Implications of Technology Learning in Energy-Economy Models of the Transport Sector

Report to the

Alliance for the Global Sustainability (AGS)

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1. INTRODUCTION

The global transportation sector, with a growing demand for its services and nearly total dependence on oil products, is a major emitter of CO_2 as well as a major concern for security of energy supply. Therefore, it becomes important to examine strategies that could drive the global transportation sector towards a more sustainable path in the long term. For doing so, it is necessary to develop adequate methodological tools that, on the one hand, capture the main mechanisms of technological change and, on the other hand, are capable of quantifying the transportation sector in the context of the global economy.

The goal of this project conducted for the Alliance for Global Sustainability (AGS) is to develop methodological tools to asses the role of technological change in transportation systems in the long run while considering the economic dimension of the problem. Specifically, the project explores methodologies that contribute to close the gap between "top-down" and "bottom-up" models, trying to combine their strengths and reduce their inherent shortcomings. The project, which started in the spring of 2002, involved two research groups, the Center for Technology, Policy & Industrial Development, Massachusetts Institute of Technology (MIT) in the U.S (H. Jacobi and A. Schäfer) and the Energy Economics Group of the Paul Scherrer Institute (PSI) in Switzerland (S. Kypreos, L. Gutzwiller, D.A. Krzyzanowski and L. Barreto). While the first group was concerned with linking the general-equilibrium top-down (EPPA) and the bottom-up, energy-systems (MARKAL) approach, the focus of the second group was the integration of technological learning by doing (LBD) in transportation technologies in the "bottom-up" component of the modelling system. MIT has successfully completed the link between the three models (without endogenous technological learning components) in a consistent framework (Schafer and Jacoby, 2003), while PSI has contributed to the introduction of LBD in the context of the MARKAL model and of a stand-alone simplified transportation model.

In this report two exercises are presented. The first analysis relates to experiments with the link between the general-equilibrium EPPA model applied at MIT, a transportation demand model and the systems-engineering MARKAL model, having incorporated the learning-by-doing mechanism in selected technologies in the latter. The second analysis consisted in the development of a simplified stand-alone, bottom-up, transportation model, which also endogenizes technology learning, but only considers the competition of transportation technologies without taking into account the fuel production chain. This simplified model has allowed the authors to gain insights into the basic dynamics of a "bottom-up" model that endogenizes technology learning, the main parameters that affect its behaviour and potential advantages and shortcomings of the formulation. This stand-alone model links also the transportation demand module, and leaves open the possibility of linkage to the more comprehensive EPPA model, but allows carrying out stand-alone analyses as well. As an example the case of North America[1] is examined, but the exercise outlined here has only an exploratory character.

The remainder of this report is organised as follows. The basic aspects of the link between the EPPA and MARKAL models are briefly described in Chapter 2, where some illustrative experiments are presented, as well as the estimation of elasticities of substitution under Learning-by-Doing conditions[2]. In Chapter 3, an alternative approach to the modelling of the transportation sector, using a stand-alone transportation model with endogenized technology learning, is introduced. Following its description, some illustrative results and a sensitivity analysis are discussed. Finally, in Chapter 4, some conclusions are drawn from the whole analysis.

2. FIRST APPROACH TO THE TRANSPORTATION MODEL

2.1. Methodology

In this research, the research team extends efforts by linking a model of transport technology with a multi-sector, multi-region computable general equilibrium (CGE) model of the international economy (EPPA). The CGE model is run in an interactive mode with models of transport sector detail, iterating until convergence is reached on key measures of inter-model consistency. With success in this combined simulation, it becomes possible to identify a set of specific technologies within the transport sector that are consistent with a particular general equilibrium simulation of climate policy.

The approach is summarized in Figure 1. The MIT **E**missions **P**rediction and **P**olicy **A**nalysis (EPPA) model, described below, is used to produce a multi-sector, multi-region simulation of economic growth, technical change, and emissions. A MARKAL or engineering-process type model of the transport sector is used to analyze particular technologies that can meet the various transportation demands within the economy, given estimates of overall economic activity and associated transport demand and the relative prices of fuel and other inputs (Kypreos 1996). Those economic conditions that impinge on the transport sector are input from the results of the EPPA simulation. To connect these two models, aggregate transport demand as estimated by the EPPA model must be divided into the appropriate split among transport modes for use in the engineering-process representation. For this step a third, Modal Splits model is applied, as shown in Figure 1. In what follows, the combination of the

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[1] USA and Canada

[2] One of the primary research goals of the PSI team

models will be described briefly. However, a greater deal of description may be found elsewhere in more detail (Schafer and Jacoby 2003) (Babiker, Reilly et al. 2001).

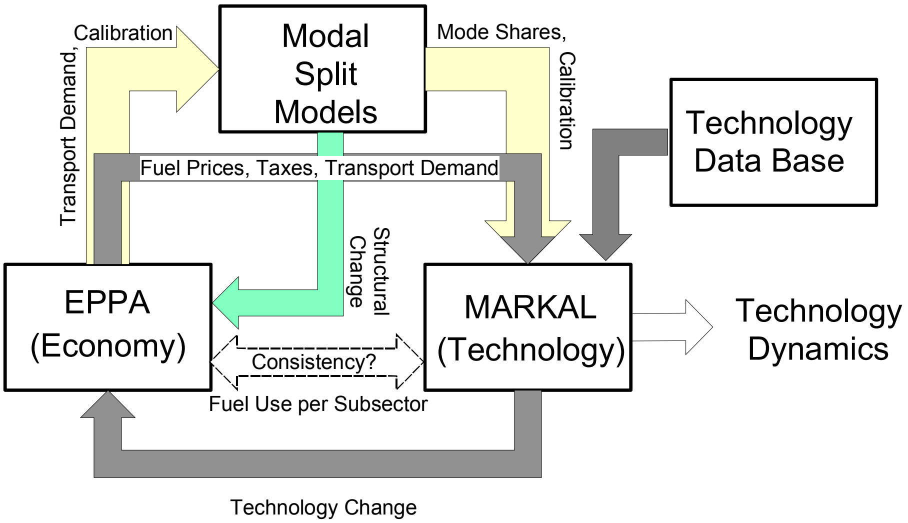


Figure 1 Linked models, consisting of the Emission Prediction and Policy Analysis (EPPA) model, the modal split models of passenger and freight transport, and the systems-engineering MARKAL model.

EPPA (Economy)

As mentioned earlier, EPPA is a dynamic CGE (computable general equilibrium) economic model. EPPA simulates the world economy with the objective of producing scenarios of greenhouse gases and their precursors, emitted as a result of human activity (Babiker, Reilly et al. 2001). These estimates within the model are done on the basis of multiple economic relationships (so called production functions), which are included in the model. The production functions for each sector describe how labour, capital and energy are used to produce outputs at best. The model uses data on population and labour intensity (with appropriate growth rates) as well as amount of fossil energy resources, to generate demands for selected types of goods (4 energy type and 5 non-energy type). EPPA however does not contain an explicit transportation section which could be used for the objectives of the project. Transportation is expressed as a set of elasticities of substitution. The diagram below illustrates in a general way the setting of transportation within EPPA (Figure 2).

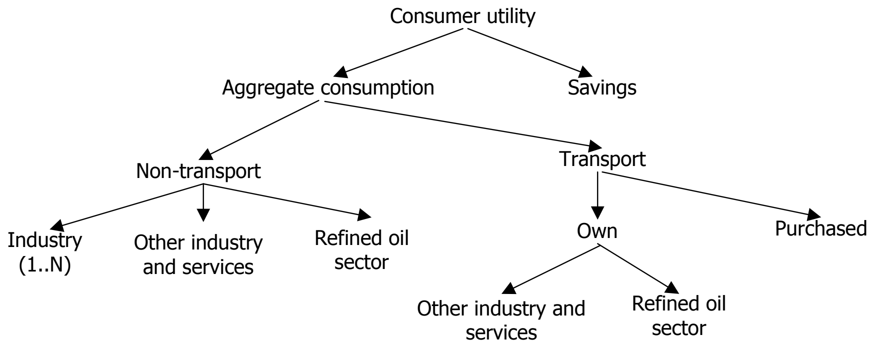
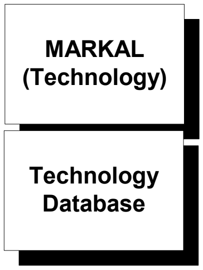


Figure 2 Structure of transportation within EPPA – household sector (Schafer and Jacoby 2003)



MARKAL (**MARK**et **AL**location) is a bottom-up, dynamic linear optimisation model (Fishbone and Abilock 1981) (Kypreos 1996). MARKAL allocates shares of technologies, which shall satisfy the demand imposed by EPPA. MARKAL in the process is aided by a technology database, which supplies to the model specification of technologies which shall be take into the optimisation.

The technological database contains detailed description of various transportation technologies. Elements of the database have been presented in further parts of this report (Table 2, Table 3 and Table 8).

Finally, in order to define the link between EPPA and MARKAL with Learning-by-Doing the following steps needed to be carried out: firstly a set of technologies which shall undergo the learning process was selected. Secondly, a series of optimisation runs with MARKAL was conducted with the aim of estimating the capital to energy substitution, based on different fuel prices. Lastly, a fitting of the obtained values was conducted to find the elasticity value.

2.2. Formulation of Endogenous Technological Learning (ETL) in MARKAL

A learning, or experience, curve shows how experience improves performance in a given activity. Thus, a generic learning curve relates a certain performance index to a quantity measuring cumulated experience (Wright 1936) (Robinson 1980). The most common specification (and the one applied here), describes the specific investment cost of a given technology as a function of the cumulative capacity, which is used as a proxy for the cumulated knowledge. The curve reflects the fact that some technologies may experience declining costs as a result of increasing adoption into the society, due to the accumulation of knowledge by, among others, learning-by-doing, learning-by-using, learning-by interacting processes and learning-by-searching (known as research & development).

The customary form to express an experience curve is using an exponential regression is presented below EQ. 1 (Argote and Epple 1990):

$$SC(C) = a \cdot CC^{-b} \qquad \text{EQ. 1}$$

Where:

SC: Specific cost (e.g. US$/kW for electricity generation technologies)

CC: Cumulative capacity

b: Learning index

a: Specific cost of the first unit

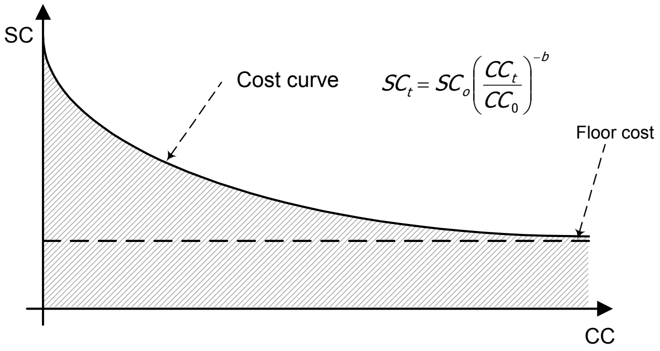


Figure 3 Graphical illustration of learning curve

The learning index *b* defines the effectiveness with which the learning process takes place.

It constitutes one of the key parameters in the expression above. Usually, for simplicity its value is not given but the progress ratio (or the learning rate) is specified instead. The progress ratio (*pr*) is the rate at which the cost declines each time the cumulative production doubles. For instance, a progress ratio of 80% implies that the costs are reduced to 80% when the cumulative capacity is doubled. The relation between the progress ratio and the learning index can be expressed as presented in EQ. 2.

$$pr = 2^{-b} \qquad \text{EQ. 2}$$

An alternative is to specify the learning rate (lr) defined as presented in
EQ. **3**.

$$lr = 1 - pr \qquad \text{EQ. 3}$$

The parameter *a* may be computed using one given point of the curve (usually the starting point SC0, C0 is specified) as presented in EQ. 4.

$$a = \frac{SC_0}{(C_0)^{-b}} \qquad \text{EQ. 4}$$

The curve is very sensitive to the progress ratio specified and to the starting point (SC_0,$C_{k,0}$). The future progress ratio of a given technology can be uncertain. Also, the definition of the starting point may pose difficulties for future, or currently in the pre-commercial stage, technologies for which data concerning actual cumulative capacity or costs may not be available or reliable.

As an illustration of the sensitivity to its defining parameters, Figure 4 presents a hypothetical learning curve with different values of the progress ratio (0.81, 0.85, 0.90) but a common starting point ($SC_{k,0}$=5000 US$/kW, $C_{k,0}$ = 0.5 GW). An additional curve with pr=0.85 but a different starting point ($SC_{k,0}$=5000 US$/kW, $C_{k,0}$=2 GW) is also presented in this figure.

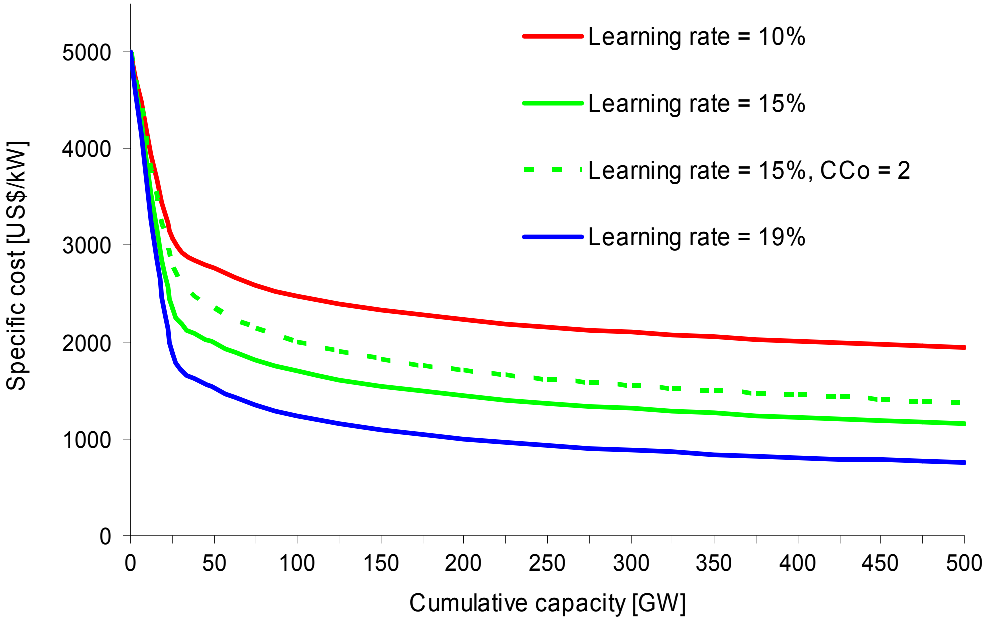


Figure 4 Learning curves for different progress ratios

The linear form in the logarithmic scale should not drive to the interpretation that ever decreasing costs can be expected. In fact, with each consecutive cumulative capacity doubling, the absolute cost reduction obtained is smaller than in the previous one. In addition, every new capacity doubling is more difficult to obtain over time - this means that eventually a high level of penetration is needed to double the capacity. Therefore, one may notice that as the cumulative capacity grows, the specific cost tends to a "boundary" value, below which it shall not fall. This value, referred to as the "floor cost", reflects the cost which the specialists believe to be a pragmatic expectation of the actual costs of a given technology at the time (and capacity installed) it reached its full maturity. Graphical illustration of the learning curve as presented above (Figure 3) indicates the discussed floor cost level.

The implementation of endogenous technological learning in the MARKAL model has been carried out by Barreto (Barreto 2001) using the Mixed Integer Programming (MIP) technique. MIP approach allows linearization of otherwise non-linear, non-convex problems.

2.3. Learning Curves for Innovative Transportation Technology

For commercial technologies such as wind turbines or gas turbines and photovoltaics it is usually possible to extract learning curves from historical data. It is, however, very difficult to make estimations of cost trends for technologies which are at the edge of market introduction such as fuel cell applications in the transport sector. Mostly only researchers working for private companies have estimates on expected cost reductions due to research and development. These companies and research centres are very reluctant to disclose cost data, since those might allow drawing conclusions on company strategies.

An example of such data for innovative powertrain technologies is displayed in Figure 5 (Cisternino 2002). They correspond to the sum of target cost for each of the fuel cell powertrain components such as reformer, processor and fuel cell stack.

Figure 5 also shows the price evolution of the mass produced internal combustion engines powertrain baseline technology, which price increases from € 2,000 in 1995 to € 2,500 in 2025. It can be assumed that the cost for this baseline powertrain could be an indicative floor cost for the innovative technologies which undergo the LBD cost reduction. One should therefore understand by this, that the alternative technology, which undergoes "learning" costs reduction, once introduced on the market starts with a price of the powertrain higher then the one of the conventional technologies. As the popularity of the alternative technology grows, the price of the alternative powertrain decreases as function of market penetration. The price of the alternative powertrain reduces from the base price, until it reaches a competitive level to the conventional powertrain (the floor cost of the alternative powertrain). As the definite lower bound of the costs reduction may not be precisely estimated at the current level of knowledge, an assumption is made how far the alternative powertrain cost can be reduced. Therefore, the price of conventional powertrain indicates what could or should be the floor cost for the "learning" technologies, as at this level, if the floor costs is at the level of conventional technologies, it is possible for the "learning" technologies to be competitive in terms of costs. This however does not take into consideration fuel price and customer preferences, which could consider other factors (for example prestige image of new technology or environmental considerations) for deciding which technological option to purchase.

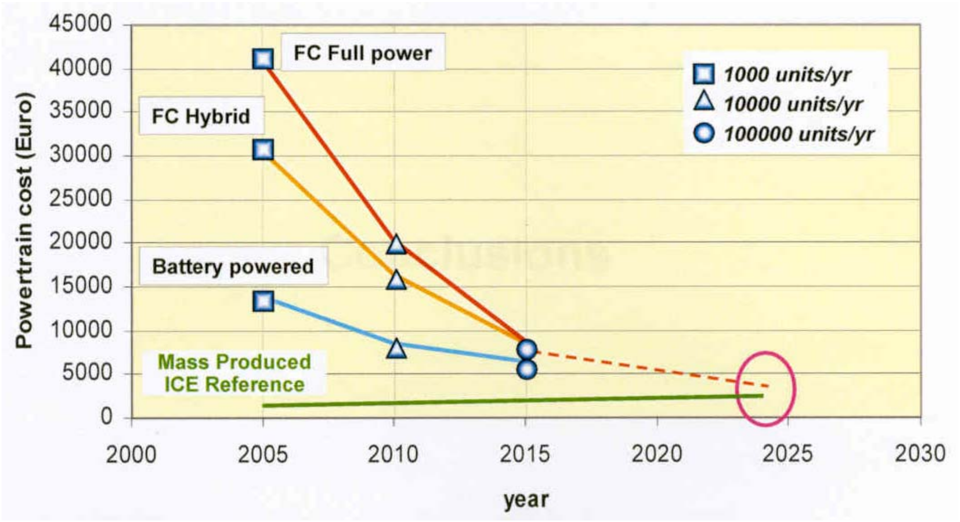


Figure 5 Projected cost reduction for innovative powertrain technologies. Full power fuel cell (FC) and internal combustion engine (ICE) powertrains have 40 kW power. The hybrid fuel cell configuration has 20 kW continuous from the FC and 20 kW peak from a battery pack, and the battery powered has 40 kW peak power with 18 kWh storage capacity (Cisternino 2002).

Figure 6 shows the learning curve (cost vs. cumulative capacity) extracted from the data by Fiat in a log-log presentation in order to determine the progress ratio and the initial investment costs. Both parameters are listed in Table 1. The initial investment costs are taken from Figure 5 and correspond to the ones at 1000 produced units per year, which seems to be lowest realistic number for mass production of powertrains. With help of the fit in Figure 6, the initial investment cost for even lower production numbers could be extrapolated.

For implementation of these innovative car technologies into MARKAL, also the fuel efficiencies are needed. Dietrich (Dietrich 2002) suggests using fuel efficiencies based on the GM/Bölkow Study (L-B-Systemtechnik 2002), as presented below (Table 2). These efficiencies correspond to a baseline car of 91 kW power, which is more than a factor of two larger than the reference powertrain presented in Figure 5. There is no data on the efficiency of the electric vehicle in the GM/Bölkow study (L-B-Systemtechnik 2002). Therefore, as an alternative for the analysis, efficiency characteristics for the electric car were taken from other sources (Weiss, Heywood et al. 2000) as 0.508 MJ/km in the time frame 2020.

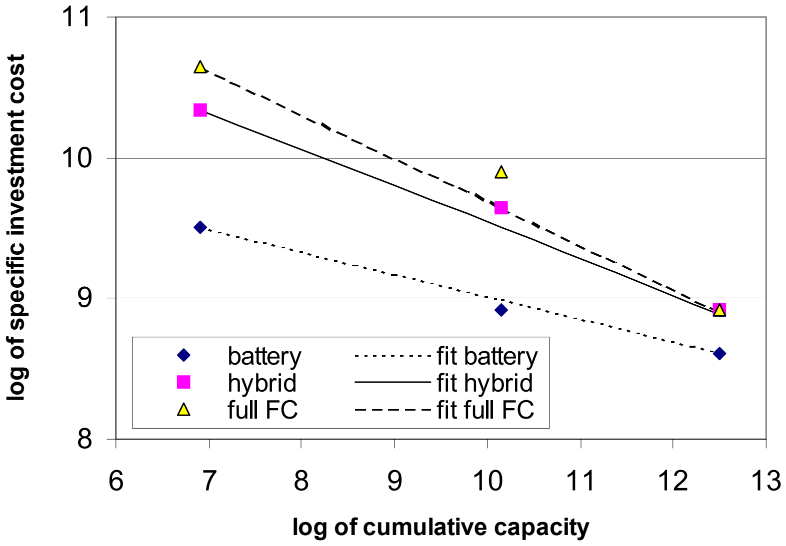


Figure 6 Learning curve of Figure 5 in the log-log representation in order to determine the progress ratios

Table 1 Estimated learning parameters for 40 kW powertrains (Cisternino 2002)

	Learning rate	initial cost at 1000 units/year (€ per powertrain)
Battery powered	10%	13,500
FC hybrid	16%	31,000
FC full power	19%	42,000

Table 2 Tank-to-wheel energy requirements for fuel cell vehicles (time frame of 2010) for reference car: Opel Zafira minivan 1.8L (gasoline), 91 kW (L-B-Systemtechnik 2002)

Vehicle type	Lower bound	Best estimate	Upper bound
	[MJ/vehicle km]		
Compressed H_2 Fuel Cell Personal Vehicle (CH2FC-PV)	1.07	1.14	1.23
Compressed H_2 Fuel Cell Hybrid-electric Personal Vehicle (CH2FCHE-PV)	1.02	1.05	1.14
Liquid H_2 Fuel Cell Personal Vehicle (LH2FC-PV)	1.05	1.12	1.21
Liquid H_2 Fuel Cell Hybrid-electric Personal Vehicle (LH2FCHE-PV)	1.00	1.03	1.12

Apart from the fuel cell technology, Dietrich (Dietrich 2002) expects a significant progress for mobile electric motors and the supplementary battery packs, which so far are still too heavy and too expensive; it is mainly the big electric motor manufacturers such as General Electric, Siemens, ABB which develop these devices, and not the automobile industry itself. The electric motor and the accompanying battery pack are assumed to be the key learning technology for all three (cluster) technologies displayed in Figure 6.

2.4. Suggested Database of Future Cars for the Present Study

The suggested database of personal vehicle technologies contains all the relevant technological characteristics essential for model runs. Table 3 displays the investment cost as well as the efficiencies for car technologies (Austin, Dulla et al. 1999), updated by A. Schäfer and made available to PSI for this study.

The investment costs[3] are calculated according to the presented formulas (EQ. 5 and EQ. 6).

$$IC = \frac{RP}{PK} \qquad \text{EQ. 5}$$

Where:

IC	Investment costs [US$ / p-km]
RP	Retail price of a vehicle [US$]
PK	Annual mileage of a vehicle [p-km]

$$PK = \frac{AM}{LF} \qquad \text{EQ. 6}$$

Where:

PK	Annual mileage of a vehicle [p-km]
AM	Average annual travel of a vehicle (~17,500 km) [km]
LF	Load factor (1.6)

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[3] [$/(1000 p-km/year)]

Table 3 Suggested data for car technologies (investment cost and efficiencies)

Vehicle category	Vehicle name	Retail prices	Investment costs	Efficiency
		[US$'95/vehicle]	[US$'95/1000p-km/year]	[p-km/MJ]
Personal Vehicle	Baseline Personal Vehicle	17,733	651	0.468
	Baseline Personal Vehicle with Light Chassis	17,951	659	0.533
	Baseline Personal Vehicle with Light Chassis and Cylinder Cut Out	18,523	680	0.601
	Baseline Personal Vehicle with Light Chassis and Hybrid-electric Powertrain	19,667	722	0.689
	Baseline Personal Vehicle (with LBD)***	21,737	798	0.876

*** The described vehicle has a hybrid (electric and conventional gasoline powertrain hybrid similar to Toyota Prius) powertrain[4]. The "learning" part of the costs is related to the costs of the powertrain. A. Schäfer estimates that the hybrid vehicle shall be US$ 2,760 (price of the extra powertrain) more expensive as compared to the Baseline Personal Vehicle. Hence the extra investment costs amount to US$ 101 per 1000 p-km/year.

Cost reduction due to learning is applied only on the second member of this sum, i.e. the hybrid powertrain. Moreover, it is assumed that the cost regression can not drop below a certain minimum value, the so called floor cost. In the present case, we arbitrarily assumed a floor cost of half the initial investment cost ($ 24.7 per kW) thus amounting to 12.35 $/kW. Similarly, since no experience values are available, the progress ratio in this run was set to 0.9 (see Table 1). The diagram below provides a graphical visualisation of the costs summation (Figure 7).

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[4] The vehicle is equipped with a conventional gasoline engine (a technology which has been mature for many years now) and an additional kinetic energy recovery system combined with an electrical motor. According to car manufacturers, the additional propulsion system has a lot of potential to be further improved in terms of economic (reduction of the additional powertrain system costs) as well as the technological performance (increase in the energy storage capacity in the batteries and reduction of size and mass of electric energy storage). Therefore, this type of vehicle has been chosen as an illustrative example for the learning technologies, in which the conventional gasoline engine technology maintains its performance and price, while the additional propulsion system is subject to costs reduction due to the learning mechanism. The learning rate for the additional powertrain has been assumed at 10%.

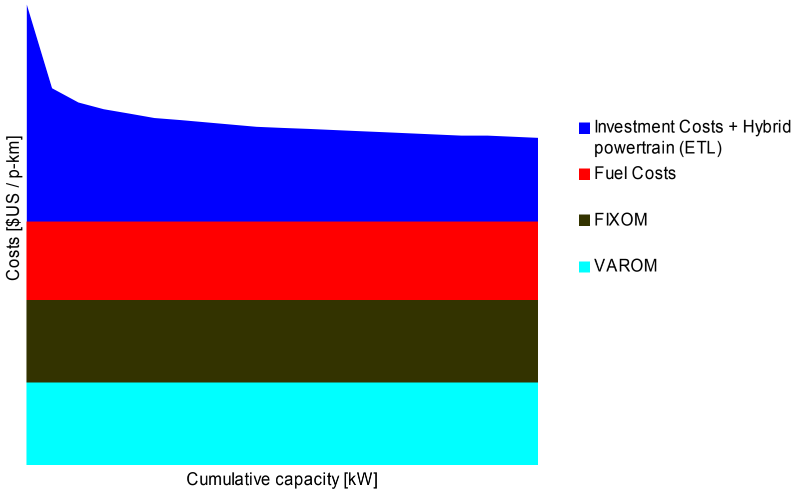

Figure 7 Suggestive graphical illustration of summation of costs (with ETL part)

2.5. Clustering for learning technologies

It has been observed that technologies which have similar or complementary characteristics co-evolve and cross enhance each other, conforming so called clusters (Gritsevskyi and Nakicenovic 2000). Technologies which belong to the cluster may benefit from learning spill-overs from other members of the cluster. Following previous efforts (Seebregts, Bos et al. 2000) (Gritsevskyi and Nakicenovic 2000) the feature of clustering has been applied in this analysis.

In this exercise, a clustering effect has been assumed for Personal Vehicles and Light Duty Trucks (both with gasoline-electric hybrid powertrains). As the powertrain component of the Personal Vehicle develops, the powertrain learning component of the Light Duty Truck also benefits (and vice-versa). The clustering value has been calculated according to the following approach.

The clustering factor has been assumed to be estimated on the basis of the power output of the hybrid powertrains expressed in kW for both classes of vehicles. According to available data, an average Personal Vehicle has power output of 154.7 PS (115.4 kW) and an average Light Duty Truck has 175.1 PS (130.6 kW) (Austin, Dulla et al. 1999). To obtain the cluster value for each car type it is necessary to divide the engine power by the number of passenger-km per year (28,200), as the demand for transportation using the mentioned technologies (hence market penetration of mentioned technologies) is expressed in passenger-km. This approach allows a link between the power output of hybrid powertrains with the market demand/supply. Table 4 lists the average engine power according to the Sierra study for both, Personal Vehicles and Light Duty Trucks. The resulting cluster values are 4.09 and 4.63, respectively. Further, dividing the investment cost in model units for the Personal Vehicle (101 $/k p-km/year) by the cluster value of 4.09 yields specific investment cost of 24.7 $/kW; a similar calculation was done also for the Light Duty Truck (EQ. 7 and EQ. 8).

$$\mathrm{CCAP}_{kc,t} = \sum_{te,kc} \mathrm{CLF}_{te,t} * \mathrm{CCAP}_{te,t} \qquad \text{EQ. 7}$$

Where:

$\mathrm{CLF}_{te,t}$ Technology specific clustering factor

hence:

$$\mathrm{CCAP}_{kc,t} = 4.09 * \mathrm{CCAP}_{t,\text{Personal Vehicle}} + 4.63 * \mathrm{CCAP}_{t,\text{Light Duty Truck}} \qquad \text{EQ. 8}$$

Table 4 Power scaling factors and cluster values for Personal Vehicles and Light Duty Trucks (Austin, Dulla et al. 1999)

Vehicle category	Average power		Cluster factor (CLF)	Specific investment cost for hybrid	Additional cost for hybrid powertrain	Additional cost for hybrid powertrain
	[PS]	[kW]	[kW/(k p-km/year)]	[US$'95/kW]	[annualised US$'95/1000 p-km]	[US$'95]
Personal Vehicle	154.7	115.4	4.09	24.7	101	2,760
Light Duty Truck	175.1	130.6	4.63	24.7[5]	114	3,110

2.6. Market penetration and maximum cumulative capacity for learning

The initially installed capacity and the maximum cumulative capacity are two more learning parameters which have to be specified in the model. In the present case, capacity refers to the amount of horse power (or kW) of hybrid powertrain engines. The initially installed capacity is proportional to the present number of hybrid cars on the US roads. For 2005, the initially installed capacity was estimated to 10,000 units. For the maximum cumulative capacity a value of 10 million cars by 2030 has been assumed, which corresponds approximately to a sales number for hybrid cars of one million in the year 2030. Compared to

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[5] Today the hybrid powertrains are mainly used in personal vehicles, however in long time perspective, one may expect that the light duty trucks may also be equipped with such powertrains. Therefore, the assumption presented here is that light duty trucks are also powered by hybrid powertrains, with the costs per kW at the same level as for personal vehicles. As the light duty trucks have a higher power output than personal vehicles, the total price of the powertrain shall be higher than for the personal vehicles.

actual total annual sales number of approximately 12 to 14 million cars, this number amounts to a market share of less than 10% in the year 2030.

In order to set the upper bounds for the market penetration of the hybrid car as well as to estimate the maximal cumulative capacity, a simple logistic model was applied. In this model, the maximum market share (as a function of time) is characterized as presented in EQ. 9.

$$S = K/(1+e^{(-b(t-dt))}) \qquad \text{EQ. 9}$$

Where:

S	Market share
K	Market potential,
b	Fitting parameter,
dt	Time corresponding to the inflexion point of the S-shaped curve.

The newly installed hybrid capacity (Figure 9) is obtained by multiplying the number of cars sold by the cluster factor and by the number of person-km/year. Correspondingly, the initial capacity amounts to 1.15 GW. The maximum cumulative capacity is obtained by integrating the newly installed capacity over the whole time period (2005 to 2030) and amounts to 1,086 GW.

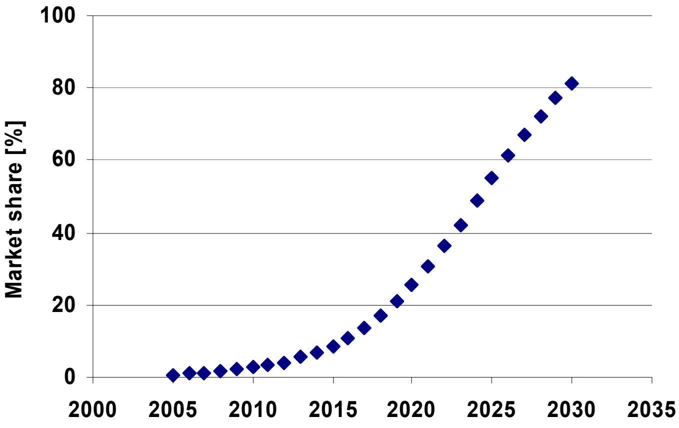

Figure 8 Market penetration of hybrid cars, as percentage of total market potential

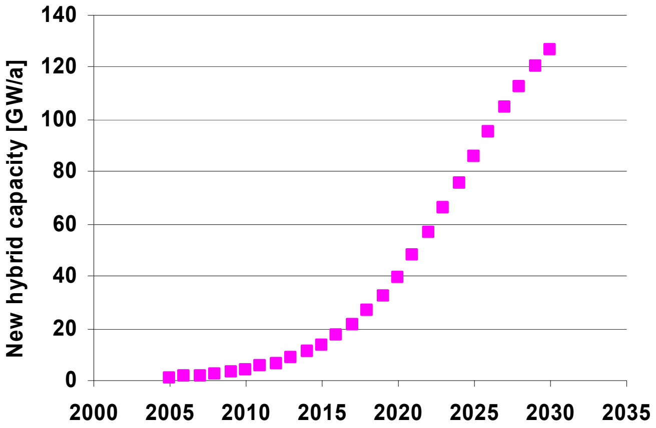

Figure 9 Market penetration of hybrid cars, as newly installed capacity

2.7. Summary of the learning parameters used in the model

After determining the specific investment cost per kW of hybrid powertrain as well as the initial and maximum capacities, a summary of the learning parameters are presented (Table 5). As mentioned earlier, assumptions are made regarding the floor cost (which is assumed to be a half of initial specific investment cost) and the progress ratio (0.9), which seem to be a plausible estimated guess. It is worthwhile to note, the value for the progress ratio (defined in Chapter 2.2) for the runs has been set to 0.9.

Table 5 ETL parameters for hybrid powertrain

Parameter	Value	Units
Initial investment cost	24.7	$/kW
Floor cost	12.35	$/kW
Progress ratio	0.9	n.a.
Initial capacity	1.15	GW
Maximal cumulative capacity	1086	GW

2.8. Model runs for first iteration

The MARKAL model was run for different fuel prices. Each run corresponds to a constant gasoline price over the whole time frame, i.e. in the run "9.9 $/GJ" the gasoline price was 9.9 $/GJ between 1995 and 2030. The fuel prices were incremented from one run to another in such a way that for each price increment a different portfolio of car technologies was introduced into the market, i.e. the fleet composition was distinct. The evolution of both, cars and light duty trucks, was observed simultaneously.

Assuming the fuel price of 0.9 USD/GJ, 100% of the market is taken over by the Baseline Personal Vehicle. Changes in fuel price show a variation in the market penetration of different technologies. Figure 10 through Figure 12 show the evolution of the car fleet as function of gasoline prices. Note that in the case of Personal Vehicles, the installed capacity is expressed as passenger-km/year. For a given year, the five bars correspond to gasoline prices of 0.9, 9.9, 30 and 55 $/GJ. The last highest price do not have anything to do with the real world but they are employed to "probe" the set of technologies with respect to the elasticity of substitution. Clearly, for the lowest fuel price, the whole car fleet is composed of baseline cars (least efficient cars) up to the year 2030. For medium fuel prices (close to reality), we observe the improved packaging car technology entering the market in 2005 and reaching almost 100% market share in 2030. For an excessively high fuel price, the more efficient technologies enter the market. The market share of hybrid car in the year 2030 is only in the percentage range due to the upper bound on capacity. In fact, since the total capacity of the hybrid technology is limited by upper bounds, this capacity has to be allocated in an optimal fashion between cars and light duty trucks by the MARKAL model. What is not shown here is that the hybrid light duty truck enters the market at a lower gasoline price than the hybrid car, and reaches an accordingly larger market share.

Figure 13 presents a summary of the runs for various fuel prices.

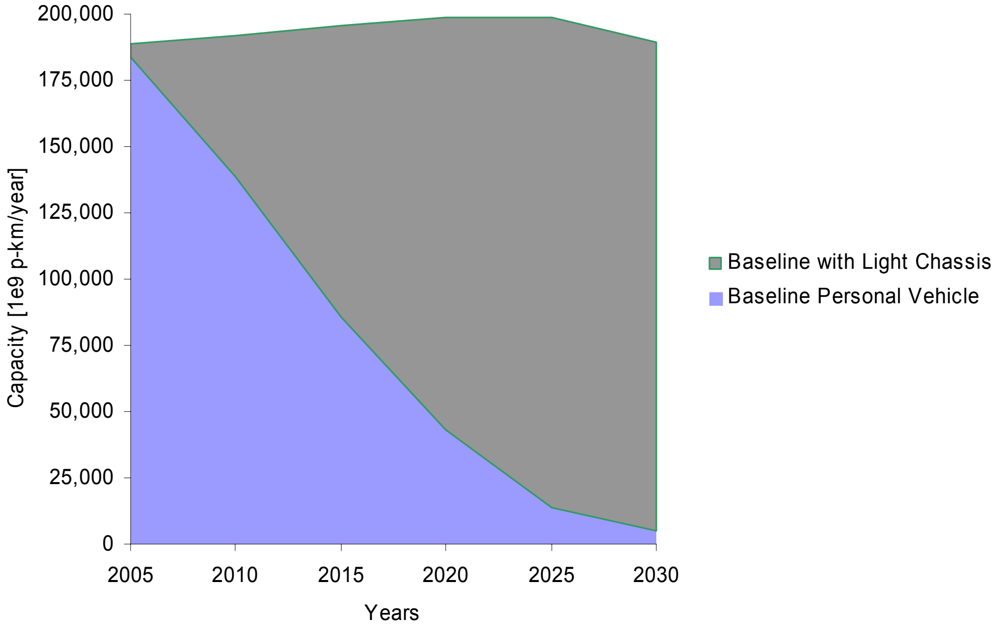

Figure 10 Car fleet composition (portfolio) as a function of time (gasoline price of 9.9 [$/GJ])

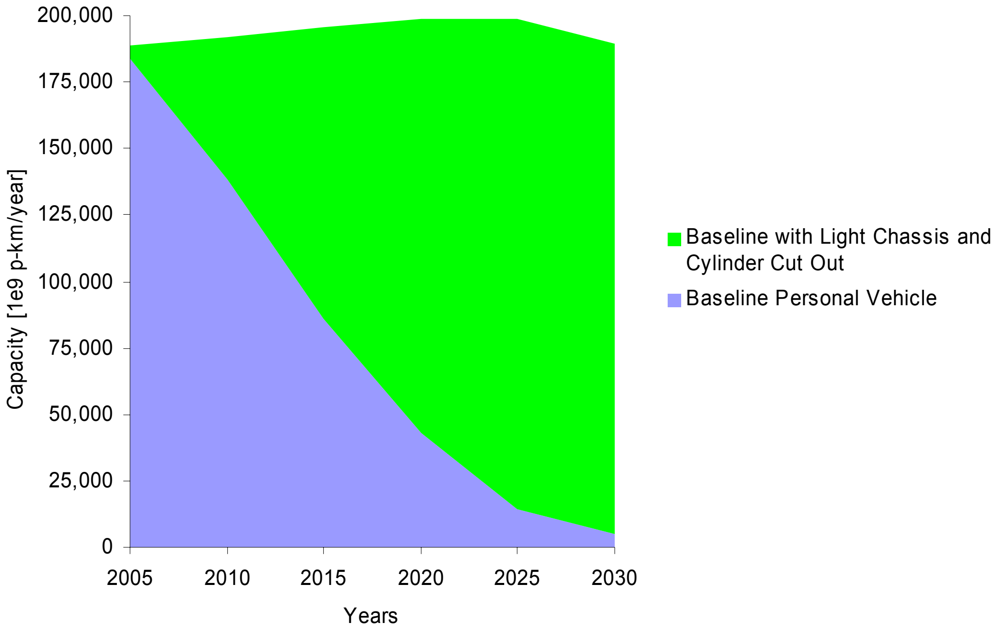

Figure 11 Car fleet composition (portfolio) as a function of time (gasoline price of 30 [$/GJ])

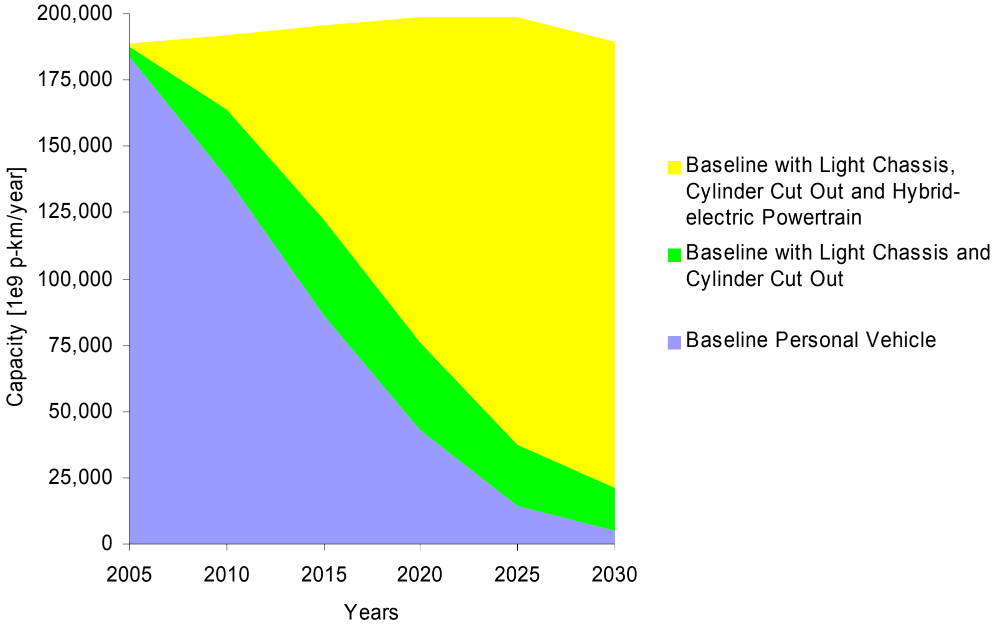

Figure 12 Car fleet composition (portfolio) as a function of time (gasoline price of 55 [$/GJ])

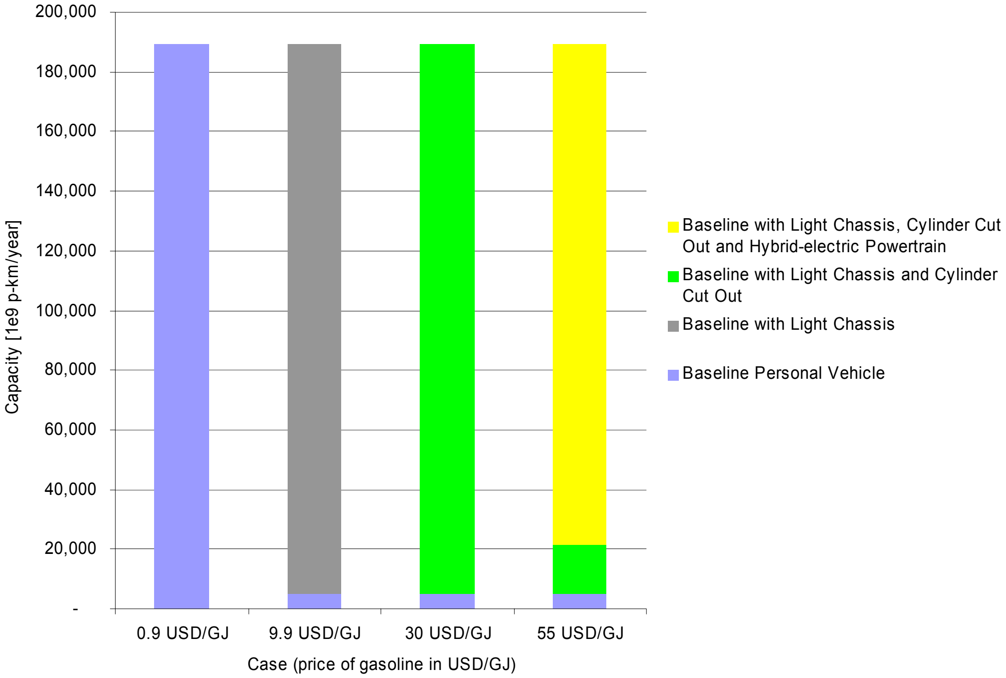

Figure 13 Car fleet composition (portfolio) for various gasoline prices by 2030

2.9. Time dependent elasticities of substitution

In order to achieve a reasonably consistent coupling between the general-equilibrium EPPA model and the energy-system MARKAL model, it is necessary to define the substitution possibilities between energy and capital in the EPPA model such that they are consistent with the representation of transportation technologies specified in the MARKAL model. This implies, among others, changing the assumption that the elasticity of substitution between energy and capital is constant over time. For such purpose, the elasticity of substitution between energy and capital is estimated with the MARKAL model for different periods of time. The resulting time profile of the elasticity is fitted by a logistic function from which a Constant Elasticity of Substitution (CES) function is approximated. The procedure used here follows the methodology outlined by Schafer and Jacoby (2003), where a more detailed explanation can be found.

For producing the elasticities of substitution between capital and energy, the energy intensity (MJ/p-km) and the levelised costs ($/p-km) are needed for a given year. These can be calculated by dividing the fuel consumption respectively, the annualized resource and technology costs, by the demand for person km. The demand for person km, an exogenous parameter in the Markal model, is displayed in Figure 14 for Personal Vehicles and Light Duty Trucks. While the transport services in the Personal Vehicle mode are almost constant in the time frame 1995 to 2030, the shares of demand for transportation satisfied by Light Duty Trucks are almost tripling in the same period.

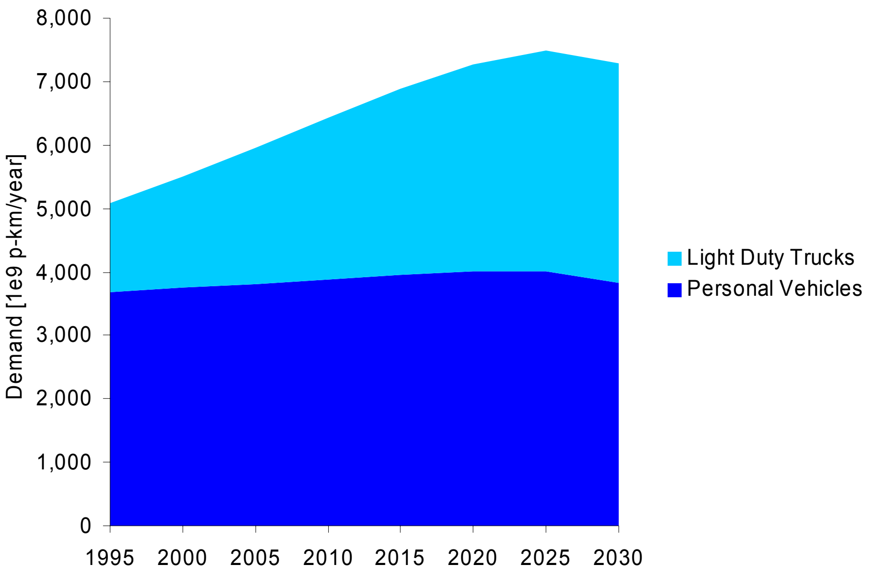

Figure 14 Demand for transportation as a function of time and vehicle class produced by the EPPA model used as input into the Markal model.

Table 6 and Table 7 display the results for the energy intensity and levelised costs, respectively. For very low gasoline prices (0.9 $/GJ) the energy intensity is increasing (as a function of time) since there is no incentive to invest into more efficient technology. At high fuel costs (990 $/GJ), however, the energy intensity decreases by more than 25% due to substitution between capital and energy.

As shown in Table 7 the levelised costs increase slightly (+3.5%) also in the cheap gasoline scenario (0.9 $/GJ) mainly due to the shift from car transportation to the mode of light duty trucks and the subsequent increase in capital intensity. This increase, however, is much more pronounced in the high price scenario where the levelised costs increase from 0.255 to 0.284 $/p-km by more than 11%.

Table 6 Energy intensity (MJ/p-km) as a function of time and gasoline price

Fuel price		Years							
[$/l]	**[$/GJ]**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
0.03	0.9	2.39	2.4	2.43	2.46	2.48	2.5	2.51	2.52
0.09	2.9	2.39	2.4	2.43	2.46	2.48	2.5	2.51	2.52
0.15	4.9	2.39	2.4	2.43	2.42	2.41	2.41	2.42	2.42
0.30	9.9	2.39	2.4	2.42	2.38	2.33	2.3	2.29	2.29
0.92	30	2.39	2.4	2.4	2.23	2.02	1.89	1.84	1.82
1.68	55	2.39	2.4	2.4	2.21	1.97	1.82	1.74	1.72

Table 7 Levelised costs ($/p-km) as a function of time and gasoline price

Fuel price		Years							
[$/l]	**[$/GJ]**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
0.03	0.9	0.255	0.257	0.259	0.26	0.262	0.263	0.263	0.264
0.09	2.9	0.255	0.257	0.259	0.26	0.262	0.263	0.263	0.264
0.15	4.9	0.255	0.257	0.259	0.261	0.262	0.263	0.264	0.264
0.30	9.9	0.255	0.257	0.259	0.261	0.263	0.264	0.265	0.266
0.92	30	0.255	0.257	0.259	0.265	0.271	0.275	0.277	0.278
1.68	55	0.255	0.257	0.259	0.266	0.274	0.279	0.282	0.284

Note that for the years 1995 and 2000 neither the energy intensity nor the levelised costs vary since the new car technologies (from Baseline Personal Vehicle with Light Chassis onwards) are not yet available. This period mainly serves for model calibration, and therefore the first two data columns of Table 6 and Table 7 are not used for determining the elasticities of substitution.

Figure 15 shows the elasticity of substitution between energy and capital. This elasticity corresponds to the relative change of levelised costs as a function of relative change in energy intensity. The relative changes are calculated for a given year (columns in Table 6 and Table 7) with respect to the lowest fuel price (in the case of 0.9 USD/GJ). For example for the year 2020 the values for the energy intensity and the levelised costs are 2.5 MJ/p-km and 0.263 $/p-km, respectively. As can be seen in Figure 15, the best fit for the year 2020 is obtained, further the elasticities of substitution can be obtained in a similar fashion for all the years of the period 2005 to 2030.

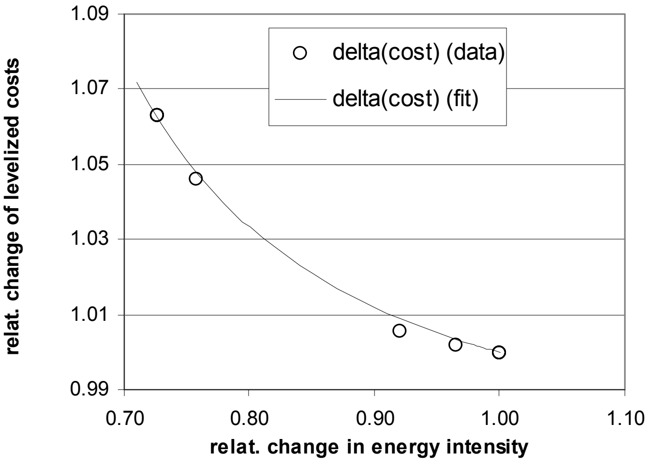

Figure 15 Fitting the elasticity of substitution for the year 2020. The dots correspond to the five values taken by the levelised costs in Table 7 (column 2020).

Repeating the above procedure for all years between 2005 and 2030 yields six elasticities of substitution which are plotted in Figure 16. Over this period, the elasticity increases and reaches a value slightly larger than 0.25. Fitting these data by a logistic curve of the form as presented in EQ. 10 yields σ_{max}=0.256, b=0.3 and dt=2013. The evolution of the elasticity of substitution is a measure of the technical progress of transportation technologies..

$$\sigma = \sigma_{max}/(1+e^{(-b\cdot(t-dt))}) \qquad \text{EQ. 10}$$

Where:

σ Elasticity of substitution (where the elasticity corresponds to the relative change of levelised costs as a function of relative change in energy intensity)

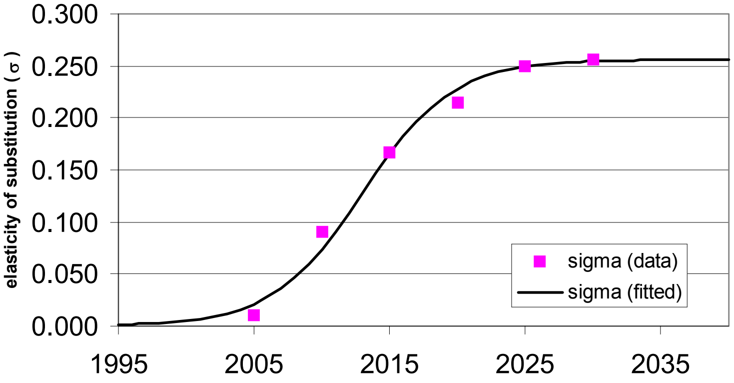

Figure 16 Temporal evolution of the elasticity of substitution capital-energy. Data obtained from the above procedure are fitted using a logistic function.

3. ALTERNATIVE APPROACH TO THE TRANPORTATION MODEL

As an alternative to the approach described in Chapter 2 above a stand alone transportation model was developed. While this model allows for the possibility to link with EPPA model, it is also useful to conduct independent analyses. In the future, a suitable combination of all these models could be foreseen.

The newly developed concept was designed to deliver results in a compatible form to those coming from the EPPA-Modal Split Model-MARKAL. A schematic description of this approach is illustrated below (Figure 17).

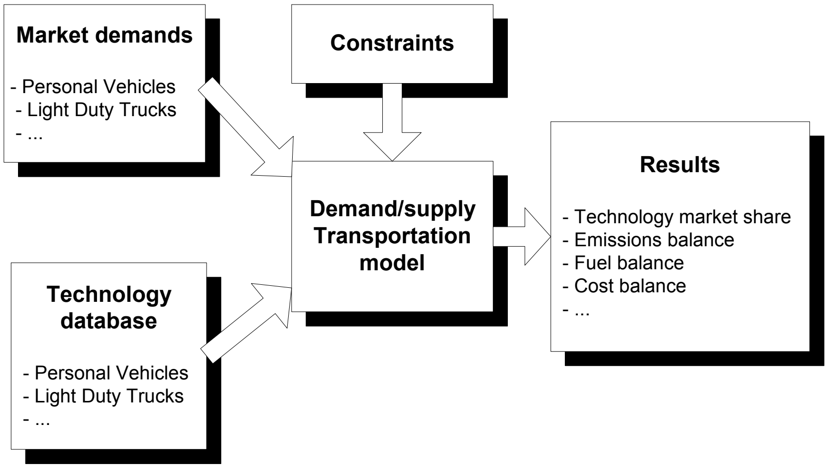

Figure 17 General schematic diagram of the transportation model

Each of the elements presented on Figure 17 shall be elaborated in the following parts of this report.

3.1. Market demand for personal transportation

The market demands considered here are overall demands for transportation, in terms of passenger kilometres ([P-km]). It is worthwhile to note that P-km's depend on the load factor of each specific mode and type of transportation technology. Appropriate load factors[6] have been taken under consideration, while the demands were calculated. In the presented work, the main focus was laid on two types of transportation: personal transportation (Personal Vehicles) and Bus Transportation.

The demand for personal transportation, which includes: Personal Vehicles (personal cars) and Buses have been calculated using the approach suggested by (Schafer and Victor 2000). This approach is based on the concept of Travel Time Budget (TTB), which indicates that world-wide, citizens spend an average, fixed amount of around 1 hour a day for commuting. This includes work-office travel, as well as vacational travel, household trips, etc. The estimated TTB includes travel by different modes of transport – ranging from bipeds, personal automobiles to public transport and airplanes. Additionally, it has been noticed that the preference of citizens to travel with specific modes of transport is dependant on the income measurement (GDP/capita). Hence, citizens of countries with high GDP/capita level tend to use faster and more expensive modes of transport (for example airplanes), while citizens from lower-income countries, with low GDP/capita, tend to use slower modes.

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[6] For passenger modes of transportation this value is usually equal to the average occupancy of Personal Vehicles of 1.6 passengers.

The above mentioned observations have been described using mathematical equations (Schafer and Victor 2000), which allow the implementation into a modelling framework. In this study, a modified version of Schafer and Victor equations was applied as to more effectively work within the modelling environment (in this exercise GAMS modelling software). In what follows, the equations used shall be presented. More information on TTB and the estimates on the dependency between preferences for mode transportation and shift to faster modes, is available elsewhere (Schafer and Victor 2000).

The overall demand for transportation, as a function of GDP/capita is defined as presented in EQ. 11.

$$TV(t) = Log\left(\frac{GDP(t)}{G} - H\right) * GDP(t)^{E*F} \qquad \text{EQ. 11}$$

Where:

TV	Overall demand for passenger transportation [passenger km]
t	Time index
GDP	GDP/capita, expressed in USD [USD'95]
G,H,E,F	constants (Schafer and Victor 2000) adopted for the GAMS code[7]

Further, out of the overall demand for transportation demands for specific modes are obtained in forms of percentage shares, which is described in the following equations (EQ. 12, EQ. 13, EQ. 14 and EQ. 15).

$$S_{Rail}(t) = I * \left(\frac{1}{(TV(t)\text{-} J)^{K}} - \frac{1}{(240000 - J)^{K}}\right) \qquad \text{EQ. 12}$$

Where:

S_{Rail}	Share of railroad transportation [%]
I,J,K	constants (Schafer and Victor 2000) adopted for the GAMS code

$$S_{HighSpeed}(t) = S * 10^{e(-T*(TV(t)-U))} + V \qquad \text{EQ. 13}$$

Where:

$S_{HighSpeed}$	Share of high speed transport (airplanes and ultra fast trains) [%]
T,U,V	constants (Schafer and Victor 2000) adopted for the GAMS code

$$S_{Bus}(t) = \frac{BK}{\left(TV(t) - TV_{Bus}(1990)\right)^{BM}} + BC \text{ - } S_{Rail}(t) \qquad \text{EQ. 14}$$

Where:

S_{Bus}	Share of bus transportation [%]
BK,BM,BC	constants (Schafer and Victor 2000) adopted for the GAMS code

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[7] Due to the precision limitations of the GAMS software, the constants were recalculated as to include the available precision rate of GAMS

$$S_{PersonalVehicle}(t) = 1 - S_{Bus}(t) - S_{Rail}(t) - S_{HighSpeed}(t) \tag{EQ. 15}$$

Where:

$S_{PersonalVehicle}$ Share of personal cars [%]

A graphical illustration of the calculated demands has been presented below (Figure 18).

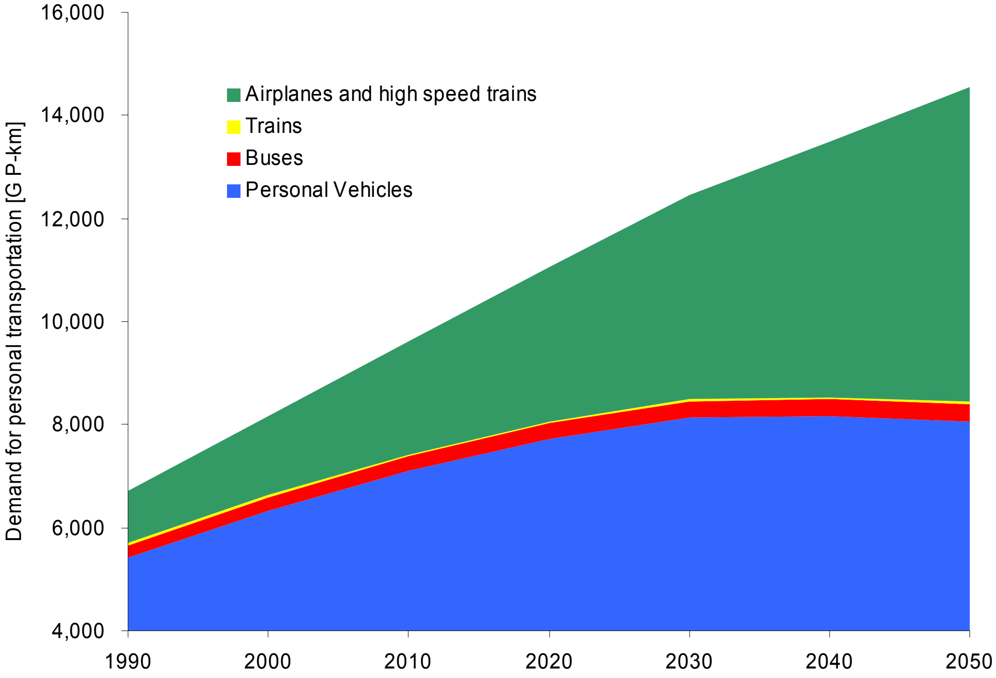

Figure 18 Graphical illustration of demand for personal transportation

3.2. Technology database

For the purpose of this illustrative analysis, we have selected two transportation modes, namely personal transportation (Personal Vehicles) and Bus Transportation. The remaining modes of transportation such as trains, SUV's or high speed transport have not been included in the modelling framework. This is due to the fact that much of the required data for the calibration of the model is unavailable or incomplete.

For each of these categories, a selection of technologies was made which shall be competing against each[8] other to satisfy the calculated market demands for given transportation modes. The selection of specific technologies which are included in the transportation model was based on the currently available technologies, which already compete on the market, as well as those which are just emerging or which are present on the market in (relatively to conventional technologies) small proportions. The predominant role for passenger transportation, when personal cars are considered, is played by conventional gasoline engine

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[8] within given types of demands for transportation

cars (currently taking over 95% of all passenger cars operating in North America). All the technologies considered have been selected also in relation to their technical potential. The cars selected were 5 seaters, with engine power in the range of 75 kW (100 PS) and weight in the range of 1300 kg.

A special role in the modelling process is played by new technologies which, as assumed, shall emerge in the near future. These are represented by the fuel cell vehicles fuelled by hydrogen and methanol (Methanol FC Vehicle and Hydrogen FC Vehicle). Primarily, an assumption has been made that the cost structure of a fuel cell vehicle is based on the price of the chassis and the additional price of a FC stack of 50kW. Therefore, the total purchase price of a FC vehicle consists of a base price for a light chassis with all onboard fuel storage facilities, control components and an electric powertrain (amounting in total to 17,500 USD) and additionally the 50kW fuel cell stack (assumed to cost 100 USD/kW at full market penetration, hence the floor cost), which brings the total cost of a FC vehicle to 22,500 USD. This price has been used following the work of others (Ogden, Williams et al. 2004), assuming that FC technologies (by the time they are available to the consumer) are already a competitive technology, able to compete with conventional technologies such as gasoline or diesel engines.

In cases which are presented further in this report, a sensitivity analysis has been conducted on the impact of different prices per 1 kW of FC stack (ranging from 100 up to 700 USD) on the market penetration of FC vehicles. The fuel cell technologies, together with the Electric Vehicle, have been selected to undergo the learning process. In the case of the FC vehicles, it is the cost of FC stack which reduces as a function of market penetration (indicated in the technology database as "Initial technological learning cost"), while for the case of the electric vehicle it is the cost of the battery pack.

As for the bus transport, the vehicles considered were also taken in such manner that they would reflect the current situation on the roads as well as the characteristics and potential of new and emerging technologies. Typical characteristics of a bus therefore project a picture of a vehicle with around 70 places for passenger capacity (in total, including around 40 sitting places), two-axle, low floor, 12 meter, with the engine power in the ranger of 150-200 kW (200-270 PS). Similarly to Personal Vehicles, a new and emerging technology has been assumed, which is a Fuel Cell bus powered by hydrogen.

Table 8 illustrates technologies and their specifications which have been used for the model.

Table 8 Transportation technology database

	Vehicle	Year of availability	Fuel type	Fuel efficiency	Initial purchase cost	Fixed costs	Variable costs	Technological Learning	Initial technological learning cost[9]
				[V-km/MJ]	[USD’95]	[USD’95/1000 v-km]			[USD’95/1000 v-km]
Personal Vehicles	Conventional gasoline	1990	Gasoline	0.3748	17,300	71.70	8.10	No	
	Advanced gasoline	2000	Gasoline	0.3946	16,500	71.70	8.10	No	
	Diesel	1990	Diesel	0.5134	18,200	71.70	8.10	No	
	Advanced diesel	2000	Diesel	0.5705	16,400	71.70	8.10	No	
	Hybrid gasoline-electric	2000	Gasoline	0.7635	20,500	71.70	8.10	No	
	Bi-fuelled gasoline-LPG	2000	Gasoline/LPG	0.4032	25,000	71.70	8.10	No	
	Bi-fuelled gasoline-CNG	2000	Gasoline/CNG	0.4032	25,000	71.70	8.10	No	
	Hydrogen fuel cell	2020	Hydrogen	1.3369	22,500[10]	26.50	8.10	Yes	588-1764[11]
	Methanol fuel cell	2020	Methanol	1.3336	22,500	26.50	8.10	Yes	588-1764
	Electric	2000	Electricity	1.7749	25,000	102.80	8.10	Yes	235
Buses	Conventional diesel	1990	Diesel	0.0450	270,000	3099.00	653.00	No	
	Advanced diesel	2000	Diesel	0.0495	270,000	3099.00	653.00	No	
	Conventional CNG	1990	CNG	0.0286	320,000	3099.00	653.00	No	
	Advanced CNG	2000	CNG	0.0323	300,000	3099.00	653.00	No	
	Hydrogen fuel cell	2010	Hydrogen	0.0856	850,000[12]	3099.00	653.00	Yes	1099-3297[13]

Note: The data presented above have been gathered from various sources (Contadini 2000; Weiss, Heywood et al. 2000; Pelkmans, De Keukeleere et al. 2001; Pridmore and Bristow 2002; Brager 2003; DaimlerChrysler 2003; Toyota 2003; Hekkert, Faaij et al. 2004; Ogden, Williams et al. 2004).

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[9] dependant on the technology this value reflects the reduction of costs related to the improvement of the powertrain and/or energy storage (in the case of the electric car – battery pack)

[10] The purchase price for fuel cell vehicles (both – fuelled by hydrogen and those fuelled by methanol) varies depending on the price of the fuel cell stack; therefore assuming the price of 1kW at 50 USD the final purchase price amounts to 20,000 USD, while assuming a higher price of 300 USD/kW this sum gets as high as 32,500 USD. In the runs different prices for fuel cells have been used, ranging from 100 up to 700 USD/kW. The final price is subject to the learning process; therefore, the initial price (for example of 32,500 USD) gets reduced as the technology penetrates the market. The learning part of the costs (in the case of fuel cell vehicles it is related to the learning process of the fuel cell stack, hence the price of 1kW of fuel cell) is included in the final purchase price, and additionally is presented in the “Technological Learning Cost” column.

[11] The initial learning costs vary depending on the price of fuel cells for a specific case study. The prices assumed have been 200, 300, 400, 500, 600 and 700 USD/kW, with a floor cost of 100 USD/kW.

[12] The purchase price, similarly to Personal Vehicles consists of the price of the chassis (assumed to be 237,500 USD/vehicle) and the price of a 250 kW fuel cell stack

[13] Price of fuel cells assumed at 200, 300, 400, 500, 600 and 700 USD/kW, with a floor cost of 100 USD/kW; the presented initial purchase cost refers to the case when the fuel cell component is at the floor cost.

3.3. Demand/supply transportation model

Having defined the demands for personal transportation (Chapter 3.1) and the technology database of market competing technologies (Chapter 3.2), a market demand/supply optimisation model (DSTM) has been created.

The demands for transportation, which are calculated outside of DSTM are fed externally to the model, similarly to applied fuel prices. The considered fuel prices are those which are available to the end user (including governmental taxes).

3.3.1. Technology cost calculation

The costs of transportation by various technologies which have been used in the model have been calculated according to the following equation (EQ. 16).

$$C_{NonETL} = \left(\frac{P_{Tech} + FIXOM_{Tech} + VAROM_{Tech}}{AM_{Tech}} + \frac{F_{Tech}}{E_{Tech}} \right) * 1000 \qquad \text{EQ. 16}$$

Where:

C_{NonETL}	Cost of travelling with a technology which does not undergo learning [USD’95/1,000 v-km]
P_{Tech}	Technology specific vehicle purchase price
AM_{Tech}	Technology specific annual mileage travelled
$FIXOM_{Tech}$	Technology specific annual fixed costs (insurance, road tax, etc.)
$VAROM_{Tech}$	Technology specific annual variable maintenance costs associated with travelling of the annual mileage (service repairs, maintenance checks, tires, etc.)
F_{Tech}	Technology specific costs of technology specific fuel
E_{Tech}	Fuel efficiency of a specific technology

The formulation of the learning part of the costs, associated with the reduction of costs as function of cumulative installed capacity has been done using the Mixed Integer Programming. The equations below illustrate this procedure (EQ. 17 through to EQ. 25), additionally a set of graphs illustrates the approach (Figure 19 and Figure 20).

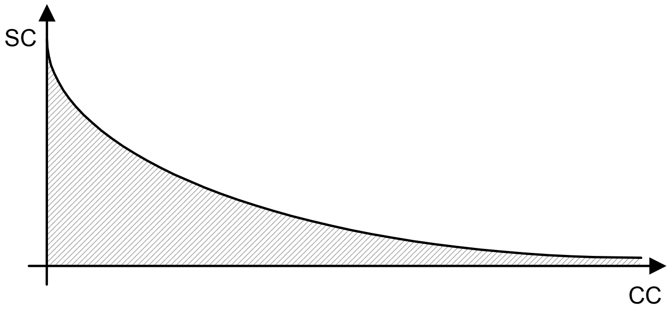

Figure 19 Representation of costs reduction according to the "learning" approach: specific cost (SC) as function of cumulative capacity (CC)

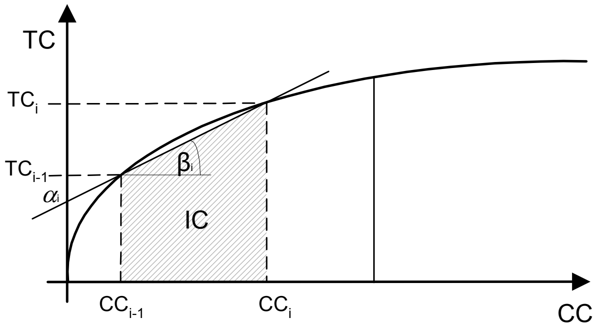

Figure 20 Representation of costs reduction according to the "learning" approach: cumulative capacity (CC) vs. total cost (TC) with indication of MIP coefficients

The cumulative capacity of a given technology tech in the period t is defined as:

$$CC_{Tech,t} = CC_{Tech,t=0} + \sum_{\tau=1}^{t} INV_{Tech,t} \qquad \text{EQ. 17}$$

Where:

$t \in \{1,......TE\}$, $t \in \{1,......T\}$ (1)

$CC_{Tech,0}$ initial cumulative capacity (the corresponding cumulative cost $TC_{te,0}$ is also defined)

$INV_{Tech,t}$ investments made on this technology in a particular period t

The cumulative capacity is expressed as a summation of continuous lambda variables.

$$CC_{Tech,t} = \sum_{i=1}^{N} \lambda_{Tech,i,t} \qquad \text{EQ. 18}$$

The cumulative cost is expressed as a linear combination of segments expressed in terms of the continuous lambda and binary delta variables:

$$TC_{Tech,t} = \sum_{i=1}^{N} \alpha_{i,Tech} * \delta_{Tech,i,t} + \beta_{i,Tech} * \lambda_{Tech,i,t} \qquad \text{EQ. 19}$$

With:

$$\beta_{i,Tech} = \frac{TC_{i,Tech} - TC_{i-1,Tech}}{CC_{i,Tech} - CC_{i-1,Tech}} \qquad \text{EQ. 20}$$

$$\alpha_{i,Tech} = TC_{i-1,Tech} - \beta_{i,Tech} CC_{i-1,Tech} \qquad \text{EQ. 21}$$

The reader should notice that, for each learning technology, one delta variable is defined for each segment of the piecewise learning curve and time period. When this segment of the learning curve becomes active, this delta variable is set to one while the delta variables associated to the other segments are set to zero.

The logical conditions to control the active segment of the cumulative curve are as follows.

$$\lambda_{Tech,i,t} \geq CC_{i,Tech} * \delta_{Tech,i,t}, \quad \lambda_{Tech,i,t} \leq CC_{i+1,Tech} * \delta_{Tech,i,t} \qquad \text{EQ. 22}$$

The sum of delta binary variables is forced to one:

$$\sum_{i=1}^{N} \delta_{Tech,\ i,t} = 1 \qquad \text{EQ. 23}$$

Using the fact that experience must grow or at least remain at the same level, additional constraints are added to the basic formulation, helping to reduce the solution time.

For t=1,.......T, te=1, ...TE, i=1,......N

$$\sum_{P=1}^{i} \delta_{Tech,P,t} \geq \sum_{P=1}^{i} \delta_{Tech,P,t+1} \quad , \quad \sum_{P=i}^{N} \delta_{Tech,P,t} \leq \sum_{P=i}^{N} \delta_{Tech,P,t+1} \tag{EQ. 24}$$

The investment cost $IC_{Tech,t}$ associated to the investments in learning technologies is computed as:

$$IC_{Tech,t} = TC_{Tech,t} - TC_{Tech,t-1} \tag{EQ. 25}$$

3.3.2. Supply/demand balance

The discounting of investment cost is included in the objective function. The following equations describe the market/supply balance and the objective function used in the model (EQ. 26, EQ. 27 and EQ. 28).

$$Demand_{Trancat,Tech,t} \leq Supply_{Trancat,Tech,t} \tag{EQ. 26}$$

Where:

$Demand_{,Trancat,Tech,t}$	Demand for a given transport category (Personal Vehicle or Bus) and technology in a given time period
$Supply_{Trancat,Tech,t}$	Supply of given transport category (Personal Vehicle or Bus) and technology in a given time period

$$Demand_{Trancat,t} \leq \sum_{ETL} ACT_{ETL,t} + \sum_{Non-ETL} ACT_{Non-ETL,t} \tag{EQ. 27}$$

Where:

$Demand_{Trancat,t}$	Demand for a given transport category [b v-km] and time period
$ACT_{ETL,t}$	Activity (market penetration) of a given "learning" technology, in a given time period
$ACT_{Non-ETL,t}$	Activity (market penetration) of a given non-"learning" technology, in a given time period

$$PVC = \sum_{t=1990}^{t=2050} \sum_{Trancat} \sum_{Tech} PV_t * \left(DISPP * ACT_{Tech,t} * \left(C_{Non-ETL} + TAX_{Tech}\right) + IC_{Tech,t}\right) \tag{EQ. 28}$$

Where:

PVC	Present value of costs, subject to minimisation by optimisation
Trancat	Transport category ("Personal Vehicle" or "Bus") index

PV	Present value factor, where $PV=1/(1+DR)^t$ and DR being the discount rate of 5%
DISPP	Discounting to Present Period factor (DISPP=7.722)
$ACT_{Tech,t}$	Activity (market penetration) of a given technology in a given time period
$C_{Non\text{-}ETL}$	Cost of travelling with a technology which does not undergo learning
TAX_{Tech}	Technology specific value of the CO_2 tax, dependant on fuel economy, fuel type and emissions rate
$IC_{Tech,t}$	Integral of costs related to the learning component of travelling by a specific technology (as described in EQ. 25)

Each development of technologies entering and already present on the market has been constrained in terms of expansion and declination. The constraints have been imposed as to more precisely describe the penetration behaviour of the selected technologies.

The fuel prices have been assumed as specified below (Table 9). Regarding hydrogen, the price has been assumed for the various sources like local and centralised steam natural gas reforming (Fergusson 2001). The prices for oil derived fuels, used in the model have been established based on the relationship between crude oil and the final price to the consumer (IFTA 2004)

Table 9 Fuel prices used in TDSM [USD'95/GJ] (Energy Information Administration 2004), (Fergusson 2001), (US Department of Energy 2003)

Fuel	Price
Hydrogen	20, 30 and 40
Gasoline	20, 30, 40, 50 and 60 USD/BBL
Diesel	
LPG	
CNG	7

3.4. Model runs for the alternative approach to the transportation model

The analysis of the development of the transportation sector is difficult to asses, mainly due to numerous factors which may have influence on the system. Preliminarily, the main objective of the study was to explore only the influence of the technological learning on market penetration of new technologies. However in the course of the analysis, it has been noticed that synergetic effects exists between other factors and technological learning, which to a significant extend contribute to market penetration of new technologies. Therefore, it has been decided to consider also other factors together with their cross-relations. The considered factors are presented below.

Technological learning – the rate at which technologies develop has potentially a strong capability to influence their market penetration. It has been assumed to consider a range of different learning rates, from very optimistic ones of 20%, to 15, 10 and least optimistic one of 5%.

Fuel cell price – analysis of costs related to fuel cell vehicles has shown that costs related to the fuel cell stack may take a considerable share of the overall costs of a fuel cell vehicle, hence influencing on the competitiveness of FC vehicles. This is dependant on the price of 1kW of FC, therefore for the cases different prices of FC have been considered in the range from 200 up to 700 USD/kW. In all cases, it has been assumed that the floor cost shall be set at 100 USD/kW.

Fuel prices – this factor influences all types of technologies, independent of the fact if they are already mature (like the internal combustion engine) or are innovative and/or not yet fully developed (like the fuel cell). Therefore, in the case of vehicles using oil based fuels, the sensitivity has been linked to the price of crude oil, for which values of 20, 30, 40, 50 and 60 USD/BBL have been assumed, and for hydrogen fuelled vehicles a price of 20, 30 and 40 USD/GJ (as earlier mentioned in Table 9).

Financial-governmental initiatives – the real-life transport sector observations indicate that changes in the sector occur not only because of market-driven initiatives (like fuel or vehicle prices) or technological improvements, but also due to governmental actions. Therefore, it has been assumed that a governmental initiative shall take place by 2010, imposing an emissions tax. The tax shall cover emissions of CO_2 originating from the transportation sector. This environmental tax shall be charged to fuel price and shall be 50, 100, 150, 200 or 250 USD/tonne of CO_2 emitted.

The following table summarises the factors used for the analysis and their values (Table 10).

Table 10 Summary of factors and their values used for the analysis of synergetic effects

Factor	Range
Learning rate (LRN)	5, 10, 15, 20%
Cost of 1kW of fuel cell stack	100, 200, 300, 400, 500, 600, 700 USD/kW
Conventional fuel price	20, 30, 40 USD/BBL
Hydrogen price	20, 30, 40 USD/GJ
CO_2 tax	0, 50, 150, 200, 250 USD/tonne CO_2

Some of the values may at first glance be seen as unrealistic (for example a CO_2 tax of 250 USD/tonne of CO_2), however the reason such values have been chosen was to illustrate the extend and the dynamics of interactions and synergies between different factors.

For the analysis of the mentioned factors an illustrative example of the hydrogen fuelled fuel cell vehicle has been used.

In the course of the analysis of the factors influencing the dynamics of market penetration by hydrogen fuelled fuel cell vehicles, it has been decided that it is worthwhile to put the results of the analysis into a practical and realistic context by means of analysing a few plausible case studies. Therefore, five cases have been designed to show in more detail the influence of application of selected factors on the market penetration of different technologies, and the illustrative example of hydrogen fuelled fuel cell vehicle in particular. The cases are briefly described below (Table 11), while their detailed results are presented in the further parts of this report (Chapter 3.4.7 through 3.4.9).

Case 1 "Base case"

In this case no CO_2 tax was imposed. Hence the system was left to optimise the market allocation based only on standard growth and decline constraints. New, alternative technologies are developing at low or moderate levels (learning rate set at 5.5%).

Case 2 – "Developer"

This case gives a higher chance to the new, alternative technologies; they develop at very dynamic rate (learning rate set at 20%).

Case 3 – "Small Taxman"

Similarly to "Base case", new, alternative technologies are developing and low or moderate level (learning rate set to 5.5%), however by 2010 a governmental initiative imposes a tax on CO_2 emissions. For every ton of CO_2 emitted a tax of 50 USD needs to be paid.

Case 4 – "Big Taxman"

Similarly to "Small taxman", a tax was imposed on CO_2 emissions by 2010. However, in this case, the tax was raised to 200 USD for every ton of carbon dioxide emitted.

Case 5 – "Green World"

This case combines the constraints of "Taxman" and "Developer" cases. In this case, the tax imposed on CO_2 emissions has been set to 100 USD for every ton of CO_2 emitted and the new, alternative technologies are developing at high rates (learning rate set to 15%).

Table 11 Summary of cases

Case		CO_2 tax [USD/tonne CO_2]	Learning rate	Oil price [USD/BBL]	H_2 price [USD/GJ]	FC price [USD/kW]	Floor cost [USD/kW]
1.	Base case	0	5.5%	30	20	500	100
2.	Developer	0	20%	30	20	500	100
3.	Small Taxman	50	5.5%	30	20	500	100
4.	Big Taxman	200	5.5%	30	20	500	100
5.	Green World	100	15%	30	20	500	100

In the following sections the synergetic effects of mentioned factors are presented. Later a few selected cases are presented and discussed in detail: the "Base case" and the one with most significant changes ("Green World"). Finally, in Chapter 3.4.9, summarised results of all the remaining cases and conclusions of synergetic effect analysis and cases are presented.

3.4.1. Fuel cell costs and learning rate influence

The first pair of factors which have been considered is composed of the learning rate and the price of the fuel cell used for the fuel cell stack as presented below (Figure 21).

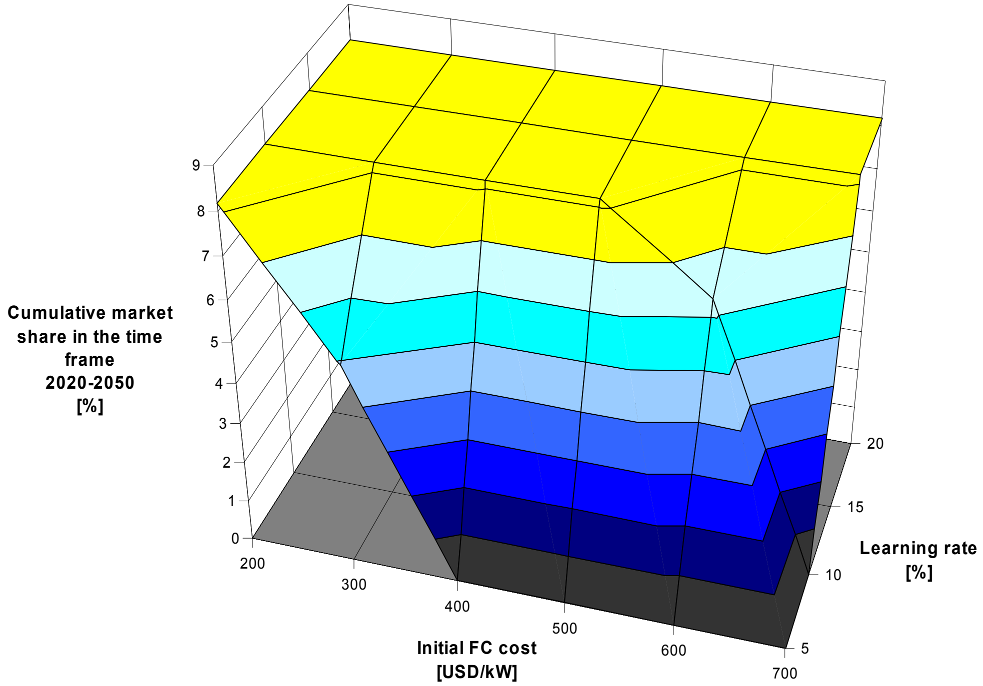

Figure 21 Influence on market penetration of hydrogen fuelled fuel cell personal vehicle as result of technological learning and price of fuel cells (Hydrogen price: 20 USD/GJ, BBL price: 30 USD)

The results of the analysis, which have been presented above, suggest that in the case of both factor a threshold values exist. In the case of technological learning one may observe that above a learning rate of 7.5% market perpetration of hydrogen fuelled fuel cell vehicles is already feasible. Looking at the price of the fuel cells, one may notice that low learning rates (lower then 7.5%) guarantee market penetration, however only if the price of the fuel cells is 300 or less USD/kW.

As mentioned earlier, the presented above analysis has been done using the assumption of the floor cost of 100 USD/kW. An interesting effect is achieved when reducing the floor cost of fuel cells to 50 USD/kW, making the fuel cell vehicle even more attractive in terms of costs reduction (Figure 22). However, one should keep in mind that this is a very optimistic assumption and should be treated as an indication and the extend of improvement of market penetration of hydrogen fuelled fuel cell vehicles in case a reduction in the floor cost would be possible.

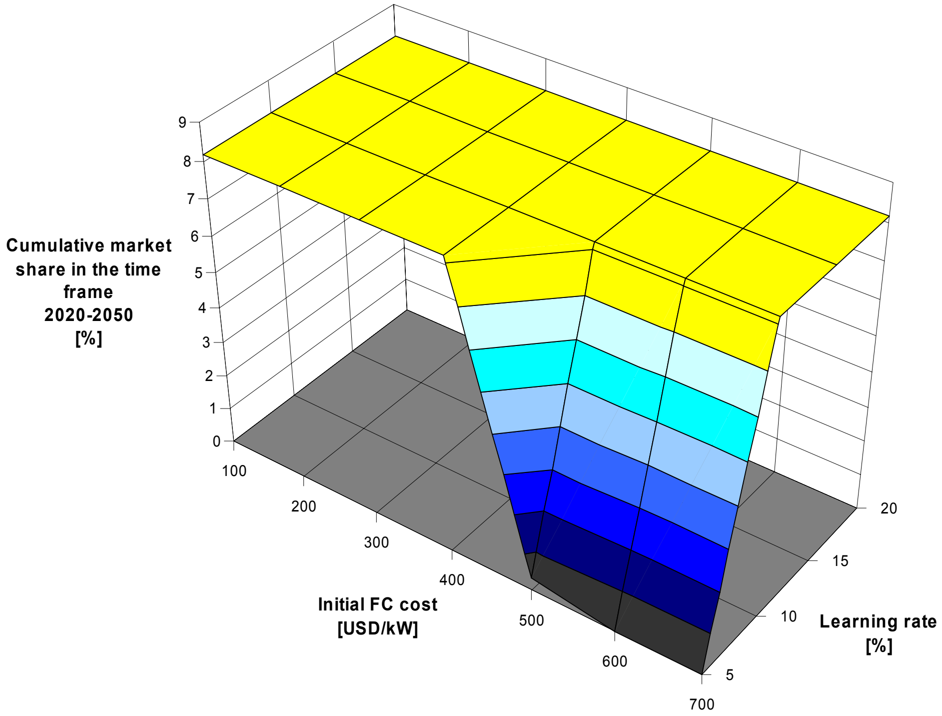

Figure 22 Influence on market penetration of hydrogen fuelled fuel cell personal vehicle as result of technological learning and price of fuel cells (alternative, optimistic case with floor cost set at 50 USD/kW) (Hydrogen price: 20 USD/GJ, BBL price: 30 USD)

Examining the graph above indicates that even at relatively high prices of fuel cells (in the range of more then 400 USD/kW[14]) market penetration of hydrogen fuelled vehicles is possible. This suggests that by lowering the floor cost from 100 to 50 USD/kW shifts the previous threshold value of 300 USD/kW to 400 USD/kW. Similarly as in the case with higher floor cost, market penetration is very sensitive to the technological learning. The analysis conducted suggests that already at least optimistic values of the learning rate of 5%, market penetration may occur. Similarly to shifting of the price threshold, here also one may observe a shift in the technological learning from 7.5% to around 5%.

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[14] The value of 400 USD/kW is in comparison to current fuel cell prices in the range of one fourth. Keeping in mind that fuel cell vehicles shall not be available in the next 5-6 years, and the current reduction of prices, one may hope that by the time fuel cell vehicles are introduced to the market, the price of the fuel cells may already be in the range as considered in this analysis.

3.4.2. Fuel cell costs and oil based fuel price influence

The second pair of factors which have been analysed in terms of influence on the penetration of hydrogen fuelled fuel cell vehicles was the price of fuel cells and price of conventional, oil based fuels (Figure 23).

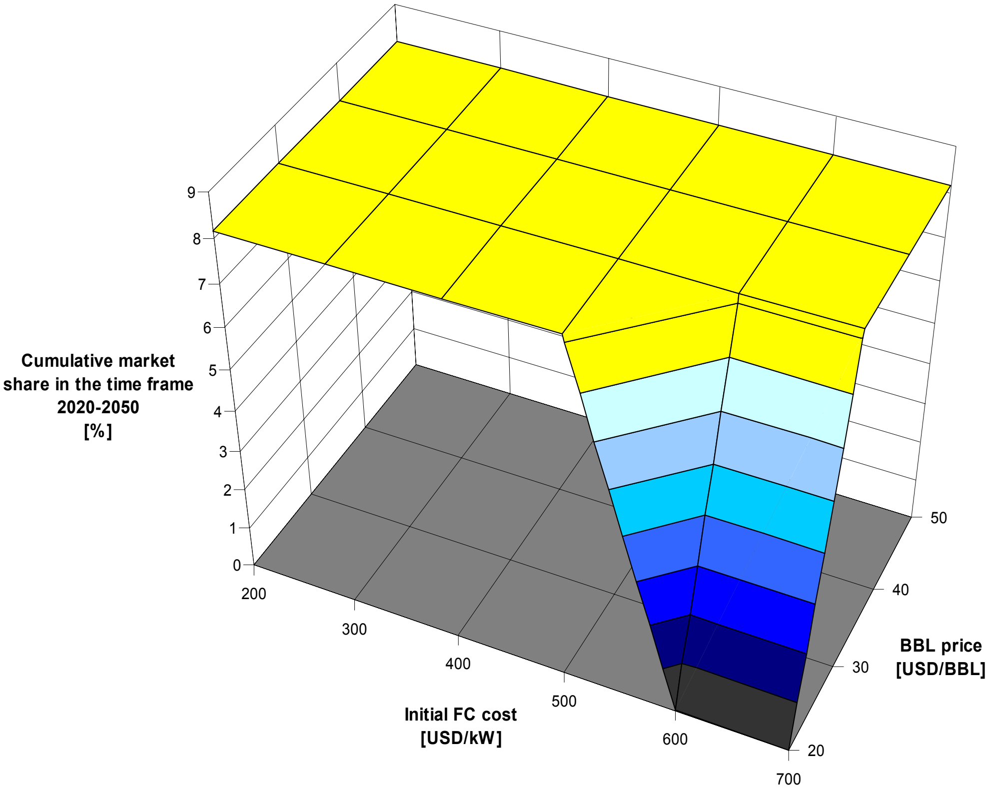

Figure 23 Influence on market penetration of hydrogen fuelled fuel cell personal vehicle as result of fuel cells and conventional fuel prices (Learning rate: 10%, Hydrogen price: 20 USD/GJ)

The results of this analysis indicate that there is no strong synergetic effects between prices of oil based fuels and fuel cells. The results suggest that to a large extend the price of oil based fuels has no effect on the market penetration, only in the case when the conventional fuels are very cheap (20 USD/BBL), while fuel cell vehicles have a disadvantageous high cost of fuel cells (more then 600 USD/kW).

3.4.3. Hydrogen and oil based fuel prices influence

The third considered pair influencing the market penetration of hydrogen fuelled fuel cell vehicles consisted of prices of hydrogen and oil based fuels as presented below (Figure 24).

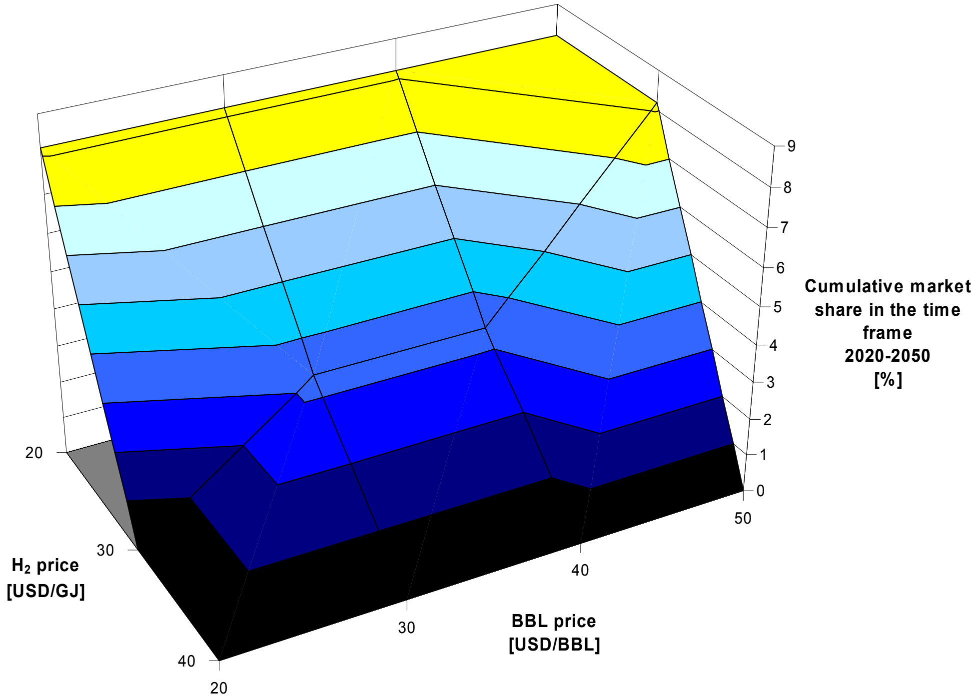

Figure 24 Influence on market penetration of hydrogen fuelled fuel cell personal vehicle as result of hydrogen and oil based fuels prices (Learning rate: 10%, initial FC price: 500 USD/kW)

The results of the conducted analysis suggest that market penetration is relatively sensitive to the variations of fuel prices. Hydrogen price below 30 USD/GJ already guarantees a full fledged market penetration of hydrogen fuelled fuel cell vehicles (price of fuel cells has been assumed to be at 500 USD/kW and a learning rate of 10%), independent on the oil based fuels price. Looking at price of oil based fuels, one may notice, that fuel prices of more then 30 USD/BBL allow for moderate or full penetration of hydrogen fuel cell vehicles. Keeping in mind the latest trends in oil prices, one may consider a rise of oil based fuels as quite probable, hence giving the hydrogen fuelled vehicles an opportunity to penetrate the market (provided the fuel cell costs are below 600 USD/kW, what has been illustrated earlier).

3.4.4. Learning rate and CO_2 taxation mechanism influence

After considering purely market driven factors (like fuel or fuel cell price) an analysis has been conducted on the influence of governmental initiatives on the stimulation of market penetration of hydrogen fuelled fuel cell vehicles. This has been done analysing the influence of CO_2 taxation mechanisms versus selected market driven factors. Therefore, the first pair selected for the sensitivity analysis consisted of the CO_2 taxation mechanism and the various levels of learning rate (Figure 25).

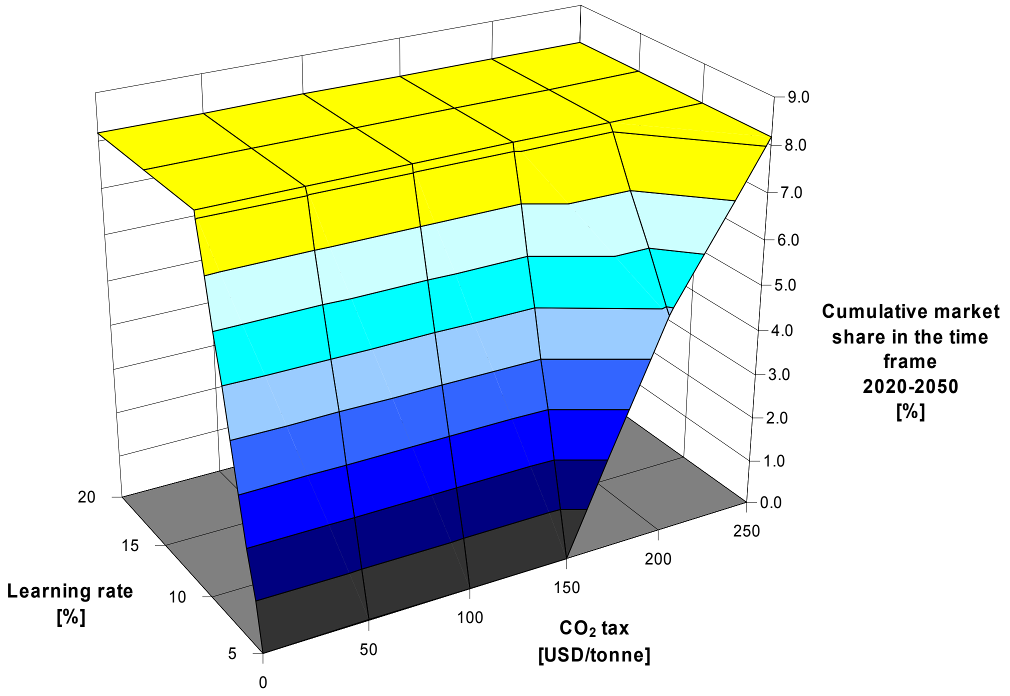

Figure 25 Influence on market penetration of hydrogen fuelled fuel cell personal vehicle as result of technological learning and CO_2 taxation mechanism (initial FC price: 500 USD/kW, Hydrogen price: 20 USD/GJ, BBL price: 30 USD)

The results of this analysis indicate (similarly to previous parts) that the system is very sensitive to technological learning. As illustrated, only higher values of the CO_2 tax allow for stimulation of market penetration by hydrogen fuelled fuel cell vehicles if the learning rates are low. However, if technological learning reaches a level of 10%, market penetration shall be possible independent of the CO_2 tax levels. The conclusion from this part of the analysis is that the taxation mechanism is a very useful tool to promote hydrogen fuelled vehicles if the technological development (expressed as the learning rate) is slow. A range of technological learning from 15-20% allows full fledged penetration, without the need for additional stimulation by such initiatives as the governmental CO_2 emissions taxation.

3.4.5. Summary of sensitivity analysis of the synergetic effects

As mentioned in the first part of this chapter, several potentially influencing factors have been selected for a sensitivity analysis, which would illustrate their impact on market penetration of hydrogen fuelled fuel cell vehicles. The results of the analysis suggest, that for each of the factors as specific 'threshold' exists above or below which penetration of hydrogen fuelled fuel cell vehicles occurs. The following table summarises the factors selected and the threshold values which have been observed from the results of the analysis (Table 12).

Table 12 Summary of factors and their threshold values promoting the penetration of hydrogen fuelled fuel cell vehicles

Factor	Threshold value
Learning rate (LRN)	10%
Cost of 1kW of fuel cell stack	600 USD/kW
Conventional fuel price	30 USD/BBL
Hydrogen price	30 USD/GJ
CO_2 tax	200 USD/tonne CO_2

The **learning rate** seems to be the most influencing factor from all which have been selected for the analysis. The results show, that for a learning rate of 10% or more, the penetration of hydrogen fuelled fuel cell vehicles is very likely to occur. In the case when the learning rate is lower then the threshold value of 10%, one should apply additional stimulating mechanisms (for example a CO2 emissions taxation mechanism) in order to allow market penetration of hydrogen fuelled fuel cell vehicles.

The second most important factor is the **price of fuel cells**. Pricing of fuel cells at a cost of more then 600 USD/kW puts the fuel cell technologies in an unfavourable market position. The cost plays a significant part in the overall costs of operating a fuel cell vehicle. One should however keep in mind that simultaneously with the cost of fuel cells below the 600 USD/kW the learning rate should be above the threshold value of 10% in order to allow market penetration of hydrogen fuelled fuel cell vehicles.

Fuel prices (for both types of fuels: hydrogen and oil based fuels) do not have such strong influence of market penetration of hydrogen fuelled fuel cell vehicles as the previously mentioned factors of learning rates and prices of fuel cells. The results of the analysis indicate that almost for the whole range of prices of both fuels, one could expect market penetration of fuel cell vehicles. Only in the extreme cases when one fuel is very expensive while the other one is very cheap (for example oil based fuels at 20 USD/BBL and hydrogen at 40 USD/GJ), the penetration is limited. Judging from the fuel prices and their historical trends, it is unlikely the transportation sector could arrive at such point without external supporting mechanisms like extensive subsidies or taxes.

The **CO_2 emissions taxation** mechanism has proven to be a good mechanism to promote hydrogen fuelled fuel cell vehicle, especially in the case when the fuel cell technologies are at low learning rates. The results of the analysis suggest however, that the factor of CO_2 taxation is not so effective if it is to be targeted as promotion of expensive (fuel cell price of more then 500 USD/kW) fuel cell vehicles. Their penetration is significantly more dependent on the learning rates then on the considered factor of CO_2 taxation.

3.4.6. Fuel cell cost and CO_2 taxation mechanism influence

Lastly, the pair consisting of the fuel cell cost and the CO_2 taxation mechanism has been analysed on the influence on market penetration of hydrogen fuelled fuel cell vehicles. In this analysis, it has been assumed that the fuel cell vehicles have a 10% learning rate, price of hydrogen is at 20 USD/GJ, while for the conventional oil based fuels the price is 30 USD/BBL.

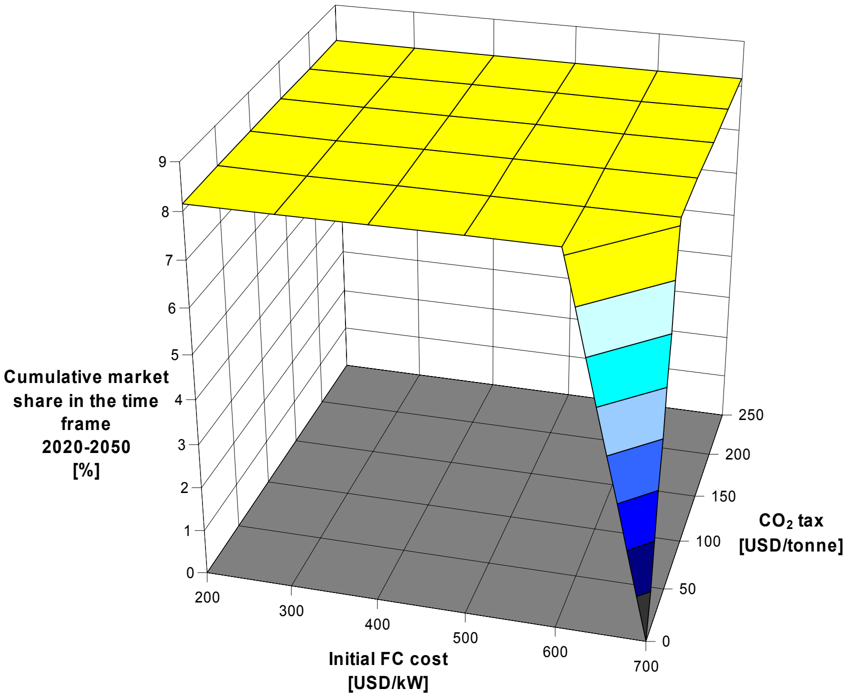

Figure 26 Influence on market penetration of hydrogen fuelled fuel cell personal vehicle as result of CO_2 taxation mechanism and price of fuel cells (Learning rate: 10%, Hydrogen price: 20 USD/GJ, BBL price: 30 USD)

The last part of the sensitivity analysis indicates that there is not much relation between the application of the governmental CO_2 emissions taxation initiative and market price of fuel cells. In the case when fuel cells are relatively expensive (more the 600 USD/kW) even a minor (around 50 USD/tonne CO_2) taxation may allow for full fledged market penetration.

3.4.7. Policy analysis case studies – "Base case"

In this case an assumption has been made that there shall be no governmental initiative for imposing a CO_2 tax on the emissions coming from utilisation of fuels in the transportation sector. The new, alternative technologies are developing at low learning rates (5.5% decrease of costs with the doubling of the installed capacity). One may observe that the market structure does not change over time, as the predominant role in the Personal Vehicle sector is still played by the gasoline-fuelled engines with a similar share of the diesel fuelled vehicles as in the year 2000 (Figure 27). However one may notice a shift towards advanced technologies such as the Advanced Gasoline or the Advanced Diesel. In the Bus sector, the tendency is to switch to more efficient CNG and Diesel-powered vehicles. Following the European experience, by 2010 pilot projects are launched to promote hydrogen-fuelled buses, nevertheless the hydrogen powered buses keep a marginal share of the market mainly restricting them demonstration projects (Figure 29). Despite their costs, FC buses operate and as artificial demand from demonstration projects is created, the FC technology in the bus sector is able to slightly reduce costs.

The costs of travelling by each the technology can be seen on additional graphs (Figure 28 and Figure 30). An extended description of the calculation of the transportation costs has been presented earlier in this report (Chapter 2.4).

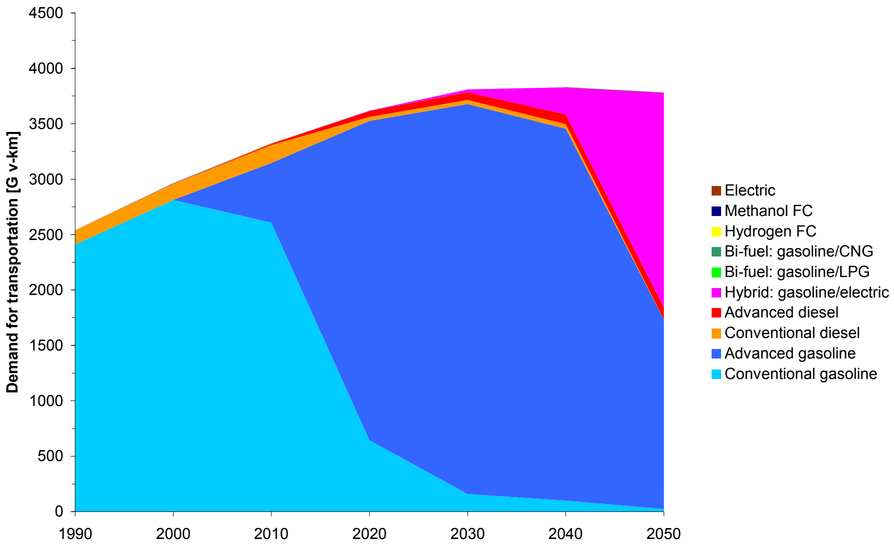

Figure 27 Base case – market shares for Personal Vehicles sector

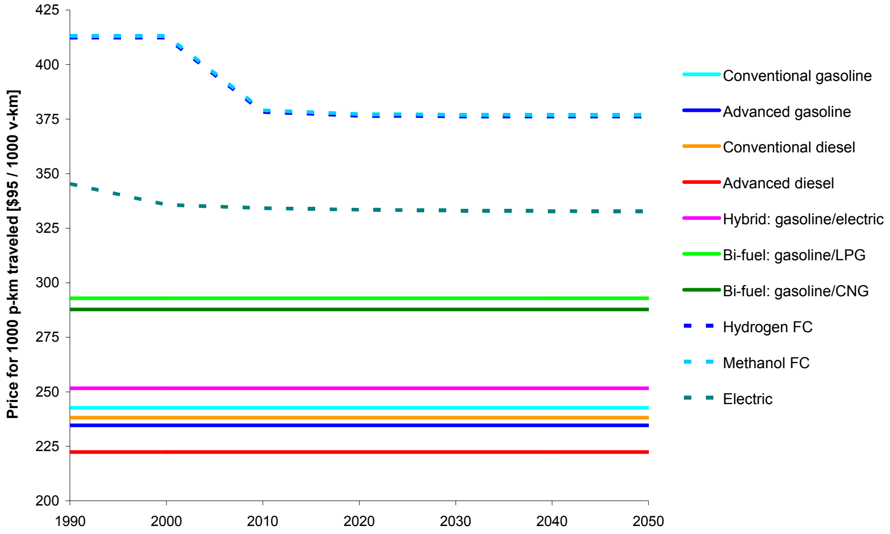

Figure 28 Base case – cost of transportation in the Personal Vehicle sector

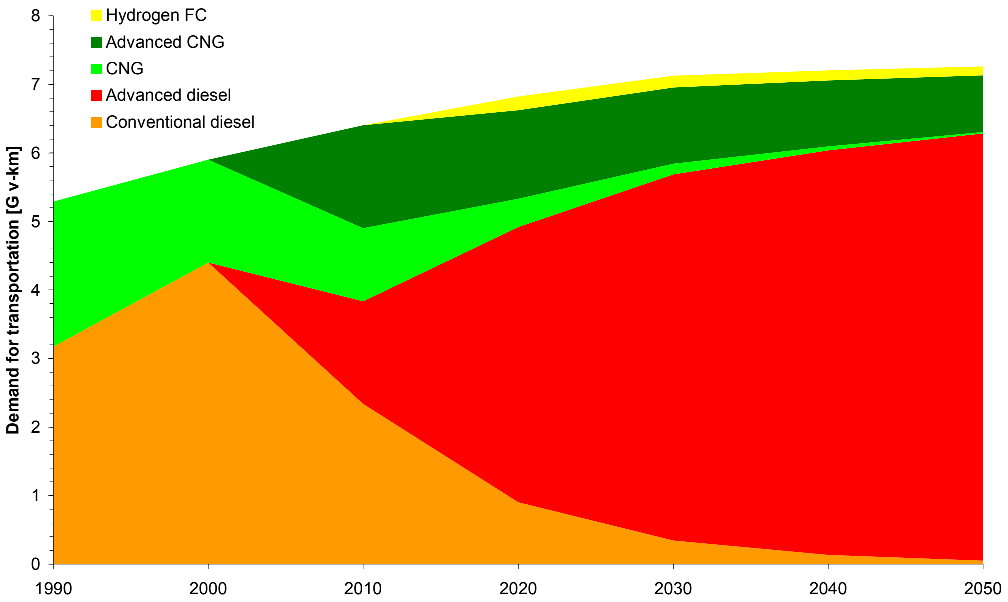

Figure 29 Base case – market shares for Bus sector

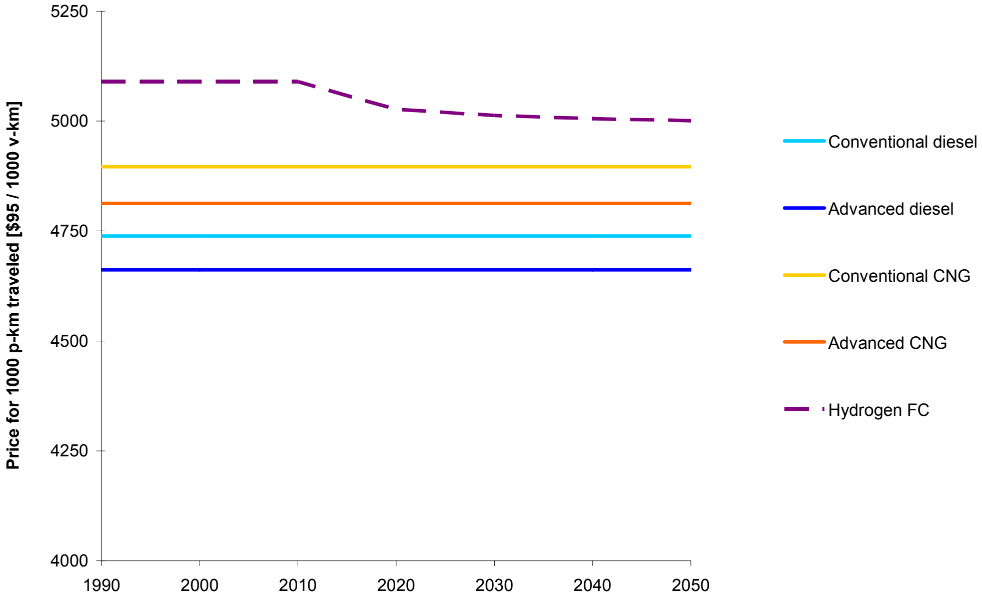

Figure 30 Base case – cost of transportation in the Bus sector

3.4.8. Policy analysis case studies – "Green World"

In this case it has been assumed that since the year 2000, the concern for the contribution from the transportation sector to global warming is growing among the governmental institutions. Therefore, by 2010 an emissions tax is introduced, requiring a sum of 100 USD is paid for every tonne of CO_2 emitted. The tax is charged to the end user, as the tax is imposed on fuel. Following the governmental constraint, vehicle manufacturers see an opportunity to expand the range of vehicles offered with vehicles fuelled by alternative fuels. The new, alternative technologies are being developed rapidly. Mass production of hydrogen and methanol fuelled fuel cell vehicles aided by high learning rates (learning rate of 15%) allow them to penetrate the market. The first new, alternative vehicles become commercially available soon after the CO_2 taxation mechanism is in force. Following the governmental initiative and the availability of alternative-fuelled transportation technologies, Private Vehicle owners slowly switch to them (Figure 31).

In the Bus sector, following the European experience, hydrogen buses are introduced by 2010. In the beginning when they are introduced, costs related with their operation are still high. However with the increasing popularity, mass production, high learning rates and CO_2 taxation mechanism in force, their market position becomes more and more competitive. (Figure 33). Despite the fact, that at the end of the period (1990-2050) presented in this report, full costs of hydrogen fuelled fuel cell buses are still higher, one should keep in mind that the presented results are only a 'time slice' in the possible future development. Following the presented trends, one may expect that with the increasing popularity, high learning rates and governmental support by means of CO_2 taxation (which favours hydrogen fuelled vehicles), FC buses shall reduce their costs even more (as to what is illustrated here) and dominate the bus sector in a longer term then what has been presented in this report.

The costs of transportation by each of technology can be seen on additional graphs (Figure 32 and Figure 34). An extended description of the calculation of the transportation costs has been presented earlier in this report (Chapter 2.4).

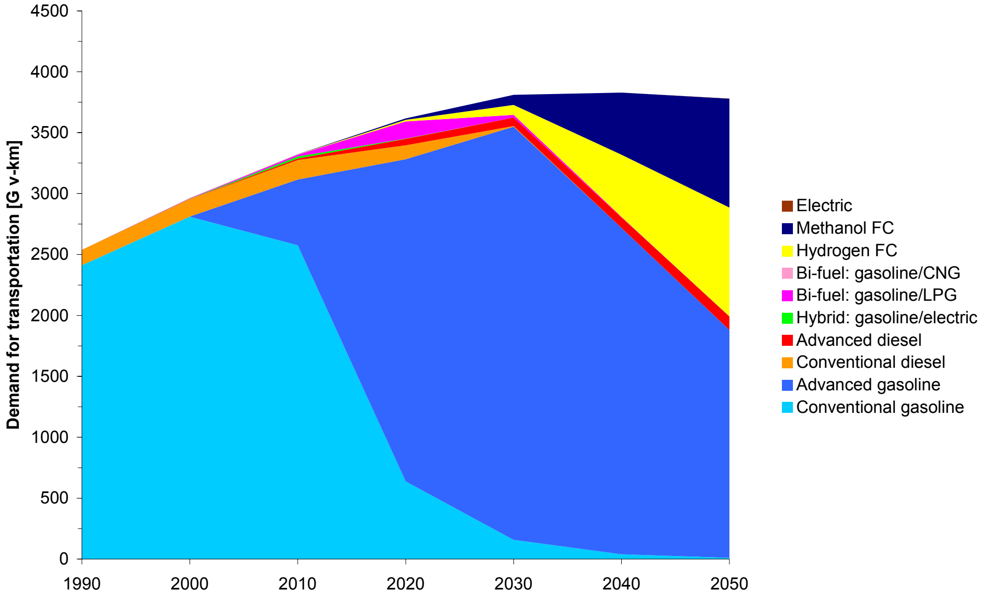

Figure 31 Green World – market shares for Personal Vehicles sector

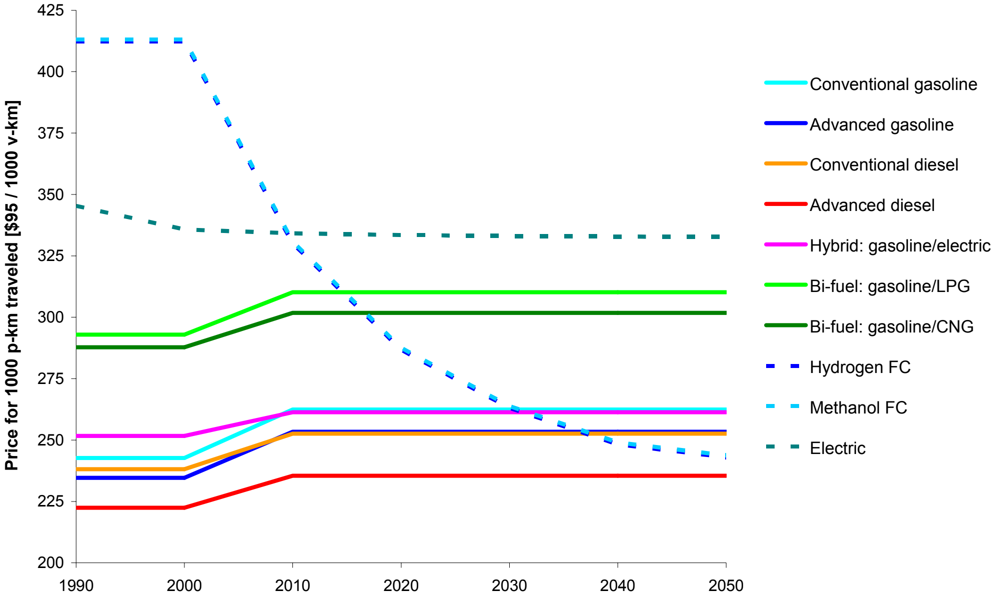

Figure 32 Green World – cost of transportation in the Personal Vehicle sector

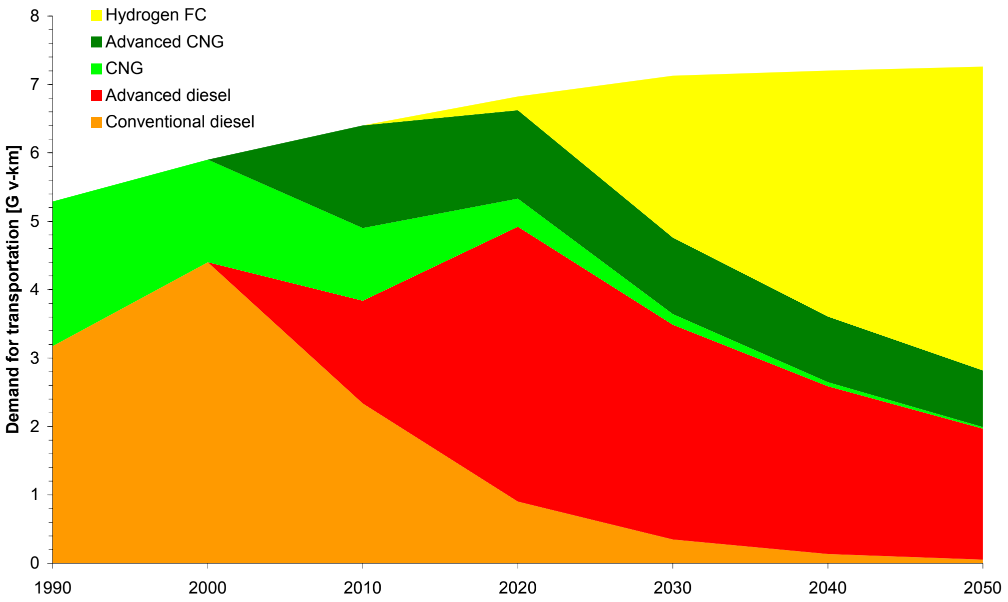

Figure 33 Green World – market shares for Bus sector

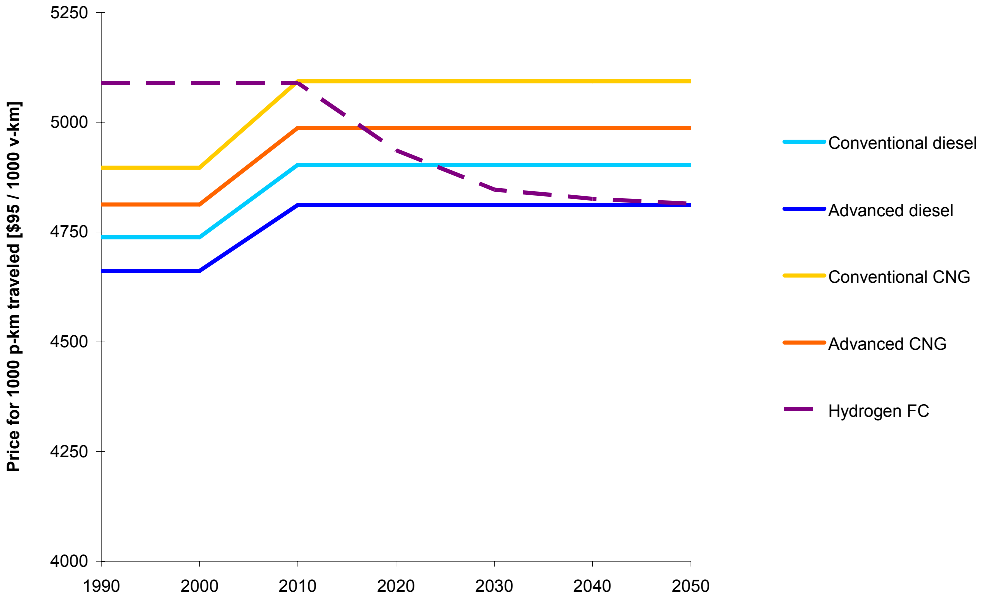

Figure 34 Green World – cost of transportation in the Bus sector

3.4.9. Policy analysis case studies – summary description of all cases

As mentioned in the earlier parts of this report, 5 cases have been analysed in terms of the impact of governmental initiative to tax CO_2 emissions and technological learning. Below, the final results in terms of market shares for both analysed sectors of Personal Vehicles and Buses are presented (Figure 35 and Figure 36).

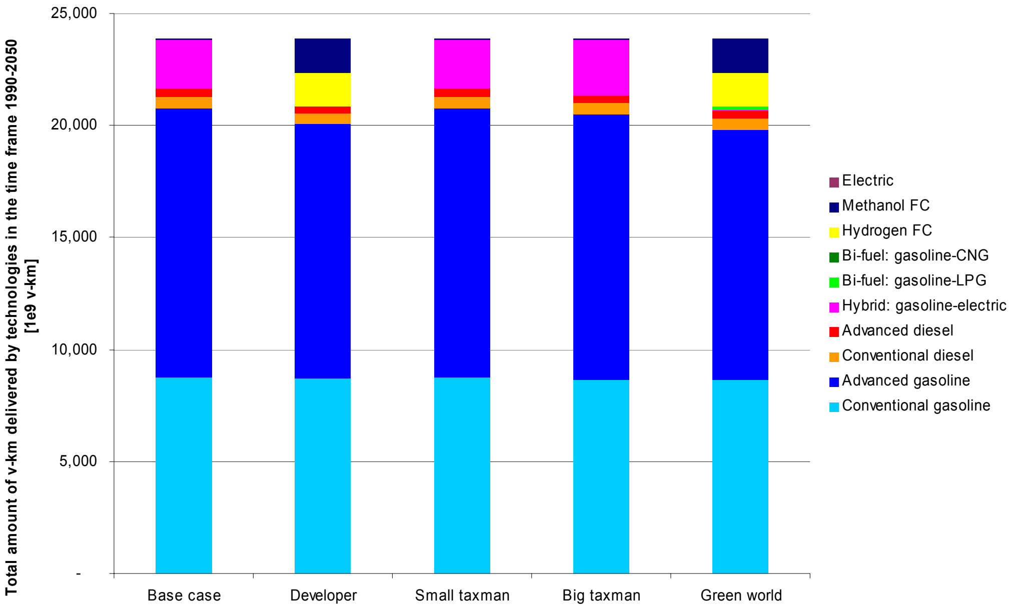

Figure 35 All cases – total amount of v-km delivered by technologies in the Personal Vehicle sector in the time frame 1990-2050

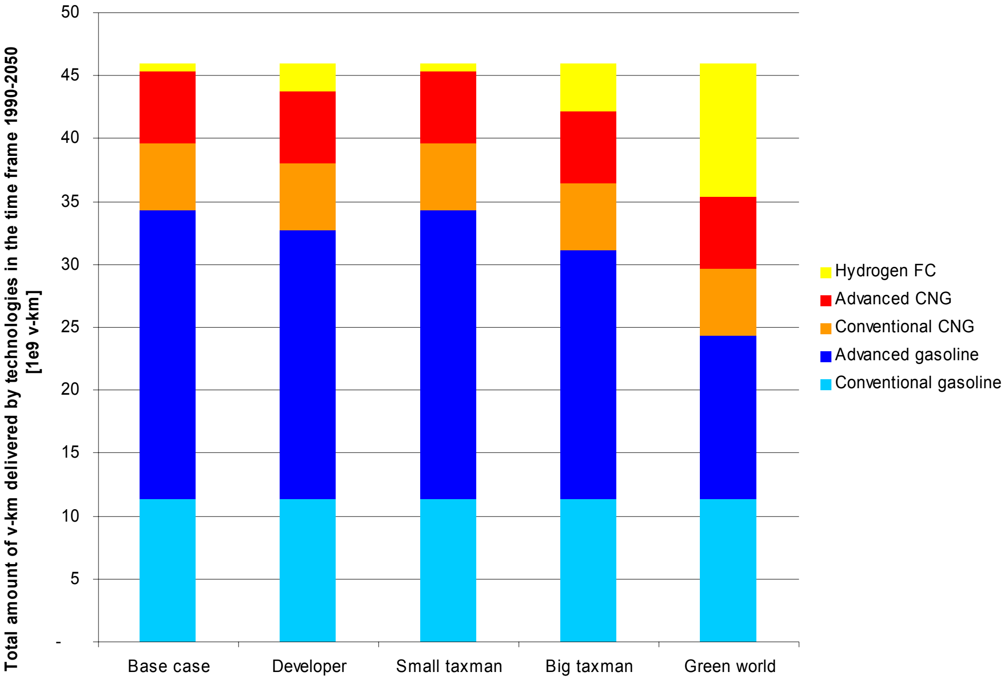

Figure 36 All cases – total amount of v-km delivered by technologies in the Bus sector in the time frame 1990-2050

The graphs above illustrate the changes in the structure of the two selected sectors of transportation in North America.

In the first case ("**Base case**"), without any alterations to the transportation sector, over the next 50 years in the personal vehicle category, the dominant role is played by vehicles powered by internal combustion engines fuelled by gasoline. Because of high purchase costs and competitiveness of conventional fuels, alternative technologies enter the market in both market segments (personal vehicles and buses) to a small extend, however without the fuel cell vehicles. As for the Bus sector, advanced diesel technologies dominate the market.

In the second case ("**Developer**") with increased learning rates, by the year 2030 alternative technologies like the fuel cell vehicles begin to enter the market. Their position becomes strong as wider acceptance and popularity rise. In the bus segment, because of high purchase costs new types of alternatively fuelled buses enter, but their penetration is not so dynamic.

In the third case ("**Small Taxman**") the introduction of the CO_2 tax in 2010 creates an opportunity for the new, alternative-fuelled vehicles. However, their development is not dynamic enough. Market shares in both market segments stay basically the same as in the Base Case, as the introduction of the CO_2 at low level does not compensate the difference in costs related to purchase price, fixed and variable operation and maintenance costs.

The Bus sector is "resistant" to changes. This is mainly due to high purchases costs of alternatively fuelled vehicles; however the Bus sector remains a key area for demonstration projects which contribute to technological development in other sectors.

In the fourth case ("**Big Taxman**") the introduction of a high CO_2 tax in 2010 puts the alternative (to conventional gasoline engine) technologies in better position. The initiative is however not strong enough to overcome the slow development process, which puts the hydrogen and methanol fuel cell vehicles in an unfavourable position.

Market shares of the fuel cell bus in the Bus market are increased – fuel cell vehicles penetrate the segment at increased rates.

In the fifth case ("**Green World**") the technological development of new, alternatively fuelled vehicles is dynamic, additionally aided by the governmental initiative of the CO_2 taxation. Combination of both factors results in market penetration of alternative fuel transportation technologies in the personal vehicle segment (a noticeable share of hydrogen and methanol powered vehicles is visible in the timeframe of the analysis).

The penetration of new, alternatively fuelled vehicles does not show strong dependence on the price of hydrogen as fuel (independent on the origins of hydrogen – from the cheapest local generation from natural gas steam reforming, to more expensive sources like centralised generation from natural gas or wind power with the necessary transportation to sell points by pipeline or vehicle). This is mainly due to the fact that because of very high fuel efficiency, as compared to conventional technologies, fuel costs do not play a dominating role in the costs structure (Figure 37 and Figure 38). However, the price of oil has a strong influence on the system. Because of this fact the conventional, oil based fuel, technologies have a relatively low efficiency (as compared to hydrogen or methanol fuelled vehicles) an increase in the fuel price has a considerable impact on the development of other more efficient, alternative technologies.

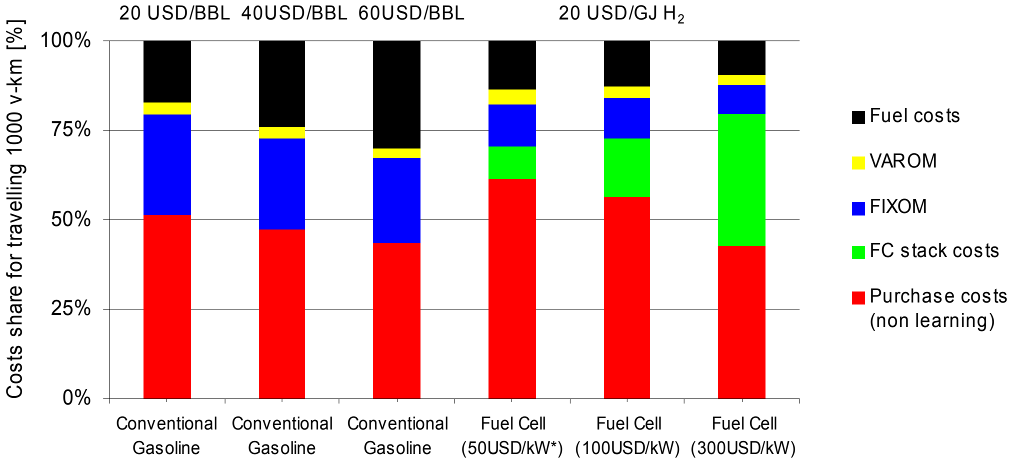

Figure 37 Costs structure of travelling 1000 v-km by conventional gasoline and hydrogen fuelled vehicles in percentage of cost shares (* indicates the structure with floor costs of the fuel cell stack)

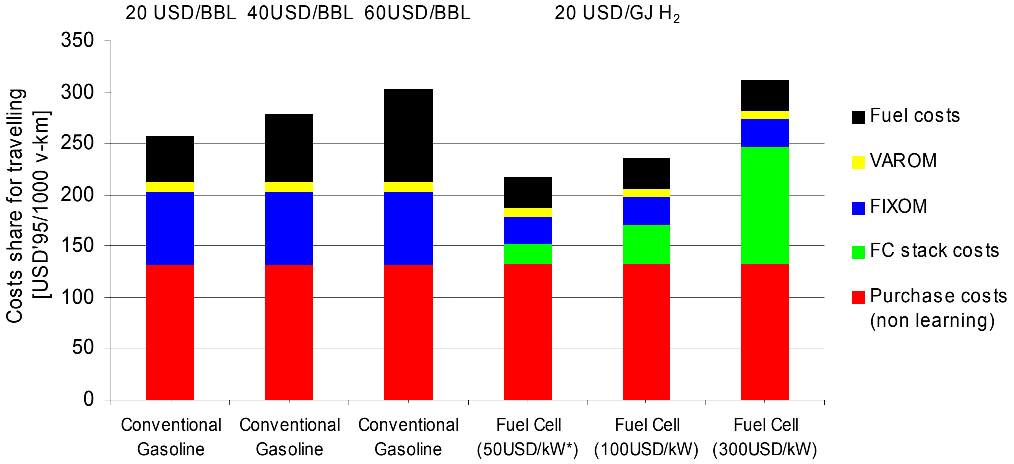

Figure 38 Costs structure of travelling by conventional gasoline and hydrogen fuelled vehicles in USD/1000 v-km (* indicates the structure with an illustrative floor costs of the fuel cell stack)

The development of the transportation system, the introduction and diffusion of fuel cell vehicles is very much dependant of the price if the fuel cell stack. The analysis indicates that a price of more then 300 USD per kW puts the new technologies in a very unfavourable market position. The difference in costs may be compensated, as to make the alternatively fuelled hydrogen or methanol vehicles competitive, if the price of oil based fuels becomes high or very high (more then 40 USD/BBL). Provided that prices of fuel cells are significantly reduced, with the additional effect of high learning rates (more then 10%) one may be expecting a rapid and dynamic diffusion of fuel cell vehicles.

The reader should note that the results depend on our assumptions made here and on the methodological approach used to endogenize technological learning. In addition, an energy-systems model, with endogenized technology learning, has a tendency to behave in an 'all-or-nothing' fashion. That is, below a 'threshold' learning rate the 'learning' technologies do not penetrate at all. Above it, it will try to penetrate the market at the highest possible speed.

4. CONCLUSIONS

In this report some methodological steps towards assessing the effects of incorporating technology learning in transportation technologies in energy-system models have been outlined. In addition, experiments have been conducted linking a "bottom-up" energy-systems model that endogenizes technology learning (MARKAL) and the general-equilibrium EPPA model. Two separate exercises are presented. The first one is a methodological exercise that shows the feasibility of linking the EPPA and MARKAL models, when technology learning is incorporated in selected technologies in the latter, and outlines a procedure to use the MARKAL model to estimate elasticities of substitution that could be used as input to the EPPA model. The results show that introduction of Learning-by-doing costs reduction mechanisms increase the elasticities of substitution. With the increasing market penetration of "learning" technologies, their price reduces resulting (as a function of cumulative capacity) in the increase of elasticity of substitution.

The second exercise, which describes the development of a simplified stand-alone transportation model, has allowed the authors to gain insights into the basic dynamics of a "bottom-up" model that endogenizes technology learning, the main parameters that affect its behaviour and potential advantages and shortcomings of the formulation. Using this simplified modelling framework, the impact of policy measures such as the CO_2 taxation mechanism, variable market conditions (changes in fuel and/or vehicle component prices) and stimulation of technology learning on the structure of some selected transportation modes is illustrated, using the case of passenger cars and buses in North America. Within their limitations, the results of the second exercise suggest that CO_2 taxation and the stimulation of technology learning could be attractive mechanisms for the diffusion of emerging, cleaner transportation technologies. Moreover, a combination of policy instruments could be more effective. However, given the stylized nature of the model used here, these results should be taken carefully.

In order to understand the results, in particular the "abrupt" changes in the penetration of some of the technologies from one case to the other, it is important to bear in mind the way the learning mechanism operates in the model. Although other factors also intervene, the potential available for cost reductions strongly influences the outcome. Learning is an increasing returns phenomenon (i.e. the more capacity is accumulated the smaller the investment costs become). Due to the underlying increasing returns mechanism, the model tends to act in an "all-or-nothing" fashion. If enough learning potential is at hand (depending on the learning rate, the starting point of the learning curve, maximum market penetration rates, potentials etc. specified in the model), the model may choose to introduce the technology as much as possible. But, if the learning potential is not sufficient to render it cost-effective, the technology will very likely remain "locked out" or left only with a marginal contribution.

The endogenization of technological learning represents an advance towards a more comprehensive treatment of technological change in energy optimization models, capturing the early investments (i.e. early accumulation of experience) required for a technology to progress and achieve long-term cost competitiveness. More importantly, it also provides a mechanism that makes an important aspect of technological change (i.e. cost development) dependent upon parameters and variables in the model (Barreto 2001; Barreto and Kypreos 2004a). However, although a step forward, it also brings a number of challenges that should be addressed in future research. Among others, the uncertainty that surrounds the learning rates of emerging technologies, the tendency of the model to behave in an "all-or-nothing" manner, the fact that the learning curves only provide an aggregate and stylized representation of the mechanisms that influence technological progress, the representation of technology clusters, and current lack of understanding of the role of R&D in technological change, have to be addressed (for a discussion see e.g.(Barreto and Kypreos 2004b)).

4.1. Possible future activities

The analysis results presented here are in many respects limited – both in terms of technological and economic representation. This is mainly due to the complexity and numerous modelling challenges that the transportation sector implies. However, presented in this analysis report, with the help of the simplified transportation model, may be extended as to broaden the understanding of the dynamics of changes in the transportation sector in many ways.

One of the potential ways to expand the representation of the transportation sector could be achieved by including fuel specific production chains. Insights into production chains may suggest potential policy mechanisms which may promote 'clean' transportation technologies. Furthermore, an extensive emissions analysis could be performed, which would not only

include direct emissions coming from vehicles, but also emissions linked to fuels, external costs as well as local pollution specifics. This broadening and further analysis could allow designing emission specific policies, targeted at given regions.
Moreover, in order to better describe market behaviour of technological and policy related changes, the model which has provided results for this analysis, may be extended by introduction of Monte Carlo Analysis - which assumes probability distribution of the input parameters which appear to be stochastic.

In addition, more efforts have to be devoted to the improvement of methodologies for "closing the gap" between "top-down" and "bottom–up" models. It is necessary to explore innovative approaches for linking energy-system models with macro-economic models. Each type of model has comparative advantages in specific energy-policy domains. However, addressing the complex issues arising from the interactions between the energy system, the economy and the environment requires comprehensive decision-support tools encompassing different aspects of a given research question. Thus, it is necessary to use them in a complementary, rather than exclusive, manner. Specifically, examining the role of technological change in the long-term transition towards sustainable energy systems, and assessing the impact of policy instruments that could stimulate the diffusion of the technologies necessary to achieve this goal, will require building on the strengths of both "bottom-up" and "top-down" modelling frameworks.

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