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Assessing threats and opportunities of induced technology change: Long and short term cycles in the carmaker industry

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Abstract

This paper introduces an industrial transformation model applied to the carmaker industry. We analyze the interaction between supply and demand as well as policy regulations supporting the diffusion of advanced vehicle technologies.

It allows assessing prospectively threats and opportunities of induced technology changes for industries. The simulation exercise provides evidence that smart governance approaches involving concerted entrepreneurial and political decision making can avert severe industrial crisis of adjustment during phases of socio-technical transitions. The overall cycle pattern seems to play out over a time period of 50 years. It is strongly influenced by the climate policy regime and the innovation investment behavior of firms. It results in a sectoral boom phase once the transition towards near zero emission vehicles has been mastered. The policy induced technology change pattern is comparable to the long wave theory in terms of its duration and the argument, that deep structural causes are innovation processes in whole technological systems. Moreover, we have identified the drivers of single short term cash cycles. Differences between cash inflow and outflow over time that are triggered by strategy and policy changes explain short term fluctuations.

Keywords: drive train technologies, eco-innovation, technology change, socio-technical transition, economic viability, CO_2 emissions

1 Introduction

The transportation sector is the second largest contributor to world CO_2 emissions by sector, and road transportation is with 75% the leading emitter within this sector [1]. But, advanced vehicle technologies may contribute significantly to CO_2 emission reduction in road transportation in the future. A cost effective CO_2 emission reduction path of -54% to -67% till 2050 (with base year 1990) has been set for the transportation sector by the European Union (EU) [2, 3].

However, history and the research on technology change have shown that successive incremental improvement patterns that are punctuated by radical innovation may have dramatic

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impacts on the competitive advantage of companies and the profitability of the whole industry [4-8]. While these research avenues point to threats and opportunities of technology change and inform technology and innovation management, recent literature highlight typical alignment processes in the broader socio-technical system at the niche, regime and landscape level that may influence socio-technical transition to more sustainable (low carbon) economies [9, 10]. Furthermore, the literature suggests that such alignment processes and transitions need to be managed in distinctive ways [11]. In particular, systemic failures such as infrastructure barriers and (institutional) lock-in effects need specific policy considerations [12]. However, the findings of these studies are only rarely used to coherently analyze different governance approaches supporting socio-technical transition. Neither their impact on technology diffusion, nor the profitability of the industry, nor the industry specific CO_2 emissions have been analyzed in a coherent manner [13]. This constitutes an important research gap. Closing this gap is important, specifically if we take into account that scenario building approaches have been identified as important tools for informing the actors involved with socio-technical transitions [14].

With our study we make one step in elaborating a scenario analysis tools that help to fill the research gap. Concretely, this study aims at identifying robust and economic feasible strategy and policy approaches for supporting the socio-technological transition towards near zero emission road transportation. Therefore, we have developed an industrial transformation model (ITM) for the carmaker industry founded in evolutionary economics and industrial dynamics including recent theorizing on socio-technical transition, as well as micro level innovation and adoption behavior. It has been validated and calibrated against data of the European carmaker industry. The purpose of this modeling exercise is to better understand the structure and dynamical interaction between the succession of eco-innovation, supply side and demand responses as well as policy regulation in the automotive industry. Our specific research focus is three-dimensional and geographical bounded. We analyze the dynamic effect of different governance approaches on, first the diffusion path of multiple competing drive train technologies, second the economic viability of market leaders, and third the prospective CO_2 emission pathways of the light duty vehicle fleet (LDV) in the EU.

Consequently, we include different aspects from different levels such as finance, production, R&D at the firm level and adoption and diffusion at the market level as well as policy pressure from the landscape level. While most aspects of this model have been dealt with in other papers [15-20] none of them study the dynamical implications of the interacting domains at once, which may lead to biased or over optimistic findings. With our holistic modeling approach and multidimensional analysis, we consider the dynamical interaction between the different sub-systems and variables at different levels in order to provide a coherent assessment of combined policy and strategy making. However the scope of the analysis is focused only on induced technology change, i.e. technological change triggered and supported by dynamical policy and strategy making and does not include behavioral and preference changes in the LDV market (i.e. we assume fixed mobility demand).

Our modeling exercise will show the decisive role of the capital stocks in the automobile industry as well as automakers' capacity to strongly invest in R&D. Policy analyses address the critical role of early investment into the infrastructure build-up and its effect on cost reductions of alternative vehicles and their diffusion pathways. In addition, the paper will investigate if anticipation of policy regulation and early responses of the supply side induce economically and environmentally advantageous transition paths. We specifically look into technology specific performance criteria, the time frame and context conditions under which internal combustion engine vehicles (ICEV), natural gas vehicles (NGV), electric range extended vehicles (EREV) and battery electric vehicles (BEV), as well as fuel cell electric vehicles (FCEV) may contribute to improved CO_2 emission reductions.

After this brief overview of the motivation, the purpose and the comments on the specific focus of the chosen modeling approach, the remainder of the paper is structured as follows. A synopsis of the relevant characteristics of the carmaker industry, and the theoretical background of the modeling exercise is provided in the second section. In the third section the model structure and its basic behavior is summarized. The fourth section presents illustrative findings of combined strategy and policy simulation. Also, the main determinants and typical behavior patterns of the simulation results are discussed. In section five, we derive practical policy and strategy implications. We conclude in section six with reflections on the modeling exercise and on the main implications of our findings with respect to the impact of socio-technical transition on the carmaker industry and its CO_2 reduction potential. Limitations and avenues of further research are pointed out.

2 Model Context

This section provides a short summary on the relevant operating figures of the European carmaker industry. Also a short outline of the theoretical background of the model and simulation experiments is given.

2.1 The Industrial Context

The carmaker industry is a capital intensive industry. The production of vehicles requires a large amount of capital in properties, plants, and equipment and binds it over a long time period. Fig. 1 shows the revenues and invested capital of the three leading European carmakers for the year 2010. VW Group had a 20% market share, PSA and Renault 14% and 11%, respectively [21].

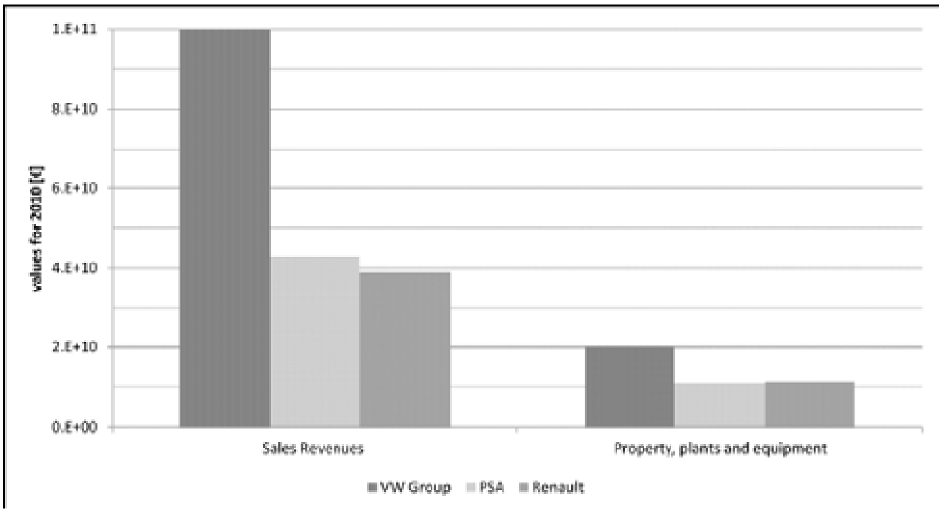

Fig. 1: Financial comparison: The comparison of financial key data of the European market leader VW Group with the second PSA and third Renault shows remarkable differences. (Source: Based on Annual Reports of the carmakers)

The LDV technologies require extremely large capital investments [22]. One the one hand the large investments allow to increase scale and cut costs, yet on the other result in huge sunk costs [23]. To recover the sunk costs a high sales volume is needed. Due to such large capital costs new technologies that are not easily integrated into mass-production are faced with high entry barriers [24, 25]. Toyota for example spent almost 1 billion Euros on the development of Prius [26], the first commercial hybrid. Nissan faced development cost of 4 billion Euros for the Leaf [27]. It would be even harder for a newcomer starting from scratch to introduce a new technology to the market. Carmakers rather start R&D partnerships with promising entrepreneurs in order to build up competitive advantages based on advanced technologies [28].

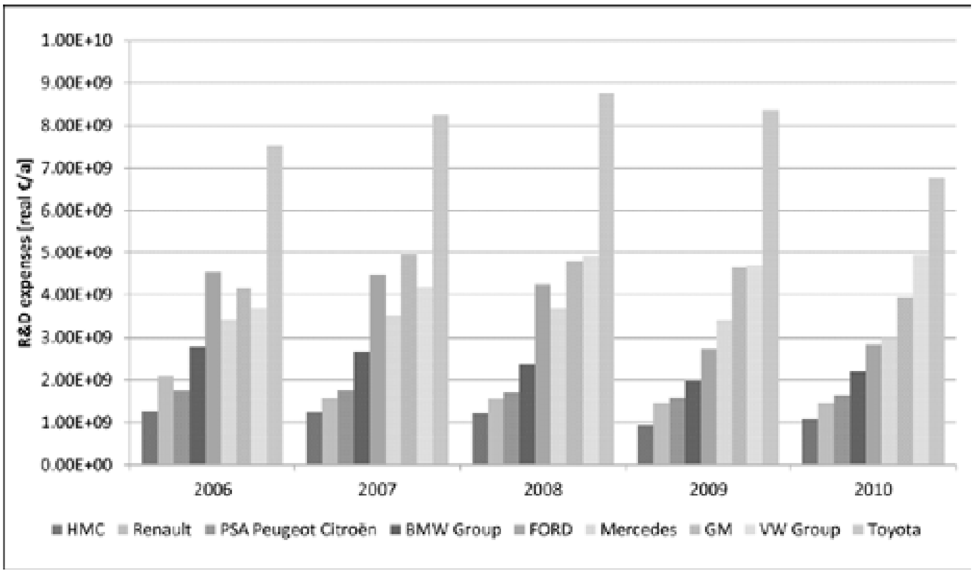

Fig. 2: R&D expenditures: The R&D expenditures of different carmakers show vast differences. Toyota is leading by multiple scales followed by VW Group. (Source: Based on Annual Reports of the carmakers)

The absolute money invested in R&D and thus the capacity to foster new technologies varies considerably across the industry. Fig. 2 illustrates the high R&D expenditures within the carmaker industry. The budget of Toyota for example is in 2010 more than six times higher than that of Hyundai Motor Corporation (HMC). Noticeable is that VW Group is the only carmaker shown in the graph that has in real terms constantly increased its R&D expenses over the last years. A logical consequence of the large differences in R&D budgets, thus, can be seen in an increasing technology transfer between carmakers. A quick open access internet research revealed that today almost all carmakers are directly involved in R&D partnerships with at least one of the other carmakers. VW Group seems to be one exception.

Many industrial characteristics such as complex operations, low margins, and high financial risks favor rather incremental technology improvements than radical change [29]. However, there are also signs that radical changes by the incumbent carmakers are possible. Strong environmental regulations do provide the urgency to elaborate the possibilities of rather radical alternative technologies while also providing a competitive space for new technologies [28]. However, a more recent study on patents reveals the continued strong dominance of the internal combustion engine also addressing environmental aspects. Further on, patents indicate that hybrid electric vehicles appear to be currently the most promising alternative [30]. Finally, from the consumer demand side stems little incentives for radical changes in the automobile industry. The environmental aspect of a car is only one attribute considered in the vehicle purchase process [31] and there, it tends to be included only indirectly via the focus on consumption which itself is an expression for kilometer costs.

2.2 The Theoretical Context

The literature on technical change has early on emphasized the strong impact of technological innovation on industries and economics [6, 32]. Therefore, the industry focused literature provided a rich basis for the model design. A detailed account of concept development and the formulation of the (dynamic) hypothesis for the industrial transformation model is given in working papers [33, 34]. Here, we will give a short summary of this work and the theoretical context on the governance of socio-technical transitions that is relevant for the strategy and policy experiments, as reported in the sections four to six.

2.2.1 Technological Transformation Processes in Industries

Technological advancement can have different effects on the industry structure (characterized by number of firms, leading companies and firm size). The literature identifies the following determinants as decisive for influencing industrials responses: organizational inertia [7, 35, 36], maturity of the new technology [4, 5, 37, 38], knowledge trading and spillovers [8, 39, 40], as well as the pressures on / within the current socio-technical regime [41, 42].

An industrial transformation framework relates their influence on the industry to four transformation modes, see Fig 3 [33]. The four different modes are separated by the dimension of availability or marketability of a new technology and the dimension valued product characteristics. These are the most important technological product attributes for the users.

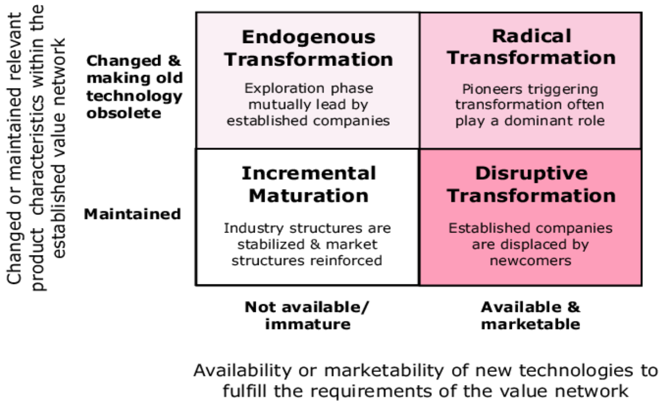

Fig. 3: Industrial transformation framework: Four industrial transformation patterns are distinguished depending on the two dimensions availability of new technology and the forming of the relevant product characteristics within an industry. (Source: Bouza 2009)

Incremental maturation can be observed if the commercialized technological improvement follows the same uncontested technological trajectory with fixed preferences in the value network. *Disruptive transformation*, (i.e. a transformation where newcomers may considerably change the industrial structure) may evolve if an available and marketable new technology in a secondary value network with slightly different preferences (e.g. niche market) starts to compete with the primary value network along its established primarily valued product characteristics. *Radical transformation* is likely to be observed, if commercial technology advancement leads to newly preferred product characteristics. In this case, pioneers of the incumbent industry but also newcomers are likely to gain a distinctive competitive advantage in the industry. *Endogenous transformation* may be observed if new product characteristics become relevant due to selection pressure while the corresponding technology is not yet available or marketable in the established industry. In this situation, where the whole industry needs to respond to changed selection pressure, joint efforts of the incumbents will result in a stable industrial evolution where the technological transformation may not change the established industry structure.

While the former transformation pathways have been described and discussed before in the literature [4, 7, 35, 38], the endogenous transformation mode has been recently suggested by Bouza (2009) [33] as it correspondence better to today's situation in the automobile industry. Based on this classification system and the above highlighted determinants of technology change, this paper argues that strong collaborative efforts and relaxed organizational inertia within carmaker's firms will result in an endogenous transformation within a consolidated industry structure.

2.2.2 Governance of Socio-Technical Transitions

According to the framework outlined above, endogenous transformation in industries depends primarily on selection pressure and not on short term competition deliberations and autonomous market driven innovation. Complementary, the modern literature on (eco-)innovation system approaches [43] point to lock-in effects and path dependencies that generate systemic barriers at different levels [12, 13, 44]. These systemic barriers may hinder socio-technological transition to greener industries – valuing near zero emission product characteristics. Foxon and Pearson (2008) argue that "the richer picture of innovation processes provided by innovation system theory should provide a useful basis for reconciling innovation policy and environmental / sustainability policy to overcome the difficulties …" [13]. Further on, they argue that this systemic view requires strong consideration of systemic failures as an addition rational for public policy design, complementing the market failure approach. Also, the identification of strategic windows of opportunities (i.e. 'techno-economic' and 'policy' windows of opportunities), and variety generation, in respect to technological and institutional options, increasingly demand the attention of policy makers. But, the systems failure concept as a rational for public policy design requires the identification of barriers and the availability of effective policy options to overcome them.

Our modeling approach and the combined strategy and policy analysis will respond to some of these guiding principles. First, our rich systemic model of the carmaker industry is seen as a strategic framework that allows for testing of combined innovation and environmental policy packages. It helps to translate the long term policy goal in effective policy and strategy designs, supporting high policy compliance. Second, the anticipated fueling infrastructure barrier for different alternative vehicles is specifically assessed [15, 45]. Finally, our approach helps to identify strategic windows of opportunities in order to effectively implement strategy and policy choices.

3 The Model

As stated in the introduction, the purpose of this modeling exercise is to better understand the structural determinants and their dynamical implications of a succession of eco-innovation, supply side and demand responses as well as policy regulations in the automotive industry. Specifically, we are interested in the dynamic interaction of industrial viability, and public policy for mitigating diffusion barriers, as well as achievable CO_2 emission reductions in the EU for the time horizon from 2000 to 2100.

From an extensive literature study no model so far has been found that dynamically combines finances, R&D, production, and the market as well as the fueling infrastructures at the same time. While most aspects have been dealt with in other papers [15-20] none of them study the dynamical implications of the interacting domains at once. Three factor mistakes tend to be made when analyzing the potential of new technologies: factor time, factor price, and factor man. The diffusion tends to happen rather fast [15, 46], and in that short period the price for new technologies will approach those of incumbent technologies [46], and customers will accept the changes without reservation [19, 46].

The system dynamics model presented here fills the identified synthesis gap and considers the dynamical complexity between subsystems and components within the firm and its environment. The basic assumptions underlying the model are based on evolutionary economics [35], industrial dynamics as highlighted above, interconnected by reinforcing structures [47], spillovers and acceptance dynamics [31, 48, 49]. Penalty taxes or the infrastructure availability does not only influence the adopter potential of alternative vehicles directly, but it has self-enforcing indirect impact on companies' revenue, company cash and the magnitude and allocation of R&D investments, as well as production capital adjustment. The challenge has been to come up with a coherent white box model with a logical structure that maps such circular causalities consistently with the real world structure. Therefore, theory and empirical data, as well as calibration and validation techniques have been used that help to build up sufficient confidence in the model structure and behavior for the formulation of robust strategy and policy implications [50].

The model has been designed to simulate five carmakers, five different drivetrain technologies and the corresponding fuels, within five different markets. The markets can be defined as sub markets in order to represent niches with alternative preferences or policy regulations. We are using averaged technologies as reference; hence, market segmentation cannot be analyzed in detail. The introduction of bio or synthetic hydrocarbon fuels is also disregarded. Furthermore, the model allows no firm acquisition. When a firm goes bankrupt, the invested capital thus cannot be integrated by one of the other companies. A crowding out of a firm thus lead to a shock as other companies need to build up production capital in order to take up the free market share.

The model concept mapped in Fig. 4 provides a high level overview of the ITM that highlights model boundary, the main model inputs and the interconnected modules with its main variables. The modules are interconnected with variable specific information flows[ii]. The landscape level comprises of the environmental policies, consumer preferences and the existing fuel infrastructure, but also income trends and population dynamics. The three modules FINANCES, R&D, and PRODUCTION capture the processes internal to the firm. The MARKET module presents the near environment. It is influenced by landscape specific inputs.

[ii] A detailed description of the System Dynamics model implemented with the software Vensim® would be beyond the scope of this paper, but can be provided by demand based on the system dynamics model documentation tool developed by the Argonne National Laboratory, Lemon IL, USA. Please contact the corresponding author of this paper.

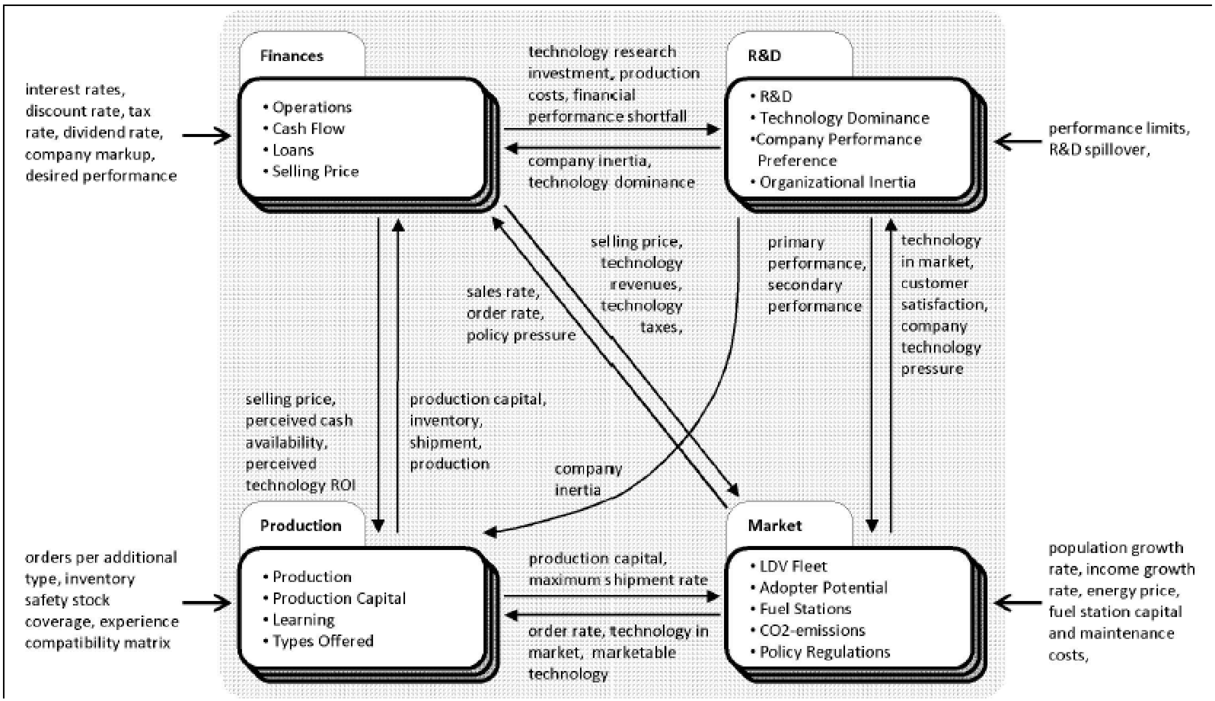

Fig. 4: Model concept: The model consists of four modules. Each module involves a set of subsystems. In addition, different classes of firms, technologies, fuels and markets are specified by subscripts.

3.1 The Feedback Loop Structure

The main feedback loops that control the transition towards near zero emission vehicles in the ITM are highlighted in the causal loop diagram shown in Fig. 5. The diagram nicely distinguishes the loops that control the incremental maturation and the endogenous transformation modes (cp. Fig. 3). On the one hand the incremental maturation is explained by the four reinforcing loops r1 to r4. The research paradigm in this mode guides the enhancement of vehicles primary performance attributes (i.e. acceleration, driving range, the refueling or recharging time, and weight as a measure for safety). On the other hand the endogenous transformation process is mainly governed by the three balancing loops b1 to b3. They balance a perceived performance gap concerning energy consumption and are related to the emergence of a new research paradigm. It guides the establishment of the technological improvement trajectory emphasizing energy consumption and CO_2 emissions per technology [51]. These attributes characterize the ‘Secondary Performance’ variable. ‘Energy Cost’ or ‘Policy Pressure’ from CO_2 emission regulations force the carmakers to intensify their R&D expenses on ‘Secondary Performance’. A prolonged induced pressure causes in a first step a research paradigm change [52-54]. Due to system inertia, once the external pressures have been reduced, carmakers would keep their new ratio between primary and secondary performance R&D constant. Where a research paradigm change is not sufficient to reduce the external pressures, carmakers will in a second step undergo a technology dominance change [55]. Their long term focus will move away from incumbent technologies towards a single or a portfolio of new technologies that are better suited for the changed regime. However, while the reinforcing loops r1-r4 have supported the incremental transformation path, they may act as barriers for the endogenous transformation path. This may occur when ever either ‘Revenues', 'Selling Price', 'Fuel Infrastructure Construction' or / and 'Additional Types' of the alternative technologies are not competitive with the established technology.

In addition, the causal loop diagram also indicates how too ambitious standards may bring the system to a collapse. R&D is linked directly with revenues that define the magnitude of R&D (b1). In order to invest in R&D, a revenue generating technology is needed. Switching to fast from one technology to another without maintaining the same revenues would result in a reduction of R&D, thus slowing down the enhancement of the performance level. Subsequently, strict policies would undermine the technological development. Without a "cash cow" the means for technology development can be vigorously limited.

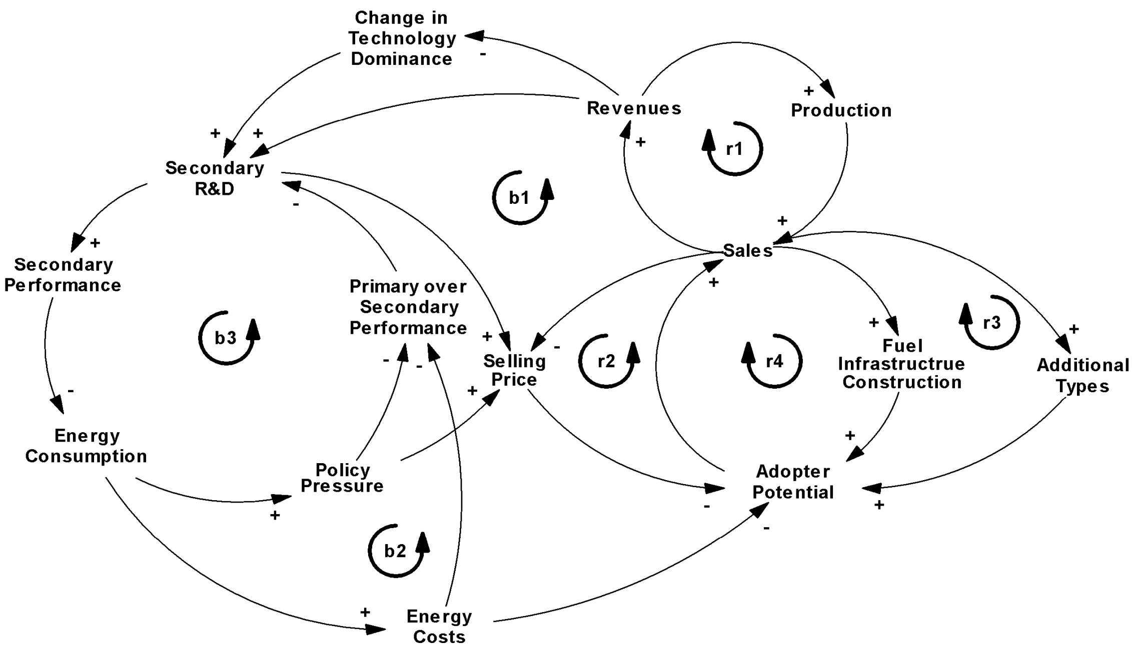

Fig. 5: Causal-loop diagram: The causal loop diagram highlights the main causal circularities of the industrial transformation towards near zero emission technologies in the carmaker industry. Positive correlations are marked with a (+) sign, negative with a (-) sign. There are four reinforcing loops (r1-r4) and three balancing loops (b1-b3).

3.2 The Reference Behavior

The reference behavior of the model describes the BASE scenario that is based on business as usual assumptions. The base year for simulation is 2000 and the time horizon is 100 years. This long time horizon helps to identify long term behavior patterns such as of over- and under-shoots or oscillation. The European market serves as reference point. We focus on the four leading carmakers. For the simulation carmakers' financial values have been adjusted for their European market shares. We use the approximation of a 20% share of the market leader and a 10% share for all three contenders [21]. Relevant thus are the magnitude and the relative difference between the market leader and its contenders. The relative size difference has been directly transferred to their invested production capital and their R&D investments. All companies show similar innovation rates per invested Euro, but the contenders need to collaborate in order to keep up with the market leader's R&D investments. While the market leader does not engage in knowledge trading, all others do. The assumption is in line with what can be observed in the current carmaker industry [56].

All companies start with a research paradigm focusing on primary performance, and ICEV is the dominant technology. Energy efficiency improvements of the hybrid electric technology are included in the assumed energy efficiency assumptions of ICEV. The mapped alternative technologies are NGV, EREV also including plug-in hybrids, BEV, and FCEV. The primary performance and the initial CO_2 emissions of the market leader's fleet are higher than those of the contenders. The average vehicle price of the leader is also set the highest. No price difference has been assumed for the remaining three.

Table 1 gives an overview of the assumed performance levels of firm 1. Table 2 shows the CO_2 emissions per fuel. The average lifetime for a vehicle, independent from technology, is set to be 17 years [57].

	ICEV		NGV		EREV		BEV		FCEV	
Performance	2000	Max	2000	Max	2000	Max	2000	Max	2000	Max
Primary										
Acceleration (s)	10	8	10.5	8	10	7	8	7	10	7
Range (km)	1100	1100	400	800	500	800	200	400	400	800
Refueling (min)	3	3	3	3	3	3	30	15	4	3
Secondary										
Consumption ($Whkm^{-1}$)	665	300	680	260	255	200	170	130	270	200
Emissions (gCO_2km^{-1})	175	80	130	50	30	25	10	7	20	15

Table 1: Primary and secondary performance assumptions: The technology specific performance levels for the primary performance attributes and the second performance attributes are provided. The technology potentials stem from expert interviews with researchers of the Swiss Federal Institute of Technology (Boksberger 2011).

In a comparison of all alternatives, BEV face the biggest challenge compared to the incumbent technology, as their secondary performance cannot offset the large primary performance deficits mainly resulting from the range and refueling performance deficit. The other three alternatives have secondary performance advantages and rather minor deficits in primary performance [58].

	Petrol	CNG*	EREV-Mix	Electricity**	H2 (electrolysis)
Emissions (gCO_2MJ^{-1})	73.2	52	30	15	20

Table 2: CO2 concentration of fuels: * CNG is mixed with Biogas. ** We assume that a low-carbon energy production has replaced the current system in the long run.

Without additional policy regulations, ICEV and NGV will remain the cheapest technologies in the future, directly followed by BEV. Forth in line are EREV. FCEV are assumed to remain the most expensive alternative in the long run [20, 52, 59-62]. Fig. 6 displays the price development for the considered vehicle technologies. The decrease in price depends on learning by search (in the first phase) as well as on learning by doing and using (mainly from 2017 to 2030). Exhibit a) illustrates the effect of an infrastructure barrier for FCEV, where exhibit b) illustrates a scenario, where the barrier has been alleviated. It results in a further price de-

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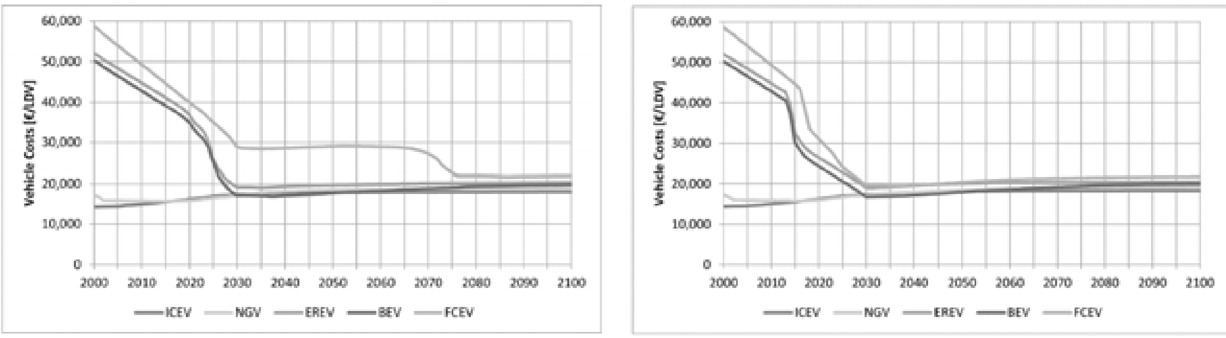
cline down to competitive levels around 2030 since learning effects could be deployed successfully.



a) b)

Fig. 6: Price development: The price development of the advanced vehicle technologies depends on the deployment of learning effects. a) illustrates a price curve with limited learning effects due to infrastructure barriers. b) illustrates price curve with fully deployed learning effects.

CO_2 emission targets follow the European regulation No. 443/2009 introducing a mandatory CO_2 emission limits for new LDV of 130 gkm^{-1} until 2015, and 95 gkm^{-1} until 2020, respectively. For the post 2020 situation, we assume a further reduction to as low as 20 gkm^{-1} until 2050. This value is low enough for purely electric alternative drivetrain technologies to become essential - under the premise that electric power is produced with as low as 15 gCO_2MJ^{-1} and synthetic fuels cannot be produced on a large scale. Validation and calibration analysis has shown that without a reasonable price reduction of alternative technologies reaching the ICEV-level, CO_2 emission standards below 60g to 80g per kilometer will be disruptive for the car industry, given customers keep their income to vehicle ratio. They can even be counterproductive, as increasing vehicle prices will motivate customers to hold on to their vehicle longer, with an undesired effect on fleet emission.

The population development is based on the UN medium scenario [63]. It will peak in 2050 and from there start to slightly decrease [64]. Real income will rise by 50% until mid century. The assumptions are based on an extrapolation of EUROSTAT values. For the utility calculation the purchase price is stronger weighted than kilometer costs. Only kilometer costs of the first four years are taken into account. The kilometers traveled per vehicle and year is kept constant. A fueling station infrastructure is no longer seen as a restraint, when 10% alternative stations of the gasoline stations are in operation [65]. This is at the lower end of what is suggested in the literature [66, 67]. We assume a fuel price scenario, where fossil fuel prices increase by 150%, natural gas by 100%, and electricity by 50% until 2050. The values are higher than forecasted in other studies [68]. We assume that electric or hydrogen driven vehicles can be used as a buffer thus profit from lower energy prices. But it is assumed that hydrogen will be produced by electrolyses, and thus remain more expensive than electricity. Hence, hydrogen faces a tradeoff between fuel costs and CO_2 emissions [69].

The resulting model behavior with these BASE run settings are displayed in Fig. 7 a-d) for the model variables 'Total LDV', 'Total CO_2 Emissions', 'Sales Share by Technology', and 'Firm Cash'. We see that within the BASE scenario, NGV, EREV and ICEV may dominate nearly equally the market around 2050, while BEV and FCEV only enter the market in the second half of this century. CO_2 emissions can be reduced substantially but will not reach the ambitious EU target of nearly 70% till 2050. Firm cash may decline till 2050 but will recover afterwards. This BASE simulation will be compared with simulation results of combined strategy and policy experiments.

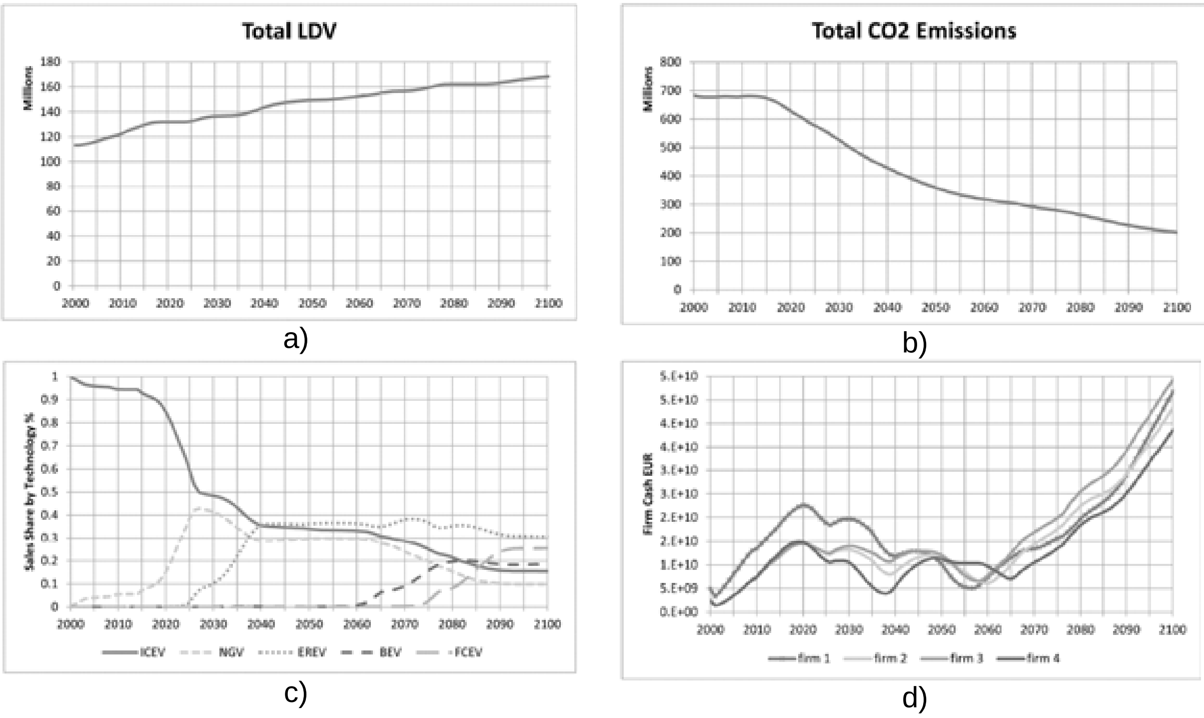


Fig.7: BASE behavior: The BASE behavior of the model is demonstrated with the four reference variables: a) Total LDV; b) Total CO_2 Emissions; c) Sales Share by Technology; d) Company Cash. The term in the bracket indicates the relevant constituent of the four classes: company, technology, fuel, market.

4 Policy and Strategy Simulation Experiments

The purpose of the simulation experiments is to better understand the interaction of industrial viability, and public policy for mitigating diffusion barriers, as well as CO_2 emission targets. To this aim we have analyzed two critical policy approaches (mitigating infrastructure barriers and enforcing policy compliance) in combination with a firm internal market introduction strategy (i.e. a firm internal cross-subvention strategy of alternative vehicles for their market introduction).

Table 3 gives an overview of the different infrastructure and non-compliance penalty policy scenario. Each policy has a low, medium, and high scenario. The infrastructure policy is additionally differentiated by fuels. This policy establishes a protected early fueling station infrastructure. For NGV 500 additional fueling station are built in 2012 yielding a level of 2000 fueling stations, the built up of electric charging stations starts in 2013 and hydrogen fuel stations in 2015. For the CO_2 emission policies, the penalty tax is either kept constant or a progression of varying magnitude is applied between 2040 and 2100 as indicated in Table 3.

Emission policy	A: Constant	B: Doubling	C: Highly progressive
Noncompliance penalty **	x	2x ***	10x ***

Fuel stations policy	1: Low	2: Medium	3: High
CNG (additional FS)	500	1000	2500
Electricity*	1200	2400	4000
Hydrogen*	1200	2400	4000

Table 3: Settings of the policy and strategy experiments: * Initial niche market value of fueling stations in 2013 for electricity and in 2015 for hydrogen. ** 100 Euro per gCO2 above emission target. *** Value in 2100.

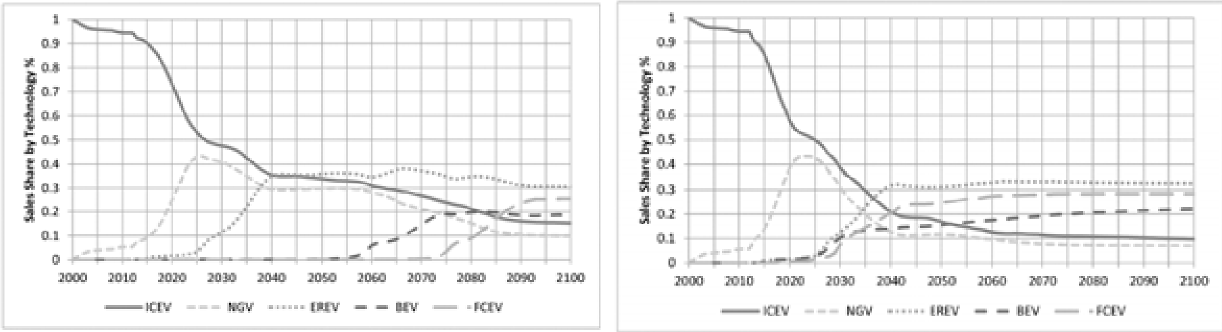
The public policy analysis has been combined with a firm internal cross-subvention strategy for the market introduction of alternative vehicles. We have furthermore compared different firm strategies. In the BASE scenario, no cross-subvention of the firms applies. In F1, the market leader cross-subvention scenario, only firm 1 applies cross-subvention that reduces the purchase price of alternative vehicles towards 150% of the ICEV option, during the early market introduction while alternative vehicle costs still are prohibitiv high. We have also analyzed the impact of an active cross-subvention strategy of the competing firm 2. The simulations show similar patterns as in F1, but its effects on the market has been less pronounced.

4.1 Simulation Results

In the following some combined policy and strategy simulation results are shown that illustrate typical behavior patterns observed in many experiments. The effects of the chosen policy and strategy settings are discussed regarding the resulting technology specific diffusion pattern (with the rate variable 'Sales Share by Technology'), regarding economic viability (with the stock variable 'Cash') and CO_2 emission mitigation (with the rate variable 'Emissions').

4.1.1 Technology Specific Diffusion Patterns

Fig. 8 compares the technology specific diffusion patterns of the combined policies 'low infrastructure availability policy' and 'low constant penalty tax' A1 (left side) with 'high infrastructure availability' and 'highly progressive penalty tax' C3 (right side) both for the proactive market leader case (F1). In the rather conservative policy environment F1A1 (that correlates strongly with the BASE scenario shown in Fig. 7) BEV and FCEV enter the mass market only in the second half of the time horizon, where as in the thightened policy environment F1C3, EREV, BEV and FCEV enter the mass market in the first quarter of the time horizon. The early market introduction is due to the improved infrastructure conditions, while the stronger replacement of the ICEV and NGV is triggered by the highly progessive penalty scheme in the second half of the time horizon. Both results show that after the transition from ICEV towards alternative technologies, no single dominant technology can be identified and that EREV, BEV, and FCEV tend to co-exist. Furthermore, in both scenarios we see no full crowding out of the ICEV and NGV.



a) b)

Fig. 8: Comparison of technology specific diffusion patterns: The technology specific diffusion patterns are influenced by different policy environments: a) with the rather conservative policy setting F1A1 and b) with the tightened policy environment F1C3. The run acronyms (e.g. F1C3) reads as follows: The first two characters indicate the applied strategy of the firm and the third and forth character indicate the applied strength of the non-compliancy penalty and the infrastructure policy as explained in Table 3.

4.1.2 Trends in Economic Viability

The typical trends of different policy and strategy packages on the economic viability are illustrated in Fig. 9. The BASE C1 approach with passive cross-subvention strategies of all companies, and low infrastructure availability as well as a high penalty tax, results in an industrial breakdown. In the first half of the time horizon, NGV and EREV help to achieve sufficient policy compliance. However, in the second half, when stronger standards and a higher penalty tax apply, the companies have not enough time and cash to ramp up the market introduction of the near zero emission BEV and FCEV. But the most striking finding of this analysis is the behavior patterns of the best perfoming policy and strategy packages F1A2, F1A3 and F1B3. It shows that active cross-subsidizing of the market leader is a rewarding strategy in the long run, even with a low infrastructure availability (F1A1). However, we can observe ‘a first worse before better’ behavior pattern, because investment into the production capital for alternative vehicles around 2020 helps to avoid high penalty payments after 2040.

The F1A1 package illustrates the long term outcome of an underinvestment behavior due to a modest fueling infrastructure in the early phase, resulting in an inferior cash performance after 2030. F1C3 on the other extrem shows how tough regulations and high penalty tax have an imense effect on the firm performance level.

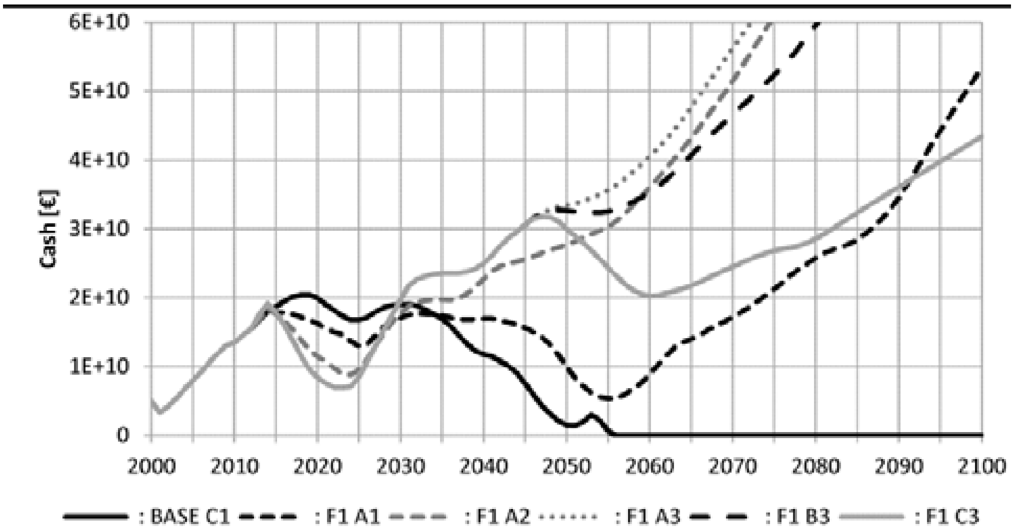


Fig. 9: Trends in economic viability: The trends in economic viability are influenced by the varying combination of strategies and policies.

4.1.3 Industrial's CO_2 Emission Pathways

Fig. 10 reveals typical trends of CO_2 emission mitigation paths induced by the different policy and strategy packages. The most interesting finding is that policy packages which are most rewarding for a proactive market leader also results in most promising CO_2 emission reduction paths. This can be seen with the F1B3 package that nearly achieves a comparable CO_2 mitigation performance as the most strict package F1C3 that yields inferior economic results for the proactive market leader, due to the high penalty tax.

We see that the best performing mitigation pathway results in a CO_2 emission reduction of around 56% by 2050 and in 79% by 2100 (base year 2000), meaning that the sectoral EU reduction target for transportation of 54-67% by 2050 remains a challenge.

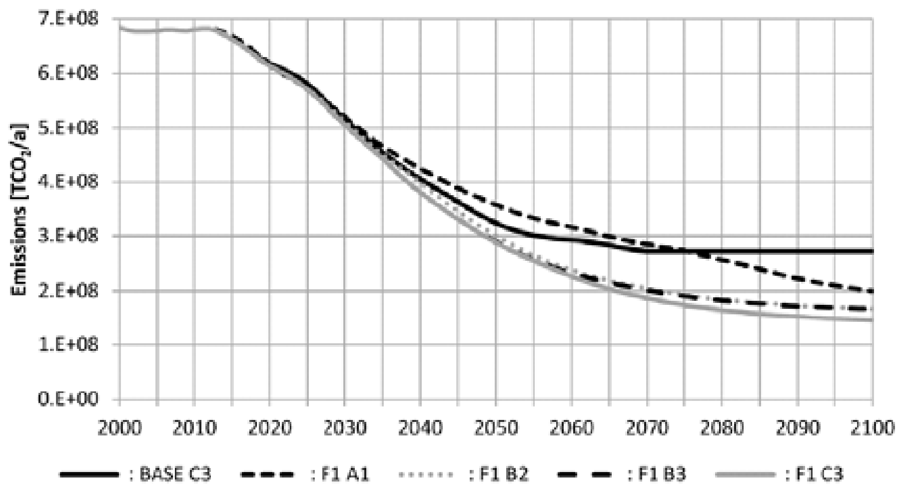


Fig. 10: Industrial's CO_2 emission pathways: The CO_2 emission pathways are influenced by the varying combination of strategies and policies.

4.2 Discussion of Simulation Results

In the following the main determinants causing typical behavior patterns of the simulation experiments are discussed.

4.2.1 Determinants and Their Effect on Technology Specific Diffusion Patterns

The simulation experiment with the conservative policy environment F1A1 (Fig. 8, left side) shows that ICEV remain the most prefered option until 2020 with the CO_2-emission limit of 95 gkm^{-1}. Stronger limits will foster the diffusion of the alternatives NGV and EREV. While NGV are cost competitive and a minimal CNG fueling station infrastructure has been in place since the year 2000, additional policy support for the infrastructure build-up would help to increase the attractiveness of NGV.

EREV do not face a public infrastructure barrier, but will become cost competitive only around 2030. That explains their strong take off at that time. For BEV and FCEV the low infrastructure availability policy seems not to be sufficient to foster their take off before 2050. The comparison with the high infrastructure availability policy shows that this policy does not primarily accelerate their diffusion rate, but enables an earlier market entry. This finding suggests that due to system inertia it may be harder to accelerate the diffusion of alternative vehicles directly than to mitigate infrastructure barriers. But the right timing of infrastructure support is important. It becomes most effective when technology enhancement depends primarily on 'learning by doing & and using' and helps to decrease technology cost. In such strategic moments, not only a lack of demand affects the development of the technology itself, but also an insufficient infrastructure is hindering the technology from reaching an attractiveness level acceptable by a large interest group. This pronounces the well-known chicken-and-egg problem of network externalities.

System inertia arises due to production capital build-up and time lags. This also explains the flat diffusion curve of alternative drivetrain technologies in an early phase. Carmakers are cautious not to ramp up their production line for alternatives too fast, as they would have to bear the risk of technology failure [70, 71].

The vehicle price assumptions applied in the model are comparable with those in the literature [20, 59, 60, 62]. The price decline and technological improvements result in the co-existence of different alternatives. No one technology out performs the others significantly, thus rather leading to a technology mix than a technology takeover. This finding corroborate a most recent conjoint analysis [72] that shows how a share of up to 40% of the customers would still buy an ICEV in 2035, even if prices would be the same for all technologies and all would show similar primary performance levels. Further on, the dominance of petrol driven vehicles is challenged by NGV and EREV and later on by FCEV and BEV, whiteout strict policy regulations, ICEV will still be on the roads in 2100, according to our findings. Also, ICEV are to be expected to remain at the low end of vehicle costs and thus stay a viable option also for suppliers.

However, NGV can be expected to play a major role over the next decades, if the current fueling infrastructure is further developed and ambitious CO_2 emission regulations for LDV become effective. Whereas the performances of NGV, EREV and FCEV can compete with those of ICEV, BEV have a hard stand. Their advantage lies with low consumption and thus low emissions. But BEV may remain a segment specific technology due to their driving range deficit unless consumers will renounce it.

4.2.2 Distinctive Effects on Trends in Economic Viability

An in depth analysis of the simulation runs in Fig. 9 shows the influence of different policy and strategy measures on the economic viability of a firm in the carmaker industry in distinctive ways. They control the strength of the 'first worse before better behavior' trend. Fig. 11 schematically points out their distinctive effects on the company cash trends.

A firm's proactive innovation behavior (i.e. cross-subvention strategy of alternative vehicles) in general decreases the company cash in the first two quartiles, while it helps to strengthen the strategic position of the company in the third quartile. However, the resulting competitive advantage depends on the policy environment.

The provision of an early fueling station infrastructure propels further investments in technology development and production capacity adjustments. Subsequently it decreases company cash in the second quartile. Likewise tightening standards and high penalties decrease company cash primarily after 2040. But such a policy environment rewards innovative companies with a higher competitive edge, i.e. they can capitalize on their earlier investments.

The overall cycle pattern seems to play out over a time period of 50 years. It is strongly influenced by the climate policy regime and the innovation investment behavior of firms. It results in a sectoral boom phase once the transition towards near zero emission vehicles has been mastered. The policy induced technology change pattern is comparable to the long wave theory in terms of its duration and the argument, that deep structural causes are innovation processes in whole technological systems [6]. According to Freeman (1988) favorable conditions for such transitions are "complementarities between innovations and the emergence of an appropriate infrastructure as well as some degree of political stability and institutions which do not hinder too much the diffusion of new technologies" [6]. Freeman (1988) agrees with Schumpeter (1961) that such techno-economic paradigms changes induce profound adjustments in social and institutional framework that may cause periods of deeper depressions [6, 73]. According to this theory and based on our findings, we should take into consideration that carmakers' second quarter of the 21st century may fall short with the first in its achieved financial progress. But an up-turn may be expected in the third quarter. However, the endogenous transformation framework (section 2.2.1) suggests that collaborative knowledge development and sharing between carmakers may rather result in a creative transition process than a creative destruction of the existing carmaker industry. However, this does not exclude the danger of a takeover of smaller carmakers by leading carmakers.

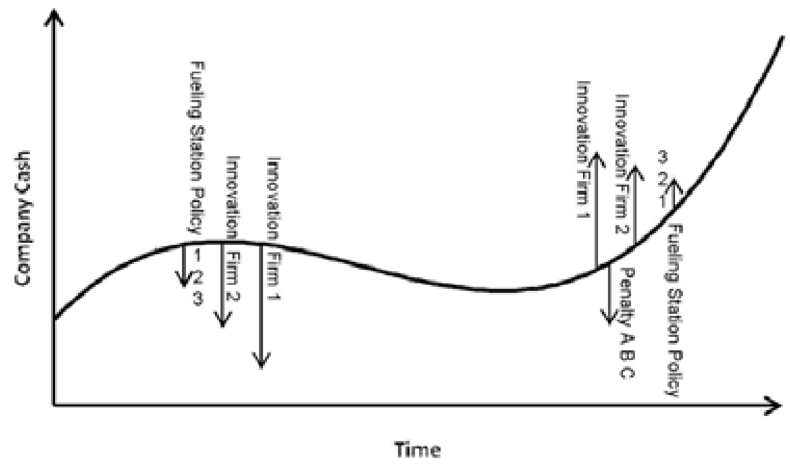


Fig. 11: Distinctive effects on economic viability: the long term view: The long term view highlights the transition decades of the first half of this century which are followed by a sectoral boom phase. The effects of the different strategy and policy settings are indicated.

Examining further the simulation results in Fig. 9, we can identify shorter distinct fluctuations within decades in the first half of the time horizon. These patterns are schematically highlighted in Fig. 12. Based on model inspection, the drivers of the single short term cash cycles can be discussed. Differences between cash inflow and outflow over time that are triggered by strategy and policy changes explain the fluctuations (A to E) in the stock variable 'Company Cash'.

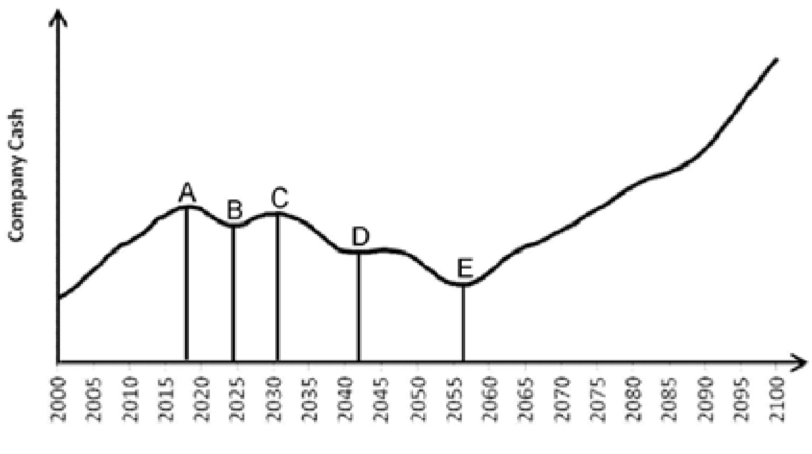


Fig. 12: Distinctive effects on economic viability: the short term view: The short term view differentiates short term fluctuations during the transition decades.

- Downturn in A: Investments into the production of NGV and cross-subsidizing strategies increases cash outflow. Alternative drive train technologies are subsidized for 10 years until 2023 for EREV and BEV as well as until 2025 for FCEV.
- Upturn in B: The subsidizing and investment for NGV production capital has stopped. Therefore cash outflow is reduced below the level of cash inflow which results in a cash increase.
- Downturn in C: The vehicles sold per year of the companies do not comply with the CO_2 emission targets, which results in growing penalty taxes that increases the cash outflow. At

the same time, capital is invested for the production of EREV, BEV, and FCEV rising cash outflow further.

- Downturn D: The progressive penalty tax is introduced in 2040. Its effects start to show, specifically when the near zero emission limit of 20 gkm^{-1} becomes effective until 2050.
- Upturn E: The transition phase towards near zero emission technologies has ended. Companies are able to capitalize on their investments and to reap scale economies resulting from the mass market penetration of advanced vehicle technologies.

In sum, the financial fluctuation of the induced technology change can be explained by the arising policy pressure and successive technology investments as well as their successive capitalization, offering a slightly different perspective to Schumpeterian business cycles.

4.2.3 Directional Effects on the CO_2 Emission Pathways of the LDV Fleet

Finally, the directional effect of the different policy and strategy measures on the fleet's CO_2 emission reduction path is systematically discussed as highlighted in Fig. 13. The build-up of the fueling infrastructure leads to earlier CO_2 emission reductions resulting from the earlier uptake of the alternative vehicles. Innovative firms improve the mid-term CO_2 emission reduction effect, too. Strong standards actually determine the overall magnitude of the CO_2 emission reduction in 2100. On the one hand strong standards with a higher penalty tax support the achievement of CO_2 reduction targets under supporting infrastructure conditions. On the other hand an insufficient infrastructure with a high penalty tax scheme (C1) may be counterproductive, as the firms loose their innovation capital or may even exit the market. The balance between cost and benefits is strongly shifted (Compare also Fig. 9 and Fig. 10).

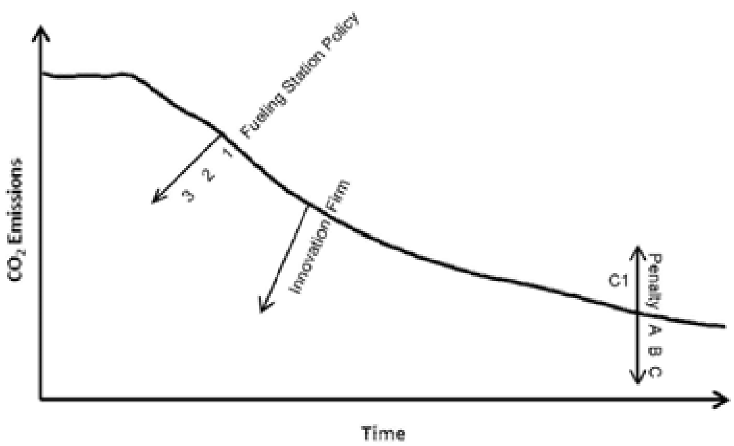


Fig. 13: Directional effects on the CO_2 emission pathway: The different strategy and policy settings have distinctive effects on the shape of the CO_2 emission pathway.

5 Strategy and Policy Implications

Based on our findings four recommendations for carmakers and eight implications for policy makers are elaborated.

5.1 Strategy Implications

First, collaboration between carmakers is a decisive strategy in order to cope with induced technology change processes and to avoid a strong adjustment crisis (i.e. industrial disruption). As a result of increasing policy pressure to reduce vehicle CO_2 emissions, it is to be expected that even more car companies need to engage in some sort of cooperation with competitors.

Second, proactive innovation behavior is rewarding during strategic moments (i.e. when learning by doing and using become crucial) and in a benign policy environment. Therefore, lobbying for a tight CO_2 emission regulation may be an important strategy for carmakers in order to reap the gain of investments into the improvement of the secondary performance, and proactive innovation behavior. Higher CO_2 emission standards and penalties create a geographical market in Europe that is hard to invade by competitors with a production cost advantage.

Third, in order to keep up customer acceptance and to accelerate the diffusion of advanced drivetrain technologies, carmakers may need to serve the highly segmented car market with a wide variety of types offered per technology. Therefore, highly flexible vehicle design platforms that allow producing a fast changing mix of drivetrain technologies and car types may be cost effective. At the same time, new car designs may rapidly become obsolete as the successive technological advancement of the alternatives lead to still better performing vehicles. Subsequently, the broader technology portfolio requires also a very flexible just-in-time production and supply chain, in order to avoid costly over- or under-supply. That being said, European carmakers still need to be sensitive to other geographical markets, with different demand characteristics and policy environments, which have not been considered in this analysis.

Finally, it is worth mentioning that the overall market size for the carmaker industry may shrink if future technology improvements lead to higher vehicle costs. Consequently, R&D efforts, and process optimization, as well as supply chain coordination needs to be directed towards vehicle cost reduction, in order to keep the car market size at least stable.

5.2 Policy Implication

First, a minimal infrastructure for alternative fuels is essential for the acceptance and diffusion of new technologies. Based on the literature and our analysis, 10% of the existing fuel infrastructure is needed in order to mitigate the infrastructure barrier sufficiently. Therefore partnerships for the build-up of adequate fueling infrastructures are a high leverage point.

Second, we have learnt that diffusion takes at least 10 years for a fleet large enough to support a self sufficient fueling infrastructure. In the mean time, the infrastructure needs to be subsidized. Whether the subsidies stem from public or private actors or a combination of both, needs to be negotiated. The timing of the infrastructure build-up is important, the strategic right moment depends again on the relevance of learning by using and doing. In order to keep the subsidies to a minimum, the infrastructure should be built up, once the alternative drivetrain vehicles approach mass production.

Third, not each fueling station generates the same turnover, it depends on its location. At the same time, the utility of the fueling station infrastructure increases with its geographical coverage, resulting in so called network externalities. Therefore, suppliers need to balance overall infrastructure coverage criteria with averaged profitability consideration. This characteristic indicates that homogenously composed supplier organizations (e.g. public private partnership) are most adequate.

Forth, the profitability of the fueling station infrastructure tends to decline with efficiency increase of vehicles, in general. This specifically turns out to be very critical for alternative fueling infrastructures. For example, with current construction costs of either H_2-stations or electric public (fast-) charging stations it is difficult to build a business case solely on selling energy. Either the cost of building charging and fueling stations need to drastically decline or new finance mechanisms need to be developed.

Fifth, a long term prospect of tightening standard setting is most important in order to reduce the environmental uncertainty for firm’s investment behavior. The emergence of near zero emission technologies till 2050 depends critically on the projected reduction level. Furthermore, tight reduction levels reward firms’ proactive search and innovation behavior, as highlighted above.

Sixth, a moderate non-compliance penalty scheme is more conducive for both the carmaker industry and overall CO_2 emission reduction. Although high taxes shift research investments from primary to secondary performance, it may trigger policy resistance further downstream. A penalty tax is added to the vehicle price that affects overall new sales and leads to a longer use of existing vehicles and a postponed scrapping. Hence a price increase extends the vehicle lifetime. Subsequently, the emission reduction potential of new cars is given away.

Seventh, in the long run a radical policy option would be to prohibit the sales of vehicles that do not comply with certain emission standards. Also stimulating earlier scrapping of inefficient vehicles is promising. For one it increases the diffusion rate as old cars are replaced faster with new more fuel efficient vehicles. In addition it prevents undesirable side-effects of price policies.

Finally, a decrease in the LDV fleet’s CO_2 emissions that goes beyond 50% seems feasible until 2050, with the applied technology development assumption, a sufficient infrastructure and stable mobility demand. But higher reduction target requires extended policy packages, focusing directly on travel behavior change. However, in this paper we did address neither consumer demand driven emission reduction nor rebound effects.

6 Conclusion

A generic industrial transformation model (ITM) has been applied to the carmaker industry in Europe. The study has highlighted main structures and dynamics influencing a socio-technical transition and has informed the formulation of strategy and policy recommendations for ecological driven innovation strategies in the carmaker industry.

This study has shown that the ITM model allows to assess prospectively threats and opportunities of induced technology changes for industries, as well as to identify promising governance approaches supporting socio-technological transitions. The simulation exercise provides evidence that smart governance approaches involving concerted entrepreneurial and political decision making can avert severe industrial crisis of adjustment during phases of socio-technical transitions. Smart strategy and policy making helps to stabilize the European carmaker industry during the induced technology change phase. Its core determinants are inter-organizational knowledge sharing, proactive innovation strategies of firms aligned with corresponding policy and infrastructure adjustments. This implies on the other hand that companies lacking adaptive and absorptive capacity may be disadvantaged in international competition, if system changes start favoring clean vehicles.

On this base, the ITM framework and model discussed, portrays the notion of 'creative transition' as an alternative to 'creative destruction' as coined by Schumpeter. However, we have also seen that this requires successive investment behavior of the carmaker industry in the next three decades. This depends on confidence in long term policy targets and corresponding financing mechanisms. Alternative drivetrains are necessary to lower the fleets' CO_2 emissions in the long run, yet they will have modest impact on CO_2 emission reductions in the years ahead, due to their slow diffusion uptake. Therefore, it is necessary to drive down the emissions of the incumbent technologies while building up the system necessary for alternative ones. However, this will remain a major challenge since the large social benefits as well the economic attractiveness of a fueling infrastructure build-up becomes effective not until a few decades have passed.

Although we are confident that the findings are robust concerning the policy and strategy implications, we would like to emphasize that the model results should not be seen as forecasts but as scenario explorations. Due to simplification, the model has several limitations. For example, fueling station construction does not take into consideration, that some fueling stations are visited more frequent then others. Also, purchase behavior, operational or driving behavior change is not considered (e.g. rebound effects). Further on, likely impacts from complementary niche markets that apply also alternative propulsion technology are not taken into account. Therefore, explosive surges of interrelated innovations as often observed in techno-economic paradigm change are not considered.

In further research, the model could be applied within stakeholder dialogs in order to inform concerted policy formulation and road mapping, but also to explore further strategy and policy approaches. Not only policy and strategy approaches may be evaluated but also the value added of a simulation based scenario analysis may be assessed.

Acknowledgments

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Literature

1. IEA, *CO_2 emissions from fuel combustion*, in *IEA Statistics*. 2011, International Energy Agency: Paris.
2. EC, *A sectoral perspective.* European Commission: Climate Action, 2011.
3. Edenhofer, O., et al., *Induced Technological Change: Exploring its Implications for the Economics of Atmospheric Stabilization: Synthesis Report from the Innovation Modeling Comparison Project.* The Energy Journal, 2006: p. 57-107.
4. Abernathy, W.J. and K.B. Clark, *Innovation - Mapping The Winds Of Creative Destruction.* Research Policy, 1985. **14**(1): p. 3-22.
5. Tushman, M.L. and P. Anderson, *Technological discontinuities and organizational environments.* Administrative Science Quarterly 1986. **31**: p. 439-465.
6. Freeman, C. and C. Perez, *Structural crises of adjustment, business cycles and investment behavior*, in *Technical Change and Economic Theory*, G. Dosi, et al., Editors. 1988, Pinter: London, New York. p. 38-66.
7. Henderson, R.M. and K.B. Clark, *Architectural Innovation: The reconfiguration of existing systems and the failure of established firms.* Administrative Science Quarterly, 1990. **March 1990**: p. 9-30.
8. Dolata, U., *Technological innovations and sectoral change: Transformative capacity, adaptability, patterns of change: An analytical framework.* Research Policy, 2009. **38**(6): p. 1066-1076.
9. Geels, F.W., *Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective.* Technological Forecasting and Social Change, 2005. **72**: p. 681-696.
10. Geels, F.W., M.P. Hekkert, and S. Jacobsson, *The dynamics of sustainable innovation journeys.* Technological Analysis & Strategic Management, 2008. **20**(5): p. 521-536.
11. Rotmans, J., R. Kemp, and M. van Asselt, *More evolution than revolution: transition management in public policy*. foresight, 2001. **3**(1): p. 15-31.
12. OECD, *Fostering Innovation for Green Growth (OECD Green growth studies)*. 2011: OECD Publishing.
13. Foxon, T. and P. Pearson, *Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime.* Journal of Cleaner Production, 2008. **16**(1, Supplement 1): p. S148-S161.
14. Vergragt, P.J. and H.S. Brown, *Sustainable mobility: from technological innovation to societal learning.* Journal of Cleaner Production, 2007. **15**(11-12): p. 1104-1115.
15. Köhler, J., et al., *A transitions model for sustainable mobility*. Ecological Economics, 2009. **68**(12): p. 2985-2995.
16. Zachariadis, T., *Assessing policies towards sustainable transport in Europe: an integrated model.* Energy Policy, 2005. **33**(12): p. 1509-1525.
17. Schwoon, M., *Learning by doing, learning spillovers and the diffusion of fuel cell vehicles.* Simulation Modelling Practice and Theory, 2008. **16**(9): p. 1463-1476.

18. Dougherty, W., et al., *Greenhouse gas reduction benefits and costs of a large-scale transition to hydrogen in the USA*. Energy Policy, 2009. **37**(1): p. 56-67.
19. Collantes, G.O., *Incorporating stakeholders' perspectives into models of new technology diffusion: The case of fuel-cell vehicles*. Technological Forecasting and Social Change, 2007. **74**(3): p. 267-280.
20. Kloess, M. and A. Müller, *Simulating the impact of policy, energy prices and technological progress on the passenger car fleet in Austria - A model based analysis 2010-2050*. Energy Policy, 2011. **39**(9): p. 5045-5062.
21. ACEA. *New Vehicle Registrations - By Manufacturer*. 2010 [cited 2011 October 12]; Available from: http://www.acea.be/news/news_detail/new_vehicle_registrations_by_manufacturer/.
22. Zapata, C. and P. Nieuwenhuis, *Exploring innovation in the automotive industry: new technologies for cleaner cars*. Journal of Cleaner Production, 2010. **18**(1): p. 14-20.
23. Christensen, T.B., *Modularised eco-innovation in the auto industry*. Journal of Cleaner Production, 2011. **19**(2-3): p. 212-220.
24. Andrews, D., P. Nieuwenhuis, and P.D. Ewing, *Black and beyond-colour and the mass-produced motor car*. Optics & Laser Technology, 2006. **38**(4-6): p. 377-391.
25. Sovacool, B.K. and R.F. Hirsh, *Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition*. Energy Policy, 2009. **37**(3): p. 1095-1103.
26. Taylor, A. *Toyota: The Birth of the Prius*. CNNMoney.com 2006 [cited 2011 December 7]; Available from: http://money.cnn.com/2006/02/17/news/companies/mostadmired_fortune_toyota/index.htm.
27. The Economic Times. *Nissan Leaf electric wins Japan car of the year*. 2011 [cited 2011 December 7]; Available from: http://articles.economictimes.indiatimes.com/2011-12-03/news/30471804_1_nissan-leaf-electric-cars-tokyo-motor-show.
28. van den Hoed, R., *Sources of radical technological innovation: the emergence of fuel cell technology in the automotive industry*. Journal of Cleaner Production, 2007. **15**(11-12): p. 1014-1021.
29. Orsato, R.J. and P. Wells, *The Automobile Industry & Sustainability*. Journal of Cleaner Production, 2007. **15**(11-12): p. 989-993.
30. Oltra, V. and M. Saint Jean, *Variety of technological trajectories in low emission vehicles (LEVs): A patent data analysis*. Journal of Cleaner Production, 2009. **17**(2): p. 201-213.
31. de Haan, P., *Erforschung des Autokaufverhaltens hinsichtlich Treibstoffeinsparung und Technologieakzeptanz. Forschungsplan zum Projekt „Entscheidungsfaktoren beim Kauf treibstofftreibstoffeffizienter Neuwagen*. 2007, IED-NSSI.
32. Grübler, A., *Technology and Global Change*. 1998, Cambridge: Cambridge University Press.
33. Bouza, M., *Comparison of possible transformation processes in the automobile industry* Proceedings of the 9th Swiss Transportation Research Conference, September 9. - 11. 2009, Monte Verità, Ascona TI, 2009.
34. Bouza, M., *Endogenous transformation in the automobile industry*. Proceedings of the 27th International Conference of the System Dynamics Society, July 26 - 30, 2009, Albuquerque, New Mexico, USA., 2009.
35. Nelson, R. and S. Winter, *An evolutionary theory of economic change*. 1982, Cambridge, MA: Belknap Press.
36. Sastry, M.A., *Problems and paradoxes in a model of punctuated organizational change*. Administrative Science Quarterly, 1997. **42**(2): p. 237-275.

37. Adner, R., *When are technologies disruptive? A demand-based view of the emergence of competition* Strategic Management Journal 2002. **23**(8): p. 667-688.
38. Christensen, C.M. and R.S. Rosenbloom, *Explaining the attacker's advantage: Technological paradigms, organizational dynamics, and the value network.* Research Policy, 1995. **24**(2): p. 233-257.
39. Cohen, W. and D. Levinthal, *Absorptive capacity: A new perspective on learningn and innovation.* Administrative Science Quarterly, 1990. **35**: p. 128-152.
40. Furman, J.L., M.E. Porter, and S. Stern, *The determinants of national innovative capacity.* Research Policy, 2002. **31**(6): p. 899-933.
41. Geels, F.W. and J. Schot, *Typology of sociotechnical transition pathways.* Research Policy, 2007. **36**(3): p. 399-417.
42. Smith, A., A. Stirling, and F. Berkhout, *The governance of sustainable socio-technical transitions.* Research Policy, 2005. **34**(10): p. 1491-1510.
43. OECD, *Special issue on "New Rationale and approaches in technology and innovation policy.* STI Review 1998. **22**.
44. del Río, P., J. Carrillo-Hermosilla, and T. Könnölä, *Policy Strategies to Promote Eco-Innovation.* Journal of Industrial Ecology, 2010. **14**(4): p. 541-557.
45. Stephens-Romero, S. and G.S. Samuelsen, *Demonstration of a novel assessment methodology for hydrogen infrastructure deployment.* International Journal of Hydrogen Energy, 2009. **34**(2): p. 628-641.
46. Schwoon, M., *Simulating the adoption of fuel cell vehicles.* Journal of Evolutionary Economics, 2006. **16**(4): p. 435-472.
47. Sterman, J.D., *Business dynamics: systems thinking and modeling for a complex world.* 2000, Boston: McGraw-Hill.
48. Ulli-Beer, S., et al., *Generic structure to simulate acceptance dynamics.* System Dynamics Review, 2010. **26**(2): p. 89-116.
49. Brownstone, D., D.S. Bunch, and K. Train, *Joint mixed logit models of stated and revealed preferences for alternative-fuel vehicles.* Transportation Research Part B: Methodological, 2000. **34**(5): p. 315-338.
50. Bouza, M., *Industrial transformation model: Model documentation.* 2010, Villigen: PSI Villigen. 287.
51. Bandivadekar, A., et al., *Reducing the Fuel Use and Greenhouse Gas Emissions of the U.S. Vehicle Fleet.* Energy Policy, 2008. **36**: p. 2754-2760.
52. Bandivadekar, A., et al., *Reducing the fuel use and greenhouse gas emissions of the US vehicle fleet.* Energy Policy, 2008. **36**(7): p. 2754-2760.
53. Meyer, I. and S. Wessely, *Fuel efficiency of the Austrian passenger vehicle fleet - Analysis of trends in the technological profile and related impacts on CO2 emissions.* Energy Policy, 2009. **37**(10): p. 3779-3789.
54. Hankey, S. and J.D. Marshall, *Impacts of urban form on future US passenger-vehicle greenhouse gas emissions.* Energy Policy, 2010. **38**(9): p. 4880-4887.
55. Utterback, J.M., *Mastering the Dynamics of Innovation.* 1994, Boston, MA: Harvard Business School Press.
56. Resent activities: Renault-Nissan (source), BMW and Toyota (source), BMW and PSA (source), but also failed attempt between BMW and Mercedes (source)
57. ACEA. *Average Car Age 2008.* 2010 [cited 2012 January 9]; Available from: http://www.acea.be/collection/statistics.
58. Boksberger, B. and S. Ulli-Beer, *Lokale Policy Roadmap 2020: Potentiale und Handlungsoptionen nachhaltiger Mobilität. Bericht im Rahmen des Novatlantis-Projekts "Erlebnisraum Mobilität".* 2011, Paul Scherrer Institut: Villigen, 7. März 2011.

59. Thiel, C., A. Perujo, and A. Mercier, *Cost and CO2 aspects of future vehicle options in Europe under new energy policy scenarios.* Energy Policy, 2010. **38**(11): p. 7142-7151.
60. Douglas, C. and A. Stewart, *Influences on the Low Carbon Car Market from 2020-2030. Final Report*. 2011, Element Energy Limited: Cambridge.
61. Streimikiene, D. and J. Sliogeriene, *Comparative assessment of future motor vehicles under various climate change mitigation scenarios.* Renewable and Sustainable Energy Reviews, 2011. **15**(8): p. 3833-3838.
62. McKinsey & Company, *A portfolio of power-trains for Europe: a fact-based analysis. The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles*. 2010, NEW-IG Secretariat: Brussels.
63. United Nations, *World Population to 2300*. 2004, United Nations: New York.
64. Due to model design constraints only half are relevant for the simulations.
65. For the whole European fleet this value would be at 8000
66. Sperling, D. and R. Kitamura, *Refueling and new fuels: An exploratory analysis.* Transportation Research Part A: General, 1986. **20**(1): p. 15-23.
67. Yeh, S., *An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles.* Energy Policy, 2007. **35**(11): p. 5865-5875.
68. Capros, P., et al., *European Energy and Transport - Trends to 2030 - Update 2007*. 2008, European Commission Directorate - General for Energy and Transport.
69. Offer, G.J., et al., *Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system*. Energy Policy, 2010. **38**(1): p. 24-29.
70. Mortsiefer, H., *"Elektroautos werden nicht alle Kundenwünsche erfüllen"*, in *Zeit Online*. 2011.
71. Spendelow, J. and J. Marcinkoski, *Fuel Cell System Cost - 2011*, in *DOE Hydrogen Program Record*. 2011, DOE.
72. Friedl, C. and K. Götz, *E-Mobil Akzeptanz*. Sonnenenergie, 2011(6).
73. Schumpeter, J.A., *Konjunkturzyklen. Eine theoretische, historische und statistische Anlyse des kapitalistischen Prozesses.* 1961, Göttingen: Vandenhoeck & Ruprecht.