Reducing the Climate Impact of Transport – Technologies and Policies for Road Transport

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Abstract: (117 words)

Assessing impacts of policies and strategies to reduce CO_2 emissions from road transport requires an integrated modeling approach. System Dynamics suits perfectly as methodology to simulate the dynamics determined by feedbacks between transport, energy, economic and environmental systems. The ASTRA model incorporates these capabilities. The paper at hand describes the structure and the dynamics of the ASTRA model and zooms into the vehicle fleet model. The dynamics considered in the technological diffusion model is explained in detail. The novelty is the explicit feedback modeling between diffusion and sales of certain technologies and their costs, when the costs move down the learning curve. Finally, the paper presents a set of different scenarios which should create a common understanding on the complexity of the transport and energy system and the potential contribution of policies and technologies to reduce the carbon footprint of car transport.

Keywords: Alternative Fuel Cars, CO_2 emissions, Integrated Modeling, ASTRA, Fuel Efficiency, Learning Curve

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1 Introduction

Today, road transport activities are the major source for CO_2 emissions from transportation in Europe. According to IEA (2011), freight and passenger road transport were responsible for 93% of all transport-related CO_2 emissions within EU27 in 2009. About two third of this emissions can be allocated to passenger transport activities. Since 1990 passenger road CO_2 emissions have been steadily increasing.

In order to meet the CO_2 emission reduction targets of the EU until 2020 (-20% compared to 1990 levels) and long-term targets to remain on the 2 degree pathway according to the IPCC, significant changes in today's passenger road transport sector have to happen. One way to achieve prospective CO_2 emission limits for transport is the reduction of transport demand by changing mobility behavior. Pricing mechanisms and other incentives are powerful instruments to induce these changes in combination with the awareness of transport burdens for the climate. Policy makers are reluctant to implement incentives that oblige the population with additional financial burdens on passenger transport as mobility is still an essential need for a functioning and growing economy. Hence, instruments leading towards less transport demand, modal shift towards rail and decreasing average trip lengths have to be accompanied by innovations reducing the fossil energy consumption of the rolling stock or an accelerated diffusion of alternative drives. The European Directive (EC) No. 443/2009 is one of the policy measures to enforce this development by setting targets to the automotive industry. The average of all new registered passenger cars should not exceed the target of 130 g CO_2 per km until 2015 and 95 g CO_2 per km until 2020. The target is differentiated for the different OEMs acknowledging their specific sales structures. Similar targets came into force also in other major automotive markets in the world.

In the long run, 95 g CO_2 per km is by far not sufficient facing CO_2 emission reduction targets of up to 80% compared with the 1990 level. Alternative drive technologies like battery electric vehicles (BEV), plug-in hybrid vehicles (PHEV) or fuel cell electric vehicles (FCEV) need to substitute fossil fuel cars in the long-term. Studies on life-cycle emissions of these alternatives (Toro *et al.*, 2006) demonstrate that implications on the transport systems need to be considered together with those on the energy system as the carbon footprint of alternative fuel technologies depend strongly on the production pathway of the energy carrier. Furthermore, CO_2 emissions from vehicle production need to be taken into account as e.g. the production of Lithium-Ion batteries is at least with current technologies a carbon-intensive process. Nevertheless, in the long run there is currently no alternative to a shift towards electrified drives in passenger cars. The remaining question is: how can policy-makers and the automotive industry accelerate the diffusion of alternative fuel technologies?

The paper at hand describes a System Dynamics modeling approach simulating the prospective decision process of purchasers of cars for one of the competing fuel technologies in EU27. The approach was applied in the context of the EU FP7 project GHG-TransPoRD[1] in order to determine feasible greenhouse gas reduction targets for each transport mode for the EU until 2050. The model takes into account the dynamics of the major constraints for a fast diffusion of alternative fuel technologies. Those are: currently high investment costs compared to conventional fossil fuel cars, the limited filling station or recharging infrastructure, insecurity about calendar life of batteries and fuel cells, lower ranges especially with BEVs and still lacking knowledge about the implications of a technological shift on individual mobility patterns. The implemented discrete choice approach incorporates the

[1] GHG-TransPoRD - Reducing greenhouse-gas emissions of transport beyond 2020 – linking R&D, transport policies and reduction targets: www.ghg-transpord.eu

major drivers of car technology choice. An adapted learning curve approach is integrated in order to simulate the feedback between costs of major components in a car depending on cumulated number of car sales worldwide and the decision process. The vehicle fleet model is implemented as a module in the ASTRA model. ASTRA is an integrated System Dynamics model simulating the feedbacks between transport, economy and environment.

Chapter 2 highlights the structure of the ASTRA model in which the vehicle fleet model is embedded. Chapter 3 presents the dynamics of the vehicle fleet model, its major causal chains and feedbacks. Results of some exemplary scenarios simulated with the model are illustrated and analyzed in Chapter 4. Finally, the paper concludes with recommendations and an outlook on the need for further research.

2 The ASTRA Model

Today, the demand for transport is closely interlinked with economic growth and the understanding of individual mobility as a major component of quality and freedom of life. Assessing the impacts of strategies to make transport greener requires considering not only transport as a closed system, but a system interacting with others. On the one hand, social, economic, energy and environmental systems are driving dynamics in the transport system. On the other hand, transport strongly influences all other systems. A simple example is the break-down of air transport in the North Atlantic area caused by the eruption of the Eyjafjallajökull volcano in Iceland in 2010. High concentration of ash in the atmosphere caused, for example, economic losses for a number of airlines or thousands of people prevented from coming home or to other destinations. The shift from fossil fuels to renewable energy carriers like electricity or hydrogen is a result of the need to reduce transport-related CO_2 emissions in order to reduce the degree of global warming and the depletion of fossil fuels. This shift means a revolution for individual motorized transport. It will influence mobility patterns set by the access to cheap-oil over decades. It also impacts the economy which needs to provide the technical solutions to reduce CO_2 emissions and the energy system which is required to enforce the use of renewable energy sources.

The System Dynamics model ASTRA (Assessment of Transport Strategies) is a tool enabling Integrated Assessment of transport policy strategies. It links the systems of transport, society, economy and environment. Furthermore, the ASTRA model has been successfully linked to energy system models like the POLES world energy model. ASTRA has been developed and applied in a sequence of German, European and global research projects by two Institutions since 1998: Fraunhofer Institute for Systems and Innovation Research (ISI) and Trasporti e Territorio (TRT). The ASTRA model consists of nine modules that are implemented as modules in separate Vensim© System Dynamics software files:

- 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).

ASTRA simulates the dynamics of the interaction of modules in the time period from 1990 to 2050. The time step is determined by a quarter year. The simulations with ASTRA are run by the Euler-Cauchy approximation that can be set in the Vensim© Software. In order to enable a modular development, each of the nine modules is modeled separately in a file that can be merged via an internal tool which is explained in detail by Krail *et al.* (2007).

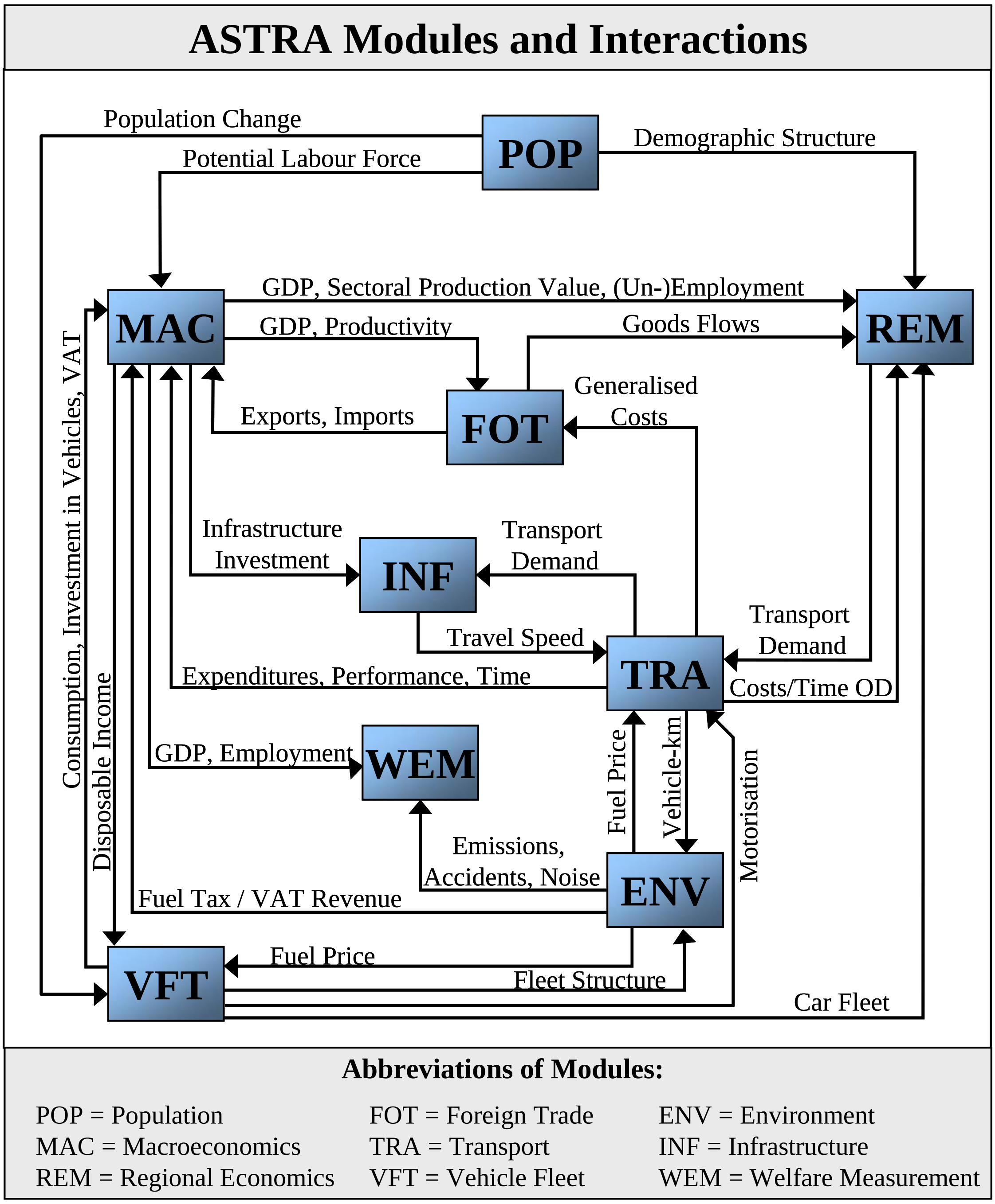

Figure 1 – ASTRA Modules, Main Outputs and Interactions

In the following a brief overview on the structure of the nine modules and their main interfaces is presented. Figure 1 highlights the main interactions between the modules. As the ASTRA model is composed by about 9.000 variables, there is a large number of feedback loops with different delays included. The following chapter specifying the design of the vehicle fleet model (VFT) describes the most important feedback loops. More detailed information about the other modules, impact chains and feedbacks can be found in Schade (2005) and Krail (2009).

The Population Module (POP) provides the population development for the 29 European countries (EU27 plus Norway and Switzerland) 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 simulates the national economic framework, which imbeds the other modules. The MAC incorporates elements of different economic theories. The model uses production functions of Cobb-Douglas type derived from neo-classical theory. 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.

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, labor and natural resources as well as the influence of technological progress that is modeled as total factor productivity. Endogenised total factor productivity depends on investments, freight transport times and labor 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 labor productivity. Employment is differentiated into full-time equivalent employment and total employment to be able to reflect the growing importance of part-time employment. The fifth element of MAC describes governmental behavior. As far as possible government revenues and expenditures are differentiated into categories that can be modeled 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. 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. The trip distribution splits trips of each zone into three distance bands within the zone and two crossing the zonal borders. Freight transport is driven by two mechanisms: Firstly, national transport depends on sectoral production value. Monetary output of the input-output table calculations are transferred into volume of tons by means of value-to-volume ratios. Secondly, international freight transport i.e. freight transport flows that are crossing national borders are generated from monetary Intra-European trade flows by the same approach.

The Foreign Trade Module (FOT) is divided into two parts: trade between the EU27 European countries (INTRA-EU model) and trade between the EU27 European countries and the rest-of-the world (RoW) that is allocated into nine regions. Both models are differentiated into bilateral relationships by country pair by sector. Trade between EU27 member states is driven by world GDP growth, by GDP growth of the importing country of each country pair relation, by relative change of sectoral labor productivity between the countries and by averaged generalized 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. 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 vehicles-km travelled (VKT) per mode, per distance band and traffic situation respectively. Based on these traffic flows and the information from the vehicle fleet model on total yearly fuel composition of the vehicle fleets and hence on the emission factors, the environmental module calculates the major greenhouse gas (GHG) and air pollutant emissions from transport: CO_2, NO_x, CO, VOC and PM_{10}. 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 besides the diffusion of fuel technologies also the diffusion of emission standards and the age structure of 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.

Finally, the Welfare Measurement Module (WEM) enables the comparison and assessment of major macro-economic, environmental and social indicators.

3 Diffusion of Alternative Fuel Cars

Modeling the technological diffusion of vehicle fleets is crucial for a holistic assessment of climate and environmental policies impacts on the economy, transport and environmental systems. System Dynamics suits perfectly as methodology for this purpose. There are several feedbacks that can be modeled best in a System Dynamics model which will be described in this chapter. Furthermore, the chapter explains the chosen approach to simulate the diffusion of alternative and conventional drives in passenger cars.

The Vehicle Fleet module in ASTRA can be differentiated into three sub-models which simulate:

- the ageing of the car stock,
- the new cars registered and
- the choice of fuel technology.

The core of the model is a classical stock–flow model. New cars registered per time period constitute the inflow into the car stock which is differentiated by age cohorts. Cars are ageing within the stock. The outflow from the stock represents both, scrapping of cars and export of cars outside the EU. With increasing age, the model supposes growing probability of scrapping or exporting. Figure 2 highlights the stock-flow character of the vehicle fleet model and shows the interaction between the three sub-models. The flow variables and the car stock variable are differentiated by age cohorts, emission standards (pre-Euro to Euro 6) and fuel technology. Several drivers determine in a linear way with varying significance the number of new registered cars per time period. The most important driver is the development of average disposable income per adult. Based on the principles of the national accounting system, ASTRA computes the disposable income of private households in real terms top down from gross domestic product (GDP) for each EU27 country. Bol (2004) and Krail (2009) describe this approach in detail. Other drivers with lower significance are the number of cars scrapped per year, the evolution of average car prices, of average fuel prices and the number of persons above 18 years. The level of motorization plays a significant role as it closes a negative feedback loop dampening the number of new cars registered. It represents a saturation factor in the market. Another feedback is closed via the interrelation between new car registrations, investment and consumption, GDP and disposable income.

Based on the time of the new car registrations, the total new cars registered are then allocated with a certain probability to emission standards. The second differentiation in this top-down process is the allocation to the available fuel technologies. This allocation is modeled in the fuel technology choice sub-model. Today, the major alternatives to the conventional gasoline and diesel cars are: compressed natural gas (CNG) vehicles, liquefied petroleum gas (LPG) vehicles, hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), extended range electric vehicles (E-REV), battery electric vehicles (BEV), bioethanol (or flexi-fuel) vehicles and fuel cell electric vehicles (FCEV). Some alternative drives are available and offered to consumers at least by some OEM since years like CNG cars, LPG, HEV and flexi-fuel cars. Other alternative drives like PHEV and BEV had their first market entry in the EU only shortly. FCEV are currently not available but some OEM announced to bring the first FCEV in 2015 to the market (e.g. Daimler). ASTRA distinguishes between six main alternative fuel technologies and the conventional technologies gasoline and diesel. For reasons of simplification, PHEV and E-REV are assigned to the group of HEV. Full HEV are diffusing in the period 2020 to 2030 to the conventional categories gasoline and diesel such that after 2030 only PHEV and E-REV are accounted to this car category.

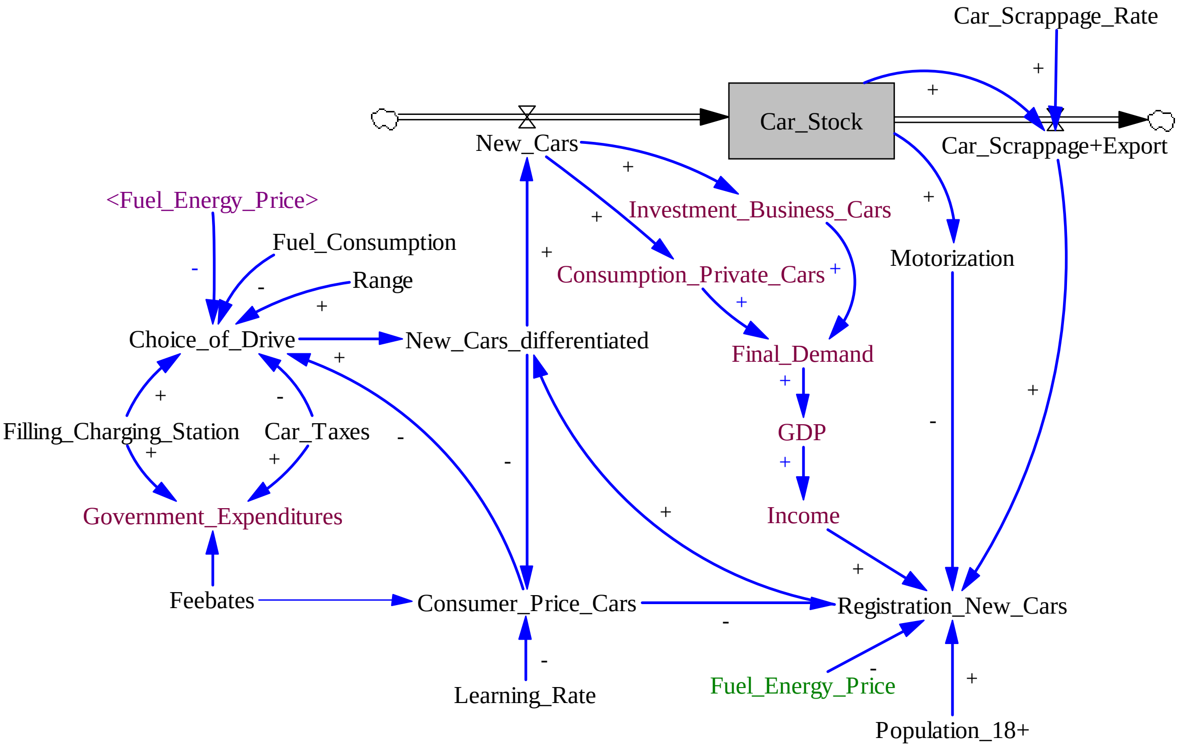

Figure 2 – Simplified Causal Diagram of the ASTRA VFT Model

In EU27 conventional gasoline and diesel cars will still dominate the vehicle fleet at least of the next decade according to experts, but the share of alternative drives is slowly increasing. According to the theory of diffusion, innovations diffuse with different speed into the market. Common to all diffusion processes is an S-shaped pathway of diffusion over time. Rogers (2003) differentiates between five stages of innovation on an S-shaped diffusion curve (see Figure 3). According to his categories current purchasers of alternative drives still belong to the first category "Innovators". In the theory of diffusion several approaches for diffusion models have been developed since the 1960s. The research made by Mansfield (1968) provided the baseline for development of epidemic diffusion models. The basic idea behind this type of models is that new technologies diffuse via spreading information and learning processes into the market. Bass (1969) developed a similar approach explaining the process how new technologies diffuse into the market due to the interaction of innovation and imitation. Common to both approaches is the logistic function leading to an S-shaped curve of diffusion.

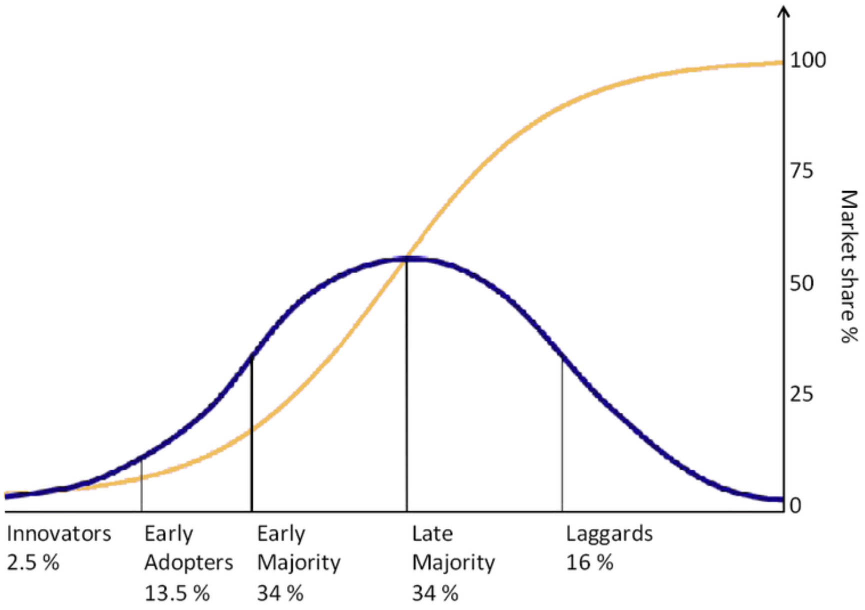

Figure 3 – Stages of Diffusion of Innovation (ROGERS 2003)

Another possibility to model the diffusion of alternative drives is given by the theory for analyzing discrete choice for which McFadden (2001) won the Nobel price the in the year 2000. Originally, McFadden applied the discrete choice theory to forecast the modal choice and transport demand in the context of planning the BART system in San Francisco. The choice for a transport mode out of a set of alternatives is similar to the choice of a suitable fuel technology in the car purchasing process. Each alternative has its consumer utilities which can be expressed by negative costs. Accessibility and availability of alternatives play a significant role for both. The accessibility of public transport is an example for a driver of modal choice, the density of the filling station infrastructure one for fuel technology choice. The possibility to integrate also non-quantitative impacts like individual preferences is very important as well.

Several US studies and a study from ARAL (2005) elaborated via costumer surveys potential factors influencing the decision of a car purchaser for a certain fuel technology. 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. The so-called residual disutility in logit functions can represent these soft factors influencing the acceptance of a fuel technology.

Similar to the application of logit-functions in the modal-split stage this model does not compute benefits but costs derived from the concept of Total Cost of Ownership (TCO) 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 const per car category cc and country *i* representing the residual disutility
	cc =	index for eleven car categories/fuel technologies
	i =	index for EU27 countries plus Norway and Switzerland

The car fleet model calculates the required average costs per vehicle-km for each fuel technology 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). The linkage to the world energy model POLES closes an important feedback loop. ASTRA calculates transport demand in terms of yearly fuel consumption which is used as an input to simulate the fuel and energy price development. Finally, fuel prices are fed back and change the transport demand, influence the economy and the technology choice.

Fuel consumption factors for fossil fuel cars are derived from HBEFA (2010). Available sales figures for specific car categories for each alternative fuel category and general information from Original Equipment Manufacturers (OEM) are used to generate average fuel consumption factors for the alternative fuel 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. 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 model via a 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. Consumer prices of alternative fuel cars as well as of conventional fossil fuel cars develop dynamically via adapted One-Factor Learning Curves (OFLC). That means that they decrease according to the following equation over time due to an assumed technological learning depending on installed capacity or in other words cumulated sales.

$$pC_{cc,t} = mQ_{cc,t}^{-\varepsilon} \qquad \textbf{eq. 2}$$

where:	pC =	consumer price for one unit (car)
	Q =	cumulative production
	ε =	elasticity of learning (learning rate)
	m =	normalisation parameter with respect to initial conditions
	cc =	index for eleven car categories/fuel technologies
	t =	year

ASTRA considers moderate learning rates derived from literature for each alternative fuel technology (Schade *et al*, 2012). Based on cumulated worldwide sale numbers, average car prices for these technologies decrease over time. It is assumed that the manufacturers will offer new alternative fuel cars without margin in the first five years. After five years these cars are sold with the average margin. This effect is implemented as other wise high costs at point of first market entry would prevent consumers to choose the new technology and would slow down the cost decrease. Besides for alternative fuel technologies, also learning effects with low learning rates are taken into account for implementing efficiency technologies in conventional gasoline and diesel cars. This part of the model has been implemented in the course of the FP7 project GHG-TransPoRD (Schade *et al*, 2012).

Assuming completely rational purchase decision behavior based on all variable and fixed costs would disregard other important drivers like the distribution grid of filling or charging stations selling the requested type of fuel. For conventional fuel types like gasoline and diesel the distribution grid is characterized 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 *et al.* (2004) concluded in their 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 approximated development of filling station numbers for each fuel types. An optimal distribution of filling stations offering alternative fuels is assumed.

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.

$$C_{cc,i} = \alpha_{cc,i} * pC_{cc,i} + taxC_{cc,i} + mC_i + vC_{cc,i} + procC_{cc,i} \qquad \textbf{eq. 3}$$

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 the choice of a fuel technology based on the simulated perceived car costs.

4 Policies and Scenarios

The model described above was applied in the EU FP7 project GHG-TransPoRD. The main objective of the project was to support the EU in defining a successful research and policy strategy for GHG reductions of transport. In this context, the ASTRA model and its vehicle fleet module were prepared to assess feasible GHG reduction targets for transport as a whole as well as for each transport mode. This presumed to analyze the prospective CO_2 reduction potentials for passenger cars over the whole range of drives. The project identified a list of efficiency technologies for ICE as well as for alternative fuel cars. For each technology, the CO_2 emission reduction potential, an outlook on the expected first market entry, the additional costs compared to a similar conventional gasoline or diesel car and the expected learning rate were collected from different studies and discussed with experts from OEMs.

Ten different scenarios were set which should create an understanding about the impacts of different policies and technologies on the development of CO_2 emissions from transport. The paper at hand presents three selected scenarios and their implications:

- *MAX E&M*: The maximum efficiency under market conditions presumes that OEMs are forced to implement the maximum set of efficiency measures for both, fossil and alternative fuel cars. Additional costs for each alternative are implemented and lead to growing car prices. On the other hand, operation costs decrease due to optimized efficiency. Induced investment for R&D and adaption of production sites are assumed as well. As opposed to the other scenarios, *MAX E&M* does not consider further policy measures promoting the choice of alternative fuel cars.
- *EV&HFC*: The electric vehicle and hydrogen fuel cell scenario assumes the same efficiency improvements as in the *MAX E&M* scenario. On top of that, it focuses on strong incentives for the purchase of alternative fuel cars. A feebate system is integrated which offers purchasers of alternative fuel cars up to 5.000 € rebate and requests fees for ICE cars of up to 1.500 € decreasing slightly over a decade. Filling and charging station infrastructure is supposed to adapt until 2050 to the density of fossil fuel filling stations. Average range of alternative fuel cars is presumed to increase up to 40% compared with the current status. Measures to promote alternative fuel technologies are implemented leading to an improved acceptance of alternative fuel cars. Finally, also induced investments in R&D are considered plus investments required establishing the production sites.
- *AMB REG*: The ambitious regulation scenario starts with the setting defined for *MAX E&M*. Additionally, alternative fuel technologies are subsidized like in the *EV&HFC* scenario. In order to compensate losses of fuel tax revenues, fossil fuel taxes increase in this scenario. Further policies like congestion charging were implemented to reduce the probability of rebound effects. Finally, the *AMB REG* scenario tests a phase-out of fossil fuel cars starting in the year 2035.

Figure 4 presents an overview on the estimated technological composition of EU27 car fleets. High efficient conventional gasoline and diesel cars in *MAX E&M* prevent alternative fuel technologies for a long time from being competitive. Hence, the fossil fuel cars are supposed to dominate the EU27 car fleet with a share of 87% until 2050. Efficiency gains are able to compensate increasing fossil fuel prices such that the comparative cost advantage of fossil fuel driven cars remains at least until 2040. The picture might look different when assuming a less development of oil resources until 2050 which is clearly an optimistic assumption by the linked POLES world energy model.

The share 62% alternative fuel cars in the EU27 car fleet in the *EV&HFC* scenario reflects the impact of the implemented feebate system in combination with accelerating the construction of the necessary filling station infrastructure. Despite that the model assumes that the costs for building the infrastructure are forwarded to consumers via higher alternative fuel or energy prices, alternative drives are the dominant technology in this scenario from 2030 to 2050. In the last two decades especially FCEV diffuse into the fleets which is a result of the feebate system in combination with fewer barriers like lacking filling station infrastructure (Figure 5).

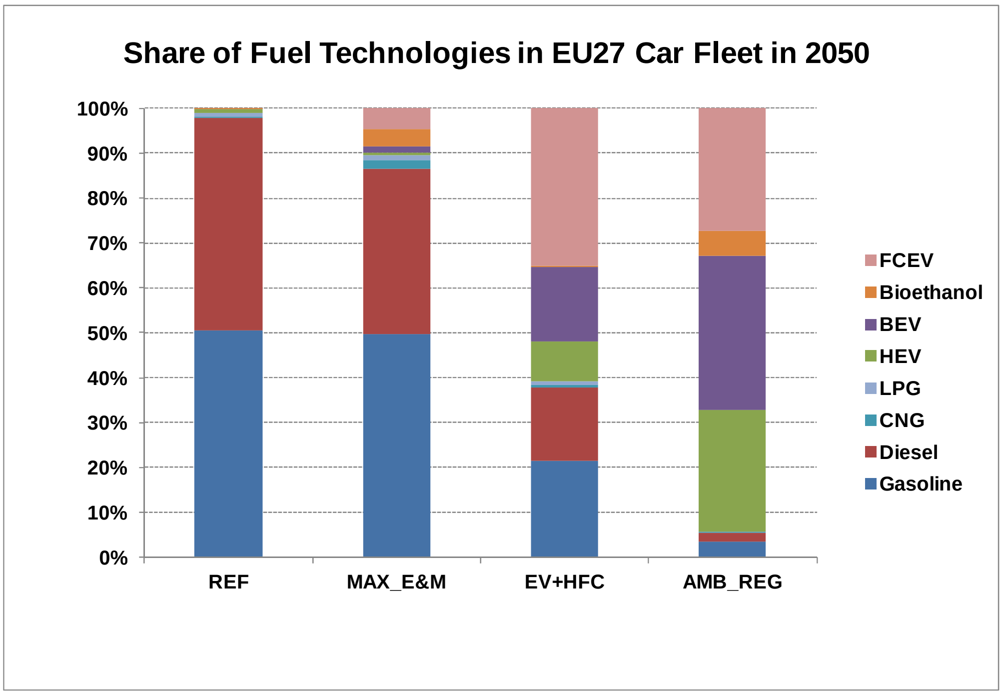

Figure 4 – Composition of EU27 Car Fleet in 2050 in all Scenarios

The most radical scenario is the *AMB REG* due to the complete phase out of fossil fuel cars from 2036 on. PHEV, BEV and FCEV account for about 89% of the whole EU27 fleet until 2050. The model assumes that about 34% of the fleet will be BEV. In this context, the ASTRA model does not consider constraints in terms of limited number of persons that can satisfy their mobility needs via BEV. The ASTRA model considers the possibility of a radical change of mobility patterns towards an increased use of new mobility concepts.

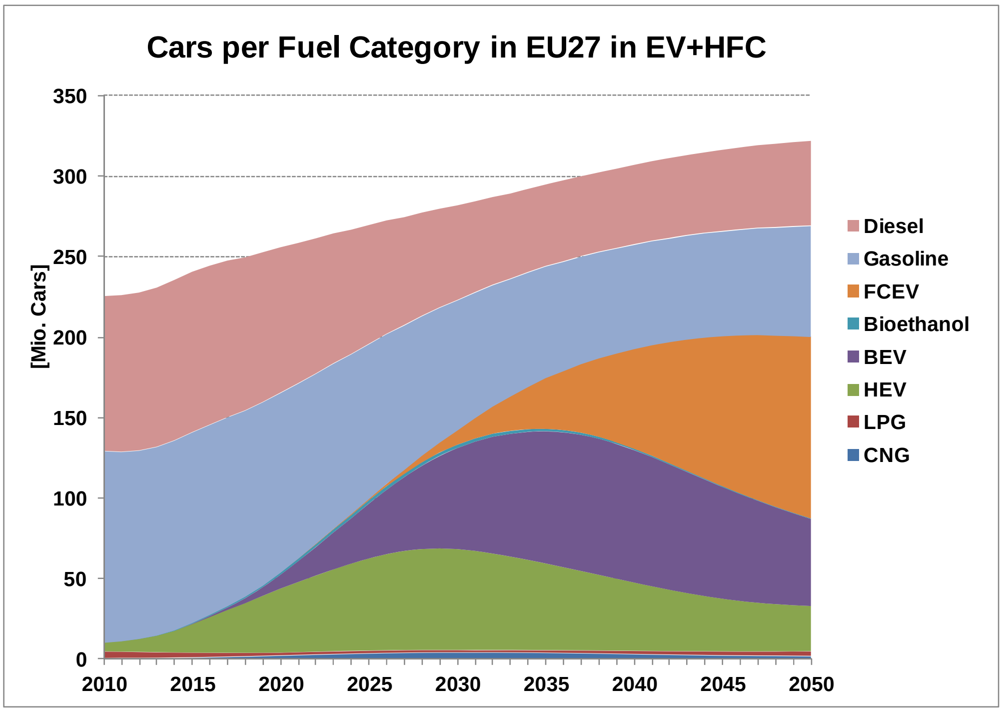

Figure 5 – Diffusion Pathway of Fuel Technologies until 2050 in EV+HFC Scenario

One of the main drivers of the diffusion of alternative fuel technologies is of course the dynamics in consumer prices. Figure 6 and Figure 7 reflect the dynamics in the *MAX E&M* and *EV&HFC* scenario induced by the application of learning curves. In *MAX E&M* alternative drives diffuse slowly into the EU27 vehicle fleet such that the technological learning is slowed down. Average prices of BEV are expected to remain over the whole simulation period above comparable alternatives. The projections show that FCEV converge only after 2040. On the other hand, a general price increase is assumed for all cars due to scarcity of natural resources used for the production of all types of cars.

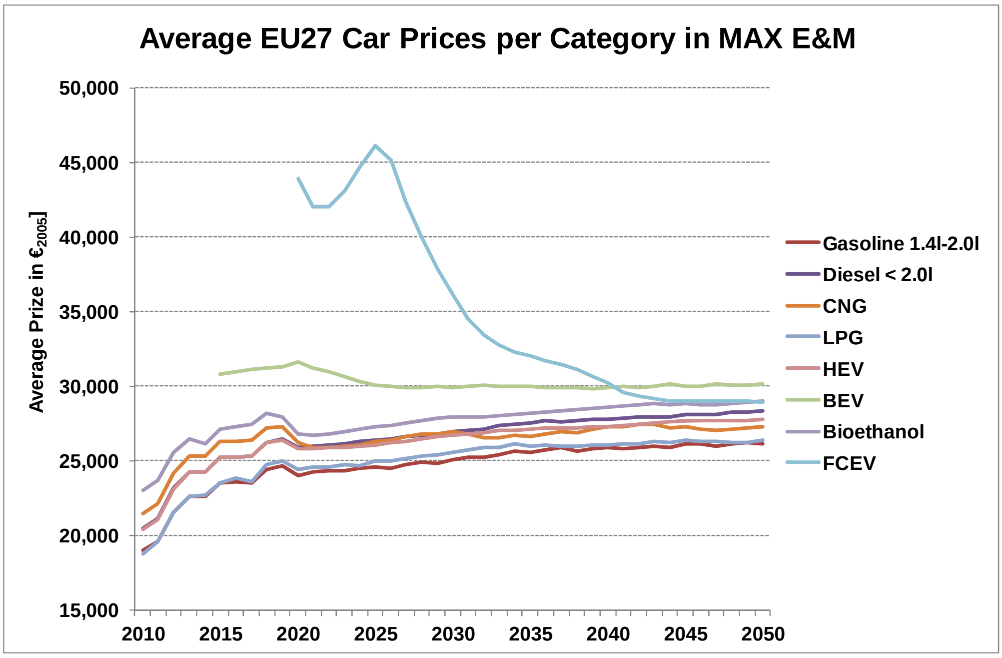

Figure 6 – Evolution of Car Costs for each Fuel Technology in MAX_E&M Scenario

The difference to the price evolution in the *EV&HFC* scenario is obvious. The implementation of a feebate system accelerates the diffusion of alternative fuel technologies and reinforces the trend via faster technological learning. This leads to converging consumer price curves such that BEV are expected to reach a similar price level as gasoline cars within the next ten years. For FCEV the trend is similar and the cost decrease pathway even steeper. In the long run the learning curve approach implemented in ASTRA leads to FCEV being the cheapest alternative.

Especially the *EV&HFC* scenario shows that higher prices can be accepted in the first years after market entry such that the category of “Innovators” or “Early Adopters” are demanding these type of cars. The comparison of both scenarios demonstrates that there is a threshold and not all prices are accepted. New technologies need a powerful incentive pushing the technology. This happens in the *EV&HFC* but also in the *AMB_REG* scenario. The price developments in both scenarios are similar until 2035. The strong regulation policy assumed in the later scenario forbidding the purchase of fossil fuel cars after 2035 leads to an even stronger diffusion of alternative fuel technologies.

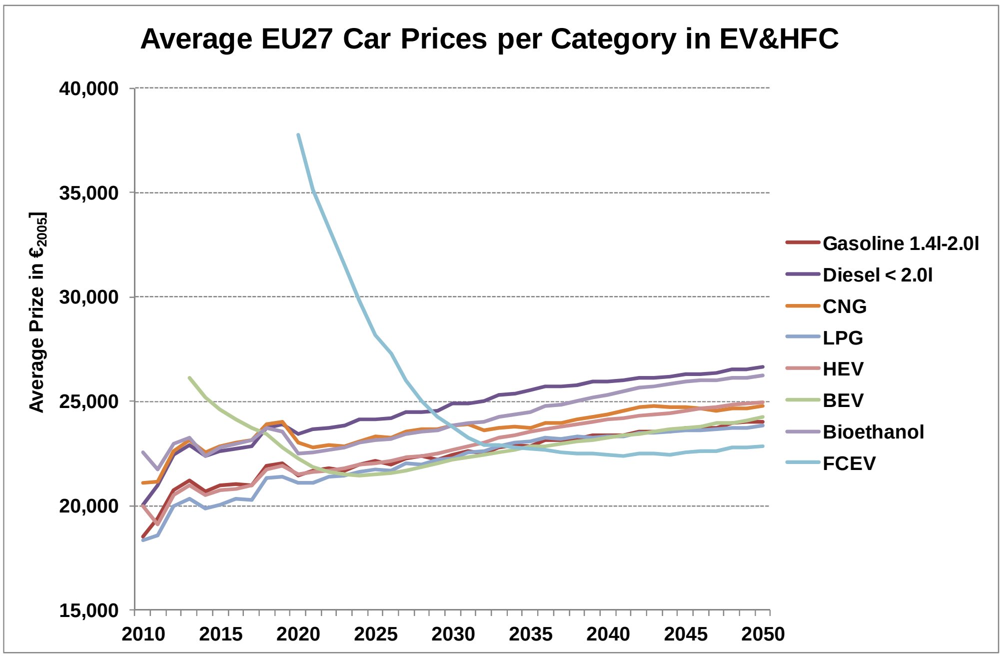

Figure 7 – Evolution of Car Costs for each Fuel Technology in EV&HFC Scenario

Figure 8 presents the technological evolution of efficiency of average new cars registered in EU27 according to the NEDC (New European Drive Cycle). It shows that the targets set by Directive (EC) No. 443/2009 of the European Parliament can be achieved or even be undersold. It also highlights that a rather quick decline of CO_2 emissions is feasible.

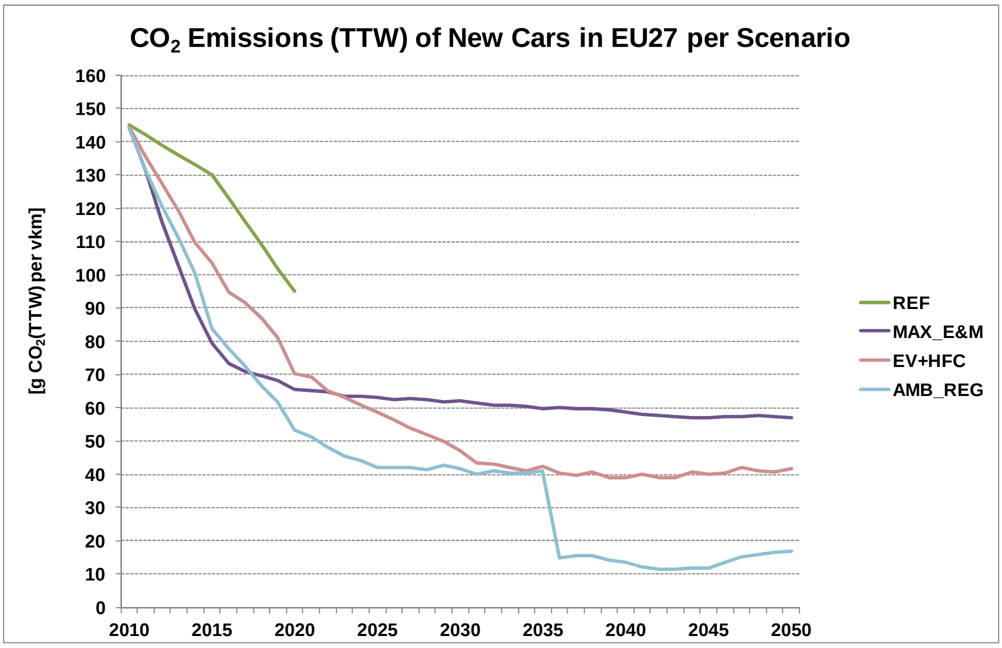

Figure 8 – Evolution of CO_2 Emissions per km from Passenger Cars for all Scenarios

The presented figures do not show the rebound effects which is a feedback of the efforts of making passenger cars more efficient and greener. Operation costs decrease which impacts the modal split. According to the ASTRA model, an increase of up 17% more passenger-km driven by car can be an expected rebound effect. At the same time the modal share of rail and non-motorized modes (especially cycling) decreases. This impact can partly be compensated by higher fuel taxes and congestion charges set in the *AMB REG* scenario but cannot be prevented completely.

Considering the total CO_2 emissions including well-to-tank emissions the strongest reduction is expected in the *AMB REG* scenario. ASTRA projects a reduction of CO_2 emissions by 73% for passenger cars compared with the level of 2010. The *MAX E&M* scenario only enables a reduction of 42% for passenger cars which stresses the importance of the diffusion of alternative drives using renewable energy carriers as opposed to just improving the efficiency of ICEs.

5 Conclusions

Simulating the impacts of climate policies in combination with technological development of passenger cars requires an integrated modeling approach. The vehicle fleet model integrated in the System Dynamics model ASTRA fulfills the major requirements on such a strategic tool. It takes into account the various feedback loops that exist and determine the dynamics of such a complex system. In GHG-TransPoRD the integrated transport, economy and environmental ASTRA model could be linked with the world energy model POLES. This is a significant progress as the implications of the expected revolutionary shift from a fossil fuel driven transport system to a renewable, electrified future transport system can only be assessed by an integrated transport and energy model. Transport demand drives the scarcity of fuel and energy and leads to increasing prices which changes transport demand again. Innovations are boosted in such an environment but the scenarios set in GHG-TransPoRD showed that this is not self-fulfilling prophecy. Powerful policy measures and binding regulation need to be established in order to accelerate the diffusion of green alternatives. The CO_2 emission targets set by the European Directive (EC) No. 443/2009 was a first step in the right direction. Nevertheless, efficiency improvements of cars with ICE are not sufficient facing CO_2 reduction targets of up to 80% compared with the level in 1990. Feebates or other mechanisms have the potential to reduce the comparative cost advantage of old technologies even in the short run. Technological learning leads to converging consumer prices over time for all fuel technologies.

As opposed to other models the ASTRA model is able to reflect rebound effects. One of the most important effects is the increasing competitiveness of the car mode compared to other modes due to efforts of making passenger cars more efficient. Despite increasing purchase prices the TCO over the whole lifetime of a car is lower compared with less efficient cars. As only perceived costs or in other words the cost of operating a car are the drivers of transport demand, a passenger car performance grows. This effect partly cannibalizes the technological CO_2 savings achieved by improving efficiency or higher share of alternative fuel cars. An optimal set of policies needs to go against such a trend by setting further policies, e.g. increasing fuel taxes or introducing congestion charging as only two out of several alternatives.

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