THE POTENTIAL OF ALTERNATIVE FUEL CARS FOR ACHIEVING CO_2 REDUCTION TARGETS IN EU27

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ABSTRACT

In order to analyse the potential and suitable incentives to accelerate the diffusion of alterative fuel cars a diffusion model is developed and integrated in the System Dynamics model ASTRA. ASTRA is an integrated macroeconomic, transport and environmental model that is developed for application of sustainability impact assessment of transport and climate policies. Six potential technologies were added to the existing fuel types gasoline and diesel: compressed natural gas (CNG), liquefied petroleum gas (LPG), hybrid, bioethanol (E85), battery electric and hydrogen fuel cells. Based on a detailed analysis of the importance of different characteristics of cars and fuel technologies, a suitable model structure is established. In a bottom-up process all necessary economic drivers are added to total costs representing the major driver of the purchase decision for a certain fuel technology. The calculation considers as well the filling station infrastructure and the tank capacity for each fuel type. Finally, average costs per vehicle-km for each fuel technology provide the quantifiable part of the purchase decision. The simulation of the probability of choosing a certain fuel technology is performed in a discrete choice function. This type of function allows the consideration of qualitative factors like security of certain technologies or the image. In a validation process, these soft factors are quantified by comparing the purchasing behaviour based on costs per technology (diesel and gasoline) and the observed behaviour in time series from 1990 to 2006.
The paper demonstrates the potential of alternative fuel technologies for passenger cars by simulating the purchasing decision in the EU27 until 2050. A policy scenario is presented describing the impacts of policy actions for promoting low emission vehicles focussing on electric and hydrogen cars. The integrated character of the ASTRA model allows the estimation of the potential of each fuel technology for reducing CO_2 emissions and achieving targets in EU27. The consideration of fuel price developments estimated by the world energy demand and supply model POLES completes this comprehensive approach.

Keywords: passenger car, technology diffusion, vehicle fleet modelling, System Dynamics, ASTRA, battery electric cars, hydrogen cars, feebate, CO_2 pricing, CO_2 emission limits

INTRODUCTION

The overall performance in the passenger and freight transport sector was characterised by a continuous growth of passenger-km and ton-km in EU27 until 2007. Average annual growth rates of +1.2% for passenger-km and +2.6% for ton-km since 2003 reflect the growing significance of transport in terms of the envisaged reduction of greenhouse gas (GHG) emissions in the EU. While all other sectors - industry, energy production, agriculture, waste and others – managed to reduce CO_2 emissions, emissions from transport grew by +15% in the last ten years. The contribution of transport to total CO_2 emissions in reached a share of 20% in 2007. Facing fossil fuel scarcity in the coming decades, these developments demonstrate the responsibility of actors in the transport sector to stop this trend. The diffusion of alternative fuel technologies for passenger cars is one possible solution for decoupling growing transport demand and CO_2 emissions. The question to be raised is how to accelerate the diffusion of alternative fuel cars efficiently.
In order to analyse the potential and suitable incentives to accelerate the diffusion of alterative fuel cars a diffusion model is developed and integrated in the System Dynamics model ASTRA. ASTRA is an integrated macroeconomic, transport and environmental model that is developed for application of sustainability impact assessment of transport and climate policies. Six potential technologies were added to the existing fuel types gasoline and diesel: compressed natural gas (CNG), liquefied petroleum gas (LPG), hybrid, bioethanol (E85), battery electric and hydrogen fuel cells. Based on a detailed analysis of the importance of different characteristics of cars and fuel technologies, a suitable model structure is established. In a bottom-up process all necessary economic drivers are added to total costs representing the major driver of the purchase decision for a certain fuel technology. Fuel prices and average consumption, taxes, maintenance costs and investment costs are considered in this calculation. Furthermore, the cost calculation considers the filling station infrastructure and the tank capacity for each fuel type in terms of fuel procurement costs. Finally, average costs per vehicle-km for each fuel technology provide the quantifiable part of the purchase decision. The simulation of the probability of choosing a certain fuel technology is performed in a discrete choice function (multinomial logit function). This type of function allows the consideration of qualitative factors like security of certain technologies or the image. In a validation process, these soft factors are quantified by comparing the purchasing behaviour based on costs per technology (diesel and gasoline) and the observed behaviour in time series from 1990 to 2006.
The paper demonstrates the potential of alternative fuel technologies for passenger cars by simulating the purchasing decision in the EU27. Based on a reference scenario considering no incentives for accelerating the diffusion of certain technologies, a policy scenario is presented describing the impacts of policy actions for promoting low emission vehicles focussing on electric and hydrogen cars. The integrated character of the ASTRA model allows the estimation of the potential of each fuel technology for reducing CO_2 emissions and achieving targets in EU27 as changing average costs per vehicle-km are used as input in the calculation of transport performance. The consideration of fuel price developments estimated by the world energy demand and supply model POLES completes this comprehensive approach.

The paper starts with a brief description of the major characteristics of the System Dynamics methodology which is used for modelling the ASTRA model. An overview of the ASTRA model structure in which the car fleet model is embedded should provide the necessary knowledge for understanding the chosen approach. A detailed description of chosen approach for modelling car fleets in EU27 and the diffusion of alternative fuel technologies is following this section. After an introduction into and an explanation of the chosen policy measures, the ASTRA policy scenario results are presented and assessed. The paper concludes with a critical analysis of the model results and a confrontation of the results with overall CO_2 reduction targets of the EU.

SYSTEM DYNAMICS

In order to develop the car technology choice model the System Dynamics methodology is applied. System Dynamics is an approach to understanding the behaviour of complex systems over time. FORRESTER (1962, 1971) developed the methodology during the 1960ies at the Massachusetts Institute of Technology (MIT) to analyse the long-term behaviour of social systems like huge industries (General Electric) or cities (Boston). He applied mathematical methods developed to analyse electric feedback control systems to social systems and created a graphical code, the mathematical foundations based on engineering approaches and the necessary software. In the end a theory and corresponding methodology was born that is based on:

- Theory of information feedback systems applied to social systems;
- Mathematics of differential analysis respectively difference equation analysis;
- Decision theory;
- An experimental model approach to the design of complex social systems;
- Digital computing for the vast amount of computation;
- A graphical scheme to represent systems of feedback loops.

Modern information feedback systems emerged at the beginning of the 20th century and by this time have been closely related to electrical systems like the first transcontinental phone lines in the United States and anti aircraft radar systems. Nevertheless, it is shown in literature that they date back until three centuries before Christ when the first water clock flow regulators have been developed. All those systems have in common that they consist of at least one closed feedback loop in which a signal dependent upon the output of the system is fed back to the input of the system in such a way that it affects its own value. The mathematician WIENER (1948) was the first to conclude that the feedback loop concept is a universal concept applying not only to mechanic and electric systems but also to humans and human systems. Forrester extended this conclusion by demonstrating that human systems including economy, society, technology and environment consist of a set of interacting feedback loops. Hence, he had to develop a theory and methodology that is able to model those interactions.
One of the first steps was to develop a scheme to graphically present the interactions within a system of feedback loops: the effect diagrams. Based on these diagrams interdisciplinary teams could discuss and develop the structure of feedback loops in their analysed social

systems. A subsequent step was to make use of the experiences gained by Electrical Engineers from analogue computers, the so-called differential analysers. With these differential analysers a mathematical formulation was provided that enabled a description of systems development over time. Forrester and his associates made use of this in developing software tools in the end using difference equations for calculating the dynamic equations of the feedback system and its development over time.

THE ASTRA MODEL

The following chapter should provide a brief overview of the ASTRA model and how the car fleet model is embedded. A more detailed description of the model and its structure can be found in SCHADE (2005) and KRAIL (2009). ASTRA (Assessment of Transport Strategies) is applied for Integrated Assessment of policy strategies. The model is implemented as System Dynamics model. The ASTRA model has been developed and applied in a sequence of European research projects by three Institutions since 1998: Fraunhofer-ISI, IWW and TRT. The ASTRA model consists of nine modules that are all implemented within one Vensim© system dynamics software file:

- Population module (POP),
- Macro-economic module (MAC),
- Regional economic module (REM),
- Foreign trade module (FOT),
- Infrastructure module (INF),
- Transport module (TRA),
- Environment module (ENV),
- Vehicle fleet module (VFT) and
- Welfare measurement module (WEM).

An overview on the nine modules and their main interfaces is presented in Figure 1. The Population Module (POP) provides the population development for the 29 European countries with one-year age cohorts. The model depends on fertility rates, death rates and immigration of the EU27 countries. Based on the age structure, given by the one-year-age cohorts, important information is provided for other modules like the number of persons in the working age or the number of persons in age classes that permit to acquire a driving license.
The MAC provides the national economic framework, which imbeds the other modules. The MAC incorporates neo-classical elements like production functions. Keynesian elements are considered like the dependency of investments on consumption, which are extended by some further influences on investments like exports or government debt. Further elements of endogenous growth theory are incorporated like the implementation of endogenous technical progress (e.g. depending on sectoral investment) as one important driver for the overall economic development.

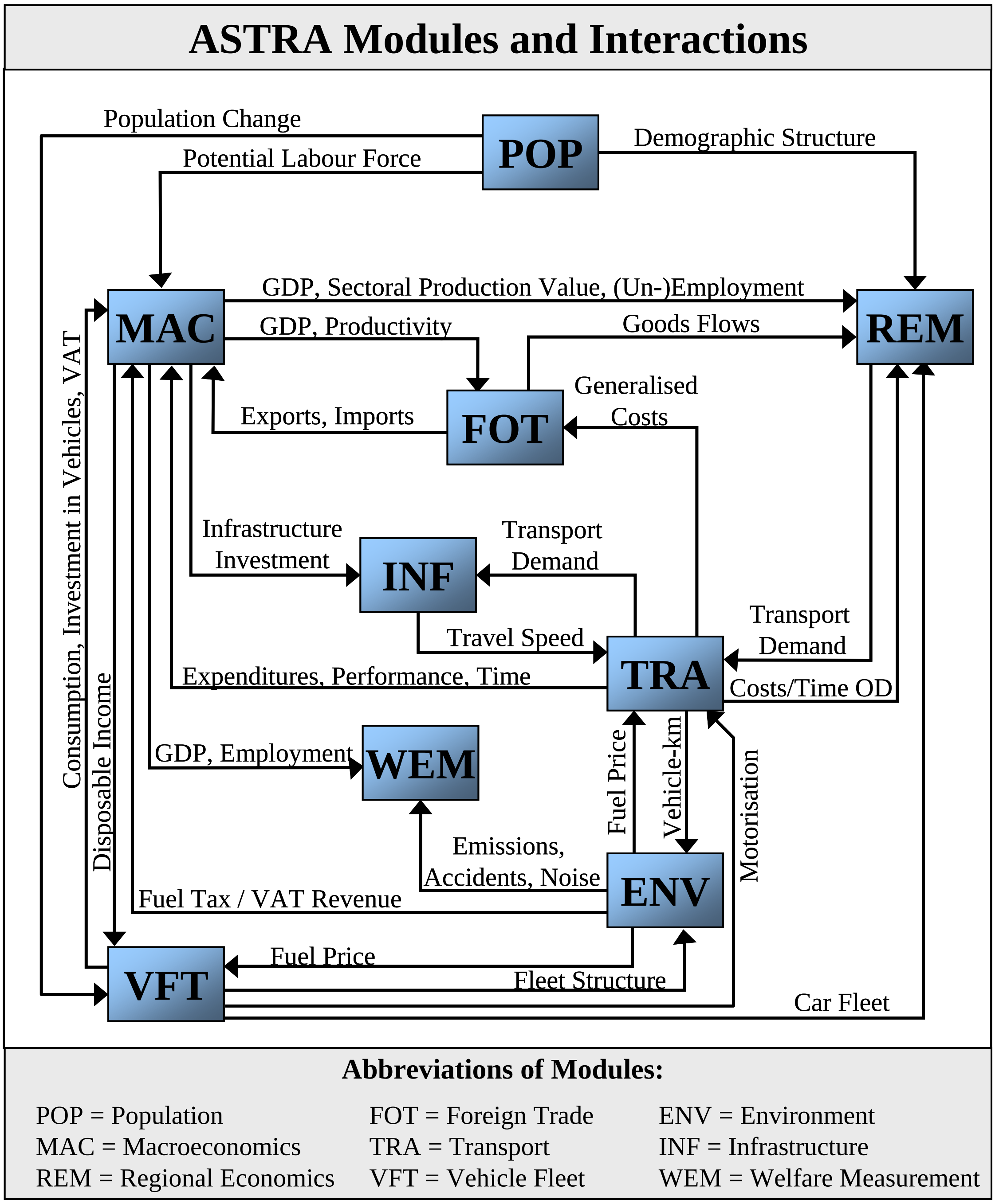

Figure 1 – ASTRA Modules, Main Outputs and their Interactions

Six major elements constitute the functionality of the macroeconomics module. The first is the sectoral interchange model that reflects the economic interactions between 25 economic sectors of the national economies. Demand-supply interactions are considered by the second and third element. The second element, the demand side model depicts the four major components of final demand: consumption, investments, exports-imports and the government consumption. The supply side model reflects influences of three production factors: capital stock, labour and natural resources as well as the influence of technological progress that is modelled as total factor productivity. Endogenised total factor productivity depends on investments, freight transport times and labour productivity changes. The fourth element of MAC is constituted by the employment model that is based on value-added as output from input-output table calculations and labour productivity. Employment is differentiated into full-time equivalent employment and total employment to be able to reflect the growing importance of part-time employment. In combination with the population module unemployment was estimated. The fifth element of MAC describes governmental behaviour. As far as possible government revenues and expenditures are differentiated into categories that can be modelled endogenously by ASTRA and one category covering other revenues or other expenditures. Sixth and final of the elements constituting the MAC are the micro-macro bridges. These link micro- and meso-level models, for instance the transport module or the vehicle fleet module to components of the macroeconomics module. That means, that expenditures for bus transport or rail transport of one origin-destination pair (OD) become part of final demand of the economic sector for inland transport within the sectoral interchange model. The macroeconomics module provides several important outputs to other modules like Gross Domestic Product (GDP). This is for instance required to calculate sectoral trade flows between the European countries.

The Regional Economic Module (REM) mainly calculates the generation and spatial distribution of freight transport volume and passenger trips. The number of passenger trips is driven by employment situation, car-ownership development and number of people in different age classes. Trip generation is performed individually for each of the 76 zones of the ASTRA model. Distribution splits trips of each zone into three distance categories of trips within the zone and two distance categories crossing the zonal borders and generating OD-trip matrices with 76x76 elements for three trip purposes. Freight transport is driven by two mechanisms: Firstly, national transport depends on sectoral production value of the 15 goods producing sectors where the monetary output of the input-output table calculations are transferred into volume of tons by means of value-to-volume ratios. For freight distribution and the further calculations in the transport module the 15 goods sectors are aggregated into three goods categories. Secondly, international freight transport i.e. freight transport flows that are crossing national borders are generated from monetary Intra-European trade flows of the 15 goods producing sectors. Again transfer into volume of tons is performed by applying value-to-volume ratios that are different from the ones applied for national transport. In that sense the export model provides generation and distribution of international transport flows within one step on the base of monetary flows.

The Foreign Trade Module (FOT) is divided into two parts: trade between the EU27 European countries (INTRA-EU model) and trade between the EU27+2 European countries and the rest-of-the world (RoW) that is divided into nine regions (EU-RoW model with Oceania, China, East Asia, India, Japan, Latin America, North America, Turkey, Rest-of-the-World). Both models are differentiated into bilateral relationships by country pair by sector. The INTRA-EU trade model depends on three endogenous and one exogenous factor. World GDP growth exerts an exogenous influence on trade. Endogenous influences are provided by GDP growth of the importing country of each country pair relation, by relative change of sectoral labour productivity between the countries and by averaged generalised cost of passenger and freight transport between the countries. The latter is chosen to represent an accessibility indicator for transport between the countries. The EU-RoW trade model is mainly driven by relative productivity between the European countries and the rest-of-the-world regions. Productivity changes together with GDP growth of the importing RoW-country and world GDP growth drive the export-import relationships between the countries. Since, transport cost and time are not modelled for transport relations outside EU27 transport is not considered in the EU-RoW model. The resulting sectoral export-import flows of the two trade models are fed back into the macroeconomics module as part of final demand and national final use respectively. Secondly, the INTRA-EU model provides the input for international freight generation and distribution within the REM module.

The Infrastructure Module (INF) provides the network capacity for the different transport modes. Infrastructure investments derived both from the economic development provided by the MAC and from infrastructure investment policies alter the infrastructure capacity. Using speed flow curves for the different infrastructure types and aggregate transport demand the changes of average travel speeds over time are estimated and transferred to the TRA where they affect the modal choice.

Major input of the Transport Module (TRA) constitutes the demand for passenger and freight transport that is provided by the REM in form of OD-matrices (i.e. matrices linking origin and destination of transport activities). Using transport cost and transport time matrices the transport module performs the modal-split for five passenger modes and three freight modes. The cost and time matrices depend on influencing factors like infrastructure capacity and travel speeds both coming from the INF module, structure of vehicle fleets, transport charges, fuel price or fuel tax changes. Depending on the modal choices, transport expenditures are calculated and provided to the macroeconomics module. Changes in transport times are transferred to the macroeconomics module such that they influence total factor productivity. Considering load factors and occupancy rates respectively, vehicle-km are calculated.

Major outputs of the TRA provided to the Environment Module (ENV) are the vehicles-km travelled (VKT) per mode and per distance band and traffic situation respectively. Based on these traffic flows and the information from the vehicle fleet model on the national composition of the vehicle fleets and hence on the emission factors, the environmental module calculates the emissions from transport. Besides emissions, fuel consumption and, based on this, fuel tax revenues from transport are estimated by the ENV. Traffic flows and accident rates for each mode form the input to calculate the number of accidents in the European countries. Expenditures for fuel, revenues from fuel taxes and value-added-tax (VAT) on fuel consumption are transferred to the macroeconomics module and provide input to the economic sectors producing fuel products and to the government model.

The main objective of the Vehicle Fleet Module (VFT) is the assessment of the structure of road vehicle fleets in terms of technological composition. All road vehicle fleets simulate the besides the fuel technology also the diffusion of emission standards and the age structure of the fleets via cohort models. ASTRA differentiates between passenger cars, buses, light duty and heavy duty vehicles. The most comprehensive model, the passenger car model, is described in detail in the following chapter.

The Welfare Measurement Module (WEM) major macro-economic, environmental and social indicators can be compared and analysed. Also different assessment schemes that combine indicators into aggregated welfare indicators for instance an investment multiplier are provided in the WEM. In some cases, e.g. to undertake a CBA, the functionality is implemented in separate tools.

MODELLING PASSENGER CAR FLEETS

The ASTRA passenger car fleet model simulates the development and technological composition of car fleets in all covered countries. The passenger car model can be differentiated into three sub-models: car purchase, car technology choice and car stock model.
The car purchase model determines changes in the absolute level of the car fleet. The number of new car purchases is supposed to be dependent on the development of various indicators, such as:

- Average income per employee derived from the MAC module,
- Trends for average fuel prices,
- Average costs for operating a car,
- Average costs for buying a car and
- The demographic development provided by the POP module.

Empirical analysis confirmed that the development of average income per employee constitutes the most important impact on new car registrations. This finding is reflected in the parameterisation of the car purchase model. As fuel prices for all fuel types are strongly related to the demand and the vehicle fleet composition, an iterative approach is applied linking the ASTRA with the energy supply and demand model POLES.
In the second step the newly purchased cars are transmitted to the car technology choice model, which simulates the probability of the choice of a certain category of car during the car purchase. The ASTRA model distinguishes between eight different technologies. Furthermore, conventional fuel technologies are further differentiated into cubic capacity ranges. The following car categories are considered in the car technology choice model:

- Gasoline cars: three types differentiated by cubic capacity (<1.4l, 1.4-2.0l, >2.0l),
- Diesel cars: two types differentiated by cubic capacity (<2.0l, >2.0l),
- Compressed natural gas (CNG) cars,
- Liquefied petroleum gas (LPG) cars,
- Bioethanol cars, i.e. cars that can run on 85 % bioethanol (E85),
- Hybrid cars,
- Battery electric cars, i.e. smaller cars running in battery-only mode,
- Hydrogen fuel cell vehicles.

Regarding the current low but increasing number of filling stations offering alternative fuels, the automotive industry developed alternative fuel car concepts that can be driven by conventional fuels as well, so-called flexi-fuel cars. The car technology choice model allocates these hybrid car categories to the alternative fuel categories (CNG, LPG and bioethanol) and not to the conventional car categories. The recent generation of hybrid cars comprise a combination of combustion and electric motors, whereas the modified model does not distinguish between hybrids equipped with diesel respectively gasoline motors. Depending on timing only advanced hybrid cars, i.e. plug-in hybrids with the ability to run for a significant distance on electricity are assigned in ASTRA to the category hybrid. As many

contemporary conventional diesel cars allow driving with biodiesel the new car category bioethanol cars (BIO) does only contain cars driving with bioethanol of type E85. The last category hydrogen fuel cell cars is supposed to cover only fuel cell technology as hydrogen internal combustion engines are not considered a reasonable option for future cars.
The decision to purchase one of the two conventional car categories (diesel an gasoline) in the previous ASTRA car fleet model was driven by aggregated factors like differences between gasoline and diesel fuel prices, different taxation and a factor representing current trends. In order to integrate the new alternative car technologies, major factors that influence the decision of purchasers are identified. Several US studies and the most recent ARAL (2005) study elaborated via costumer surveys potential factors influencing the decision of a car purchaser for a certain car respectively fuel technology.

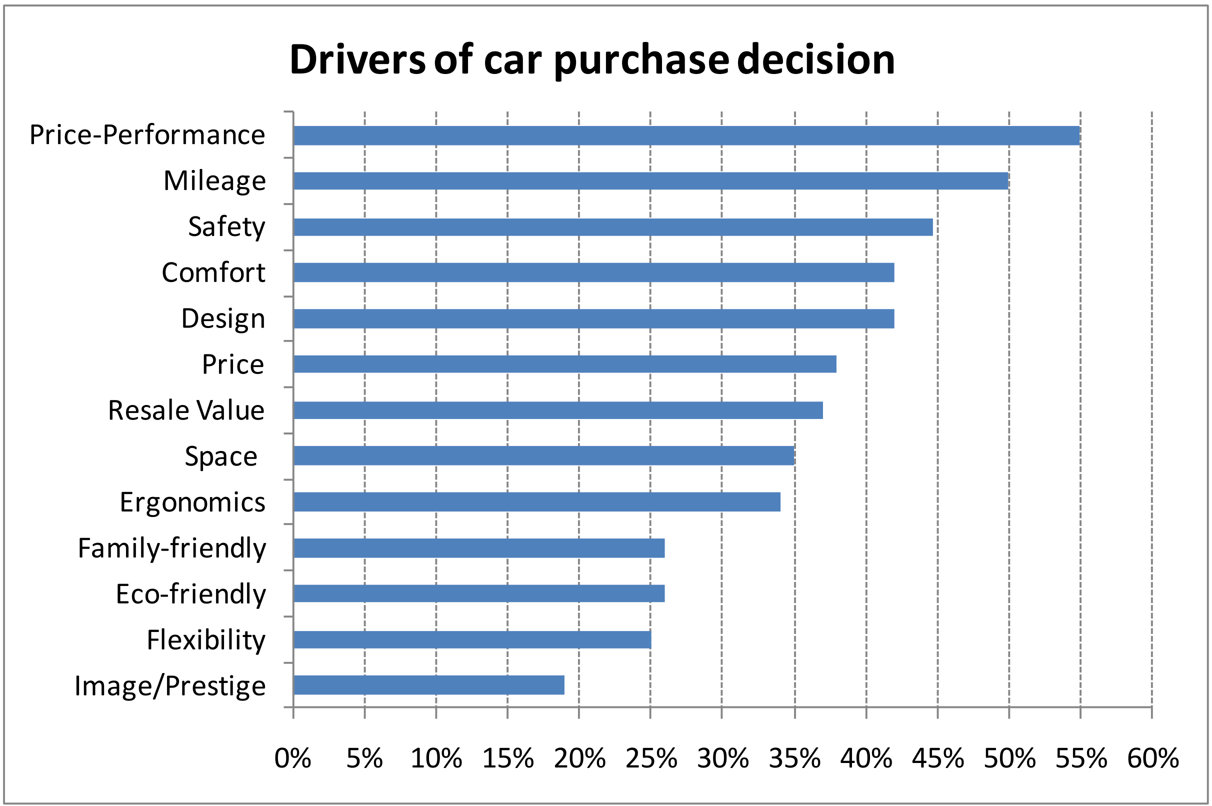

Figure 2 – Drivers of car purchase decision derived from ARAL (2005)

In the following the European study from Aral is focused, as the new purchase decision model simulates the European market. Figure 2 – provides a detailed overview of the survey. According to this study the costumers set a high value on economic efficiency for new cars. Price in combination with the provided performance of a car is the most significant factor with 55% followed by the mileage of the car. Compared with older surveys the factor safety lost significance but, nevertheless, safety still plays an important role for 47% of all interviewed customers. Besides economic and technical factors influencing the car purchase decision the study included also soft factors like design, image and prestige. In contrast to the economic factors they are supposed to be not as important. The low importance of factors like the environmental-friendliness of a new car indicates that alternative fuel cars can only diffuse successfully into the European markets when they can be purchased and

operated for an adequate price. Based on the cognitions of this survey and the feasibility to quantify drivers in a System Dynamics model the car technology choice model focuses on the economic efficiency as major impact of the purchase decision.
Due to the characteristics of the purchase as a discrete choice for one out of eleven car categories respectively technologies, a logit-model is supposed to be the most sophisticated approach for simulating this decision. The implemented logit-function requires specific user benefits of all eleven car technologies that can be chosen. Similar to the application of logit-functions in the modal-split transport modelling stage this model does not compute benefits but costs that can be put into the logit-function as negative benefits according to the following equation.

$$P_{cc,i} = \frac{\exp(-\lambda_i * pC_{cc,i} + LC_{cc,i})}{\sum_{cc} \exp(-\lambda_i * pC_{cc,i} + LC_{cc,i})} \qquad \textbf{eq. 1}$$

where: *P* = share of purchased cars per car category *cc* and country *i*
pC = perceived total costs per vehicle-km per car category *cc* and country *i*
λ = multiplier lambda per country *i*
LC = logit constant per car category cc and country *i* representing the disutility
cc = index for eleven car categories/technologies
i = index for EU27 countries plus Norway and Switzerland

The car technology choice model calculates the required average costs per vehicle-km for each car category in a bottom-up approach. First, the model computes variable costs per vehicle-km based on average fuel consumption factors for each technology and country-specific fuel prices provided by the POLES model described in KRAIL ET AL. (2007). Fuel consumption factors for conventional cars are derived from HBEFA (2004). Available sales figures for specific car types for each alternative car category and general information from Original Equipment Manufacturers (OEM) are used to generate average fuel consumption factors for the six new car categories.
Besides variable costs the model also considers fixed costs for each car category. Fixed costs per car category and country are determined by car-ownership taxation, registration fees and purchase costs per country and car category as well as country-specific average maintenance costs. All elements of fixed costs are transformed into costs per vehicle-km by the division of average yearly mileages per car category and country. Average values for yearly mileages are based on car passenger-km and car-ownership taken from “Energy and Transport in Figures” (CEC 2005) and average occupancy rates taken from the TRANSTOOLS (CHEN ET AL. 2005) model. As the conversion of purchase costs into costs per vehicle-km requires information on average lifetime per car category, this is derived from the car stock cohort model via feedback loop. Similar to the approach for computing the average fuel consumption factors for alternative fuel cars, average purchase costs for alternative fuel cars consider sales figures from the last years.
Assuming completely rational purchase decision behaviour based on all variable and fixed costs would disregard other important drivers like the distribution grid of filling stations selling the requested type of fuel. For conventional fuel types like gasoline and diesel the distribution grid is characterised by a good quality in all EU27 countries. At present, owners or prospective costumers of alternative fuel cars have to cope with the burden that the

procurement of alternative fuels requires significantly longer additional trips or is even not feasible due to lacking filling stations. JANSSEN (2004) concluded in his paper on CNG market penetration that successful diffusion of new car technologies depend on a uniform development of technology and filling station infrastructure. Taking into account these significant impacts due to fuel supply differences, the model has to consider the quality of filing station grids as well. Hence, the four mentioned cost categories have to be completed by so-called fuel procurement costs.

In order to generate these costs per vehicle-km for each car category and country the model requires input in terms of filling station numbers for each fuel category diesel, gasoline, LPG, CNG, electric current, E85 and hydrogen. Conventional filling stations are derived from national statistics offices and automobile associations. Alternative fuel filling station numbers were taken from European Natural Gas Vehicle Association[1] and other databases[2]. Due to the lack of information about the spatial distribution of filling stations the modified model assumes a homogenous distribution. This leads to an average surface area for each fuel category that has to be served per filling station. The model considers the optimisation efforts of mineral oil groups in locating new filling stations efficiently by assuming a central location in a unit circle representing the average surface area. In order to calculate an average distance that has to be driven for refuelling a car three situations for the car-owner are conceivable:

- refuelling requires no extra trip because the filling station is located on the way to another destination,
- refuelling requires an extra trip for the car-owner starting in an area near the filling station (25% of maximum distance) or
- refuelling requires an extra trip for the car-owner starting in an area far away from the filling station (75% of maximum distance).

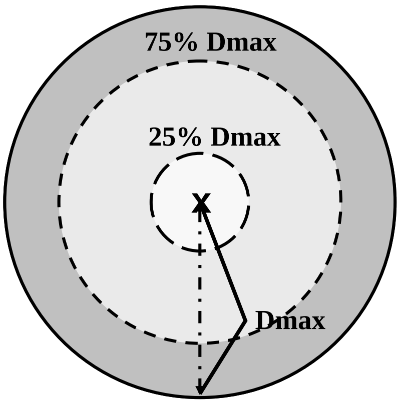

Figure 3 – Estimation of average distance to filling station

Weighting the option without extra-trip by 25%, the situation near by 50% and the far away option by 25% the model simulates an average trip distance for each refuelling action. Average cruising ranges per car category allow the calculation of total yearly kilometre that have to be driven for refuelling a car with a certain technology. Finally, the model simulates

[1] European Natural Gas Vehicle Association (ENGVA): http://engva.org
[2] Data extracted from: http://www.gas-tankstellen.de, http://www.erdgasfahrzeug-forum.de and http://www.h2stations.org

the fuel procurement costs by multiplying the yearly kilometres with fixed and variable costs per vehicle-km and adding the opportunity costs generated via value of time and required time for the procurement trips extracted from the ASTRA Transport (TRA) module.
The following equation describes the simulation of perceived total car costs per vehicle-km that are composed of variable/fuel, purchase, taxation, maintenance and fuel procurement costs. Furthermore the model considers the importance of the purchase costs level for the calculation of perceived costs by setting a car category and country-specific weighting factor.

$$C_{cc,i} = \alpha_{cc,i} * pC_{cc,i} + taxC_{cc,i} + mC_i + vC_{cc,i} + procC_{cc,i} \qquad \textbf{eq. 2}$$

where: *C* = perceived car cost per vehicle-km per car category *cc* and country *i*
pC = purchase cost per vehicle-km per car category *cc* and country *i*
taxC = taxation/registration cost per vehicle-km per car category *cc* and country *i*
mC = maintenance cost per vehicle-km per country *i*
vC = variable/fuel cost per vehicle-km per car category *cc* and country *i*
procC = fuel procurement cost per vehicle-km per car category *cc* and country *i*
α = weighting factor representing the significance of purchasing costs
cc = index for eleven car categories/technologies
i = index for EU27 countries plus Norway and Switzerland

Finally, the logit function simulates the probability of cars purchased for each of the eleven technologies based on the simulated perceived car costs. Figure 4 illustrates the structure of the chosen approach for simulating the share of each technology on total cars registered. An optimal set of parameters could be identified for the weighting factor α, logit parameter λ and the logit const LC in the process of calibration. All parameters are calibrated with the Vensim® internal optimisation tool. Time series data for car registration per country disaggregated into car categories are taken from Eurostat online database. Several lacking datasets, especially for alternative fuel car registrations, required further data sources like data from ACEA and other sources. The calibration could be performed only for technologies that have been until 2008 present on European markets. Hence, the purchasing behaviour for battery electric and hydrogen fuel cell cars expressed via parameters in the discrete choice function had to be assessed in a qualitative way. This has been done by consolidating the single parameters of all other technologies into a kind of average set of parameters. This approach assumes that the purchasing behaviour will be driven in a similar way for the coming technologies by the various impacts considered.

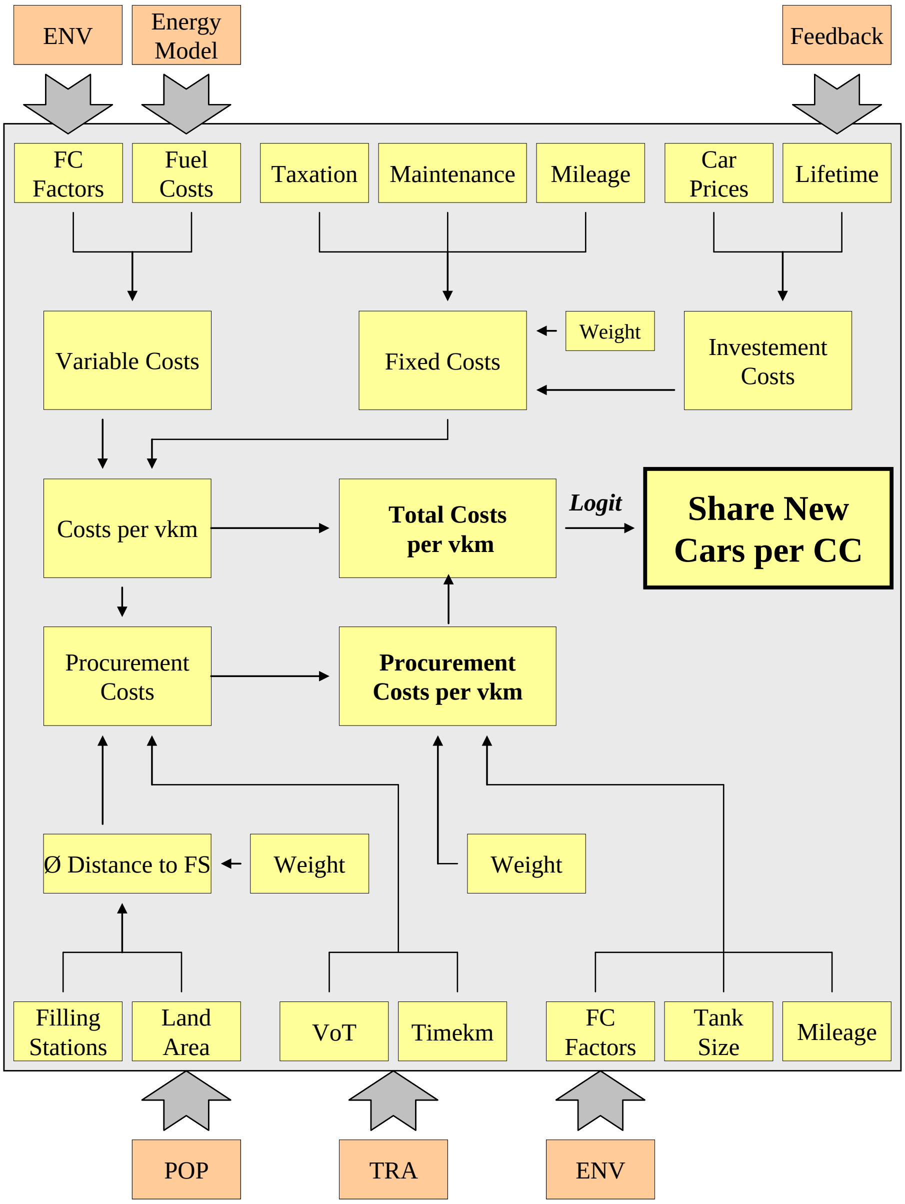

Figure 4 – Structure of the ASTRA car technology choice model

After simulating the share of new cars per car category with the car technology choice model this share is multiplied with the total number of new cars registered per country. Figure 5 demonstrates the implemented feedback loop in the car fleet model. Starting with an initial share of cars per car category, emission standard, country and age for each simulation period the new purchased cars are added while all scrapped cars in the different age cohorts are subtracted by the model. The number of scrapped cars is one of the drivers of total new registered cars per year, as the model assumes that a certain share of all scrapped cars is replaced by new ones.

The point of time when a new car is purchased determines to which emission standard it belongs and which emission factors have to be applied to model its emissions. ASTRA distinguishes nine emission standards (2 pre-euro standards, Euro 1 to a not yet determined Euro 7 standard). For example, if a car is purchased in 2005, it is assumed that it complies with the Euro 3 standard.

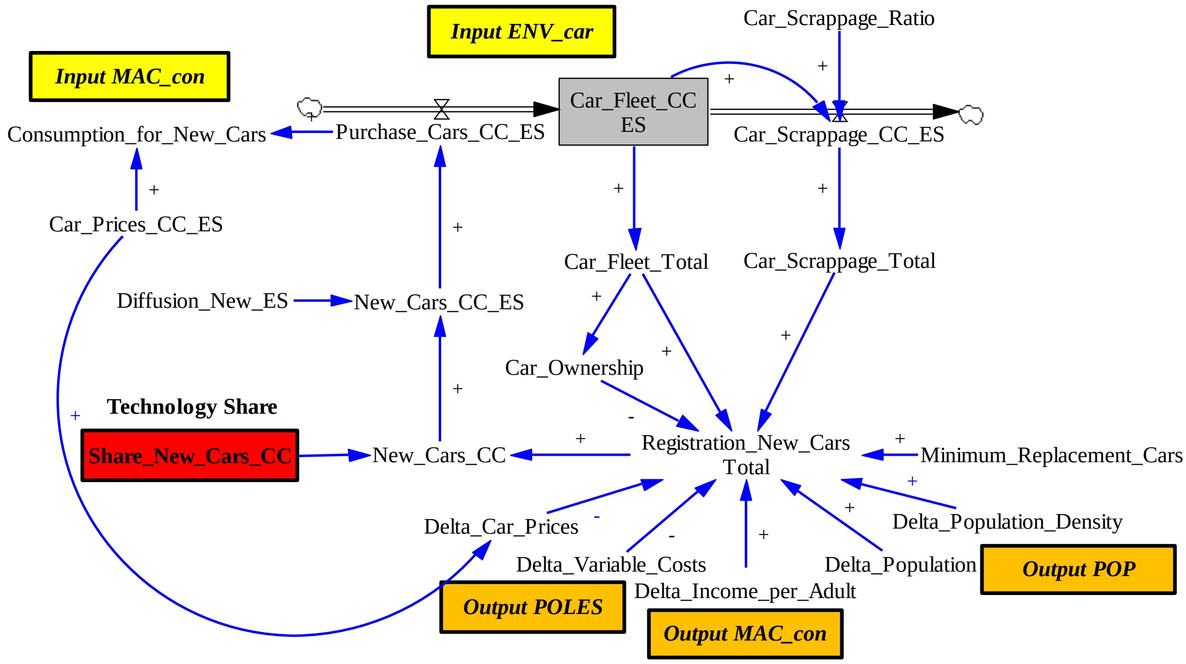

Figure 5 – Overview of the ASTRA car fleet model

POLICY OPTIONS

In this section, all policies that are considered in the policy scenario analysis in this paper are presented. In order to demonstrate potentials of policies to accelerate the diffusion of low carbon vehicles, all policy options are integrated in one policy scenario. All policy measures focus on influencing the diffusion of alternative fuel technologies respectively should have a potential for leading towards a low carbon transport system. Findings in the literature on their effects are described to derive the assumptions on potential CO_2 reductions or on changing car purchasing behaviour induced by these measures implemented in the ASTRA model.

CO2 labelling of new passenger cars

CO_2 labelling is an information tool aiming at rising awareness of energy efficiency of car purchasers. In Europe, a label similar to the one used for household appliances (showing seven colour-coded bars for the efficiency classes A (very efficient) to G (very inefficient)) is being used or considered by several countries (DE HAAN ET AL. 2009). However, countries vary markedly in how they classify vehicles. If they define energy efficiency in an "absolute" way, the rated CO_2 emissions directly determine the efficiency class of a vehicle. An alternative policy base results from the notion of "relative" energy efficiency, which is computed by normalizing energy consumption to car size represented by, e.g. floor space, curb weight or car length. The specific design of a labelling scheme might be important for its effects, especially when other measures such as vehicle taxation are directly linked to its categories. A study of PETERS ET AL. (2008) suggests that a relative system succeeds better

in addressing more consumers. However, a relative system potentially allows people to switch to cars with higher relative efficiency without actually lowering absolute CO_2 emissions. Here, it is important to find the optimal trade-off.
In the literature, a few studies have been made on the impact of labelling on CO_2 emissions of new cars. Their results vary with the methods used. Based on a survey in Austria, E.V.A. ET AL. (1999) studied the impact of labelling on the consumer's car purchase decision. They came to a rather optimistic estimation concluding that, on average, 4-5 % lower specific fuel consumption and CO_2 emissions of newly registered cars could be obtained. ITEN ET AL. (2005) analysed the impact of the Swiss energy label, which was introduced in 2003. Amongst others, they conducted a discrete choice analysis of Swiss consumers to study the effect of the label on car choice. In this study the reduction potential was estimated by 0.4 % less fuel consumption per year.
For calculating the CO_2 reductions induced by CO_2 labelling of new passenger cars within the ASTRA model, it is assumed that labelling can have a moderate impact on the car purchasing decision. It increases the probability that consumers will choose more efficient cars. Such a moderate estimation of the resulting effect on CO_2 emissions might range around 3 % reduction considering that, fuel efficient cars are available and that the level of awareness is significantly higher than in the reference scenario.

Feebates on new passenger cars

In order to promote low emission vehicles such as the upcoming battery electric or fuel-cell cars, feebates constitute an efficient incentive. Feebate systems combine rebates for very energy-efficient vehicles with additional fees for very inefficient vehicles (DE HAAN ET AL. 2009). Various possible types of feebate schemes and design options appear in the literature (GREENE ET AL. 2005; JOHNSON 2006; PETERS ET AL. 2008).
A study of Iten et al. [2005] indicates that the implementation of a feebate system (here: rebates funded by a general increase of the vehicle registration tax) based on the Swiss energy label would enhance the impact of such a label. Assuming a rebate of €1200 for 'A' labelled vehicles and of € 800 for 'B' labelled vehicles funded by an increased purchase tax, they estimated that the specific fuel consumption of the new car fleet could be reduced by 1.6 %. In another Swiss study based on simulations, DE HAAN ET AL. (2009) assumed incentives of € 2000 only for 'A' labelled cars (again funded by an increase of the vehicle registration tax) and concluded that they would induce CO_2 emissions reductions of between 3.4 and 4.3 % for new car registrations. In the study of COWI (2002), the reduction potential of CO_2-based vehicle registration systems across selected European countries was estimated to range between 1.8 % (for Italy) and 8.4 % (for Denmark). Combining CO_2-differentiated vehicle registration and ACT results in reductions ranging from 4.3 % (for Finland) and 8.5 % (for Denmark).
It should be noted that the above mentioned studies only considered the effects of car choice models on consumers. In a small country without large car manufacturers, manufacturers might not be encouraged by a national feebate system to adopt more efficiency technologies (LANGER 2005). However, if feebates are introduced in large countries that represent a relevant share of the car market or at EU level, studies modelling feebates on a broader level which also consider manufacturer's behaviour predict quite large effects (over 20 %

reduction in average CO_2 emissions) which are mainly due to the manufacturers' response [e.g. GREENE ET AL. 2005].
Based on the findings of these studies, a feebate system is implemented in ASTRA by rebating car purchasers of energy efficient cars emitting less than 100 g CO_2 per vehicle-km with € 50 for each Gramm of CO_2 less than 100. Car purchasers that decide to buy cars with higher carbon intensity have to pay additional fees in the same way. The feebate system is supposed to be introduced in 2012 leading in a stepwise process to the total feebate of € 50 until 2015. The feebate system determines after 15 years, as then a significant share of low carbon vehicles should be on the market leading to lower prices for those cars. Until 2030, the emission limit declines continuously down to 80 g CO_2 per vehicle-km. Additionally, ASTRA considers the revenues gained by the incentive which turn at a certain point of time into additional expenditures.

Subsidies for enhancing filling station infrastructure for alternative fuel cars

As mentioned above, feebates on new passenger vehicles, in particular rebates for very efficient ones can also be effective in promoting the diffusion of alternative fuel vehicles, such as fuel cell cars. Those technologies require a special filling station infrastructure. As their diffusion shows specific characteristics and requirements, in the following, we present some conclusions which can be drawn based on the experiences with the introduction of natural gas vehicles (CNG) in various countries.
With regard to the vehicle-to-filling-stations ratio, countries with a large number of CNG cars show a ratio of 1000 vehicles per filling station (JANSSEN ET AL. 2006), which seems to be the optimal balance between profitability for filling stations and consumer convenience and thus very decisive for market development. This ratio could be a useful indicator to monitor the effectiveness of government policies and make policy adjustments based on its values, either to promote vehicle adoption or to stimulate the installation of filling stations. With regard to Germany, JANSSEN ET AL. (2006) point out that in 2003, Germany showed a high ratio of filling stations to CNG cars with a quickly growing filling station infrastructure of approximately 250 public filling stations (+150 non-public), whereas the current 18,000 CNG cars only show a moderate growth rate. This may have been a major barrier to the diffusion of NGVs in Germany.
Based on this finding an accelerated development of filling station infrastructure offering alternative fuels is assumed in the ASTRA policy scenario. In order to push this development, revenues gained from CO_2 pricing are refunded in terms of subsidies for new filling stations. The car technology choice model considers this assumption via decreasing fuel procurement costs influencing the car technology choice.

CO_2 emission regulation for passenger cars

This regulation aims at improving the efficiency of conventional engine technologies and to develop the diffusion of alternative fuel engine technologies by the car manufacturers. The regulation is setting pathways for CO_2 emission limits of passenger cars and light duty trucks. Though it can be expected that after 2020 the emission limits will be strengthened to consider technical progress, the policy scenario analysed in this paper did not implement such an extension of the measures due to the uncertainty of progress. Climate policy on the level of Member States foresees a target of 80 g CO_2 per vehicle-km for cars in 2030. Hence, the implemented regulation is setting CO_2 limits for average new car fleet with a limit value of 130 g CO_2 per vehicle-km in 2015 and 105 g CO_2 per vehicle-km in 2020. This regulation is transmitted into the ASTRA model via increasing average car prices, a reduction of emission factors and additional investments.

Inclusion of air and road transport into EU-ETS

Pricing measures have a significant potential to set incentives to change behaviour towards more energy efficient and climate efficient choices. The focus of pricing policies is on policy measures that are in the pipeline of implementation e.g. due to the fact that strategic policy papers foresee their implementation. Further, they consider that the economic crisis as well as the decreased use of fossil fuels both requires alternative funding and revenue mechanisms from transport. The EU decided to include air transport into the EU Emissions Trading System (EU-ETS). In order to complete the ETS system and thus come closer to a situation in which the whole CO_2 emissions of the EU are subject to the emissions cap defined by international agreements, ASTRA assumes also an inclusion of road transport into the EU-ETS from 2020 onwards. The system would be an upstream-approach on fuels, which can be handled in the models the same as a fuel tax i.e. increasing the total fuel cost.

POLICY SCENARIO RESULTS

This section describes the scenario results for the chosen set of policy options from the simulation with the ASTRA model. Some results are presented in absolute terms for the policy scenario, some in relative terms compared with the reference scenario excluding the options chosen for policy scenario. The characteristics of an integrated modelling approach like in ASTRA allow the estimation of impacts on vehicle fleets, emissions, economy and transport. Figure 6 illustrates the relative change of main indicators for EU27 induced by the policy measures and incentives. ASTRA assesses a slight decline of GDP by -1.6% compared with the reference scenario until 2050. GDP would decrease even less, if transport tax revenues would not decline as significant. Alternative fuel cars are not supposed to be burdened by a fuel tax. As their share increases due to the incentives significantly, the total government revenues including CO2 pricing and feebate revenues decrease by about -16% until 2050. Despite the small negative impact on GDP, the labour markets remain stable caused by the employment effects of new transport technology developments.
While economic growth remains nearly stable compared with the reference scenario, the measures in the policy scenario induce significant reductions of transport related CO_2 and NO_x emissions by -25.2% respectively -20.7% until 2050. Passenger and freight transport activity are expected to be influenced as well by the policy measures by a decrease of -6.4% of pkm and -10.2% of tkm until 2050, but not as significant as the emissions. This indicates that the fuel efficiency improves due to the policy options, which is also partly responsible for

only small losses in motorisation compared with the reference scenario. Negative impacts of fees and other additional costs emerging for car purchasers are balanced by decreasing fuel costs and taxes induced by higher energy-efficiency of newly registered passenger cars.

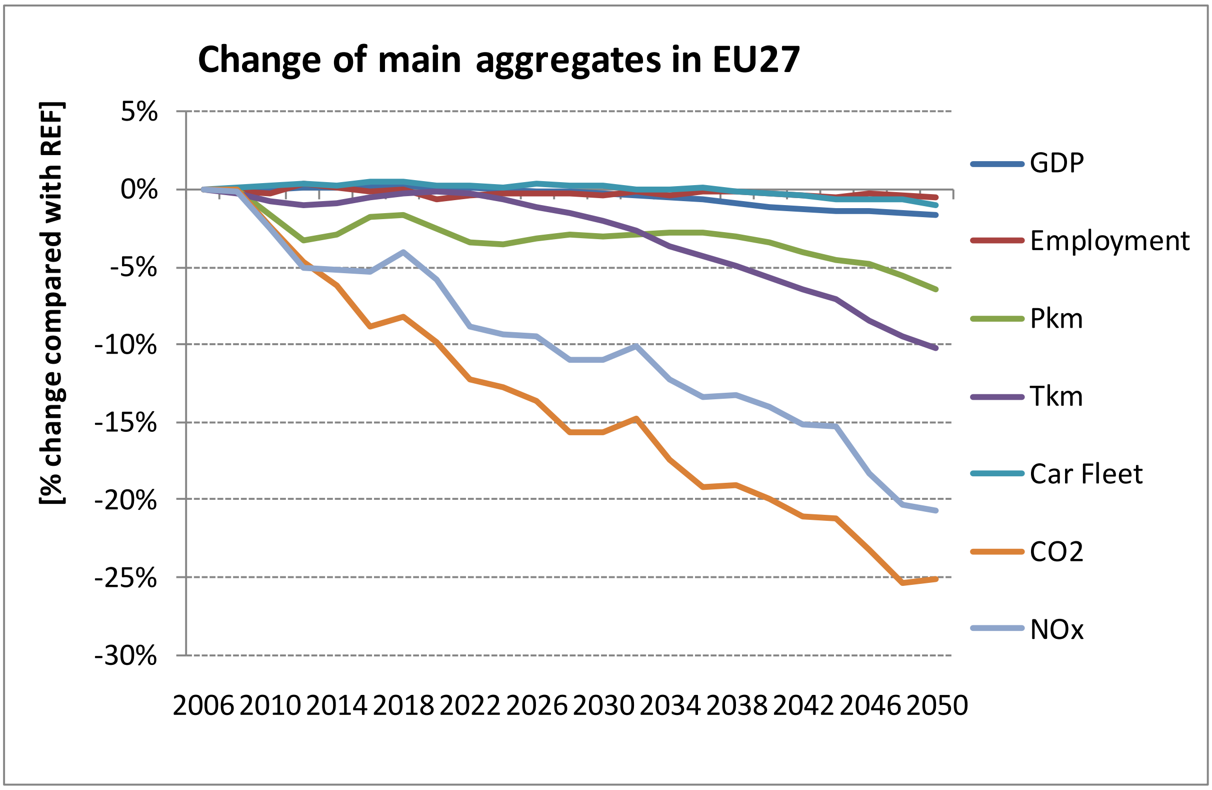

Figure 6 – Change of main indicators in policy compared with reference scenario

The strong increasing car-ownership in Eastern Europe is expected to continue which is the main driver of still growing numbers of cars in EU27 until 2040. Figure 7 shows the estimated evolution of car fleets in EU27 in the policy scenario. Around 2040 the maximum number of cars is achieved which is influenced on the one hand by the demographic trends in the EU27 and on the other hand by the determination of the feebate system. Policy options drawn in this scenario lead to a significant increase of the alternative fuel share in the total EU27 fleet from 4.4% in 2010 up to 24.8% in 2050. Growing numbers of filling stations offering hydrogen for fuel cell cars and a parallel price decline initiate strong growth rates of new registered fuel cell cars starting in 2030. ASTRA projects about 29 million fuel cell cars in the EU27 car fleets. The estimated trend for battery electric cars demonstrates the constraints that those cars are and will be supposed to have by only low mileages without re-charging. Hence, battery electric cars driven mainly in urban areas are expected to reach a maximum number of 37.8 million cars in 2035 declining to about 23 million cars in EU27. The small number of hybrid cars seems to be a weak point in this simulation. According to the definition of this category only the most advanced hybrid technologies are covered by this group in ASTRA. Cars like the Toyota Prius are assigned at first to the hybrid category but are transmitted to the respective conventional car categories after an assumed period of time. Bioethanol, CNG and LPG cars are still present in the expected car fleet by low numbers of 3.6 million up to 4.8 million until 2050. The rising number of CNG cars until 2022 indicates the development of

CNG prices simulated by POLES which increase significantly after 2025. An astonishing result seems to be the renaissance of gasoline cars after 2035. Two trends lead to this development: the high potential on increasing fuel efficiencies of gasoline cars and the assumed price trend simulated by the POLES model. Assumptions on oil resources are compared with other studies rather optimistic leading to the described trend. Due to this optimistic view, ASTRA estimates that around 78% of the total car fleet will still depend on fossil fuels in 2050.

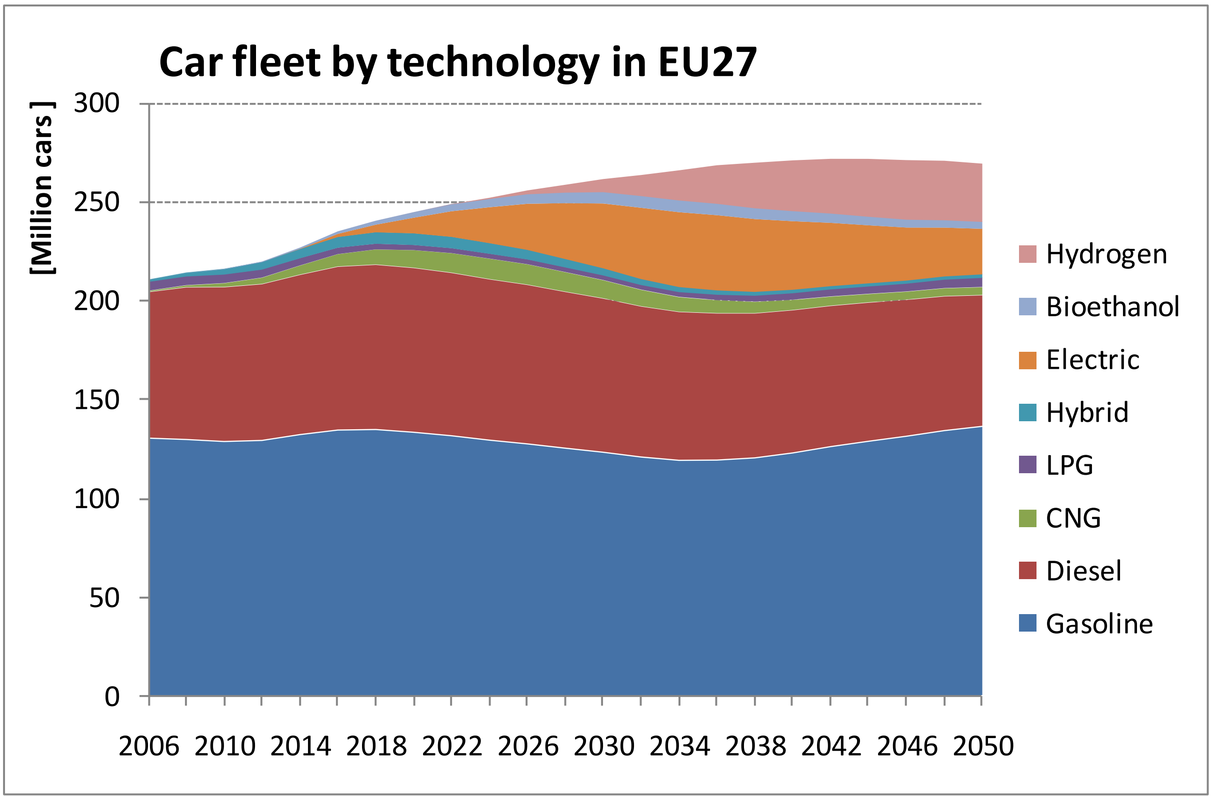

Figure 7 – Car fleet by fuel technology in policy scenario

Figure 8 provides an overview on the differences between reference and policy scenario in terms of car fleet composition. It allows an insight on the direct and indirect impacts of the policy options realised in the policy scenario. Overall the figure reflects the accelerated diffusion of battery electric and hydrogen fuel cell cars until 2050. These technologies mainly substitute conventional car technologies. Especially gasoline cars are expected to be replaced driven by higher fees implemented via the feebate system. Around 34 million gasoline cars, 14 million diesel and 700 thousand CNG cars are expected to be present in the EU27 fleet of the year 2050.

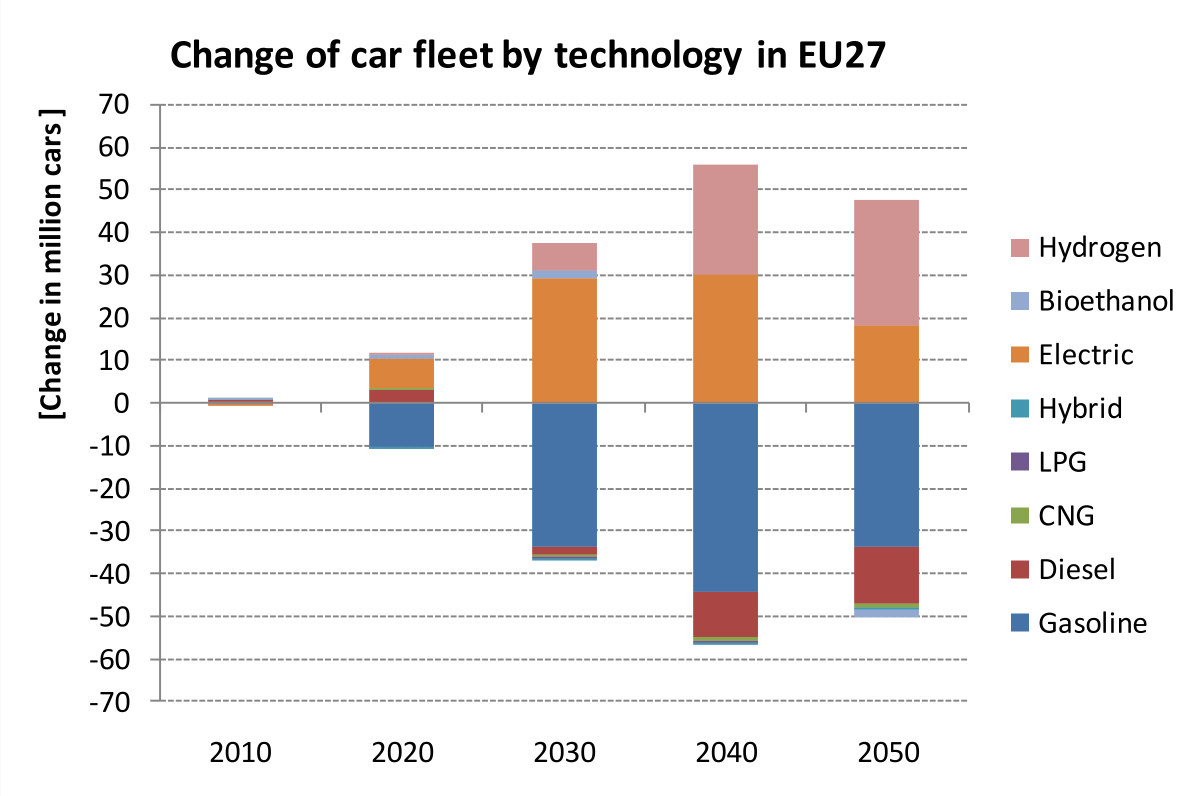

Figure 8 – Change of fuel technology in policy compared with reference scenario

Figure 9 illustrates the policy impacts on CO_2 emissions (well-to-wheel) for each freight and transport mode. According to the objective in this paper the major part of total emission reduction in the policy scenario is contributed by passenger car transport. ASTRA estimates about 166 Mt of CO_2 less emitted by passenger cars until 2050. The technological composition of the car fleets, the development of fuel efficiency and the induced decreasing passenger transport activity play an important role for the relative reduction of CO_2 emissions from car transport. Based on the experiences gained in studies like iTREN-2030 (SCHADE 2010) especially the binding CO_2 emission regulation and the feebate system can be considered as most powerful measures in this policy scenario. The introduction of an ETS system for air transport in 2010 and road transport in 2020 is reflected by about 23 Mt less CO_2 emissions from passenger air transport and 116 Mt less CO_2 emissions from road freight transport until 2050. ASTRA assesses a decline of total CO_2 emissions by 311 Mt CO_2 until 2050 compared with the reference scenario.

According to the ASTRA results, the policy options considered lead to decline of transport-related CO_2 emissions by -13.5% in 2050 compared to 1990. In the reference case, transport-related CO_2 emissions are supposed to increase between 1990 and 2050 by 15.7%. Regarding the CO_2 emission reduction targets set by the EU for 2020 and 2050, the transport system in the policy scenario is expected to be still far away from the envisaged overall reduction targets of -20% until 2020 respectively -80% until 2050. In absolute terms, ASTRA estimates even an increase of transport-related CO_2 emissions until 2020 by about 6.5% compared with 1990.

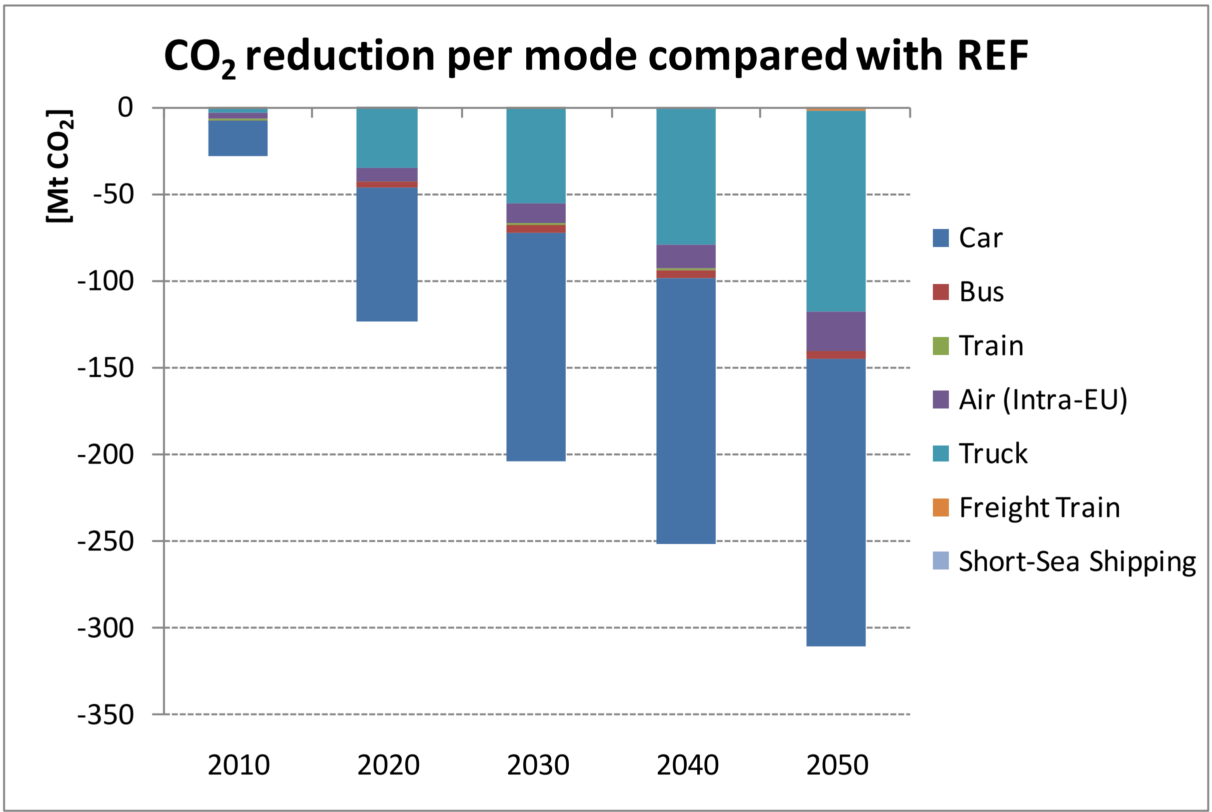

Figure 9 –Change of CO_2 emissions (well-to-wheel) per mode in policy scenario

CONCLUSION

The main objective of this paper was the quantitative assessment of policy options leading to an accelerated diffusion of alternative fuel and low carbon cars in EU27. The potential of several measures for leading passenger car transport towards a low carbon sector was analysed by simulating the measures with the ASTRA model. For this purpose, the reader was introduced into the ASTRA modelling approach and the underlying System Dynamics methodology. The structure of the car fleet model was described in detail in order to allow a deep insight into the functioning of the model. Before the analysis of results all chosen policy measures integrated into one policy scenario were presented including all relevant assumptions. Finally, the paper provided an overview on the most interesting results. An impact assessment comparing results of the policy with the reference scenario was carried out in order to demonstrate the potential of the policy options for reducing transport-related CO_2 emissions.
Compared with the reference scenario the set of measures in the policy scenario led to expected savings of about 311 Mt CO_2 until 2050. The combination of several efficient measures induced an accelerated diffusion of battery electric and hydrogen fuel cell cars until 2050. According to the chosen assumptions, the CO_2 reduction potential of these measures is expected to be limited. ASTRA estimates a decline of CO_2 emissions from passenger cars by -21% until 2050 which is compared to the targets for all sectors rather

pessimistic. Behavioural reactions in terms of significantly changing transport activity were rather moderate such that the major contribution to the emission reduction was provided by the technological development of car fleets in EU27.
It can be confirmed that the impacts of the measures would have clearly higher impacts if fossil fuel prices would increase stronger until 2050 than expected by the POLES energy model. On the other hand, incentives and policies improving the competitiveness of low carbon technologies in transport have to be accompanied by measures leading to a behavioural change in transport.

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