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D6.1 Report on enhanced model algorithm and model calibration

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Classification and Approval

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1 Introduction

Within the collaborative project eMAP, feasible deployment paths of electrified vehicles (EV) are analysed up to 2030. The scope of the study covers electromobility diffusion in passenger car markets, i.e. take-up of plug-in hybrid vehicles (PHEV), battery electric vehicles (BEV), range extended electric vehicles (REEV) and fuel cell electric vehicles (FCEV). For the analysis, the vehicle market model VECTOR21 (Vehicle Technologies Scenario Model) is used specifying consumer demand and market supply of electromobility in Finland, France, Germany, Italy, Poland, the United Kingdom and the EU28. VECTOR21 is simulating the competition between conventional and alternative powertrains for the new vehicle market. Using relevant costs of ownership, the least cost- and CO_2-intensive car is chosen by the customer. A description of the detailed scenario results is given in Kugler et al. (2015). For more background information on the supply side of the electromobility market, refer to Frieske et al. (2015) and Kleiner et al. (2015).

Work package 6 aimed to provide detailed, knowledgeable and traceable scenarios for the market penetration of low-carbon vehicles until the year 2030. An important part of this work package was the extension and calibration of the vehicle scenario model VECTOR21 to the scale of the European Union, which is covered by this report. Besides the modelling of the European vehicle markets in Germany, Finland, Poland, France, Italy and United Kingdom as well as the upscale for EU28, VECTOR21 is also used to investigate the influence of new car sales on the vehicle stock in the respective countries. This allows drawing conclusions for e.g. the development of the total energy consumption and resulting well to wheel CO_2 emissions of the car stock of each country or even the entire European Union within the timeframe of the eMAP project, i.e. between the years 2010 and 2030.

The aim of this report is to explain briefly the concept of the VECTOR21 scenario model, and, in more detail, the work done to enhance and adapt VECTOR21 for the eMAP project. Hence, this report features also information about the calibration of this tool with respect to the different conditions in the considered vehicle markets and countries.

This report is structured in the following way: Chapter 2 explains the basic concepts of the VECTOR21 model. Chapter 3 is dedicated to the modelling of the European market, and how this target was achieved during the eMAP project. In Chapter 4 the calibration of the VECTOR21 scenario parameters is covered, e.g. the setup of annual vehicle mileages or of the vehicle base prices.

2 Concept of the Vehicle Technology Scenario Model VECTOR21

Modelling the European new vehicle market is an ambitious task. The simulation tool VECTOR21 (Vehicle technology scenario model, Figure 1) models virtual markets of vehicle propulsion technologies and customers buying new vehicles with a dynamic least-cost approach in order to fulfil specified CO_2 targets for the future new car fleet. This chapter will explain the basic concepts of the VECTOR21 simulation tool, whereas the subsequent chapters will deal with the adaption and enhancement of VECTOR21 to cover the European vehicle market.

VECTOR21 was developed to calculate the future market share of different powertrains and fuels. This is however a problem which includes a number of different groups of actors which are basically manufacturers, sales departments, car buyers and users, and policy makers. The development of the VECTOR21 tool started in 2007 at DLR with its first released version published by Mock (2010) covering the German new cars market.

One of the main drivers, for which VECTOR21 was designed, is CO_2 legislation. In the European context, it is a European wide target, which has to be met by all OEMs individually (COM 2007). However, due to the nature of this regulation, a multitude of solutions i.e. different shares of different powertrain and efficiency technologies are conceivable. For example, depending on the market segment share of the OEM, higher emitting vehicles can be balanced by a certain number of vehicles emitting below the target or a smaller number of zero-emission vehicles. This is part of each car manufacturer's strategy and has to be implemented by their sales departments and branch offices. VECTOR21 calculates a least-cost solution from the perspective of the customers and taking into account general framework conditions in order to meet the CO_2 target in the total new vehicle fleet.

VECTOR21 includes different models and algorithms to calculate market shares. In the eMAP project, a simple RCO[1]-based approach was chosen, because it is the approach with the lowest data needs which can be met in EU countries most likely. Utility-based approaches are much more complex and need more sophisticated data for the agent-model which simulate the customers.

Within the model's approach, five main ingredients play a central role: vehicle technologies and their development, customers with their respective requirements and characteristics, manufacturers with their factories and production lines, policy with the rules and regulations, and the infrastructure which is necessary for new powertrain concepts like electric or fuel cell vehicles.

[1] In contrast to total costs of ownership (TCO), relevant costs of ownership (RCO) contain only those costs, which are relevant for the purchase decision like purchase costs, energy costs, incentives or taxes. Not included are for example replacement costs for tires or brakes as well as the changing of oil.

The following chapters will describe the model approach, how all these ingredients are merged in order to calculate different scenarios for the composition of the future European vehicle market.

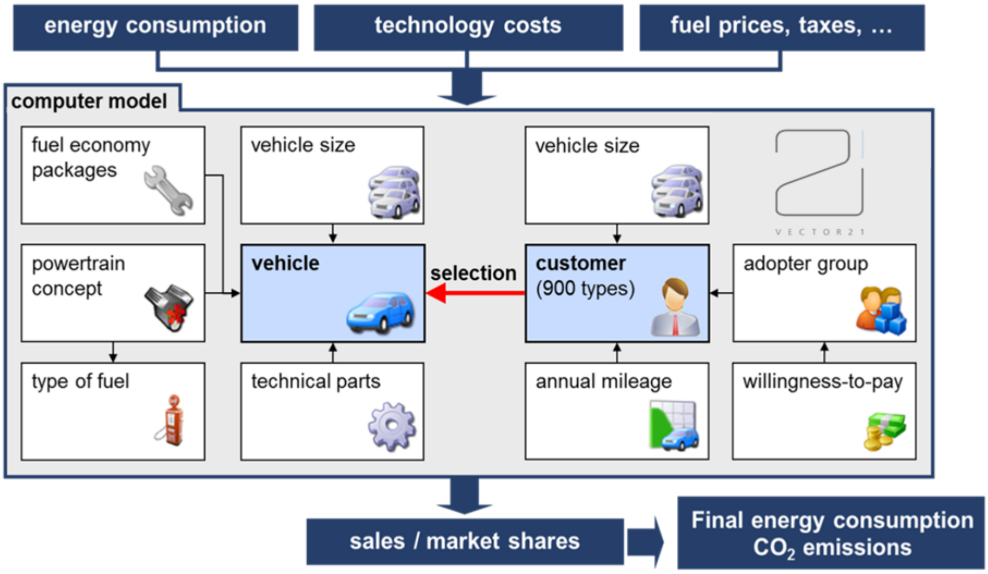

Figure 1: Concept of the agent based market model VECTOR21

2.1 Vehicle technologies

VECTOR21 provides a flexible and powerful environment to take into account an unlimited number of technologies to influence the future energy consumption and fuel paths. Typically three to four different vehicle segments are used to characterise the car market, for each of them a corresponding set of technologies are described. The model would also allow for more vehicle segments; however, this comes by costs of computation time and power, and not the last by the need to provide techno-economic input with the data for all vehicle segments. Therefore for the European markets, typically three segments are used: small, medium and large cars.

Secondly, the different powertrain concepts are distinguished. Figure 2 shows six major powertrain concepts which are under discussion today as options for the near future:

- conventional combustion engines, which can use gasoline, diesel and CNG as a fuel;
- autonomous hybrid powertrains which can use break-energy recovery, and which could be powered by gasoline, diesel and CNG as well as their conventional predecessors;
- plug-in hybrid powertrains which in addition can be recharged from the electricity grid;
- range extended EVs
- battery electric vehicles, and
- hydrogen fuel cell EVs.

These are already 10 powertrain concepts, but more could be defined like e.g. LPG versions and different sizes and approaches for hybrids. Considered as the most important, in VECTOR21 typically the described 10 powertrain concepts are pre-configured. Please refer to eMAP-Deliverable 5.1 (Frieske, 2015) for a detailed description of the selected powertrains.

One of the strength of VECTOR21 is the support to handle the technology development over time. From a conceptual point of view of the model, technical parts and fuel economy packages are distinguished. Technical parts offer the possibility to model their costs dynamically by time or production volume. Fuel economy packages are technology bundles which offer a specific increase in fuel efficiency on top of the reference vehicle, and which can include technical parts in their description. Fuel economy packages are pre-defined for each powertrain concept and vehicle size (segment) because the effect of different efficiency technology can't simply be added as their total effect is often less than the sum of single effects. The technology bundles used in the eMAP-Project are derived from literature and/or calculated by vehicle simulations, and the set of parameters was subject to expert validation (see Frieske, 2015). The configuration used in eMAP is summarized in chapter 4.

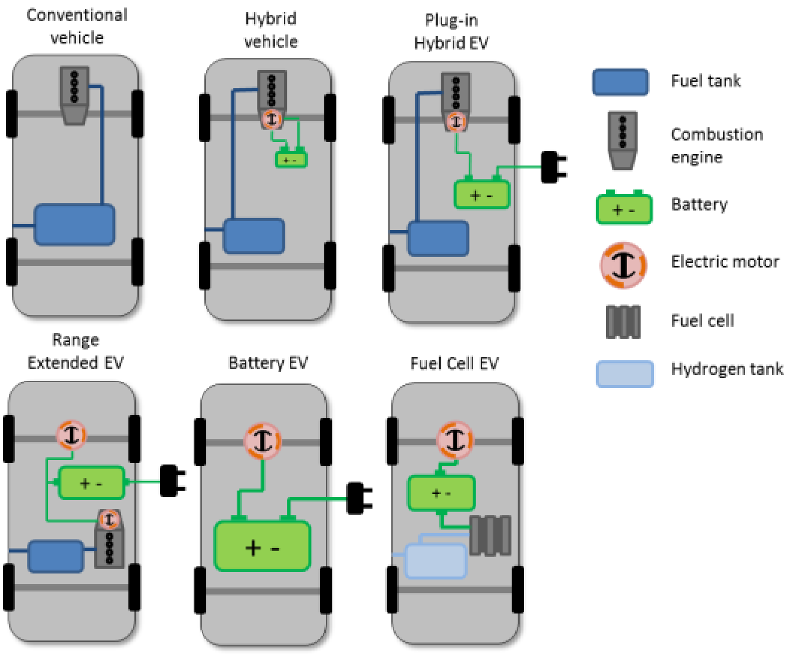

Figure 2: Powertrain concepts used in eMAP (Klötzke et al. 2015)

2.2 Customer representation

One of the key steps in the simulation of the market uptake is the purchase of the vehicles. VECTOR21 includes a set of agents which represent all vehicle buyers that purchase a vehicle in the given year. The standard configuration of the model includes 3 vehicle segments, for each segment the annual mileage distribution in 60 categories and a distinction of the purchase decision takers in 5 categories, called adopter groups.

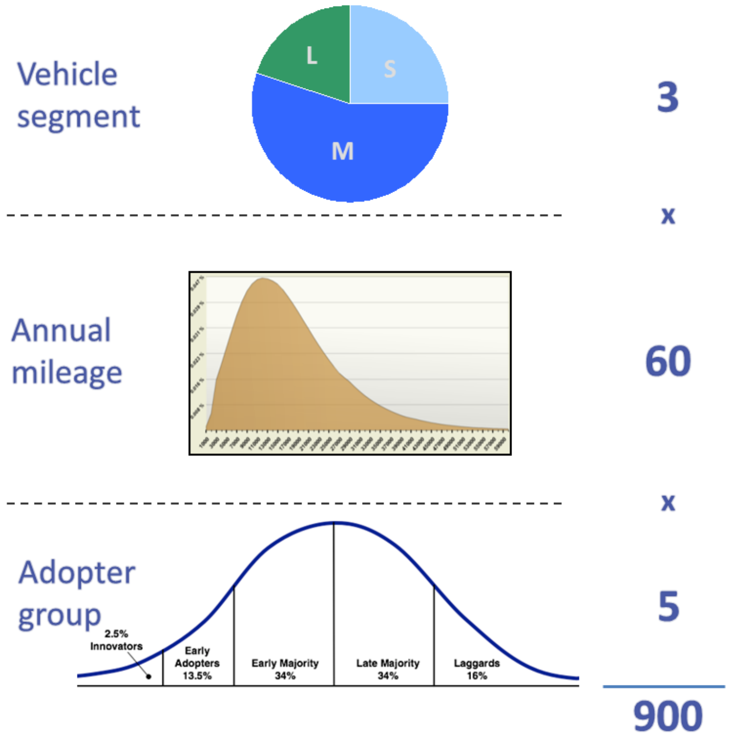

Figure 3: Characterisation of customers (agents) in VECTOR21 (for adopter groups see Rogers (2003))

For the eMAP-project, the ability of VECTOR21 to hold multiple customer representations, one for each passenger car market, was developed and implemented. The collection of the data and the calibration for each market is described in Chapter 4 and Kugler et al. (2015).

2.3 Manufacturer strategies

Another major driver for technology uptake scenarios is the availability of the technology on the market itself. Manufacturers may pursue different strategies to fulfil the CO_2 emission targets for cars they sell in Europe. Depending on their product portfolio, e.g. with more or less small, medium, large and luxury cars, the OEMs may take different options for actions to reach CO2 targets, for strategic, competitive, alliances or other reasons. Basically today there is the question, how much can be drawn from efficiency and what needs to be the contribution from plug-in vehicles.

The focus of the VECTOR21 model algorithm is on cost-optimal solutions from the perspective of the end customer. However more strategic questions from the perspective of the manufacturers are subject of the scenario development process.

There is the issue of “burden sharing” between segments. This means how much effort is taken in the different vehicle segments to adopt more expensive but efficient technologies or alternative fuels and propulsion technologies. On the other hand, serious research, development, engineering and production planning steps need to be performed by manufacturers before the final product (car) is available on the market. This may take 3-5 years depending on innovation level of the technologies and the experience the manufacturers and suppliers have already with the technologies. While the issue of technological readiness is handled within the technology-section of the model, the production capacities, availability in the stores, and in the end the strategies of the individual manufacturers and brands is dealt with in the scenario development process.

Another degree of freedom of the manufacturer is the burden sharing between countries, i.e. between its European sub-markets. For reasons of competition, customer preferences, financial strength of the customers etc. the manufacturers may choose in which country to offer which number of alternative vehicles and to which prices. In order to account for product planning of manufacturers and potentially limited production capacities at a certain point in the future, VECTOR21 is able to take constraints of production capacities into account. As the issue of 'market supply by manufacturer' also applies in this respect, this feature was enabled to take effect also on a per country basis in the enhanced eMAP-version of VECTOR21. Therefore the algorithm now uses constraints depending on country, vehicle size and powertrain. As a consequence, customers may not always be able to purchase the vehicle which could be the most economic for them.

2.4 Regulation and policies

To calculate and analyse potential solutions for the EU's strategy to improve the fuel economy of cars sold on the European market is the key purpose of the VECTOR21 model. Therefore key elements of the EU legislation with its mandatory emission reduction targets for new cars are implemented. The phase-in of CO_2-limits started in 2012 in European Union. In the first step, until 2015, only a part of the new vehicles had to meet the target value. The target value is calculated with the cross vehicle weight, relating to a reference mass which represents the average weight of the European new vehicles, to ensure that the target value of 130 g/km is met (COM 2007). This reference mass will be redefined in 2015 and is valid from 2016 on. From 2020 on, the target value will be 95 g/km, accompanied by another phase-in, whereby only a part of the new vehicles has to meet the target values. From 2021, the average emissions of all vehicles have to meet the target values.

The penalty payments for overrunning the target values are staggered and time-dependent. Between 2012 and 2018 the first g/km above the CO2 limit, 5 € fall due, 15 € for the second and 25 € for the third g/km. If the transgression is more than 3 g/km, the entire penalty payment of 95 € / (g/km) falls due, which is also the case from 2019 on, for every transgression.

The so-called super-credits for low-emitting vehicles (< 50 g/km) are taken into account between 2012 and 2015 as well as between 2020 and 2022. These vehicles are multiplied by a changing factor; hence, they count as multiple vehicles in the calculation, whereby the average emissions are reduced (2012: 3.5 x, 2013: 3.5 x, 2014: 2.5 x, 2015: 1.5 x, from 2016: 1.0 x, 2020: 2.0 x, 2021: 1.67 x, 2022: 1.33 x, from 2023: 1.0 x)(EC 2015)

2.5 Solving process

This section describes the solving process which determines how many vehicles with which technology can possibly be expected in the market for each year under all constraints.

Time-forward approach

The VECTOR21-solver computes strictly in time forward, from the starting date to the future in time steps, which are typically set to years. For each time step, the optimum solution is calculated. Starting values for the reference market situation concerning the market situation in year zero as well as cost estimates for technical parts at specific production volumes are set. After each time step, the cumulative sold volumes on technical parts are consolidated as an input for the next time step. For the eMAP–project, the algorithm was adopted to allow running for multiple countries in sequence.

Constraints

The solution set is restricted by constraints formulated in the model. Typical constraints are e.g. availability of new technology, availability of infrastructure like H2-refuelling stations, availability of production capacities to a certain volume etc. The VECTOR21-solver checks constraints on a time-step basis. The average CO2-fleet target in the EU is for the solver a special constraint. It is not automatically hit, but it can also be 'overshot'. I.e. if technology and cost progress develops positively compared to reference technologies, it can become a fast-selling item, so that CO2-targets are over-fulfilled. Presently there is no mechanism to avoid this by e.g. re-balancing again to give higher-emitting technologies a second chance.

RCO-based purchase decision

There are different solvers/approaches available in VECTOR21 to calculate an optimal solution based on techno-economic and ecologic data on fuels and vehicle technologies, and on customer purchase rational, preferences and willingness-to-pay. The most sophisticated is the utility based approach which integrates financial aspects as well as technical and ecological criteria in the purchase decision process. Due to data needs to describe car buyers' behaviour; this approach could not be followed for the extension of the model to the European scale.

For the eMAP project the 'relevant-cost-of-ownership' (RCO) approach was identified as the most promising way to be transferred in a consistent way to all countries under assessment. The difference between 'total-cost-of-ownership' (TCO) and RCO is, that because the model always compare relative on a vehicle-to-vehicle basis, certain cost which are not affected by this comparison can thus be eliminated.

The relevant costs are calculated as the total costs of ownership, including both variable and fixed costs. Purchase costs, energy costs, non-recurring and annual taxation as well as subsidies are part of the model. Four years are assumed to be the relevant time horizon for the purchase decision following e.g. ADAC (2015). Further issues like loss of value, maintenance and insurance are not considered at the moment.

Beyond all constraints, the individual agent may get offered several different vehicles like different fuels, different powertrains with differing fuel saving packages etc., and thus with different attributes like CO_2 emissions and costs. The model pre-selects those within the lowest RCO and lowest RCO plus the agent's willingness-to-pay for a more recent product and/or more innovative technology. Within those, the one with the lowest CO_2 emissions is selected.

Equilibrium and optima

The most favoured VECTOR21-approach and the one used in the eMAP project values the market power of the customers highest, i.e. their purchase decision determines the solution in the time step, which can also be observed in the real world. However, the agents' individual decisions within the constraints do not lead automatically to the desired solution. They miss the collaboration aspect in order to reach an overriding objective as e.g. the CO_2-target in the new vehicle fleet. This is addressed in the VECTOR21-model by shifting the solution space between demand and supply. The approach taken in eMAP is to proportionally shift over all vehicles in relation to their distance to the CO_2 target, which in turn generates results which could also be interpreted as a supply side constraint or phasing out of high-emitting vehicles.

In this way, the development of market shares over time with phasing in of new technologies is generated which can be characterised as a cost-optimized path from the perspective of the customers (car buyers) to reach a CO_2-target in the new vehicle fleet in each market.

3 Extension of VECTOR21 to European scale

The task set in the eMAP project, to describe development paths for the European car fleet, requires an extension of VECTOR21 to European scale (EU28). However, the required effort to gain data sets of sufficient quality for each of the 28 countries of the European Union, as well as the corresponding complexity to model, calibrate, validate and calculate for these 28 countries would be tremendous. Thus, a more subtle approach was chosen: Only the countries of the eMAP partners, i.e. Germany, Finland and Poland were modelled in VECTOR21, in addition to the three largest European new vehicle markets of the United Kingdom, France and Italy. Altogether, these markets represent about three quarters of the EU28 new passenger car sales (Figure 11).

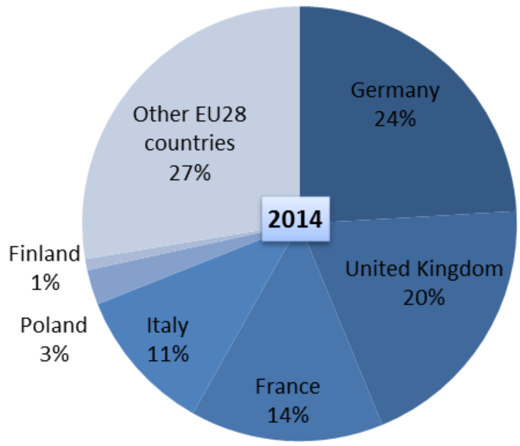

Figure 4: Market shares of VECTOR21 markets in 2014 - new passenger car sales (ACEA 2014, Eurostat 2015)

Furthermore, seen over a period of 2001-2011, the new vehicle markets in Germany, France, UK, Italy and Finland have the same share of small, medium and large diesel cars (+/- 0.7 percentage points in 2011) as EU15 countries[2] (see Figure 5).

Likewise, and for the same time period, the vehicle size segment shares of the new vehicle markets in Germany, France, UK, Italy and Finland correspond to those (+/- 0.9 percentage points in 2011) of the EU15 countries, which can be seen from Figure 13.

[2] EU15: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxemburg, Netherlands, Portugal, Spain, Sweden and UK. Compared as total number of diesel cars per segment.

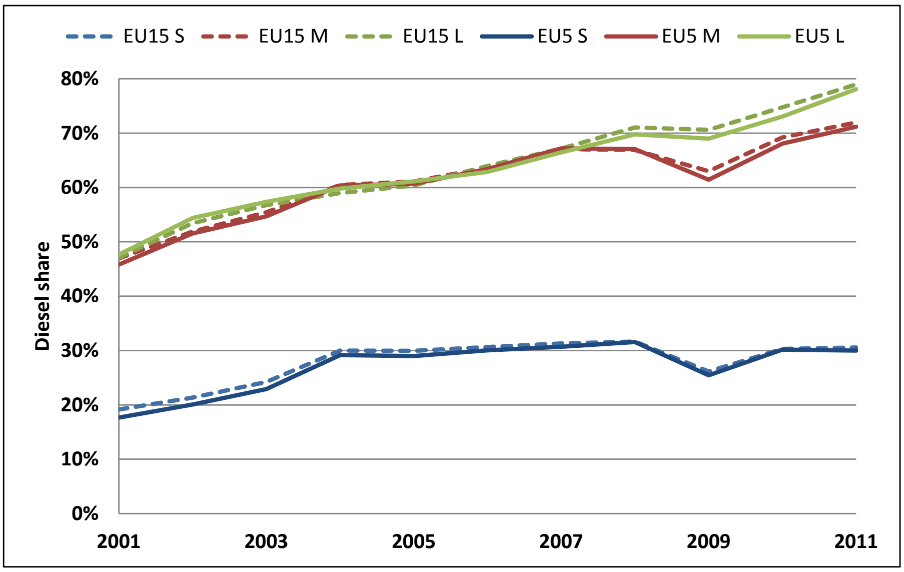

Figure 5: Diesel share per segment (Small-Medium-Large) in DE, FR, UK, IT, FI (EU 5) and EU15 (ICCT 2013, HIS 2014)

Although the previous two comparisons do not include 13 countries and corresponding vehicle markets from the EU28, the mentioned six vehicle markets modelled in eMAP are still representative for the whole EU28 since those 13 countries not considered above have a combined market share of only 6-7 % between 2011 and 2014 (ACEA 2014, Eurostat 2015). Hence, the EU28 new vehicle market can be described with a high degree of fidelity by the six markets of Germany, the United Kingdom, France, Italy, Poland and Finland, which is implemented in eMAP with a constant upscaling factor of 1.377 for the new passenger car sales.

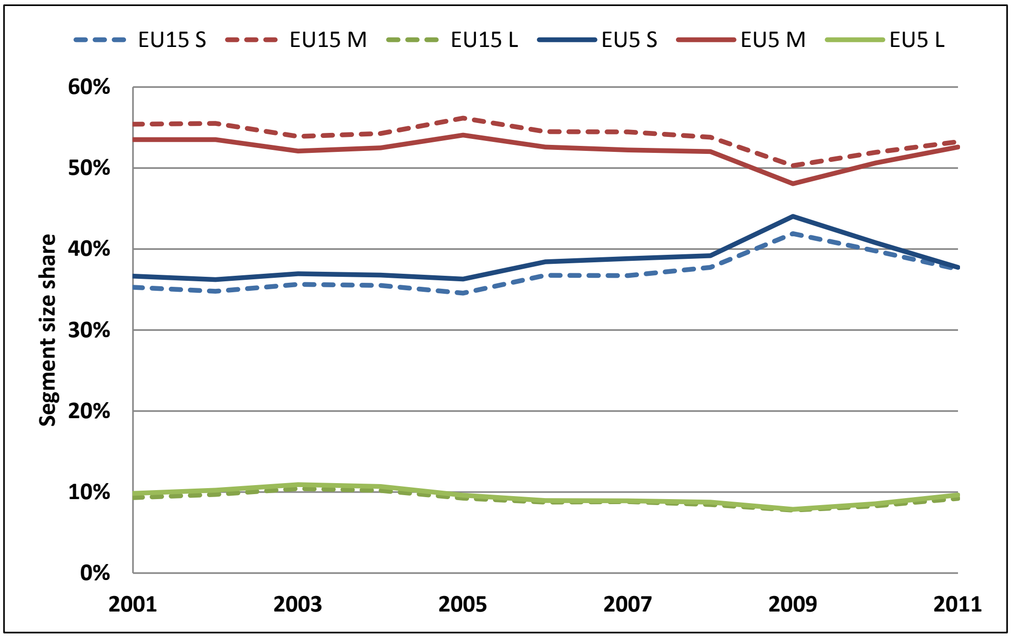

Figure 6: Segment size share (Small-Medium-Large) in DE, FR, UK, IT, FI (EU5) and EU15 (ICCT 2013, IHS 2014)

Similar to the new vehicle markets, seen over a period of 2002-2012, the existing fleet of the six modelled markets has been representing 66-68% of the EU28 stock (see European Union et al. (2014) and Figure 14). Therefore, results for the vehicle stock of EU28 can also be obtained by upscaling the vehicle stock of the modelled six countries with a constant factor of 1.491.

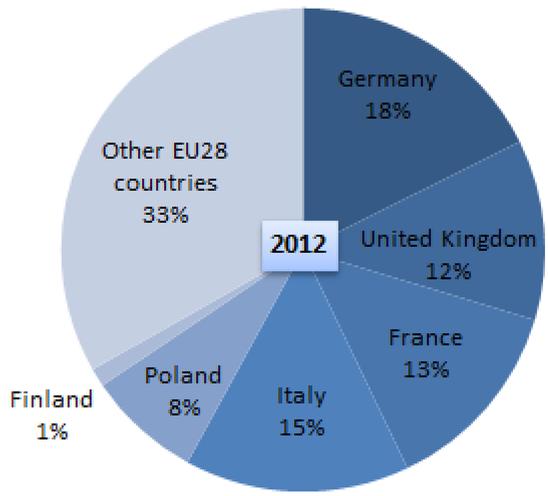

Figure 7: Market shares of VECTOR21 markets in 2012 – stock (European Union et al. 2014)

Based on the preceding analysis of how the vast effort to model the European new vehicle market could be kept at bay, VECTOR21 was extended and enhanced to model the six aforementioned markets. Figure 8 shows a schematic representation of the extended VECTOR21 model. It can be seen that the vehicle technologies are assumed to be similar in all considered countries, whereas the market settings and customers are modelled individually for each country. With results available from each of these countries, the global upscaling of vehicle sales, which is required to estimate component production costs in later years (see also chapter 4), is enhanced and more precise than in earlier versions of VECTOR21.

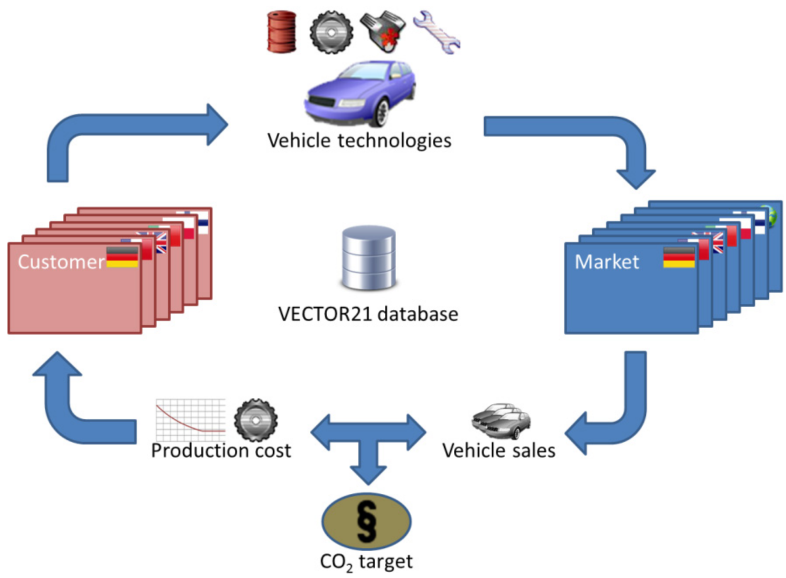

Figure 8: Schematic representation of the VECTOR21 tool extended to European scale

Especially the integration of country-specific market settings and customers required substantial changes to the programme code and database model. Since the assessment basis for purchase incentives, purchase taxes and vehicle ownership taxes differ for each of the six investigated countries, significant enhancements were necessary in order to correctly consider these taxation schemes. The extended version of VECTOR21 considers country-specific value added taxes, vehicle registration fees and annual taxes on ownership. Additionally, the credits or taxes according to Bonus-Malus-system in France are considered, as well purchase taxes in Finland and Poland. Details about these regulations and taxes are explained in detail in Kugler et al. (2015). Furthermore, the different country-specific conditions regarding the refuelling/recharging infrastructure and its development, vehicle supply, as well as fuel and vehicle costs needed to be implemented in the VECTOR21 model. The description of the customer-side considers the different purchasing powers, annual mileage distributions and vehicle size segment shares for each country. This does not only add complexity for the calculation of Relevant Costs of Ownership (RCO), but also with regard to the modelling of the European CO_2 emission targets (see section 2.4). These emission targets need not to be fulfilled by each individual country but only in the European average, i.e. individual size- or country-specific CO_2 emission averages of the new vehicle fleet may be significantly above or below these targets. This creates many degrees of freedom to achieve the set emission targets and thus adds to the new complexity of the enhanced modelling tool.

The calculation effort of VECTOR21 increases linearly with the number of simulated markets. Thus, although a restriction onto 6 vehicle markets was given, the original VECTOR21 calculation algorithm would not have been efficient enough to keep the simulation runtime at a manageable level. As a consequence, significant improvements regarding the algorithm speed were implemented with the enhanced VECTOR21 version, which cut down the total runtime for a full simulation to about ten minutes.

3.1 Improvements to the vehicle stock model: Vehicle imports

Polish and Finnish new vehicle registrations feature, to a significant proportion, imports of used cars that were previously registered in another country. Vehicle imports contribute about 75% to new vehicle registrations in Poland, whereas in Finland the share of vehicle imports on new registrations is still about 15%. Due to these large relative contributions it is necessary to consider the vehicle imports in order to obtain a sufficiently precise vehicle stock model for these countries.

Since VECTOR21 does not include a second-hand car market, a new model to consider vehicle imports was developed within the eMAP project. Therefore, the decomposition of the vehicle imports with respect to vehicle age for both countries was analysed. It can be seen that the average age of imported vehicles is about 10 years in Poland and 7.5 years in Finland. Then a Gaussian functions to the Polish and Finnish vehicle import age distribution data was fitted– the resulting fit functions are shown in Figure 9. There the relative contributions of imported vehicles to new registrations are shown. The larger area below the Polish curve in comparison to the Finnish curve indicates the larger impact of imports in Poland on the new registrations.

After the analysis of the age distribution the composition of the imports with respect to the vehicles' powertrains was examined. In the years before 2010 both countries imported mainly gasoline and diesel cars, but almost no CNG-powered cars. Therefore, the ratio of diesel to gasoline vehicles from the imports to the same ratio of new vehicle sales in both countries can be compared. The result is a high correspondence of the diesel shares for vehicle imports and new vehicle sales. Hence it can be assumed that the share of powertrains for the vehicle imports will also coincide in the future with the powertrain shares of the new vehicle sales. Regarding the amount of imported vehicles, the relative share of imported vehicles is constant over time, as it has been almost constant over the past ten years was assumed.

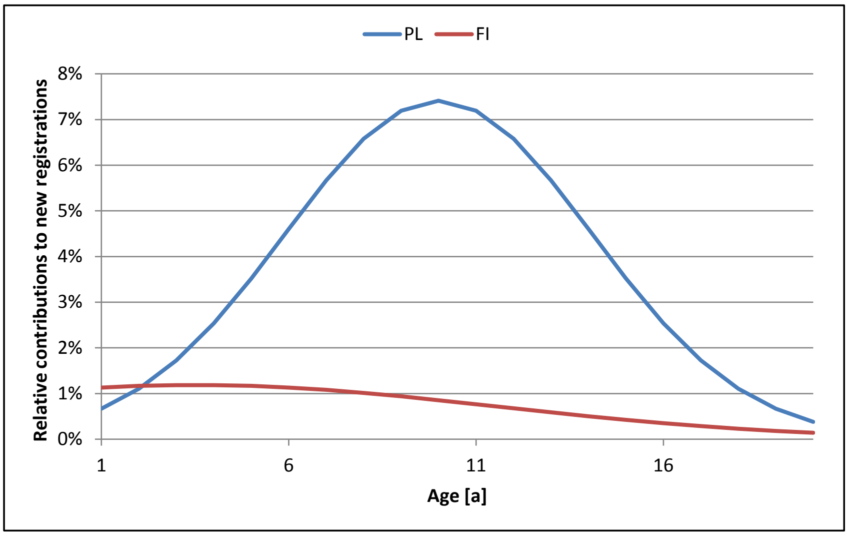

Figure 9: Relative contributions by age of imported vehicles to new vehicle registrations in Finland and Poland.

With the defined approach to calculate the amount, age and powertrain share of the vehicle imports the energy consumption and annual vehicle mileage to model cohorts of imported vehicles is still needed. Since statistical data about the annual vehicle mileages differentiated with respect to imported old or new purchased vehicles lacks, it is assumed that imported vehicles have the same average annual mileage than newly purchased ones. Furthermore, the same mileage decline and vehicle survival functions for imported and newly sold vehicles are used. Finally, it is necessary to set average energy consumptions per vehicle kilometre for the imported cars. Since these cars stem almost exclusively from other European countries it is supposed that the energy consumption of an imported car is best described by the European average of this quantity corresponding to the new vehicles in the same year where the imported vehicle was built. For example, eight year old small gasoline vehicles that are imported in the year 2010 are assumed to have the energy consumption of the European average for small gasoline vehicles sold in 2002. The described efficient model for vehicle imports in Poland and Finland allows an accurate analysis of the vehicle stock in these countries.

4 Calibration of the scenario model

The enhanced scenario model described in previous chapters, needs, in order to create meaningful and realistic results, thoroughly calibrated and validated input data. This chapter is dedicated to the description of the employed data calibration methods, which ensure the quality of the eMAP results.

4.1 Vehicle technologies

For the project it was assumed that the vehicle parameters, i.e. energy consumptions or technology bundle parameters, are identical in all European countries, and may only differ with respect to scenarios (cf. Kugler et al. (2015)). Figure 10 shows the development of the energy consumption on the example of vehicles of the small segment in dependency of the technology bundle level.

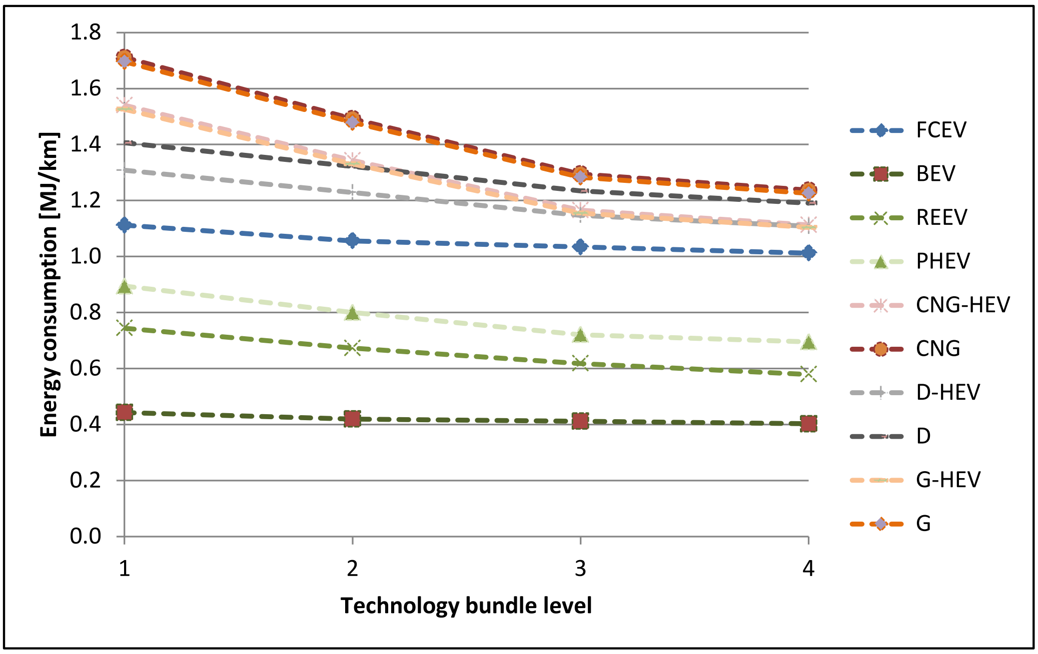

Figure 10: Energy consumption of small vehicles by powertrain and technology bundle

4.2 Customers

Each simulation on the enhanced VECTOR21 model considers 5400 different customer groups, which are associated to the six modelled car markets, three vehicle size segments, five innovation adopter groups and 60 different groups of annual mileage. Whereas the shares among the vehicle size-segments are country-specific, and may vary over time (see Kugler et al. (2015)), identical proportions of the customers among the adopter groups are assumed for each country and year. However, the willingness-to-pay surcharges for vehicles with less CO_2 emissions was adjusted according to the Purchasing Power Parity of each country, which is also described in detail by Kugler et al. (2015). Within each vehicle size segment, several car classifications have been condensed (Table 1).

Table 1: European and VECTOR21 car size classifications, as well as exemplary market shares for the German new car market in 2010

VECTOR21 vehicle segment	European car classification	New vehicle share in Germany
Small	A, B	28.0%
Medium	C, D, S, J, M	59.3%
Large	E, F, LCV	12.6%

Due to its strong influence on the RCO calculation, a considerable amount of work has been conducted to obtain realistic annual mileage distributions for each country and corresponding vehicle size segment. The Finnish and German mileage distributions, the German ones can be found in Figure 11, were fitted to empirical data (cf. Kugler et al. (2015)), whereas the distributions for the other countries had to be constructed from the average annual mileage of the corresponding vehicle stock. The approach for the construction of the annual mileage distributions is described in the following paragraph.

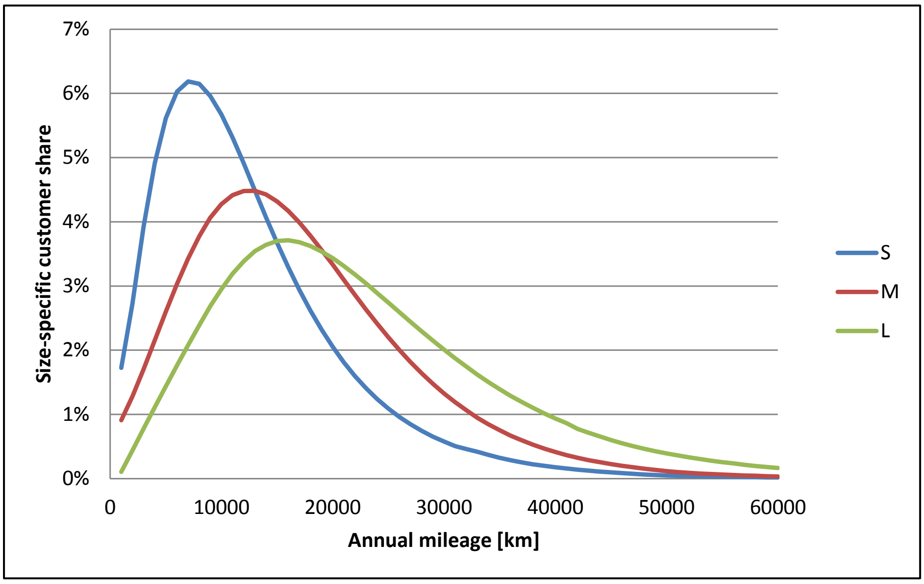

Figure 11: German mileage distribution of new vehicles in dependence of vehicle size

On average, new vehicles have a higher annual mileage than older ones. In order to obtain the average mileage m^i of a new vehicle in country i from vehicle stock data, it is needed to multiply the given average annual mileage of a vehicle in the stock by a correction factor f, that is constructed from the age distribution $A^i(a)$ and the mileage decline distribution $D^i(a)$ of the given vehicle stock and country in the following way:

$$f = \sum_{a=0}^{25} A^i(a) * D^i(a)$$

In the previous formula the considerations is restricted to a maximum vehicle age a of 25 years. The vehicle size has a large impact on the average mileage of a car – larger cars have a higher annual mileage than smaller ones. In order to reflect this behaviour, annual mileage averages m_s^i for each vehicle size s is constructed under the constraint

$$\sum_{s=1}^{3} m_s^i * S_s^i = m^i$$

Here, S_s^i corresponds to the share of new vehicle sales for the corresponding vehicle size and country. Furthermore, the mileage distribution function of all customers (not split by vehicle segment) is assumed to take a form similar to the same mileage distribution in Germany, but differs from the German distribution only by a stretching factor. Thus, m_s^i is estimated using a linear combination of the German market shares S_s^G and German mileage averages per vehicle size m_s^G, according to the following formulae:

$$m_1^i = \frac{m^i}{m^G}\left[\frac{\min(S_1^G, S_1^i)}{S_1^i} m_1^G + \frac{\min(S_2^G, \max(0, S_1^i - S_1^G))}{S_1^i} m_2^G + \frac{\max(0, S_1^i - S_1^G - S_2^G)}{S_1^i} m_3^G\right]$$

$$m_2^i = \frac{m^i}{m^G}\left[\frac{\min(S_2^i, \max(0, S_1^G - S_1^i))}{S_2^i} m_1^G + \frac{\min(S_2^i, S_2^G, \max(0, S_2^G + S_1^G - S_1^i))}{S_2^i} m_2^G + \frac{\min(S_2^i, \max(0, S_1^i + S_2^i - S_1^G - S_2^G))}{S_2^i} m_3^G\right]$$

$$m_3^i = \frac{m^i}{m^G}\left[\frac{\max(0, S_1^G - S_1^i - S_2^i)}{S_3^i} m_1^G + \frac{\min(S_2, \max(0, S_1^G + S_2^G - S_1^i - S_2^i))}{S_3^i} m_2^G + \frac{S_1^G + S_2^G + S_3^G - S_1^i - S_2^i}{S_3^i} m_3^G\right]$$

In these formulae, m^G represents the total average annual mileage of new cars in Germany. It is also assumed in the previous formulae, that $m_s^i \leq m_{s+1}^i$, which causes the asymmetric form of these equations with respect to m_s^i and m_s^G. For details about the market shares S_s consult Table 2, which shows these market shares of new cars sales in the year 2010 in dependence of the vehicle size and country, whereas Table 3 specifies the total average annual mileage of new cars for Germany and Poland, as well as Finland, France, Italy and the UK. For the latter countries we used the above described method to calculate size-depending annual mileage averages.

Table 2: Share of new car sales by vehicle size and country in 2010 (IHS 2014)

Country	Small	Medium	Large
Germany	28.0%	59.3%	12.6%
Italy	56.0%	32.0%	12.0%
France	43.0%	44.0%	13.0%
United Kingdom	35.6%	53.6%	10.8%
Finland	17.7%	73.6%	8.7%
Poland	33.5%	63.3%	3.2%

Table 3: Average annual mileage in units of 1000 km of new vehicles by country and by car segment (own calculations based project data)

Country	Small	Medium	Large	Average
Germany	12.7	17.3	22.3	16.6
Italy	11.5	13.3	16.8	12.7
France	15.3	18.6	23.1	17.8
United Kingdom	17.6	22.3	28.8	21.3
Poland	7.3	11.2	15.0	10.1
Finland	16.2	23.0	30.7	22.4

In order to create a reasonable annual mileage distribution a discretized Beta distribution that was stretched to the desired range (1,000 to 60,000 km) was employed. The first shape parameter $\alpha = 0$ was set to obtain the steep increase of the German and Finnish mileage distributions at low mileages, which can be also observed in Figure 11. The second shape parameter was fitted in order to obtain the correct average annual mileage of the corresponding vehicle segment and country. An example for mileage distributions created with the method described afore can be found in Figure 18.

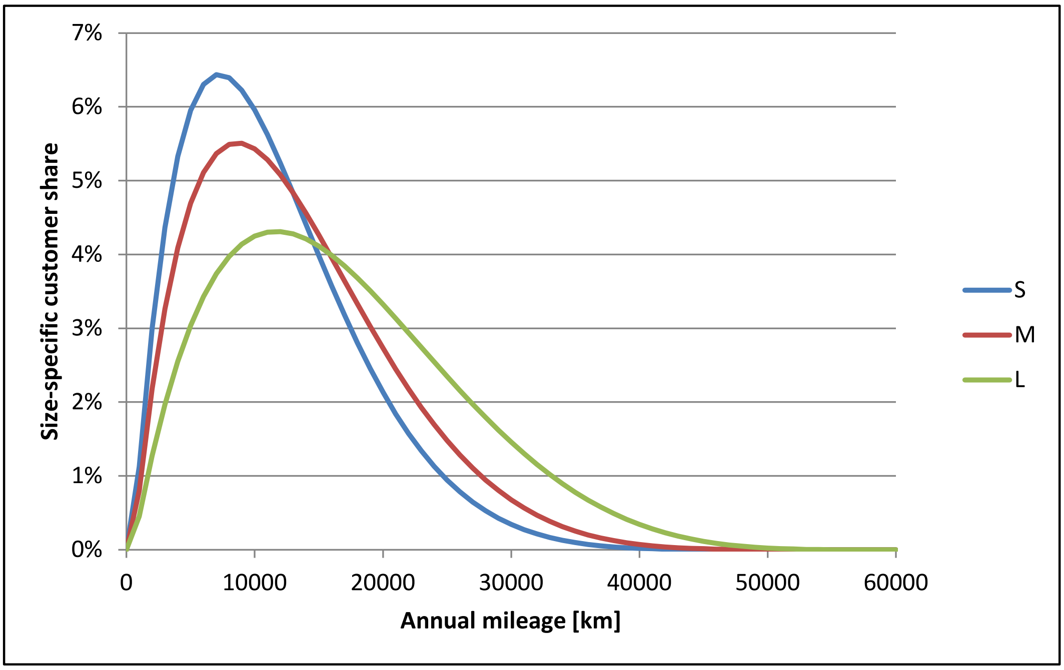

Figure 12: Estimated Italian annual mileage distribution of new vehicles by vehicle size

A parameter with a great impact to the purchase decision is the level of innovativeness. This is represented by the different adopter groups (innovator, early adopter, early majority, late majority and laggards). Within the definition of the adopter groups, the requirement on the infrastructure and the willingness-to-pay was set. With a decreasing level of innovativeness, the required infrastructure coverage for the vehicles energy distribution increases (see Table 4).

Table 4: Required infrastructure coverage of different adopter groups

Adopter group	Required refuelling/charging coverage
Innovator	1%
Early Adopter	14%
Early Majority	50%
Late Majority	85%
Laggards	100%

The willingness to pay a surcharge for more innovative technologies increases with an increasing level of innovativeness (see Table 5). It is also differentiated between customers of small vehicle and those of medium and large vehicles, since customers of small vehicles are supposed to be more price-sensitive.

Table 5: Willingness-to-pay for German customers of different adopter groups and vehicle sizes

Adopter group	Small vehicles	Medium/Large vehicles
Innovator	5%	10%
Early Adopter	4%	7%
Early Majority	2%	3%
Late Majority	1%	1%
Laggards	0%	0%

4.3 Fuel and energy prices

Fuel and energy prices have a large impact on the annual costs of a car, thus, a detailed calibration of these parameters is essential.

The price of hydrogen fuel was taken from McKinsey (2011) and is assumed to be identical in all countries. Due to a liberal market of natural gas, similar behaviour of the CNG net price in all countries is to be expected, hence, national differences were only accounted for with respect to taxes and fees. Regarding the estimates of electricity prices: Due to the strong influence of taxes, fees and apportionments, as well as the high increase of the German electricity price in the past years, a detailed analysis of all electricity price components, also including production and transport cost from Nitsch et al. (2012), was used to create a German gross electricity price scenario. Other countries do not show such an extreme increase in the electricity price, which is why linear extrapolations were employed to obtain national electricity price scenarios. Gasoline and diesel prices, however, were modelled using the following method.

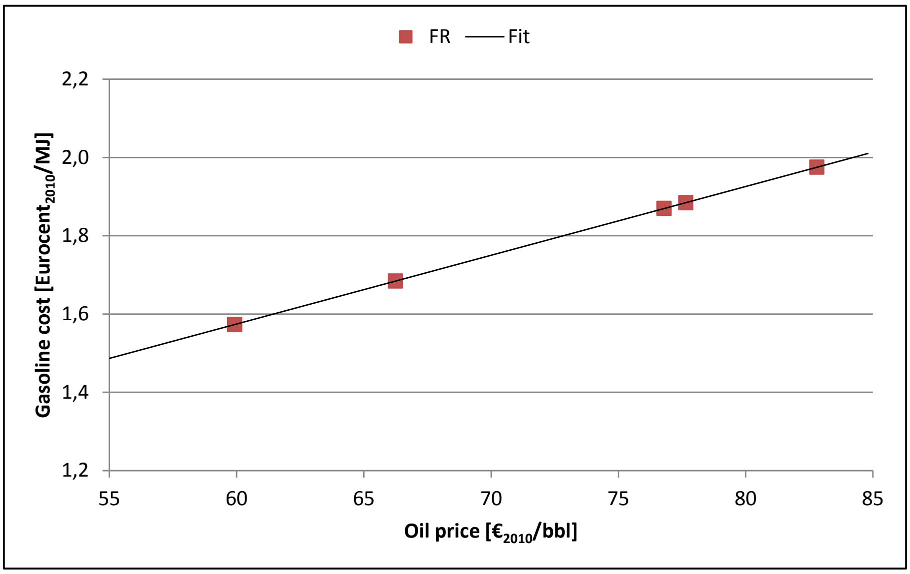

Figure 13: Estimate for historical gasoline cost in France versus historical oil price, including a linear fit

In order to obtain high quality fuel prices in each country, the dependency of the past gasoline and diesel cost (without taxes and fees) on the crude oil price was analysed via a regression analysis. Figure 13 shows the dependency of gasoline cost (production + redistribution) in France between the years 2010 and 2013 on the oil price development. The low variation of the gasoline cost from the linear fit illustrates that this method allows quite accurate estimates for conventional fuel cost if the crude oil price is provided.

This method was then used to extrapolate the future gasoline and diesel net prices on the basis of the eMAP crude oil price scenario. In a last step, taxes and fees were added to obtain the gross prices – the resulting gross price scenarios for Finland, Germany and Poland can be found in Kugler et al. (2015). The eMAP crude oil price scenario differs from the IEA (2013) scenario, as at the time of its creation the price development for the years 2012-2014 could not be foreseen. Thus, the actual crude oil prices until 2014 was used for eMAP and then assumed a gradual return of the crude oil price to the IEA (2013) price level until 2020. Both scenarios are depicted in Figure 14.

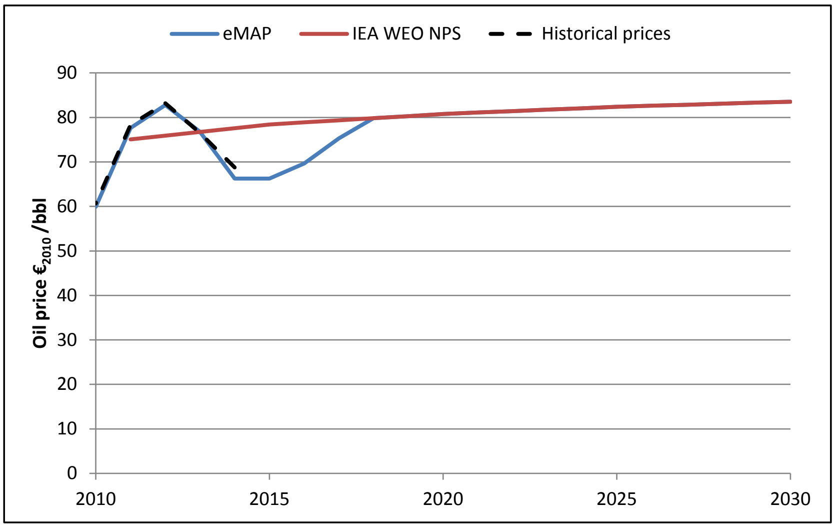

Figure 14: Historical Crude oil price (dotted), IEA oil price scenario (IEA 2013, red line), eMAP oil price scenario (blue line)

4.4 Learning curves

The specific form of the component price learning curves for the eMAP project was implemented in the following way (see Figure 15 and Mock (2010)): The production cost of a given component drop exponentially with cumulative units of production, in accordance to the learning rate. After the floor costs are reached, no further cost decrease can be achieved. The net price of the component, however, which also includes the components' margin, is first kept constant at an initial price level, until a target margin is reached, which in this case is 35% relative to the production cost. Only then the net price is also decreased up until the production costs reach their floor value.

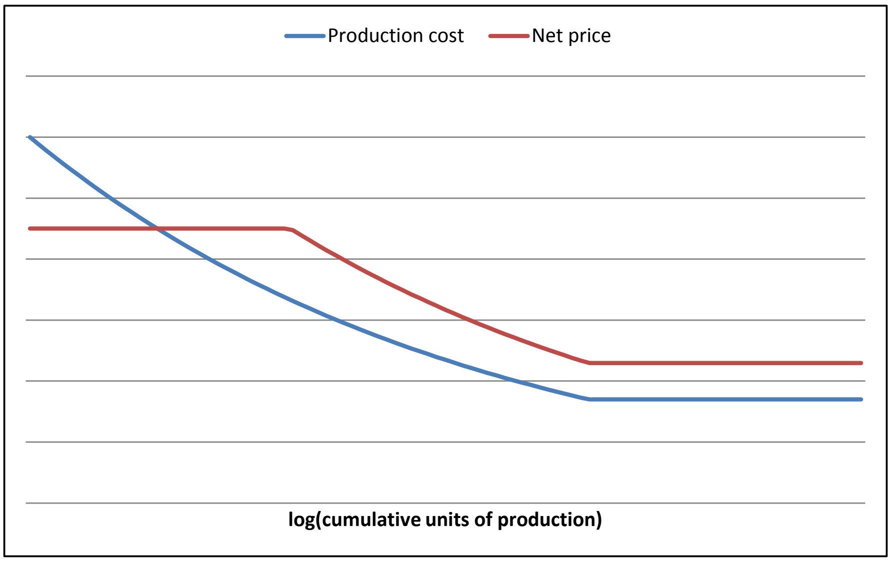

Figure 15: Schematic representation of production cost and net price development over cumulative units of production

Since component prices depend on the cumulative units of production, the price development is not an input to the VECTOR21 simulations, but is calculated during the simulation process depending on the vehicle sales. The relevant input parameters are: Initial production cost c_i, initial cumulative units of production u_i, initial net price p_i, targeted margin m_t, floor cost c_f and learning rate r. These parameters were carefully selected in order to achieve learning curves that match the estimates of experts. Please refer to Frieske et al. (2015) for further details about these expert estimates. For the Business-as-Usual scenario learning curve parameters are shown in Table 7. The influence on battery prices of the Technology-Driven scenario, which features a learning rate for traction batteries of $r = 0.87$, can be investigated in Kugler et al. (2015).

Table 6: Learning curve parameters for important vehicle components in the eMAP Business-as-Usual scenario

Component	u_i	c_i /€$_{2010}$	c_f /€$_{2010}$	r	p_i /€$_{2010}$	m_t /%
Battery	300,000 kWh	600	170	0.90	450	35
Electric motor	1,400,000 kW	29	10	0.93	25	35
Power electronics	1,400,000 kW	25	8	0.93	25	35
Fuel cell system	5,000 kW	192	36	0.85	144	35

4.5 Stock

For the calibration of the vehicle stock suitable country- and size-specific functions for the vehicle survival and mileage decline are necessary. For all considered countries but Finland and Poland these figures were obtained from TRL (1999), whereas for Finland and Poland the European average, presented in the same publication, was used. In addition to the survival and mileage decline functions, the vehicle stock model of VECTOR21 requires appropriate initial distributions for vehicle cohorts that represent the vehicle stock at the beginning of the year 2010, i.e. the first year of the VECTOR21 simulations in eMAP. The following information regarding these vehicle cohorts is required: For each powertrain and year between 1986 and 2009, the initial amount of vehicles, the initial average annual mileage as well as the average energy consumption per vehicle kilometre. The required data sets were obtained from various sources and were then harmonized with the previously presented vehicle survival and annual mileage decline functions in order to provide a consistent initial vehicle stock cohort distribution for each country.

VECTOR21 does not only calculate new vehicle sales, but also integrates these new vehicles into the vehicle stock. It is thereby possible to analyse many important parameters of the vehicle stock, such as the CO_2 emissions, the total energy consumption or the energy consumption per fuel. The following paragraphs explain the VECTOR21 stock model.

Each year, a cohort of newly registered cars enters the vehicle stock, whereas vehicles are removed from the cohorts of previous years due to a variety of reasons, e.g. scrapping or export. Over the years, more and more vehicles are removed from cohorts in the vehicle stock, reducing their amount of vehicles. However, vehicles that have reached a certain age are regarded as old-timers, and may no longer be scrapped, but are instead restored and, thus, remain in the stock. Nevertheless, we neglect vehicles with an age over 25 years, as their influence on energy consumption and CO_2 emissions is comparably small due to the low annual mileage associated with these vehicles.

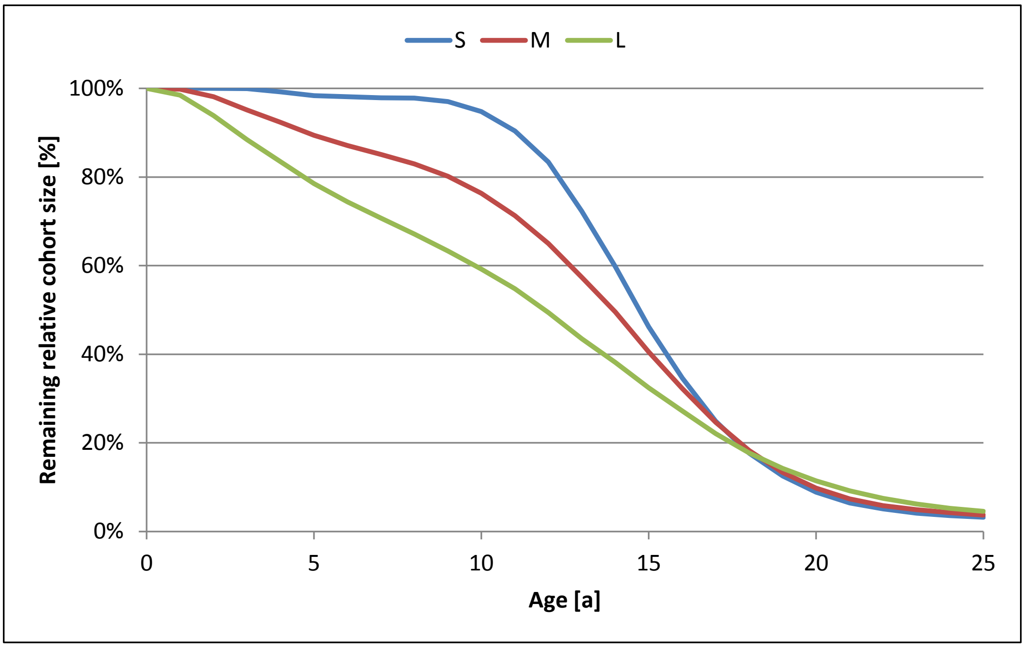

Figure 16: Survival functions by vehicle size of vehicles in Germany

The change of the cohort size over the years is described by the vehicle survival function, which can be seen in Figure 16: Survival functions by vehicle size of vehicles in Germany. It is shown for gasoline vehicles in Germany, the remaining relative cohort size in dependency of vehicle age. It can be seen that the survival functions for the three vehicle size segments differ considerably. Therefore, VECTOR21 considers individual and country-specific survival functions for cohorts differing by vehicle size and powertrain. Since there are no empirical data available on survival functions for vehicles with alternative powertrains the gasoline vehicle survival functions is also used for vehicles with alternative powertrains in the eMAP project.

Beside that vehicle cohort sizes are reduced over time, one must also account for a decline of the average annual vehicle mileage over the age of vehicles (see, e.g. Caserini et al. (2013)). Figure 17 shows the relative decline of annual vehicle mileage as a function of vehicle age in Germany.

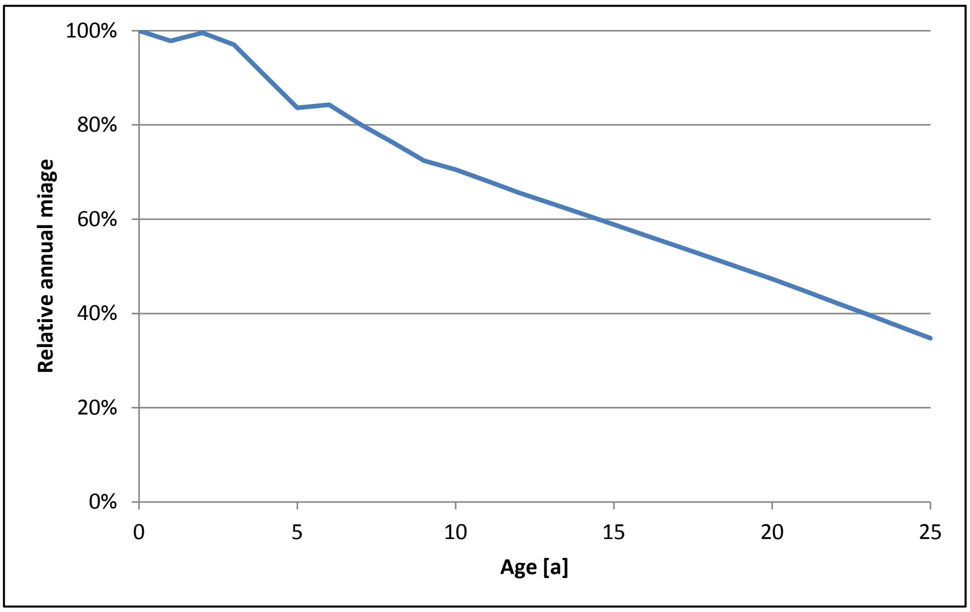

Figure 17: German decline of the annual mileage as function of vehicle age.

4.6 CO_2 targets

In section 2.4 it was mentioned, that VECTOR21 accounts for CO_2 emission targets differing by vehicle size segment. Within the extended model, European mass averages are used to set the segment-specific emission targets. An example of such size-specific targets can be seen in Table 7. It shows, for each year and vehicle size, the associated CO_2 targets from the Business-as-Usual scenario. The CO_2 targets presented in this table do not drop all of a sudden in 2021 and 2030, as the official European legislation would suggest, but are reduced constantly. This is necessary to be able to perform the calculations.

Table 7: Business-as-Usual CO_2 targets (presented in g/km) depending on the vehicle size

Year	Small	Medium	Large
2015	115	136	157
2016	108	129	150
2017	101	122	143
2018	94	115	136
2019	87	108	129
2020	89	104	120
2021	84	99	115
2022	82	97	112
2023	79	95	110
2024	77	93	108
2025	75	91	106
2026	73	88	103
2027	71	86	101
2028	68	84	99
2029	66	82	97
2030	64	79	95

There exist more than but one solution how to fulfil the CO_2-emission regulation. As mentioned before, a burden sharing between vehicle segments and countries can be applied. Due to the different impact of the CO2-emissions of the vehicles on the taxation or bonus-malus payments, the path the countries chose varies significantly. An example can be seen in Figure 18. Here it can be seen, that countries with a strong link of these fees to the vehicles' emissions, like Finland and France, have a pretty progressive course, while countries with a less strong relationship, like Poland, show a very slow development towards lower CO2-emissions. This is particularly true for the large segment.

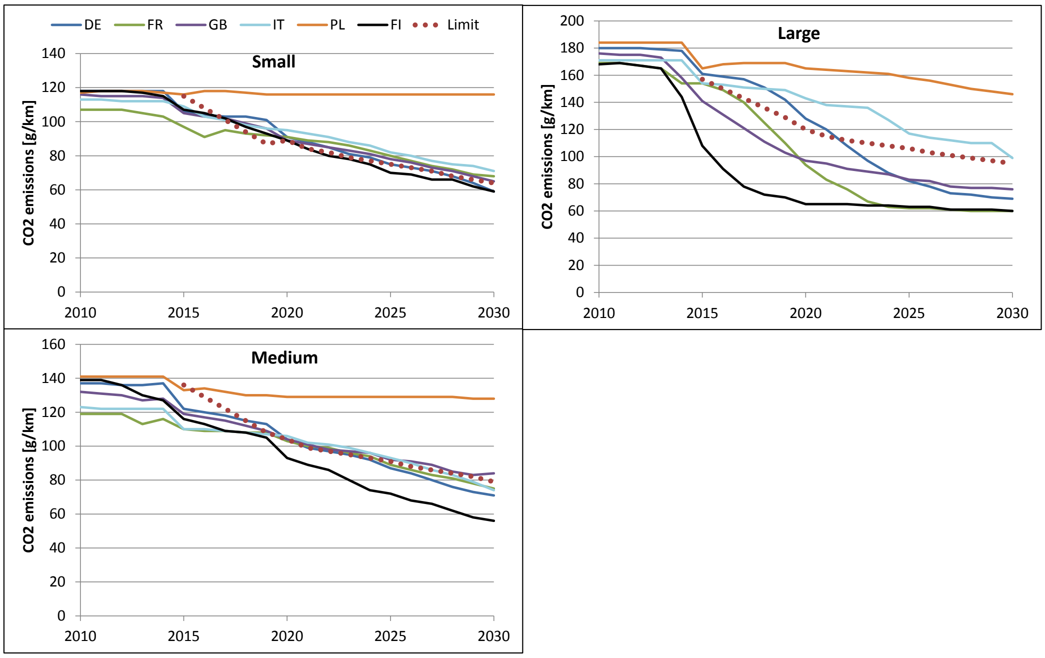

Figure 18: Development of average CO_2 emissions for new vehicles as well as the emission target for large cars in eMAP.

5 Summary

The described enhancements, extensions and calibrations for the VECTOR21 model allow a detailed analysis of the future new vehicle markets, not only in Germany but also in Poland and Finland, as well as France, Italy and the United Kingdom. This makes it possible to analyse the development of the car stocks, their powertrain composition, as well as the correlated total energy consumption and CO_2 emissions. The implemented country-specific systems for annual and one-time taxation and incentives, as well as possible modifications to these parameters facilitate a decisive understanding of effect mechanisms to promote the uptake of electromobility and low-emission vehicles in the near future of the European countries. This achieved progress of the VECTOR21 model is the foundation of all results presented in Kugler et al. (2015).

Besides those important advancements regarding the VECTOR21 model, significant progress was also achieved with respect to the calculation efficiency. The revised programme code has significantly shorter runtimes than previous versions of this tool, although about six times as many calculations were to be performed per simulation run. This allowed a more thorough parameter study as before and ensures the high quality of the project results.

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