0.003 \cdot \text{hhSize}_{i} + 0.07 \cdot \text{nHSD}_{i} + 0.10 \cdot \text{nEP}_{i} \\
+ 0.27 \cdot \text{holiday}_{i} + 0.11 \cdot \text{kidD}_{i} - 0.0001 \cdot \ln(\text{co2Price}_{i,t}) 
\] (33)

And furthermore assuming that the fuel price dependent parameter (\(\text{fuelPrice}_{n,i,t}\)) within the vehicle purchase function of households (see equation (32)) with the value -0.151 is replaced by the value of -0.3, the following equation (34) holds:

\[
\text{fuelCombustion}_{n+1,i,k} = 0.684 + 0.476 \cdot \ln(\text{fuelCombustion}_{n,i,k}) - 0.3 \\
\cdot \text{fuelPrice}_{n,i,t} + 0.031 \cdot \ln(\text{mileage}_{n,i,k}) + 0.045 \cdot \ln(cc) \text{ if } \text{newCarD} = 1 
\] (34)

The reduction of the price elasticity parameter within the VMT reaction function of households (equation (33)) has a small effect on the certificate price which amounts to 90 euros in the closed trading scheme. The impact due to the change in the fuel combustion decision (equation (34)) is much stronger and leads even to an achievement of the reduction target without any fuel price changes. The average

102 The specific fuel consumption of petrol cars declined from 8.8 to 8.2 litres per 100 kilometres and for diesel cars it declined from 7.3 to 6.9 litres per 100 kilometres between 1998 and 2007 (BMVBS, 2008a).
specific fuel combustion of vehicles declines by 1.3 litres/100 kilometres. This corresponds to a situation where since the initial trading period only vehicles with an average specific fuel consumption of about 5.25 litres/100 kilometres (e.g., a VOLKSWAGEN Polo) would be purchased – the reduction target will be achieved without any fuel price increase, too. 103

Again, the truth will lie somewhere in the middle. Thus, even in the closed trading scheme the certificate price might not increase above 100 euros, instead remaining at a level around 90 euros per ton.

The impact of the closed upstream certificate trading scheme on freight forwarders is much stronger. With a certificate price of about 90 euros, freight forwarders face additional costs of about 20 euros per shipment. For longer European shipments, additional costs may even amount to more than 300 euros. The resulting mileage reduction of about 4.3\% 104 due to changes in the modal shift equals a fuel price elasticity of about -0.2. This elasticity is considerably higher than the elasticities of minor price changes (among others Bühler and Jochem, 2008).

It is unclear how freight forwarders will be able to absorb these surcharges. It is conceivable that other taxes paid by freight forwarders could be reduced at the same time in order to ease their financial burden. This will lead to a lower willingness to reduce fuel demand, but will keep freight forwarders in the market. The modal split will however improve due to the altered costs and the effect on the total CO₂ emissions is negligible due to its low share.

5.4 Conclusions IV

There are four relevant markets when simulating the impacts of an upstream CO₂ emissions certificate trading scheme in German road transport on traffic participants in a meso economic model. These are:

- The passenger VMT market of households,
- the freight VMT market of freight forwarders,
- the vehicle market, and
- the newly established market for trading CO₂ certificates.

These markets are represented in a simplified way in the meso economic model, which integrates some features of the multi-agent modelling approach described in

103 When a constant car replacement and the average car age of about 8 years are assumed one can state that (more than) 50% of the fleet is younger than 8 years. And assuming that the average fuel consumption in 2012 is about 7.5 litres. If every new purchased car has a fuel combustion of 5.25 litres/100 kilometres the average fuel combustion will be 6.38 litres per 100 kilometres in 2020. This matches even a reduction target of 15%.

104 This 4.4\% reduction is a realistic value since according to Walter (2006) the modal shift potential for combined transport is about 13.9\% of container transport. As the container transport is considered in this thesis the calculated modal shift of about 4.4\% is far below the maximum modal shift potential of 13.9\%.
Chapter 4 such as, e.g. the heterogeneity, reactivity, social ability and autonomy of agents. Traffic participants in the model represent individuals based on empirical data from the German Mobility Panel or the database from Bühler (2006). In the same way, their reaction functions are based on empirical results and statistical estimations from these data sources.

The meso economic model features two scenarios: an open and a closed certificate trading scheme. In the open certificate trading scheme, the obligated oil companies can trade certificates with companies already included in the existing EU-ETS. In the closed emission trading scheme, this is not possible: road transport has to achieve the emission reduction on its own.

Within the model, oil companies receive one percent more certificates than they would need to satisfy the fuel demand by traffic participants for the first trading period. The distributed number of certificates is then reduced by 1.5 % per year from the second trading period onwards. The trading period is limited to one year and banking certificates to future periods is allowed, but not borrowing from future periods. Analogous to the current EU-ETS, certificates are allocated for free according to the historical market shares of oil companies (grandfathering).

Freight service providers can avoid these additional costs only by changing their modal split. This is possible for longer distances of more than 50 kilometres. In the model, the modal choice decision of freight forwarders is made according to the logit model developed by Bühler (2006). Furthermore, increasing fuel efficiency is assumed for the truck fleet. This is represented in a simplified way by an average decrease in the specific fuel consumption of 1.5 % per year. However, because there is a 1.5 % annual increase in the demand for road freight transport, this more or less cancels out the effect with regard to the generated CO₂ emissions.

In road passenger transport, traffic participants can respond to increasing fuel prices by reducing their VMT, or by replacing their car with a more fuel-efficient one. Both decisions are accomplished by an estimated response function specified by a panel regression using GMP data.

The model results show that, as expected, very high certificate prices of more than 100 euros may occur in the closed emission trading scheme, whereas in the open trading scheme, traffic participants’ willingness-to-pay for comfortable transport far exceeds the marginal abatement costs of CO₂ emission reductions in industry. Hence, in the open trading scheme, road transport does not drastically cut its CO₂ emissions and oil companies buy certificates from the other EU-ETS sectors to balance their certificate accounts. The high certificate prices in the closed emission trading scheme results from a constant behaviour of traffic participants. However, it is likely that traffic participants will adjust their reaction functions due to their greater awareness to climate change and to the higher fuel prices. Thus a certificate price of about 100 euros would be more realistic. This will result in a fuel price increase of above 0.25 euro per litre and cause an average additional financial bur-

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105 In the post 2012 phase of the EU-ETS the share of freely allocated certificates will increase for some sectors – this might be resumed to the road transport sector.
den for households of more than 20 euros per month. Freight service providers face additional costs of more than 20 euros per shipment on average, but of possibly more than 150 euros for some inter-European shipments. A change in the awareness of the population with regard to climate change (i.e. that households try to reduce their VMT and change their car purchase behaviour) has a considerable certificate price reducing impact within the closed emission trading scheme.

In Chapter 6, these results are used to analyse macroeconomic variables such as the Gross Domestic Product, employment, income, and fleet stocks as well as the environmentally-relevant air pollutants of carbon monoxide, volatile organic compounds and nitrogen oxide by applying the system dynamics simulation model ASTRA.
6 Macroeconomic impacts through a CO₂ certificate trading scheme

Introducing a CO₂ emission trading scheme in German road transport will have impacts on a microeconomic level, as discussed in the previous chapter, but may also affect macroeconomic and environmental issues. These issues can be examined using the system dynamics model ASTRA. For this the calculated CO₂ certificate price of 90 euros for road transport is included in the ASTRA model. The macroeconomic variables considered are the Gross Domestic Product (GDP), employment, disposable income and government revenues. The environmental impacts include emissions of carbon monoxide, carbon dioxide and nitrogen oxide as well as volatile organic compounds (VOC). In the following paragraphs, an outline of the ASTRA model is presented before its main results are highlighted and contextualised with the microeconomic results of the previous chapter.

6.1 The system dynamics model ASTRA

System dynamics models are able to represent systems in various disciplines (especially with a cybernetic background) by considering feedback loops and emphasising the interdependencies between stocks and flows. They do not calculate optima but rather possible developments of the system according to predefined scenarios and are much more flexible than many other model approaches with respect to changes in model structure and parameters. They are classed as experimental computer simulation models and can be applied to troubleshooting techniques and expert ratings in particular (Rothengatter and Schaffer, 2006:166). They are convenient to simulate long-term forecasts with high uncertainties in calculating several possible outcomes (scenarios) (Schade and Rothengatter, 2005).

Within the ASTRA project, the first version of the ASTRA (ASsessment of TRAnsport strategies) model was developed under the fourth Framework Programme (FP) of the European Commission by the Institute for Economic Policy Research (IWW), Karlsruhe, Trasporti e Territorio (TRT), Milan, Marcial Echenique and Partners (ME&P), Cambridge, and the Centre for Economics and Business.

However, the assumptions of both models are not congruent. The following results should therefore demonstrate whether an upstream CO2 certificate trading scheme in road transport is economically acceptable and how other environmental impacts are influenced. A main difference is the macro economic focus and the consideration of trends and dynamic developments (especially in the vehicle fleet). A further central assumption in the ASTRA model is the fuel price increase of about 30 % and a vehicle fleet share of CNG cars of about 10 % in 2023 already in the baseline scenario.
The aim was to generate a tool to assess the long-term economic and environmental impacts of European transport policy. The ASTRA model was subsequently further developed and applied in the fifth FP of the European Commission in the TIPMAC (Ponti et al., 2002, and Schade et al., 2004), IASON (Bröcker et al., 2004), LOTSE (Krail et al., 2004) and TRANS-TOOLS (TNO et al., 2006b) project, in the sixth FP in TRIAS (Fhg-ISI et al., 2008a) and HOP (TRT et al., 2008) among others and within many other scientific policy consulting projects such as IKEP (Fhg-ISI et al., 2008b) or KlimaInvest2020 (BSR-Sustainability et al., 2008). ASTRA is based on the system dynamics methodology. It covers interzonal as well as interzonal traffic at NUTS2 level for 29 European countries, comprising the 27 EU Member States plus Switzerland and Norway. The simulation time horizon is from 1990 to 2050. A comprehensive overview of the model can be found in Schade (2005) and Krail (2009).

Figure 32 demonstrates the interrelationships between the nine modules of the ASTRA model and highlights the most important inputs and outputs which are described below.

The ASTRA Population module (POP) generates the demographic framework for the Macro-economic module (MAC) with its six sub-models and the Regional Economics module (REM) based on age cohorts. The aim of the MAC is to provide an aggregate macroeconomic environment in which all the other eight modules are embedded. The MAC incorporates an endogenous growth component that is able to simulate the generate growth effects of policies and a sectoral interchange component that considers the impacts of sectoral interdependence between the 25 economic sectors107 of each of the national economies. POP, MAC, and the Foreign Trade module (FOT) integrate the macroscopic information about national- and European-level influences into the model while other modules operate on a micro- or meso-level. This has the advantage that feedback loops which commence on the micro- or meso-level in one of the modules (e.g. transport expenditures for one mode in one distance band in the Transport module (TRA)) and then culminate in an effect on the national level (e.g. changes in sectoral consumption and gross-value-added) can influence the originating module such that the feedback loop is closed, e.g. in this case by the integration of the MAC module. Closing the feedback loop implies establishing either macro-micro-bridges (e.g. from Gross Domestic Product and sectoral output to goods flows) or the opposite micro-macro-bridges (e.g. from transport investments into vehicle fleets to overall investments). The TRA provides the VMT per mode and per distance band, respectively, to the Environment module (ENV). Based on these traffic flows and the information from the Vehicle Fleet module (VFT), which simulates the composition of the vehicle fleets of all road modes, the environmental module calculates the different emissions, fuel consumption and fuel tax revenues. The Welfare Measurement module (WEM) allows a comparison of major macroeconomic, environmental and social indicators. Finally,

107 Classified according to the NACE-CLIO-system.
the Infrastructure module (INF) provides the network capacity for the different transport modes.

There are various well-known theoretical concepts integrated in the model. For instance, neo-classical production functions are implemented in the MAC to calculate the potential output of the national economies. On the other hand, the

**Figure 32: Overview of the ASTRA model (Krail, 2009)**

There are various well-known theoretical concepts integrated in the model. For instance, neo-classical production functions are implemented in the MAC to calculate the potential output of the national economies. On the other hand, the
production functions include endogenous total factor productivity that is borrowed from endogenous growth theory. The calculation of investments follows Keynesian theory to some extent as investments depend on consumption and, as an additional element, on exports. The core of transport modelling is based on the classical 4-stage transport model applying logit-functions based on generalised costs, e.g. to calculate the modal split.

The ASTRA model comprises more than 5,000,000 objects implemented in the standard system dynamics software package Vensim®. These objects could be variables, i.e. equations, constants or data input. More than 300,000 objects are level variables and in that sense are dynamic variables. Two major types of level variables can be distinguished: delay or lag variables and accumulating variables of which the former make up the greater share of level variables in the model. One scenario simulation between 1990 and 2040 saving annual results generates 870 megabytes of output data. About 12,000 time series are used to calibrate ASTRA for the period 1990 until 2005. All monetary values are calculated in real values of 1995 euros. Most variables are calculated excluding all taxes. The basic time period for most modules, e.g. MAC, FOT, VFT, is one year.

Forecasting the economic impacts of a policy instrument is difficult as its effects are usually multi-level and the net effect is often unclear. Computer simulation is a suitable approach to provide possible scenarios. In contrast to the microeconomic analysis of the previous chapter, the focus here is on aggregated macroeconomic values and emissions. To simulate the introduction of the above defined CO₂ emission trading scheme into the ASTRA model, the fuel prices determined in the meso economic model in the previous chapter are transferred to the ASTRA model. Other influences are neglected including the recycling of the increased profits of the oil companies. This allows a comparative analysis of the main parameters of the two models such as the change in transport performance or vehicle demand.

6.2 The business-as-usual scenario

In order to have a basis for comparison, a reference (Business-as-Usual – BaU) scenario is usually defined to start with to see how the world would look without the policy instrument being examined. In a second simulation run, the corresponding policy instrument is integrated into the model. Subsequently, the results of the two model runs can be compared and the impacts of the policy instrument are presented in relation to the BaU scenario. The applied BaU scenario was developed by Krail (2009) and its main characteristics are outlined in the following paragraphs. The interested reader is referred to Krail (2009).

The BaU scenario considers the policy framework set by already taken decisions as well as European transport strategy documents like the White Paper on European transport policy for 2010 (EC, 2001) and it refers mainly to the baseline scenario developed within the TRIAS project (IWW et al., 2007). Unlike the assumptions in Schade (2005), the GDP development in countries outside Europe was changed.
This so-called world GDP is a driver of exports in the Foreign Trade (FOT) module. A cyclical development was superimposed on the simulation results of the project ADAM (University of Cambridge et al., 2007). The BaU scenario settings in the TRA module consist mainly of the prospective travel costs which were defined according to the bottom-up approach by Trasporti e Territorio (TRT) which considers every single element of travel costs (De Ceuster et al., 2005).

For the VFT module, two assumptions were made on the cost development and the diffusion probabilities of alternative car technologies. Car taxation is assumed to stagnate on the most recent documented level in each country. Taxation rates and fees are taken for each country for the historical period from 1990 to 2006. The second cost category that is influenced by the BaU scenario is the development of car prices for each of the eleven car categories modelled (including alternative technologies).

One of the major characteristics of the ASTRA MAC module is the mainly endogenous calculation of the economic development of the 29 European countries. The development of the main economic indicators is depicted in Figure 33 for Germany. The Gross Domestic Product increases similar to the national investments with an average annual growth rate of about 1%. Employment decreases by about 0.6 % per annum mainly due to the decline in the employable population. At the same time, disposable income increases by about 1.4 % per annum which leads to an
overall income increase of about 50% in 29 years. The annual increase in government revenues is assumed to be about 0.5%.

While the number of vehicles in Germany remains more or less constant until 2040, the technological composition of the car fleet changes. Considering EU27 car fleets, the established technology choice model provides the following picture for the period between 2000 and 2040. The share of conventional fossil fuels decreases from about 100% to about 70% in 2040. Major market share increases are observed for hydrogen, bioethanol, electrical\textsuperscript{108}, and CNG technologies, which approach a market share of 5.8%, 5.9%, 6.4%, and 8.4%, respectively, in 2040. The assumption of a moderate mineral oil price development after 2030 is mainly responsible for this rather pessimistic view of the future diffusion of alternative car technology. The declining share of diesel- and petrol-fuelled cars until 2040 indicates another interesting trend. Car purchasers who decide to buy a conventional car will purchase significantly fewer powerful cars with large cubic capacities. In the year 2040, only 5.6% of conventional cars will have more than 2.0 litre cubic capacity. Despite high CNG prices, CNG technology emerges as the most important alternative car technology in the mid-term for the EU27. The action plans of countries like Germany, Italy, Sweden, Austria, and the UK which support the diffusion of CNG cars on the market by improving filling station infrastructure play an important role in this trend. These assumptions are rather optimistic.

The development of freight transport performance in terms of freight ton-km is mainly influenced by export activities simulated in the FOT module and national production values computed in the sectoral interchange model of the MAC module. According to the baseline scenario projections, ton-km will increase by 71% until 2040 for the EU27.

Based on the output of the TRA module and the differentiation of vehicle fleets into technologies and emission standards, the ASTRA model is able to estimate the resulting transport-related emissions. ASTRA considers the emissions caused by fuel combustion in engines as well as the emissions from vehicle and fuel production. The development of the main air pollutants and CO\textsubscript{2} emissions from road transport are presented in Figure 34 for the BaU scenario. The CO\textsubscript{2} emissions of road transport are assumed to decrease by 1.3% per annum due to car downsizing and alternative technologies. A similar decrease (-0.9%) is observed for CO emissions. NO\textsubscript{x} emissions show the strongest decrease of -4.3% per annum due to new standards and alternative technologies. However, VOC emissions increase by 0.3% per annum due to the larger number of CNG cars in the EU27 car fleet, which emit significant amounts of methane (CH\textsubscript{4}) which is classed as belonging to the group of VOC emissions.

\textsuperscript{108} This positive trend is the result of recently achieved milestones in battery development for electric cars (see Chapter 3) which have improved the mileage and the time required to charge the battery.
In the following, all the results are presented in relation to this BaU scenario and only refer to impacts in Germany even though the ASTRA model considers all the other 28 European countries in the simulation.

6.3 Economic impacts

Due to the free initial allocation of certificates to the oil companies based on their historical market shares, the oil companies only have to pay for additionally purchased certificates. However, they still might include the marginal costs caused by the purchase of these additional certificates to all their certificates by following the approach of opportunity cost calculation as described in Chapter 5. Hence the oil companies may charge the traffic participants for all the certificates even if they have paid for only some of them. This leads to windfall profits as were observed on the energy market in the first phase of the EU-ETS. In ASTRA, this money is withdrawn from the market – which is an unrealistic assumption and leads to an underestimation of the positive macroeconomic effects. The model results can therefore be interpreted as a rather pessimistic estimation of the impact. If the certificates were auctioned, however, the revenues would go to the government or indirectly to the households which would lead to more positive results. Furthermore, as the time horizon of ten years is rather short for a system dynamics model, all the results are presented until 2040 even though the price increase due to the implementation of the
upstream CO₂ emission trading scheme only takes place between 2013 and 2023 and the surcharge on the fuel price of the BaU scenario remains constant thereafter. The long-term effects of the fuel price increase are often superior to the short- or medium-term effects due to the profits of the realised investments in the long-term (see, e.g. Figure 35).

Figure 35: Impacts on macroeconomic values (closed certificate trading scheme, 90 euros per ton of CO₂)

The ASTRA simulation results of the increased fuel prices of about 13 % (which is about 1.2 % per annum) show a decrease in the VMT of households and freight forwarders and increased investments in more efficient vehicles similar to the results of the meso economic model in the previous chapter. Additionally, influences can be observed on GDP, employment, disposable income, government revenues and the vehicle fleet (see Figure 35).

The effect on the Gross Domestic Product (GDP) is a priori unclear. A reduced VMT and a decreased fuel demand lead to a lower GDP on the one hand, but the

However, the amounts of the decrease in the VMT of households and the investments in the vehicle fleet of the ASTRA model do not correspond exactly to the results from the meso economic model which is particularly due to the different assumptions about the BaU scenario (i.e. a further increasing VMT and vehicle population). According to the ASTRA results, the CO₂ emissions in road transport already decrease in the BaU scenario by 10 % between 2013 and 2023, and by another 3.5 % due to the certificate trading scheme. The price increase in the BaU scenario is 13 % thus the corresponding elasticity is much smaller than in the meso economic model.
modal shift and the increased readiness to invest in the vehicle fleet have a positive impact on the GDP on the other hand. The negative impact may outweigh the positive effect in short- to medium-term considerations, but in the longer view, the positive effect might be stronger. This explains the development of the GDP curve determined by the ASTRA model (see Figure 35) which declines between 2013 and 2032 to about -0.2 % of the BaU scenario and then starts to increase in relation to the BaU scenario after 2032.

Similar influences can be observed for employment. A first decline between 2013 and 2023 to -0.4 % compared to the BaU scenario is then reversed to an increase between 2024 and 2040, when employment levels nearly reach the value of the BaU scenario. This results from the inelastic fuel demand of households and the associated additional burden on their budget which leads to decreased spending on other consumer goods. This brings about a drop in employment in other sectors. Through the investments in more fuel-efficient vehicles, this additional burden declines over time and households might even save money due to their more efficient vehicles in the long run. The development of employment in the vehicle sector remains more or less constant as the technological change in the vehicle fleet creates more jobs in sectors other than the traditional automobile sector, e.g. chemicals (for batteries and so on).

Even though investments in the vehicle market increase considerably, overall investments are assumed to decline according to the ASTRA results. The net investments in the German economy will be more than 0.5 % lower than in the BaU scenario in 2023. Afterwards, investments increase again to a value exceeding the BaU scenario value by more than 0.1 % in 2040.

Disposable income was chosen to measure income effects. In the ASTRA model this is determined using a top-down approach which takes the GDP from the system of national accounts (SNA)\textsuperscript{110} and then divides this by the number of employed persons. As described above, the rather inelastic fuel demand initially leads to a decreasing GDP. However, the transfers and the income flows to and from foreign countries and economic depreciation remain widely unaffected. Hence the impact on disposable income resembles the impact on GDP. Disposable income declines to about -0.4 % with regard to the BaU scenario in 2023 and increases in the following years to almost the BaU value in 2040.

Due to the reduced VMT and thus a decreased fuel demand of traffic participants, inevitably there is a drop in government revenues because of the fall in energy, petroleum, and value added tax payments. Other effects are a decrease in income tax and social contributions due to lower employment and a decrease in revenues from the German motorway charge for trucks, the Lkw-Maut, and vehicle taxes. The net effect in the ASTRA model is estimated to be -0.37 % below the BaU value in 2023.

\textsuperscript{110} According to the SNA, disposable income is calculated from the GDP by subtracting the balance of the primary income and the economic depreciation plus the balance of transfers to foreign countries.
Besides these macroeconomic effects, the vehicle fleet also changes its composition even though absolute numbers remain stable (-0.25 %). Only the HGV fleet decreases by about 2.4 % with regard to the BaU scenario in 2023.

Other studies have results which show even higher impacts. For example, a study by the EIA (2008b:ix) for the US concluded that the price for CO₂ may even exceed 100 euros in 2030. This would lead to a decrease of GDP by about 0.8 % and a decrease of consumption by about 1.1 % compared to an economy without a CO₂ certificate trading scheme or a CO₂ tax.

6.4 Environmental impacts

The main ecological effects determined by the ASTRA model concern the environmentally-relevant pollutant emissions of carbon monoxide (CO), nitrogen oxide (NOₓ) and volatile organic compounds (VOC). In contrast to CO₂ emissions, which are globally relevant to the climate, the impact of these air emissions is a local one.

Recently, the younger and more efficient car and truck fleet as well as the decreased VMT of households have contributed to a stronger reduction of local air emissions than was the case for CO₂ emissions. The diffusion of the catalytic converter and stronger standards¹¹¹ contributed to a considerable drop in these emissions, but air pollution is still a problem in large cities on hot and windless days. The usual low concentration of CO is harmless, but increased concentration, as observed in underground car parks, can lead to dizziness and very high concentration can even be fatal (“carbon monoxide poisoning”). Nitrogen oxides are harmful in combination with other substances. The concentrations in major cities suffice to affect organisms sensitive to toxicity when nitrogen oxide reacts with water vapour to form acids. They also affect the growth of plants especially through their contribution to smog, high ozone levels (O₃) and acid rain.

¹¹¹ The EURO standard alone with its requirements concerning CO and NOX emissions contributed to a strong decrease in air pollutants.
The ASTRA model results show a reduction in air pollutants of up to 8% within passenger road transport in 2040 compared to the BaU scenario due to the increase in fuel prices of about 1.2% p.a. between 2013 and 2023. Compared to the BaU scenario, CO emissions drop by 3.5% and NOX emissions by 2.2% in 2023 with a continuing downward trend. VOC emissions decrease by 1.7% until 2023 (see Figure 36) but then increase after this because of the greater demand for natural gas vehicles. These decreases in emissions are mainly due to the diffusion of more efficient vehicles in the fleets and their alternative fuels and engines.

6.5 Conclusions 

The results of Chapter 5 show that a closed certificate trading scheme in road transport with a CO₂ emission reduction target of about 10.5% might increase the fuel price by about 20%. This outcome was transferred to the system dynamics model ASTRA to determine further macroeconomic and ecological impacts for Germany.

112 The combustion of natural gas results in a significant amount of methane emissions which are classified as VOC emissions.
All the results of the ASTRA model are presented in relation to a reference (BaU) scenario determined by Krail (2009). The fuel prices which increase by 1.2% between 2013 and 2023 cause traffic participants to reduce their VMT and increase their investments in more fuel efficient vehicles within the ASTRA model which is similar to the results of the meso economic model in Chapter 5.

The ASTRA model also shows impacts on the Gross Domestic Product (GDP), investments, employment, disposable income and government revenues which amount to about -0.1 to -0.5% in 2023. The impacts on the local air pollutants of carbon monoxide (CO), nitrogen oxide (NOx) and volatile organic compounds (VOC) are to decrease these by -1.7 to -3.5% compared to the BaU scenario between 2013 and 2023. This is particularly due to investments in modern less-polluting vehicles and the reduced VMT of households.
7 Summary, conclusions and outlook

This thesis first shows that some characteristics of multi-agent simulation are suitable to represent fundamental properties of road transport – especially when considering the decisions of actors in road passenger transport. Second, it applies a micro-based, meso economic model to analyse the impacts of an upstream CO\textsubscript{2} certificate trading scheme on road transport. The developed model includes some characteristics of the multi-agent simulation approach. An analysis of the impacts on macro-economic parameters completes the thesis.

The following section recapitulates the main findings of the thesis, draws conclusions and provides an outlook for further research.

7.1 Summary

In recent years, the total CO\textsubscript{2} emissions of the European road transport sector have continued to increase. This is also true for Germany over the last few decades, even though emissions have fallen slightly recently as the VMT have stagnated and the specific fuel consumption of vehicles has been reduced. This reduction has been achieved simultaneously with increased performance and vehicle weight. Despite this minor achievement, considerable remaining CO\textsubscript{2} emission reduction potentials are still believed to exist, especially in road passenger transport. This belief is based on the idea that reversing the trend towards heavier vehicles and higher engine performance would lead to cheap and significant CO\textsubscript{2} emission reductions. Furthermore, a more critical and aware modal choice of households could make another contribution to CO\textsubscript{2} emission reduction. However, no total CO\textsubscript{2} emission reduction is expected in road freight transport because of the continued considerable increase in demand expected here in the future. One possibility to mitigate the strong rise in CO\textsubscript{2} emissions from freight transport is the increased use of combined transport, where the developed model identified a remarkable emission reduction potential.

It has been demonstrated that the realisation of CO\textsubscript{2} reduction potentials depends on corresponding policy instruments or on changing cost structures. In road transport, a certificate trading scheme and revised labelling for passenger cars are considered forward-looking policy instruments. For CO\textsubscript{2} emission reduction in German road transport, many studies recommend the introduction of an upstream certificate trading scheme which obliges oil companies to hold the corresponding number of certificates for the fuel sold. This trading scheme has the advantage that all the necessary data are already available for the calculation of the energy tax, that the certificate trading market is assumed to be non-monopolistic and non-oligopolistic, that the corresponding CO\textsubscript{2} emission reduction target can be achieved accurately, and that the system is economically efficient and system conform. One disadvantage is
that the affected oil companies cannot influence the CO₂ emission reductions directly, but only indirectly by modifying the fuel price.

As a reaction to higher fuel prices, traffic participants can either reduce the VMT or invest in more fuel-efficient vehicles with alternative driving technology or other technical measures. Their reaction is inelastic so that significant price increases only result in small CO₂ emission reductions. To analyse these reactions, a meso economic model was developed which includes selected characteristics of multi-agent simulation. These multi-agent models are now being increasingly applied in the social sciences and try to overcome some of the disadvantages of classical economic models, but generate their own shortcomings at the same time. Multi-agent models have the advantage that they can take social principles within groups into account without neglecting the singularity of their individuals. In economics, they fall into the category of microeconomic models and are distinguished from the neoclassical models in particular by their dynamic representation of systems and their not omniscient agents who make decisions based on individual heuristic rules rather than on pure utility maximisation. This leads to fundamental differences in the results where new structures arise within the system due to their autonomous self control. This makes multi-agent models suitable for markets where dynamics within the system are relevant and where the classical assumptions of rational decisions, complete information, homogeneous individuals and profit maximisation do not apply. Most of these characteristics are observed in road passenger transport.

No strict definition exists due to the short evolutionary history of multi-agent modelling. For multi-agent modelling in economics, the characteristics developed by Wooldridge (2002) are often given as pivotal. Many applied models differ significantly from Wooldridge’s characteristics but are still termed multi-agent models if software agents are incorporated (Axelrod, 2005:11). According to Wooldridge (2002), a multi-agent model is characterised by autonomous, reactive and proactive agents with a certain social ability.

This thesis developed a meso economic partial model to assess the impacts of an upstream CO₂ certificate trading scheme in the German road transport sector. Characteristics of multi-agent models such as heterogeneity, reactivity, social ability and autonomy are incorporated. The model simulates four markets: (1) The fuel demand market of motorised passenger traffic (fuel demand of households), (2) the fuel demand of road freight transport (fuel demand of freight forwarders) both of which are directly served by oil companies (fuel supply of oil companies); (3) the investment market which consists on the demand side of the vehicle demand of households and freight forwarders and on the supply side of the supply of new cars by car manufacturers and of used cars by households. (4) Finally, the certificate market is introduced to trade certificates between oil companies (in a closed system) or with other sectors (in an open one). The represented households and their passenger cars are based on data taken from the German Mobility Panel (GMP) and the freight forwarders on a database from Bühler (2006).

The model contains two scenarios which can be selected by the model user. The first scenario allows oil companies to trade CO₂ certificates with other sectors of the
EU-ETS as well (open certificate trading scheme), whereas the second scenario does not permit inter-sectoral trade (closed certificate trading scheme). Within the first scenario, oil companies can balance their accounts in the EU-ETS to meet the total road transport fuel demand. In the closed scheme, CO₂ emission reductions have to take place within the road transport sector itself and oil companies can only trade certificates with each other. A complete trading period lasts one year and in every trading period the number of CO₂ certificates allocated by the government is reduced by 1.5%. The initial number of allocated certificates is 1.5% more than the number actually required to satisfy the initial fuel demand of traffic participants. Hence, an overall emission reduction of about 10.5% over ten years is specified in the model. Analogous to the EU-ETS, free certificates are allocated to the oil companies based on their historical market shares (grandfathering).

The represented freight forwarders can only avoid increased fuel prices by shifting freight from the roads to combined transport, i.e. modifying the modal split. This modal choice decision is modelled with a logit model developed by Bühler (2006). Additionally, it is assumed that there is a 1.5% decrease in the specific fuel combustion of trucks per annum. However, the simultaneous increase in transport performance demand by the same amount results in an unchanged fuel demand of freight forwarders in the reference case.

In road passenger transport, traffic participants can react by either reducing their VMT, or by buying more fuel-efficient cars. Both options are incorporated into the model using a reaction equation determined through a panel regression with GMP data. The VMT reaction function is based on a regression from Frondel et al. (2007).

The main finding when comparing the open and closed trading schemes is the very high certificate price in the closed scheme. In the open scheme, the actors’ willingness-to-pay for transport activities far exceeds the marginal CO₂ emission abatement costs of the industrial sector. Hence, in this case, road transport continues to emit unchecked amounts of CO₂, other sectors reduce their emissions and oil companies buy certificates from the EU-ETS to balance their accounts.

In the closed emission trading scheme, certificate prices exceed 100 euros per ton. This high price results if it is assumed that traffic participants behave consistently. However, it is more likely that traffic participants adjust their reaction functions due to their greater awareness of climate change and sensitivity towards higher fuel prices. Thus a certificate price of 90 to 100 euros is probably more realistic. This is equivalent to a surcharge of about 0.25 euros per litre on the corresponding fuel price which results in an average additional burden of about 20 euros per month and household, or about 20 euros per shipment for freight forwarders. However, some households have to accept additional costs of more than 150 euros per month and some freight forwarders about 300 euros per shipment.

The results of the model were then incorporated into the system dynamics model ASTRA in order to analyse the impacts on macroeconomic parameters such as the Gross Domestic Product, employment, disposable income, government revenues, and the impacts on pollutant emissions such as carbon monoxide, carbon dioxide, and nitrogen oxide as well as on volatile organic compounds (VOC). These results are analysed against the ASTRA reference (business-as-usual) scenario.
The increased fuel price of about 13% (1.2% per annum) leads to a decrease in VMT and an increase in investments in new fuel-efficient vehicles. This outcome is similar to the results of the micro-based, meso economic model. The impacts on the Gross Domestic Product, employment, disposable income, government revenues and investments are between -0.5 and -0.1% in 2023 compared to the business-as-usual scenario of ASTRA. In the long run, when assuming an additional constant surcharge on fuel of about 13% between 2023 and 2040, an impact on the economic values of between -0.25 to +0.1% can be observed in 2040. Air pollutants such as carbon monoxide, carbon dioxide, and nitrogen oxide as well as volatile organic compounds (VOC) are reduced by between 2 and 3% until 2023 due to increased investment in new technologies and reduced VMT. However, the increased demand for natural gas-powered vehicles causes rising VOC emissions which even result in an increase in total emissions of about 1.5% in 2040 compared to the business-as-usual scenario of ASTRA.

7.2 Conclusions and outlook

Multi-agent models are suitable for simulating the German road transport system. The attributes of multi-agent models given by Wooldridge (2002) such as heterogeneity, autonomy, reactivity, proactivity, and social ability can be found in road transport. Due to the evolutionary development in road transport, it is important to represent the dynamics of this complex system besides the observed bounded rationality of traffic participants. This is managed within a meso economic partial model applying attributes of multi-agent modelling.

The developed model adequately represents the German road transport system in an impact assessment of an upstream certificate trading system. Further developments could improve the habitualised algorithms of the modal choice, the transport decisions of households as well as the influence of social criteria and their learning ability. The learning ability of agents has been empirically observed among others for the car purchase decisions of households. Such developments hold a considerable potential to represent road transport decisions even more realistically. This might also be true for other sectors\textsuperscript{113} where multi-agent models are able to enrich classical economic models.

With regard to the European perspective and meeting the global challenge of reducing CO\textsubscript{2} emissions, it makes sense to harmonise policies within the European Union and expand the developed model to other countries. This is particularly important as the German road passenger transport sector has already managed to reverse the CO\textsubscript{2} emissions trend in contrast to most of the other European Member States (EEA, 2008:17).

\textsuperscript{113} Up to now, numerous multi-agent models exist only in the electricity market (among others Sensfuß, 2008).
In conclusion, this thesis has shown that implementing a certificate trading scheme in road transport is a very efficient way to reduce CO$_2$ emissions. An open trading scheme is considered superior to a closed one with the same reduction target because of the additional financial burdens placed on households and freight forwarders in the closed scheme. A certificate trading scheme is not a magic bullet for reducing CO$_2$ emissions from transport, but it could get the ball rolling towards the vision of (almost) emission-free transport.
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**APPENDIX I – REPASt: Packages and classes applied in the model**

### Table A1: Packages and classes of the REPASt JAVA library

<table>
<thead>
<tr>
<th>Package/Class</th>
<th>Description</th>
<th>Transport relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analysis Package</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OpenSequenceGraph</td>
<td>A graph that displays a connected series of points (a sequence).</td>
<td>√</td>
</tr>
<tr>
<td>NetSequenceGraph</td>
<td>A graph that captures a series of points (sequences) specialized for network statistics.</td>
<td>O</td>
</tr>
<tr>
<td>OpenHistogram</td>
<td>Dynamic bar chart. The OpenHistogram class allows the user to histogram data generated by a collection of objects.</td>
<td>O</td>
</tr>
<tr>
<td>Histogram</td>
<td>A histogram plot allowing the user to histogram data from a list of objects.</td>
<td>O</td>
</tr>
<tr>
<td>Plot</td>
<td>A generic point plotting class.</td>
<td>O</td>
</tr>
<tr>
<td>DataSource(interface)</td>
<td>Interface for data sources whose data is recorded by DataRecorder</td>
<td>√</td>
</tr>
<tr>
<td>NumericDataSource</td>
<td>Interface for data sources whose data is recorded by DataRecorder and is numeric.</td>
<td>O</td>
</tr>
<tr>
<td>Sequence(interface)</td>
<td>Interface for objects that are the source of data to be plotted by a sequence graph.</td>
<td>O</td>
</tr>
<tr>
<td>BinDataSource</td>
<td>Interface for objects that can provide double values to compute bins for a histogram.</td>
<td>O</td>
</tr>
<tr>
<td><strong>Engine Package</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SimModelImpl</td>
<td>A partial implementation of the SimModel interface.</td>
<td>√</td>
</tr>
<tr>
<td>Schedule</td>
<td>Manages the execution of BasicActions (Action Groups, SimActions, and SimListActions) according to a simulation clock.</td>
<td>√</td>
</tr>
<tr>
<td>SimInit</td>
<td>Creates and initializes a simulation.</td>
<td>√</td>
</tr>
<tr>
<td>BasicAction</td>
<td>Abstract base class for any action in a simulation that can be executed by a Schedule.</td>
<td>√</td>
</tr>
<tr>
<td>Package/Class</td>
<td>Description</td>
<td>Transport relevance</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>ActionGroup</td>
<td>A collection of BasicActions to be executed by a schedule. The BasicActions in the ActionGroup can be executed sequentially in the order they were added or randomly.</td>
<td>✓</td>
</tr>
<tr>
<td>Space Package</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Object2DGrid</td>
<td>A discrete two dimensional grid whose cells contain Objects.</td>
<td>✓</td>
</tr>
<tr>
<td>GUI Package</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DisplaySurface</td>
<td>Basically windows. Handles the drawing of Displayables and the probing of probeables.</td>
<td>✓</td>
</tr>
<tr>
<td>ColorMap</td>
<td>A customizable map of java.awt.Color(s) to Integers.</td>
<td>✓</td>
</tr>
<tr>
<td>Value2DDisplay</td>
<td>Displays 2d arrays of values (Integers or ints).</td>
<td>O</td>
</tr>
<tr>
<td>Object2DDisplay</td>
<td>Displays Discrete2DSpaces and the objects contained within them.</td>
<td>✓</td>
</tr>
<tr>
<td>Drawable (interface)</td>
<td>Interface for those objects in 2D spaces that wish to be drawn on a DisplaySurface by a Displayable.</td>
<td>–</td>
</tr>
<tr>
<td>SimGraphics</td>
<td>A Wrapper around java.awt.Graphics2D.</td>
<td>O</td>
</tr>
<tr>
<td>SimUtilities</td>
<td>Static Utility methods for RePast simulations.</td>
<td>–</td>
</tr>
</tbody>
</table>

With:

- ✓ applied in the model
- O recommended
- – possible
APPENDIX II – Descriptive statistics of variables used in the regressions

Table A2: Descriptive statistics of GMP variables used in the regressions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>$fuelPrice_{n,i,k}$</td>
<td>[euros/litre] double {0.5-5}</td>
<td>1.24</td>
<td>1.89</td>
<td>0.65</td>
</tr>
<tr>
<td>$lnPrice$</td>
<td>ln[euros/litre] double {-0.7-1.6}</td>
<td>0.21</td>
<td>0.64</td>
<td>-0.43</td>
</tr>
<tr>
<td>$hhType_i$</td>
<td>integer {1-4}</td>
<td>2.23</td>
<td>4.00</td>
<td>1.00</td>
</tr>
<tr>
<td>$rType_i$</td>
<td>integer {1-5}</td>
<td>2.26</td>
<td>5.00</td>
<td>1.00</td>
</tr>
<tr>
<td>$mileage_{i,t}$</td>
<td>[km per day] double {0-200}</td>
<td>43.6</td>
<td>238</td>
<td>0.00</td>
</tr>
<tr>
<td>$lnVMT_{i,t}$</td>
<td>ln[km per month] double {2-9}</td>
<td>6.80</td>
<td>8.73</td>
<td>2.48</td>
</tr>
<tr>
<td>$hhSize_i$</td>
<td>[persons] integer {1-6}</td>
<td>2.58</td>
<td>6.00</td>
<td>1.00</td>
</tr>
<tr>
<td>$nHSD_i$</td>
<td>[numbers] integer {1-6}</td>
<td>0.78</td>
<td>4.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$nEP_i$</td>
<td>[numbers] integer {1-6}</td>
<td>1.06</td>
<td>3.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$kidD_i$</td>
<td>boolean {0 und 1}</td>
<td>0.18</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$fuelCombustion_{n,i,k}$</td>
<td>[l/100km] double {2-20}</td>
<td>7.89</td>
<td>16.81</td>
<td>1.04</td>
</tr>
<tr>
<td>$lnComb_{n,i,k}$</td>
<td>ln[l/100km] double {0.7-3}</td>
<td>2.04</td>
<td>2.82</td>
<td>0.04</td>
</tr>
<tr>
<td>$dieselD_{n,i,k}$</td>
<td>boolean {0 und 1}</td>
<td>0.22</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Variable</td>
<td>Unit</td>
<td>Mean</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>-----------------</td>
<td>------------</td>
<td>-------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>premium_{n,i,k}</td>
<td>boolean</td>
<td>0.27</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>holiday_{i}</td>
<td>boolean</td>
<td>0.15</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>carAge_{n,i,k}</td>
<td>[year]</td>
<td>7.29</td>
<td>47.00</td>
<td>0.00</td>
</tr>
<tr>
<td>cc_{n,i,k}</td>
<td>[ccm] double</td>
<td>1715.20</td>
<td>5000.00</td>
<td>594.00</td>
</tr>
<tr>
<td>ln(cc)</td>
<td>ln[ccm] double</td>
<td>7.42</td>
<td>8.52</td>
<td>6.39</td>
</tr>
<tr>
<td>incomeClass_{i}</td>
<td>integer</td>
<td>5.75</td>
<td>9.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>
APPENDIX III – STATA regression results of the logit model of vehicle purchase

Table A3: Regression results of the logit model of vehicle purchase

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SD-Value</th>
<th>t-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>lnkm0</td>
<td>0.1233571</td>
<td>0.0980967</td>
<td>1.26</td>
<td>0.209</td>
</tr>
<tr>
<td>trend95</td>
<td>**0.8775019</td>
<td>0.3811733</td>
<td>2.30</td>
<td>0.021</td>
</tr>
<tr>
<td>trend96</td>
<td>**1.093051</td>
<td>0.4426429</td>
<td>2.47</td>
<td>0.014</td>
</tr>
<tr>
<td>trend97</td>
<td>**0.8939293</td>
<td>0.2763154</td>
<td>3.24</td>
<td>0.001</td>
</tr>
<tr>
<td>trend98</td>
<td>**0.6727185</td>
<td>0.2741852</td>
<td>2.45</td>
<td>0.014</td>
</tr>
<tr>
<td>trend99</td>
<td>**0.9832347</td>
<td>0.3065518</td>
<td>3.21</td>
<td>0.001</td>
</tr>
<tr>
<td>trend00</td>
<td>**0.5894546</td>
<td>0.2781314</td>
<td>2.12</td>
<td>0.034</td>
</tr>
<tr>
<td>trend01</td>
<td>0.4498127</td>
<td>0.2854404</td>
<td>1.58</td>
<td>0.115</td>
</tr>
<tr>
<td>trend02</td>
<td>**0.4936133</td>
<td>0.2811923</td>
<td>1.76</td>
<td>0.079</td>
</tr>
<tr>
<td>trend03</td>
<td>0.4044728</td>
<td>0.2723949</td>
<td>1.48</td>
<td>0.138</td>
</tr>
<tr>
<td>trend04</td>
<td>-0.087432</td>
<td>0.306241</td>
<td>-0.29</td>
<td>0.775</td>
</tr>
<tr>
<td>rtyp1</td>
<td>**-0.3734032</td>
<td>0.1579308</td>
<td>-2.36</td>
<td>0.018</td>
</tr>
<tr>
<td>rtyp2</td>
<td>-0.2129178</td>
<td>0.1885724</td>
<td>-1.13</td>
<td>0.259</td>
</tr>
<tr>
<td>rtyp3</td>
<td>**-0.484583</td>
<td>0.2003989</td>
<td>-2.42</td>
<td>0.016</td>
</tr>
<tr>
<td>hhtyp1</td>
<td>-0.106256</td>
<td>0.2095087</td>
<td>-0.51</td>
<td>0.612</td>
</tr>
<tr>
<td>hhtyp2</td>
<td>**-0.5217727</td>
<td>0.2381997</td>
<td>-2.19</td>
<td>0.028</td>
</tr>
<tr>
<td>hhtyp3</td>
<td>**-0.3583928</td>
<td>0.2040562</td>
<td>-1.76</td>
<td>0.079</td>
</tr>
<tr>
<td>lnalter0</td>
<td>**0.4936715</td>
<td>0.0832776</td>
<td>5.93</td>
<td>0.000</td>
</tr>
<tr>
<td>lnverb0</td>
<td>**0.5735483</td>
<td>0.1469149</td>
<td>3.90</td>
<td>0.000</td>
</tr>
<tr>
<td>luxus</td>
<td>**0.576559</td>
<td>0.2745889</td>
<td>-2.10</td>
<td>0.036</td>
</tr>
<tr>
<td>lncci</td>
<td>-0.0204719</td>
<td>0.1750284</td>
<td>-1.17</td>
<td>0.242</td>
</tr>
<tr>
<td>_cons</td>
<td>-0.4761707</td>
<td>1.739027</td>
<td>-0.27</td>
<td>0.784</td>
</tr>
</tbody>
</table>

Log likelihood: 807.84043
LR chi2(21): 99.38
Prob > chi2: 0.0000
Pseudo R^2: 0.0579
APPENDIX IV – STATA regression results of the vehicle age determination (Equation (31)) and fuel combustion (Equation (32)) of the purchased car

Table A4: Regression results for the determination of the car age of the purchased car

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>trend</td>
<td><strong>0.541</strong></td>
<td>0.019</td>
</tr>
<tr>
<td>rtype1</td>
<td>0.264</td>
<td>0.167</td>
</tr>
<tr>
<td>rtype2</td>
<td>0.314</td>
<td>0.190</td>
</tr>
<tr>
<td>rtype3</td>
<td>0.004</td>
<td>0.203</td>
</tr>
<tr>
<td>rtype4</td>
<td><strong>0.527</strong></td>
<td>0.188</td>
</tr>
<tr>
<td>hhtype1</td>
<td>*-0.356</td>
<td>0.179</td>
</tr>
<tr>
<td>hhtype2</td>
<td><strong>-0.406</strong></td>
<td>0.208</td>
</tr>
<tr>
<td>hhtype3</td>
<td>-0.239</td>
<td>0.176</td>
</tr>
<tr>
<td>ln(Age)</td>
<td><strong>0.526</strong></td>
<td>0.071</td>
</tr>
<tr>
<td>ln(cc)</td>
<td><strong>-0.419</strong></td>
<td>0.136</td>
</tr>
<tr>
<td>Constant</td>
<td><strong>2.917</strong></td>
<td>1.123</td>
</tr>
</tbody>
</table>

Observations: 346  Prob > F  R²
0.0000  0.194

Note: * denotes significance at the 5 %-level and ** at the 1 % level, respectively.

Table A5: Regression results for the determination of the fuel combustion of the purchased car

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(fuel combustion)</td>
<td><strong>0.476</strong></td>
<td>0.047</td>
</tr>
<tr>
<td>fuel price</td>
<td>*-0.152</td>
<td>0.077</td>
</tr>
<tr>
<td>ln(VMT)</td>
<td>*0.031</td>
<td>0.015</td>
</tr>
<tr>
<td>ln(cc)</td>
<td>*0.045</td>
<td>0.022</td>
</tr>
<tr>
<td>Constant</td>
<td><strong>0.685</strong></td>
<td>0.235</td>
</tr>
</tbody>
</table>

Observations: 334  Prob > F  R²
0.0000  0.245

Note: * denotes significance at the 5 %-level and ** at the 1 % level, respectively.
APPENDIX V – Meso-economic model – description of classes

Co2Model.java
The Co2Model.java class is the pivotal class in the model. It administretes all REPAST functions. It is responsible for the generation, scheduling and the controlling of the model. It generates the graphical display.

Co2Market.java
The Co2Market.java class represents the certificate trading exchange market where the oil companies trade certificates. Here, the formation of prices takes place.

Household.java
The Household.java class represents all households of the model with their characteristics (household size, children dummies, ...) and vehicles (from the Car.java class). The car replacement decision and the VMT decision is made in this class. They are based on the GermanMobility Panel.

Car.java
The Car.java class represents all passenger vehicles and their characteristics (age, specific fuel combustion, ...). They are based on the German Mobility Panel.

Carrier.java
The Carrier.java class represents the freight forwarders with their characteristics and include the modal choice decision. The average truck fleet is saved here.

Trip.java
The Trip.java class represents all transport orders which are passed on to the Carriers.java class on a daily basis. They are based on the database from Bühler (2006).

FuelCompany.java
The FuelCompany.java class represents the oil companies affected by the emission trading scheme. They balance their certificate accounts and trad certificates on the Co2Market.

Db.java
The Db.java class generates a database of all relevant data for a model run. It imports in the initializing period of the model the data from the CSVReader.java class and generates the corresponding households, vehicles, trips and freight forwarders for the model run.
**CSVReader.java**
The CSVReader.java class reads the underlying data sets for the households, vehicles, freight forwarder and their trips from the corresponding .csv-files from the German Mobility Panel and the Bühler-Database and pass the data to the Db.java class.