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H_2 or e^-? Two scenarios for hydrogen as an automotive fuel

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Preface

"Yes, I am familiar with 'strategic niche management'. But I always wonder what it brings at the end of the day". These words, or words of similar meaning, were part of the very first discussion about the topic of my graduation project. There is an unmistakably sceptical ring to them, but the project has nonetheless been pursued – the thesis that lies in front of you is the fruit of it.

The quote serves to introduce two things I learned in the process of producing this thesis. First, what strategic niche management, or, more precisely, the Multi-Level Perspective that underlies it, indeed brings at the end of the day. I must admit that I was not able to offer an adequate reply at the time. I feel that, having completed this thesis, I can now tell that the insights resulting from the application of this perspective definitely have added value.
Second, I have learned the value of a sharp, sceptical, and open mind. Being open to every fact, idea, theory, and assertion that I came across in the course of my research, but also question them very critically, has been of utmost importance. Doing research, a sceptical mind is most indispensable.

This is not in the last place because the future of personal mobility – the topic of this thesis – is hotly debated. That the current system is unsustainable is more or less agreed. That changes are technically possible too – alternatives such as electric and hybrid cars were already on the road at the beginning of the previous century. The discussion is on *how* change will, or should, happen. And that is where this thesis contributes.

The opening quote is from Gert Jan Kramer. I very much appreciate his open and sceptical mind in the insightful discussions that we had. I am grateful that he offered me the possibility to write this thesis at Shell Global Solutions in Amsterdam and in the context of the THRIVE project.
I would also like to thank Geert Verbong, who has been my supervisor at the Eindhoven University of Technology. Although he shattered my idea that research in this area can be conducted in an entirely objective way, he also taught me how to gain insight from the many opinions, visions, and expectations that are around in the field.

Finally, I would like to thank Gijs Mom and the various THRIVE participants for discussions that greatly advanced my knowledge on a variety of (technical) topics.

Amsterdam, 5 April 2009
Bas van Bree

"He who lives by the crystal ball, soon learns to eat ground glass."

-- Edgar Fiedler (1929-2003) --

Executive summary

Personal mobility is an indispensable element of modern-day society. It has seen a tremendous increase over the past century, much of it due to the diffusion an improvement of the car. However, the system of personal transportation of which the car is part is running into problems. Fossil fuel resources are finite. Moreover, they are to a large extent located in politically unstable regions, which makes it plausible that supply issues will arise before resources are physically depleted. Furthermore, the use of fossil fuels in an internal combustion engine is the cause of all sorts of environmental stresses.
It is not a stretch of the imagination that the current system will change in the future. The problems outlined above can be solved by eliminating the use of fossil fuels (petroleum and diesel) in cars. Hydrogen is one of the more promising alternative fuels. Yet, it is by no means clear yet how the introduction of hydrogen will take place. Hence the research question of this thesis:

In what ways are hydrogen vehicles for use in personal transportation likely to develop?

In the Netherlands, a consortium of four organizations has joined in the project THRIVE to study how a refuelling infrastructure for hydrogen vehicles can be rolled out. They develop a model to determine the geographical and temporal developments of the rollout: numbers of hydrogen vehicles and refuelling stations over time.
The objective of this thesis is to support that work by taking a qualitative approach. A multi-level perspective (MLP) is adopted to study a possible transition to hydrogen. The MLP distinguishes three levels (figure 0.1). The middle level, the socio-technical regime, reflects a consistent configuration of several elements that enable the current system: technology, users (and their preferences), industry, policy, and science. These elements are in a state of dynamic equilibrium: although there is plenty of change, the system reproduces itself. The interactions between the actors at the regime level are governed by a set of institutional rules, e.g. user preferences, laws, and mutual expectations. At the lowest level, technological alternatives to the current regime are developed in niches. At the highest level, landscape developments take place, out of the sphere of influence of the actors in the regime. Landscape developments can put pressure on the regime, making it impossible to continue in the existing configuration. This can open a 'window of opportunity' for niche technologies to replace the regime technology. Most likely, the configuration in the socio-technical regime will change to accommodate the new technology and landscape pressures.
Based on the MLP, an analysis of the socio-technical regime in which the car is embedded has been carried out. The relevant actors are the car industry (referred to as original equipment manufacturers, OEMs), the oil industry, consumers, governments, and lobby groups. In the THRIVE project, the biggest need was more insight in the OEM-consumer relationship, so that investigation of institutional rules of this relationship was the focus of further analysis.

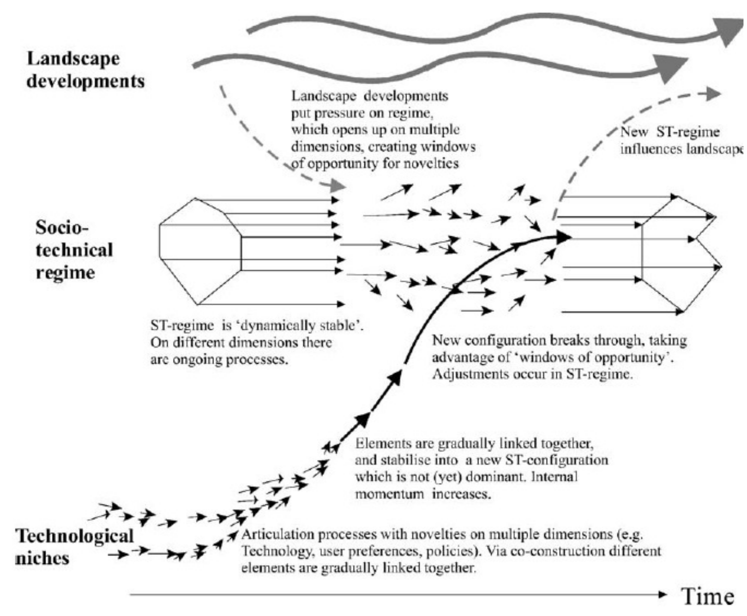

Figure 0.1 Illustration of a transition in the MLP. Source: Geels (2004a, p. 915)

	Consumer -> OEM rules
C1	Any product offering (including radically new ones) must be able to address symbolic-affective motives for car use on top of instrumental ones.
C2	Sufficient variety (in terms of models, brands, etc.) must be available in the product offerings of a particular technology for it to grow into a mass market technology.
C3	Consumers expect new product offerings to improve (incrementally) over old ones, except on attributes that are above their 'threshold' of marginal utility.
C4	The importance of attributes is (becomes) larger as their role in the trade-offs of the purchase process is (becomes) larger.

	OEM -> Consumer rules
O1	OEMs have a profit motive. They will continually update their product portfolio to offer the most profitable product mix.
O2	External pressure, such as government regulation and changing consumer preferences, is needed to alter R&D and product development search routines.
O3	The industry seeks to organize itself in the most profitable way, allocating design and production processes to the firms that can perform them most effectively.

Table 0.1 Institutional rules governing the OEM-consumer relationship.

Seven institutional rules were found to govern this relationship (table 0.1). Consumers attach meanings to their car. Any new product offering must be able to tap into these meanings to be successful (C1). Additionally, since groups of consumers (i.e. market segments) want to express different meanings, sufficient variety must be present in the cars offered of a particular technology for it to grow into a mass market technology (C2). Analysis of the development of cars in recent history found that cars improve incrementally on a number of attributes (e.g. size, safety, comfort, etc.). Consumers have come to expect new product offerings to improve over the previous offering, albeit only slightly, and will be reluctant to settle for less than what they currently have (C3). Consumers strike a balance between various attributes. Attributes become more important in the purchasing process as their impact on the trade-offs that the purchase process entails are larger (C4).

OEMs were found to engage in an upgrading process. They incrementally improve their existing line-up on a variety of attributes, often beyond levels that matter to consumers. They also extend their product lines by increasing the variety of models on offer. This way, they optimize the profitability of their product portfolio (O1). Under pressure, e.g. from governments through emissions regulation or from consumers if fuel prices rise, they change their R&D search routines away from this upgrading process (O2). The last rule states that industry structure is changing. In search for the most profitable division of tasks, OEMs are outsourcing more and increasingly complex tasks to suppliers (O3).

	Internal regime tensions
T1	Both consumers and OEMs have a preference for larger, safe, and comfortable cars. This puts a strain on the fuel economy of cars, which is exacerbated in times of inflated fuel prices. Shocks in fuel prices therefore imply difficult periods for the regime.
T2	Both consumers and OEMs have a preference for larger, safe, and comfortable cars. This puts a strain on the emission levels of cars (notably CO_2) and meeting regulated emission levels is increasingly difficult.
T3	The PLC in the car industry is shortening. OEMs are focusing on product-line extensions instead of product innovation. This is a sound short-term strategy, but innovation is necessary to address the challenges of the long term.

Table 0.2 Tensions in the socio-technical regime of the car.

These interactions between consumers and OEMs lead to a number of tensions in the regime (table 0.2). Increasing fuel prices, concerns over supply of fossil fuels and increasing environmental stresses are landscape developments that exacerbate the regime tensions. The institutional rules provide guides how these developments can allow niche-technologies to break through and solve the tensions. Two scenarios have been developed to illustrate how hydrogen vehicles might replace conventional vehicles. Acknowledging that hydrogen is not the only alternative, its closest ‘competitors’ to replace fossil fuels, battery-electric vehicles and hybrid vehicles, are considered in the scenarios too.

In the first scenario, Large-Scale Experimentation, emission regulations tihgten in two ways. At a (supra)national level, stringent targets for various emission types are adopted, while at a local level, governments adopt policies to discourage use of polluting cars to improve local air quality. At the same time, governments of all levels actively stimulate experimentation with alternatives. Experiments with electric vehicles are in the scale of hundreds of vehicles and focus on urban areas, while hydrogen experiments scale up to the order of thousands of vehicles, including the requisite infrastructure. Nonetheless, regime actors still invest in improving the internal combustion engine.
As emissions regulation tightens, this starts to change. OEMs are affected by the regulation in two ways: directly through fines, and indirectly through consumers that are affected by the regulation as well. Consumers switch to smaller cars and express an interest in alternatives. At this point, the regime actors start abandoning the internal combustion engine and focus on implementing an alternative. However, the two alternatives require significant infrastructure investments and exhibit returns to scale. A power struggle emerges. Hydrogen proves to be the winner, for three reasons: (1) consumers are reluctant to change their habits, (2) fuel cells are better able to meet their technological development targets, and (3) the coalition supporting hydrogen proves more powerful.
Regime actors scale hydrogen experiments up. Only a few models have been used in the experiments up to this point – now, existing models are extended to include a hydrogen version. Via their interest in the (limited-variety) alternatives, consumers have shown to be willing to relax rules C1 and C2. Moreover, they are happy to settle for less improvements, at least for the attributes that were less important them anyway (C3). This is convenient for OEMs, that grasp this opportunity to (temporarily) stop the upgrading process (O1). Interestingly, changes are now occurring without external pressure (O2).
As more models are introduced, the situation in the regime returns to that prior to the transition. The layout of the hydrogen infrastructure resembles that of the current infrastructure. The car is still largely the same, with the exception that it is now powered by a fuel cell. And perhaps most importantly, the institutional rules, relaxed during the transition, return to their old state.

The other scenario is called Gradual Breakthrough. In this scenario, fuel prices rise continuously and in a volatile manner. This causes fuel economy to move up the priority list and consumers revert to smaller cars during price shocks. This hurts OEM profit margins, who turn their search routines to reconciling fuel economy with their current model line-up. The internal combustion engine is improved, but improvements also come from the addition and substitution of modules such as start-stop technology and regenerative braking. This gradually transforms the car into a hybrid and then a plug-in hybrid vehicle. Consumers change their behaviour to recharging their vehicles overnight. The internal combustion engine is demoted to a ‘range extender’.
Consumers like driving on electricity, primarily because it provides protection from price shocks. The adoption of the various innovations occurs rapidly, because they are incorporated in the existing model range. On the one hand, consumers want vehicles that can cover their daily commute on battery-stored electricity. They will not accept battery enlargements beyond this point, which imply carting around expensive dead weight. A market segmentation based on daily travel needs emerges. In this respect, consumers do not expect gradual improvements to their vehicles anymore, changing rule C3. For OEMs, this means they lose an important instrument in the upgrading process (rule O2).
On the other hand, consumers want to travel further with their vehicle without using the internal combustion engine. Two options are available: fast charging or implementing hydrogen fuel cells. The latter solution wins, for a combination of three reasons: (1) consumers express a preference for hydrogen refuelling, which resembles their current refuelling habits, (2) fuel cells meet their development targets, and (3) the coalition supporting hydrogen proves most powerful.
A hydrogen infrastructure is rolled out. This is concentrated along highways, because fuel cells are used as range extenders only. The role of the oil industry has diminished in this scenario: the majority of trips is covered by using electricity obtained from the grid rather than hydrogen. Utilities have grown more powerful at the expense of oil companies.

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List of abbreviations

AFV	-	Alternative Fuel Vehicle
ASC	-	Alternative Specific Constant
bbl	-	barrel
CAFE	-	Corporate Average Fuel Efficiency
CARB	-	California Air Resources Board
CV	-	Conventional Vehicle
DfT	-	Department for Transport
ECI	-	Environmental Change Institute
ECMT	-	European Conference of Ministers of Transport
ECN	-	Energy research Centre of the Netherlands
EPA	-	Environmental Protection Agency
ETI	-	Energy Technologies Institute
EV	-	Electric Vehicle
FCV	-	Fuel Cell Vehicle
HEV	-	Hybrid Electric Vehicle
HV	-	Hydrogen Vehicle
ICE	-	Internal Combustion Engine
IEA	-	International Energy Agency
IPCC	-	Intergovernmental Panel on Climate Change
MLP	-	Multi-Level Perspective
MPV	-	Multi-Person Vehicle
OEM	-	Original Equipment Manufacturer
OPEC	-	Organization of the Petroleum Exporting Countries
NYMEX	-	New York Mercantile Exchange
PBC	-	Perceived Behavioural Control
PHEV	-	Plug-in Hybrid Electric Vehicle
PLC	-	Product Life Cycle
SP	-	Stated Preference
STSc	-	Socio-Technical Scenario
SUV	-	Sports Utility Vehicle
THRIVE	-	Towards a Hydrogen Refuelling Infrastructure for VEhicles
TNO	-	Netherlands Organisation for Applied Scientific Research
TPB	-	Theory of Planned Behaviour
TRI	-	Transport Research Institute

1 Introduction

Personal mobility is one of the cornerstones of our economy. Not being able to use modern personal transportation would deprive the majority of the developed world of access to jobs, schools, and vacations. The economy depends on access to such resources – in fact, personal mobility is closely correlated with economic growth, even more so than transportation of goods (Owen, 1987).

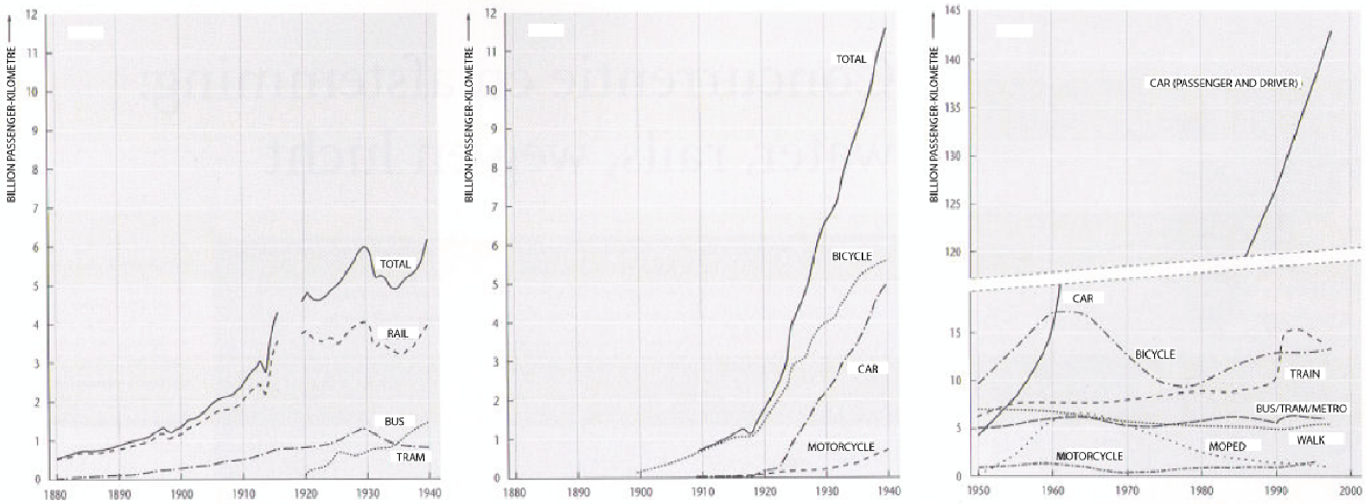

Figure 1.1 **Growth of personal transportation in the Netherlands. The left-hand and middle panel cover the same time period (1880-1940) but show different modes of transportation. The right-hand panel covers the period from 1950-2000.**
Source: http://www.techniekinnederland.nl/nl/images/4/49/Grafieken_passagiersvervoer.jpg.

The growth of personal transportation has been astounding (figure 1.1). The total number of passenger-kilometres travelled by bicycle, car, and motorcycle in the Netherlands increased more than tenfold in the period 1880-1940. The amount of passenger-kilometres travelled by car has increased almost thirtyfold since World War II. Indeed, the car represents the single most used mode of transportation in the developed world (Owen, 1987). The Netherlands are no exception (figure 1.2).

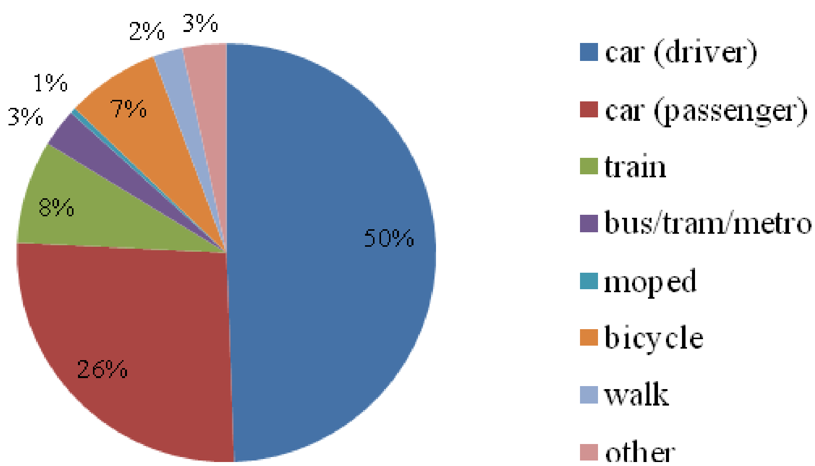

Figure 1.2 **Modal split in Netherlands in 2007, based in oassenger-kilometres**
Source: Rijkswaterstaat (2008).

That does by no means imply that the car represents the ultimate solution for personal transportation. Car use comes with a host of problems: among others use of the finite stock of fossil fuels, air and water pollution, noise production, and traffic-related injuries and deaths (Banister et al., 2000). Additionally, problems such as congestion suggest that there are imbalances in the system.

Despite these problems, the car has developed into an indispensable element of personal transportation. The history of the car goes back for more than a century. In this time the transportation system has developed to accommodate the car and vice versa, resulting in a firm lock-in of the car.

Many of the problems can be traced back to the use of fossil fuels in an internal combustion engine (ICE). Two types of lock-in explain the persistence of the car powered by an ICE: technological and institutional (Unruh, 2000). Current car design has evolved from a desire to equip carriages with an own means of propulsion. The early days of experimentation spawned a multitude of options to make a carriage movable ('mobilis') by itself ('αυτος'). Eventually, the current configuration gained popularity – a 'dominant design' had been established. This dominant design led to increasing returns from adoption. For instance, increasing production volumes caused unit costs to decrease (Langlois and Robertson, 1989; Friedlaender, Winston, and Wang, 1983). Learning economies accelerated development of the ICE and consumer uncertainty about ICE performance decreased. These developments contributed towards the technological lock-in of the ICE.

Besides these advantages of the ICE-equipped car at a firm level, interactions with other developments are a source of institutional lock-in. For instance, a network of places where fuel was available rapidly emerged, becoming more valuable as more ICE-powered cars entered the roads and vice versa. Automobile producers have joined forces in associations and worker unions have been formed. These associations tend to have an interest in maintaining the current dominant design (Galbraith, 1967). That they can be powerful is illustrated by the significant portion of production that is directly or indirectly linked with automobile production. The automotive industry accounted for approximately 7% of total manufacturing output in Europe and 6.5% of employment in the manufacturing industry in 2002 (European Commission, 2004). Institutions can also take a more abstract form. For instance, consumers have grown accustomed to the level of performance that the ICE provides, including a certain range. They have shaped their travel habits around this. To a large extent, in some countries more than others, they have grown to be dependent on their cars (Litman and Laube, 2002).

Governments contribute to institutional lock-in as well. For instance, a number of taxes is based on the use of the ICE. Especially in Europe, fuel taxes represent a large source of income for governments. In the Netherlands, no less than 57% of the pump price of petroleum consisted of taxes and excise duties in 2008 (BOVAG-RAI, 2008). In a broader context, there are more taxes that depend on car use and purchase, such as road taxation.

The major consequence of this lock-in is that the position of the car equipped with an ICE seems unassailable. From an economic standpoint, the current situation is optimally efficient – alternatives have to follow a path similar to the one the ICE-car has gone, implying that they are less efficient in the first stages of development and can never threaten the status quo.

That is, of course, as so often in economics, if all else remains equal. Yet, changes are impending. The problems that the current system faces are increasing. For instance, congestion has been on the rise up to the point that in many countries traffic jams have grown into a daily phenomenon and represent a significant part of (external) automobile costs (Litman, 1999). This thesis will focus on three developments that take place relatively independent of those directly or indirectly involved in car production, use, and maintenance:

1. *Exhaustibility of fossil fuels*
   Although much controversy surrounds this issue, there is a broad consensus that the stock of fossil fuels that are now used to power cars is finite. Current car use can therefore not continue indefinitely.
2. *Geopolitical issues in supply of fossil fuels*
   Fossil fuel resources from which automotive fuels are produced, notably the ones that are relatively easy to extract, are to a large extent located in politically unstable regions. This implies that issues relating to the exhaustibility of fossil fuels are due before they are physically depleted.

3. *Increasing environmental stresses*
   In its latest report, the Intergovernmental Panel on Climate Change acknowledges that climate change is to a large extent driven by human action (IPCC, 2007). This has led to a broad consensus that the emissions related to burning fossil fuels are a major cause of climate change. A significant part of these emissions are attributable to the use of ICEs in cars. Since anthropogenic climate change is now on the political agenda, future policies are expected to aim for significant reductions of emissions from cars.

These developments hold the potential to erode if not the position of the car in general, then at least the use of an ICE to power it. Alternatives that address one or more of these pressures on the car are available. This study examines the potential for fuel cells to replace the ICE and hydrogen to replace fossil fuels. Such a new configuration of the car holds the potential to solve all three tensions. Hydrogen can be made from a variety of sources, both fossil and non-fossil. If produced from a non-fossil pathway, none of the three tensions apply. Note that even if produced from fossil fuels, emissions are less than half of what ICEs currently produce (HyWays, 2008; more details are in chapter 6).
Using hydrogen as an automotive fuel is not the only solution to the problems of car use. The issues will therefore not be studied in isolation. The interaction between the three tensions outlined above, the way the car is locked in, and development of alternatives form the basis of this thesis. These are the building blocks for a number of scenarios that describe how the ICE might disappear from the use in cars, in some cases changing the way the car is perceived and used along the way. Two scenarios are the result of the exercise; the remaining chapters provide an explanation of how they came about. The ordering of the chapters is related to the research methodology, which is explained in the next chapter. A detailed outline is therefore postponed to the end of chapter 2 (and is summarized in table 2.2).

2 Research question, setting, objectives, and methodology

Changes to the current system of personal mobility can come in many forms. For instance, disappointed by the performance of the current mobility system, travellers might shift to modes of transport other than the car. Alternatively, travellers could revert to purchasing smaller cars. Both solutions mitigate all three pressures mentioned in the introduction, although further changes are required to abolish them altogether. They can be accomplished using current technology and they have been observed in the past (BOVAG-RAI, 2008; FHWA, 2008).
More radical changes can be envisioned. Futurists have proposed automated guided vehicles that replace road systems[1]. Another idea is to do away with the concept of automobile as a personal possession for city use. Within cities, small electric vehicles (EVs) can be retrieved from a rack and driven to the destination, where they are returned to yet another rack and recharged. Fees are calculated on the basis of the number of kilometres travelled[2].

2.1 Research question

However, given the strong lock-in of the car in the current system, its role is likely to remain largely unchanged in the coming decades. Pressures on the current regime must then be dealt with within the platform that the car currently offers. That will be the scope of this thesis – the development of technology that is used to power vehicles for personal transport. Therefore, its research question is formulated as follows:

In what ways are hydrogen vehicles for use in personal transportation likely to develop?

This question is very broad. The next section restricts the scope somewhat, and scope will be narrowed down further in chapter 3.

2.2 Research setting and objectives

This study has been carried out as part of a project named Towards a Hydrogen Refuelling Infrastructure for Vehicles (THRIVE). The objective of this project is to study "what the development of a hydrogen infrastructure for hydrogen vehicles (HVs) with respect to nature and size could look like in the Netherlands" (THRIVE, 2007). The focus of this thesis is therefore on the Netherlands. However, to be not too restrictive, if appropriate research carried out in other areas has been used nonetheless. Wherever possible, use is made of material that is specific for the Dutch situation.

More specifically, the research was carried out in the form of an internship at Shell, one of the partners in THRIVE. Three other organizations take part in THRIVE: the Energy research Centre of the Netherlands (ECN), Linde Gas Benelux, and the Netherlands Organisation for Applied Scientific Research (TNO).
THRIVE aims to study several aspects of a hydrogen infrastructure. Among the desired results is a model to calculate several scenarios for the spatial development of an infrastructure. This thesis seeks to complement this aspect. The conclusions can be used to support the assumptions surrounding the model's input parameters, as well as to interpret its outcomes.
This can be made more specific. The model simulates the time-dependent, spatial development of infrastructure required to fulfil the demand for hydrogen generated by HVs. An input parameter of the model is the uptake rate of HVs. Additional support for this parameter comes from the work in this thesis. Specifically, there is an assumption on the amount of competition that is present between several alternative fuels. The scenarios provide insight in how this competition might develop, qualitatively supporting quantitative assumptions about ultimate market shares.
A second objective is aiding the interpretation of the outcomes of the allocation model. Depending on different assumptions for the input parameters, the allocation model will generate various outcomes

[1] See, for instance, the idea of the JPod, a monorail-type system for personal transportation at http://www.intelligenttransportation.com/.
[2] A project by MIT's media lab. See http://cities.media.mit.edu/projects/citycar.html.

for the development of the hydrogen infrastructure. These outcomes can be compared to the scenarios outlined in this paper. Similarities and differences can aid in interpreting and calibrating each of the models (THRIVE as well as the scenarios).

As the next chapter will illustrate more elaborately, policy advice is not the main objective of the scenarios. This does not imply that policy issues and government influence are left out of the equation, but the question what specific policies are conducive for which alternative fuels is beyond the scope of this study. Instead, the government is assumed to exert a particular influence on the interaction between industry and consumers in each of the scenarios[3].

The scenarios are *not* meant as predictions of the future. Rather, they are a structured method to devise plausible ways for the introduction of hydrogen as an automotive fuel. The scenarios are meant to stretch mental maps (Elzen and Hofman, 2007), and to inform strategic decisions. They should be interpreted in the sense that if trends and rules that underpin a certain scenario are observed more frequently in the near future, the dynamics that are associated with that scenario are also more likely to unfold. Perhaps the best way to realize that the scenarios developed here are not predictions is that they are *designed* to incorporate hydrogen – that is their objective.

2.3 Methodology

Technology and society are dependent on each other. Technology has no purpose without society and technology cannot be produced without society. Society is thus involved in production as well as diffusion and use of technology. This way, technological innovation has driven much of society's progress. A purposeful study of innovation thus needs to link technology and society. Such linkages are central to the concept of socio-technical systems, as these are defined as "the linkages between elements necessary to fulfil societal functions" (Geels, 2004a, p. 900). Figure 2.1 is a graphical representation of the elements that make up a socio-technical system. Not all of these elements are studied equally intensively here, although the broad categories production, distribution and use are all covered. As the next chapter will explain in more detail, focus is on those elements that are prominent in the relationship between the car industry and consumers.

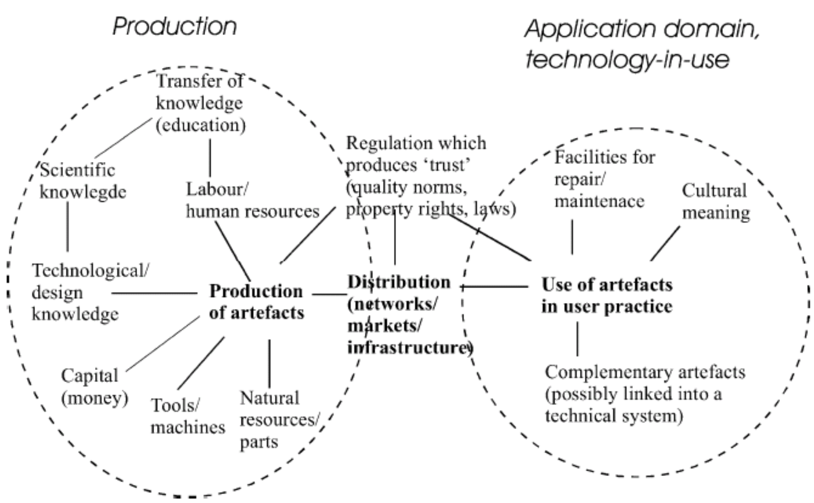

Figure 2.1 Elements of a socio-technical system. Source: Geels (2004a, p. 901).

System innovations are defined as "a transition from one socio-technical system to another" (Geels, 2004b, p.2). This thesis focuses on the development of the technology that is used to propel a car, more specifically technology that enables the use of hydrogen as a fuel. If only the automobile (i.e. the technology/artefact) were to change, such a change is arguably too small to represent a transition.

[3] Within THRIVE, policy advice is part of the work package of ECN Policy Studies.

However, many other elements (e.g. regulation, infrastructure, and perhaps cultural meaning) are likely to change as well. Viewing the adoption of hydrogen as a system innovation is quite sensible.

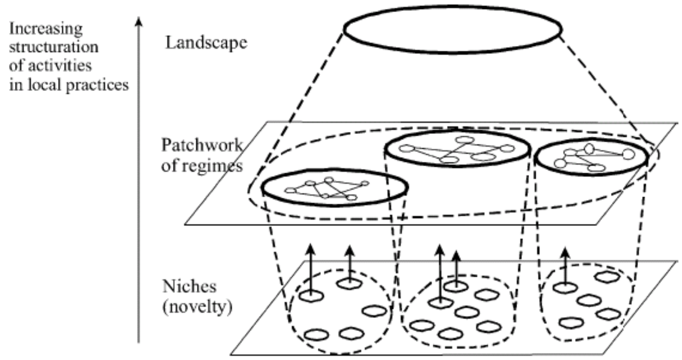

Figure 2.2 The three layers of the MLP. Source: Geels (2002, p. 1261).

2.3.1 The Multi-Level Perspective

Socio-technical systems open the door to study system innovation. This leads to the question what changes in socio-technical systems look like. Is each transition unique or do similarities exist? To answer this question properly, further analytical distinctions are necessary. One useful framework in this respect, the Multi-Level Perspective (MLP), provides these (Geels, 2002). This perspective distinguishes three layered levels (figure 2.2). Socio-technical regimes form the middle of these layers. On top of the socio-technical *system*, the socio-technical *regime* also comprises of (1) the actors involved in the socio-technical system as well as (2) the rules and institutions that govern their behaviour. The interactions between these three elements are described in figure 2.3. These interactions can be considered the cause of lock-in, as they typically reproduce the current system.

The explanation for change to a different socio-technical system lies in the other two levels. The 'upper' level is formed by the socio-technical landscape. The landscape level represents the "wider exogenous environment" (Geels, 2004a, p. 913). These are developments that are beyond the sphere of influence of the actors in the socio-technical system. Physical constraints are part of this level, but also less tangible aspects such as public opinion and shared (cultural) beliefs. Changes in this level can have impacts on developments in the socio-technical regime.

A similar pressure can come from the third level, niches. Niches are "protected or insulated from 'normal' market selection of the regime" (Geels, 2002, p. 1261). They are places in which new technology can develop relatively undisturbed. Examples are situations in which new technology is applied in settings or configurations that are not mainstream and in which drawbacks such as high costs are offset by other, favourable characteristics (e.g. reliability, small size, etc.). Possibly, such technologies can – after continuous development in niches – compete with and replace mainstream technologies.

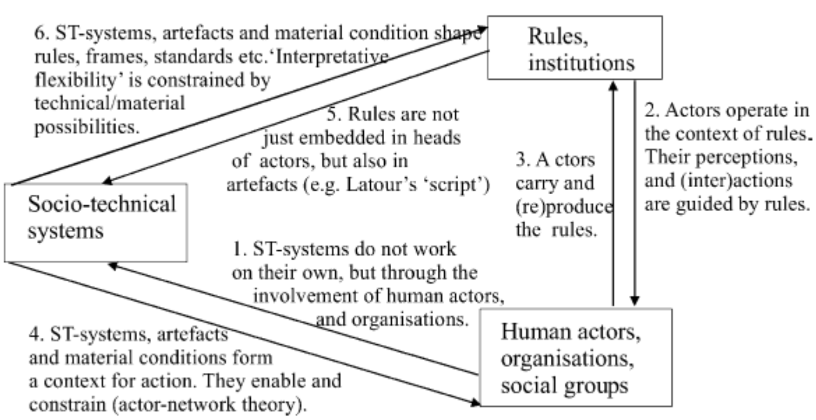

**Figure 2.3 The three elements of a socio-technical regime and the interrelationships.
Source: Geels, 2004a, p. 903.**

The MLP can be used to analyze the dynamism between the three levels, which can originate in more than only technological aspects. Landscape developments can put pressure on the current socio-technical regime. If, as a result, the actors in the current regime can no longer sustain the current socio-technical system (e.g. because of technological limitations, but also because of changing user preferences, regulation, etc.), a window of opportunity opens for niche technologies. And if at least one of these technologies has developed in such a way to be able to replace the old technology and accommodate the landscape pressures, a transition can take place (figure 2.4).

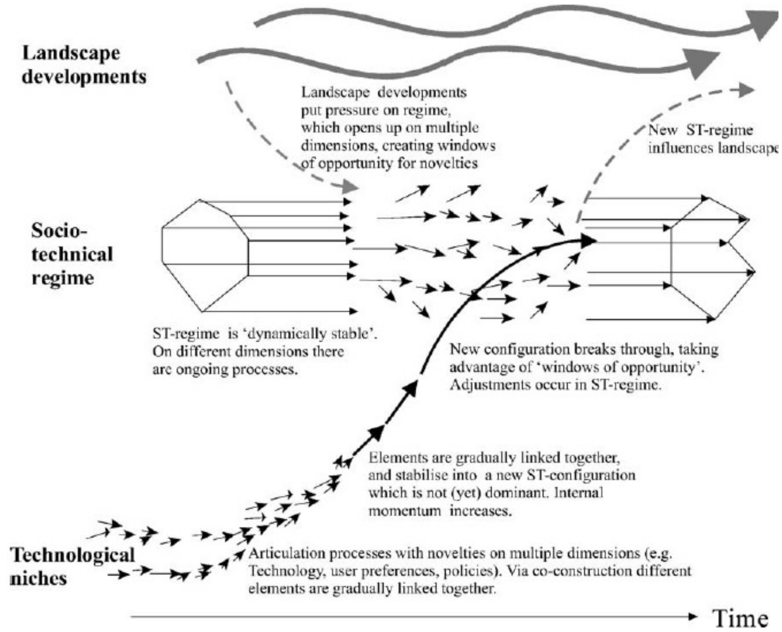

Figure 2.4 Illustration of niche breakthrough. Landscape pressures create a 'window of opportunity' that niche technologies can use to break through. Source: Geels (2004a, p. 915).

2.3.2 Transition pathways

The questions how changes take place exactly, and whether patterns can be determined, remain unanswered in the MLP. Geels and Schot (2007) fill this void. They draw up a typology of four transition pathways. Paths differ with respect to two criteria: (1) the timing and (2) the nature of interactions. The timing of interactions pertains to the state of development of the niche – are niches fully developed at the time of transition or not? The nature of the interaction relates to whether the developments on landscape and niche level on the one hand, and in the regime on the other hand, are in accordance or run counter. Landscape developments can reinforce or disrupt regime developments, whereas niche developments can compete with regimes or develop symbiotic relationships with them. The pathways and their differences with respect to the two criteria are listed in table 2.1.

Pathway	Timing of the interaction	Nature of the interaction
Transformation	Niche-innovations have not yet fully developed.	Moderate landscape pressure; disruptive change.
De-alignment and re-alignment	Niche-innovations have not yet fully developed.	Divergent, large and sudden landscape pressure; avalanche change.
Technological substitution	Niche-innovations have fully developed.	Large landscape pressure; specific shock, avalanche change, or disruptive change.
Reconfiguration	Niche-innovations have fully developed.	Symbiotic niche developments; landscape pressure leads to local problems.

Table 2.1 Timing and nature of the interactions of the four transition pathways, based on Geels and Schot (2007).

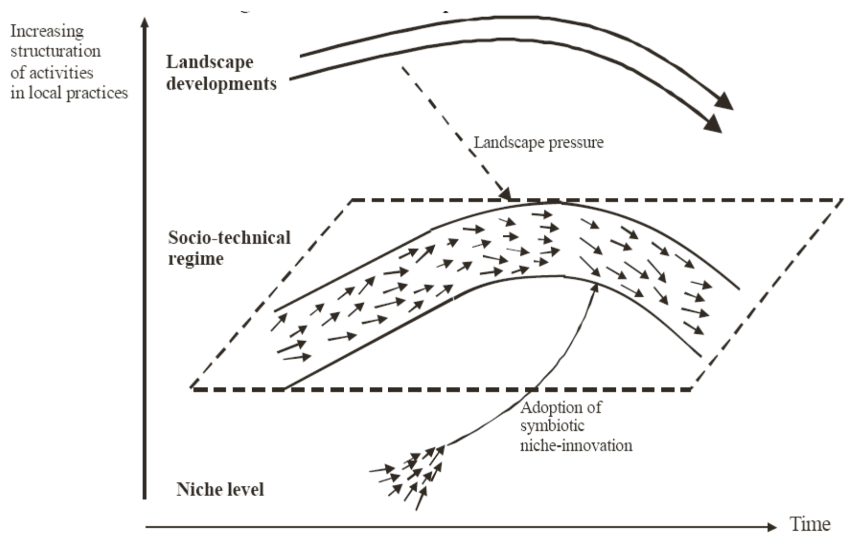

Figure 2.5 **Illustration of the transformation pathway. Adoption of niche-innovations solves pressure exerted by landscape forces. Source: Geels and Schot (2007, p. 13)**

In the *transformation pathway*, a moderate form of landscape pressure causes a need for change in the socio-technical regime. This pressure cannot be addressed adequately using the current elements of the regime. However, niche-innovations have not yet fully developed and consequently cannot address the pressure either. The situation is solved through the adoption of elements of symbiotic niche-innovations by the regime. The regime survives, the regime actors are still the same, although their guiding rules and institutions are slightly altered, as is the configuration of the socio-technical system. The process of the transformation pathway is depicted in figure 2.5.

Landscape pressure is more severe in the *de-alignment and re-alignment pathway*. Also, it comes suddenly and is divergent, implying that it is impossible for the regime to adapt by simply altering

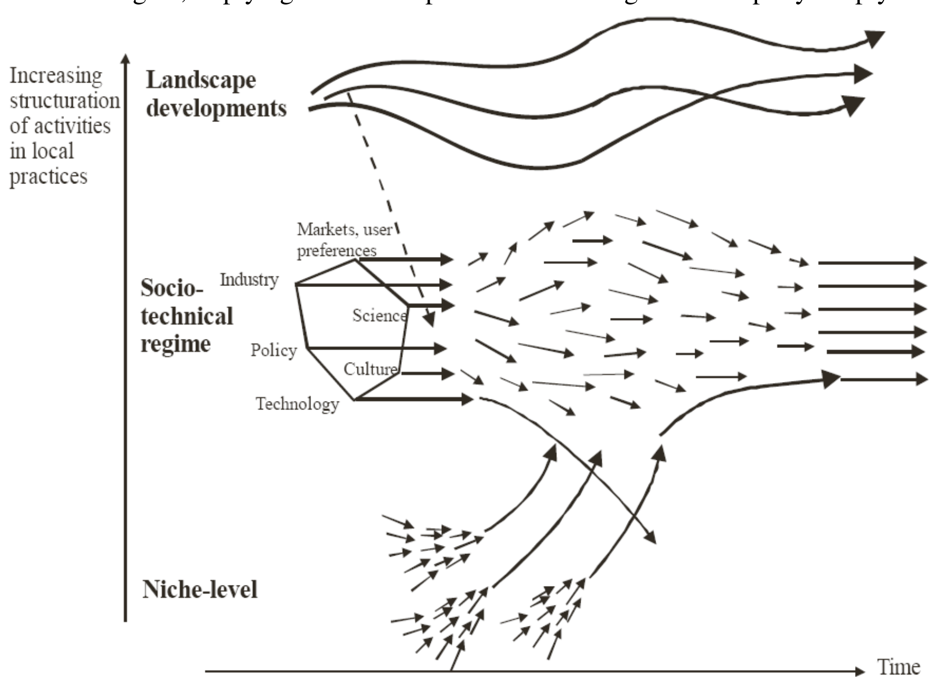

Figure 2.6 **Illustration of the de-alignment and re-alignment pathway. Competition between niche-innovations results in a new regime arrangement capable of handling the landscape pressure. Source: Geels and Schot (2007, p. 16)**

search routines and guiding principles. Instead, actors lose faith in the incumbent regime and it falls apart, opening opportunities for niche-innovations to fill the void. Yet, there is not one niche-innovation that has developed far enough to satisfactorily 'jump' into the gap. Instead, there is competition between multiple niche-innovations. Eventually, one of these will become preferred over the others. It gains momentum and becomes institutionalized into a new, stable regime. See figure 2.6 for a graphical illustration of the de-alignment and re-alignment pathway.

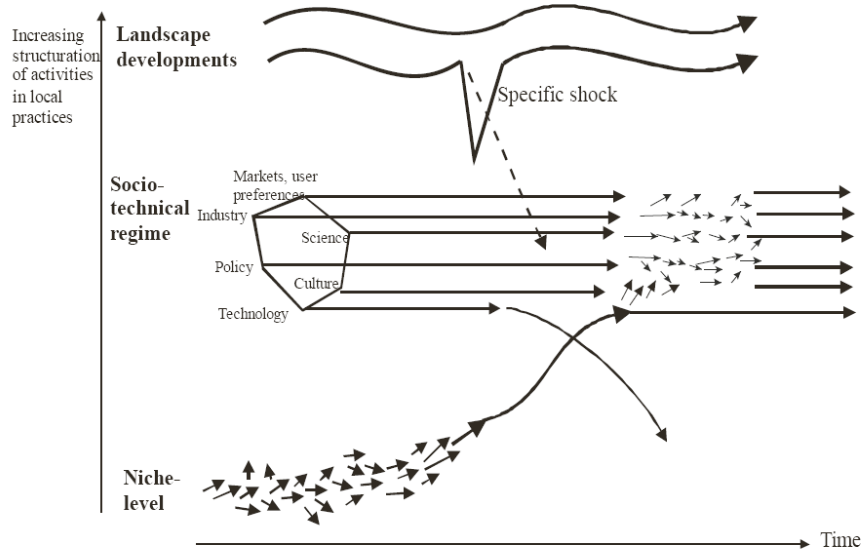

Figure 2.7 **Illustration of the technological substitution pathway. Although niche-innovations have developed fully, the well-entrenched regime has been able to 'keep them out'. A specific shock at the landscape level nonetheless prompts a breakthough for one of them. Source: Geels and Schot (2007, p. 18).**

In the *technological substitution pathway*, the regime is well established and entrenched. Therefore, niche-innovations, that have developed fully and by actors external to the regime, do still not have the opportunity to break through. Landscape pressure that is especially severe and pronounced is needed to destabilize the regime. A 'window of opportunity' opens that niche-innovations can use to enter the mainstream market. This will not be easy as current regime actors will invest in incremental improvements of the incumbent technology ('sailing ship effect'). Eventually, the niche-innovation takes over, putting new regime-actors in charge and often dismissing former actors. The technological substitution pathway is illustrated in figure 2.7.

The dynamics of the *reconfiguration pathway* make it 'the odd one out' in this typology. Landscape pressure is not so severe in this case, and comes in waves. More importantly, niche-innovations do generally not compete with the regime, but are symbiotic. Therefore, they are easily incorporated in the regime in times of increased pressure. The architecture of the regime is considered to have a modular nature, which simplifies such add-ons and (small-scale) substitutions.
The adoptions of small elements of niche-innovations do in itself not constitute radical innovation, let alone a transition. Rather, the accumulation of component innovations can over time lead to major reconfigurations. This is a key difference when compared to other pathways, in which a niche-innovation eventually replaces the old socio-technical system.
In this pathway, regime actors survive, but are complemented by actors that initially produced the niche-innovations. The changing socio-technical systems can also provoke changes in the rules and institutions of the regime. See figure 2.8 for a graphical illustration.

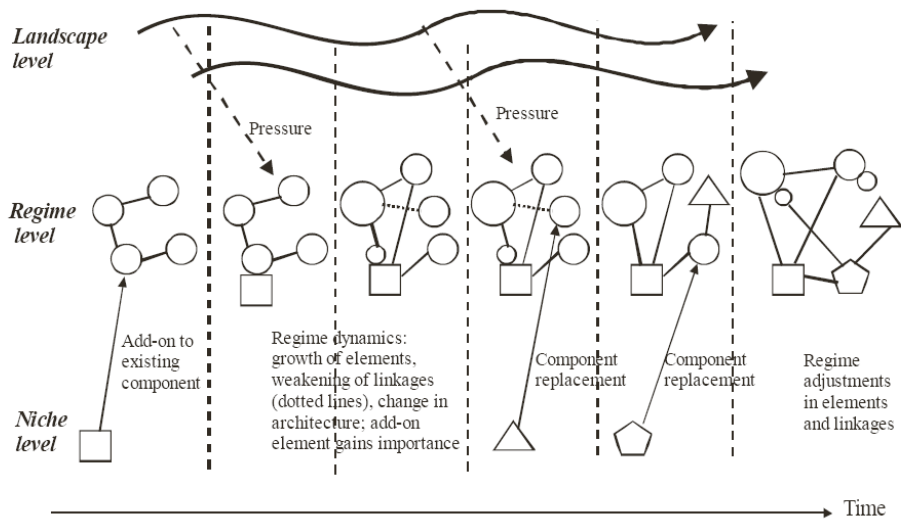

Figure 2.8 **Illustration of the reconfiguration pathway. Addressing subsequent landscape pressures, the regime adopts elements of symbiotic niche-innovations. Eventually, a new architecture emerges, such that a transition has taken place. Source: Geels and Schot (2007, p. 20)**

The four transition pathways are ideal types. It is unlikely that any transition will proceed exactly along the lines of one of the pathways. Rather, elements of more than one pathway will be discernable in a particular transition.

2.3.3 Socio-Technical Scenario methodology

There are two ongoing challenges in transition studies: (1) to improve the understanding of long-term technological change and (2) to generate tools and perspectives for the analysis of technological change that can improve governance of technological change (Genus and Coles, 2008). The MLP has found useful application in both categories.

Hitherto, the MLP has mainly be applied to *historical* transitions, thus addressing the former category. Recently, the MLP produced a method that contributes to research in the second category, the Socio-Technical Scenario (STSc) methodology (Elzen and Hofman, 2007). This method is concerned with the *future* developments of socio-technical regimes. Contrary to other scenario methods, that typically define one or more ‘driving forces’, this methodology takes the transition paths outlined in the previous section as a point of departure. An analysis of the recent developments on all three MLP-levels forms the basis for the prediction of the future development of a socio-technical regime.

Such developments take the form of regime and niche patterns that are part of MLP research. Transitions (long-term) are made up of series of these patterns (short-term). Regime patterns can be technical change (e.g. internal technical development, add-on/hybridization) or societal/behavioural change (e.g. technology diffusion, changing expectations and rules). Niche patterns are taken from Hoogma, Kemp, Schot, and Elzen (2002) and comprise the following:

- niche accumulation
- niche proliferation
- niche dissolution
- development from technological niche to market niche

The niche patterns can be triggered by mechanisms, both technical/conceptual (e.g. a novelty internal to the regime, niche splitting) and societal/behavioural (e.g. emergence of a new user group or new actors, enactment of new policies).

Observing and extending patterns and mechanisms is the first of two conceptual ‘building boxes’ of the STSc methodology. The other considers the placement of the patterns and mechanisms in time. Four consecutive episodes are part of STSc:

1. *Disconnection episode*

   Interactions between the landscape and regime levels make up this episode. Increased landscape pressures on the regime open up a window of opportunity for niches.

2. *Linking episode*
   Niches use these windows to influence and interact with the incumbent regime.
3. *Transformation episode*
   This episode sees (the) niche(s) take the upper hand and replace the old regime.
4. *Evolution episode*
   As this episode sets in, the former niche settles as the new regime. The regime moves into dynamic stability, with evolution through incremental innovation.

Conveniently, the methodology provides a plan to compose the building blocks and combine them into socio-technical scenarios. The seven steps of the plan are outlined below.

1. *Specification of the scenario objectives*
   This sets the backdrop for the scenarios. Since it is impossible to study every single aspect of a socio-technical regime, the scenario objectives provide the necessary basis for demarcation. If a specific user group for the scenarios exist, objectives should be geared towards the needs of these groups.
2. *Analysis of recent and ongoing dynamic*
   This step forms the empirical basis for the scenarios. Trends, patterns, and mechanisms resulting from this analysis are the building blocks for the scenarios.
3. *Elaboration of potential linkages*
   These building blocks are combined into 'transition seeds' in this step. Transition seeds are linkages of developments across MLP-levels that hold the potential to initiate a transition.
4. *Design choices*
   This step links back to the first one. Depending on what the scenarios are intended to accomplish, their depth and form needs to vary. Therefore, choices such as timeframe, which linkages to use, level of detail, etc. must be made before proceeding.
5. *Development of scenario architecture*
   These decisions being made, a brief outline for each of the scenarios can be drawn up. These must be consistent for each episode with respect to which pressures and characteristics initiate change, what this change looks like, and what links are formed.
6. *Elaboration of scenarios*
   Building on the scenario architectures, the scenarios can be elaborated into narratives. Again, the level of detail will depend on the scenario objectives.
7. *Reflection and recommendation*
   This final step reflects on the scenarios. Commonalities and differences are outlined, and recommendations relating to the scenario objectives follow from the conclusions.

Elzen and Hofman (2007), as well as Verbong and Geels (2008), have applied the method to derive scenarios for the development of the electricity sector in Europe, demonstrating that it is workable.

2.3.4 Methodological challenges

Yet there are also drawbacks to these frameworks. Genus and Coles (2008) list nine points of criticism. Eight[4] of these seem to partly overlap, so that they are more conveniently represented by their commonalities, which are the following:

1. *The imperfections of case study methodology*
   All applications of the MLP are based on the study of individual cases. Yet, the MLP has been applied to various cases in an unsystematic way, especially with regard to the operationalization of the framework. Furthermore, the analyses have been based on secondary (historical) sources, despite their alleged drawbacks. Also, the focus of some of the case studies has been on technology, to the detriment of the co-evolution of society and technology that forms the core of the MLP. Consequently, different case studies have been concerned with different core research questions.
2. *Extensive researcher discretion*

[4] The ninth point is about the theoretical status of MLP: different case studies employ different versions. This point is less relevant in the context of this thesis.

This is related to the previous point. Case studies allow more interpretational freedom to a researcher. This has had a number of consequences. A transition has in itself been loosely defined, so that the time-scale studied and system boundaries – that are up to the discretion of the researcher – determine what is considered a transition. This makes it hard to operationalize the distinction between the three empirical levels empirically (Berkhout, Smith, and Stirling, 2004). Perhaps more problematic is that selection of case studies, and selection and interpretation of information pertaining to the cases, has been up to the discretion of the researcher as well. This lends the MLP a poor empirical basis.

3. *The problematic role of agency*
   In many of the case studies, the role of agency and politics is downplayed. Rather, the emergence of new technologies and configurations is based on the congruence of the elements of the three levels of the perspective. The possibility of individual actors to 'steer' the process is underestimated. On the other hand, there is a tendency to position transition managers as external to transition contexts, overstating the impact they may have on the politics of others.

These points lead to the question what the best use of the MLP is: a heuristic device (a sort of lens) that provides a convenient way to organize data or a robust method that provides a sound basis for the empirical comparison and characterization of transition? Angus and Nor (2007) attempt to apply the MLP in the latter sense, but operationalization problems make formal empirical research difficult.

2.3.5 Methodological framework used

This thesis will use STSc as a methodological framework to describe how technology could evolve to include the use of hydrogen as automotive fuel. As such, the problems indicated above for the MLP are relevant for this thesis. Fortunately, some of the points of criticism have already been addressed by Geels and Schot (2007). For instance, they propose as the level of analysis organizational fields, from which system boundaries can be deduced.

Furthermore, the problems that others have spotted on the role of agency are the core of their work. Agency is intertwined with institutional rules. On the one hand actors act according to regulative, normative, and cognitive rules, while on the other, actors create these very rules. There is thus a dual structure. Rule changes occur through two kinds of processes: evolutionary-economic and social-institutional. The former process represents indirect rule change – market selection of product variations determine rule changes, without direct actor influence. Strategic choices in the organizational field represent agency here.

In the latter process, interaction among social groups changes rules. Rules serve as a 'sensemaking tool' in this context. In their interaction, there is a period during which groups build a shared interpretation (of e.g. a technology). 'Closure' is attained once this shared interpretation has been accomplished. Here, actors thus bring about rule changes directly. The various transition pathways incorporate these two types of agency.

The other two points of critique remain. As with other applications of the MLP, this study is necessarily restricted to the case $n = 1$. This implies that its methodology must be carefully designed to counter the drawbacks of a case study approach as much as possible. Note that these drawbacks are captured by exactly the two other points of Genus and Coles' critique.

Before proceeding to how these issues are handled in this study, it is informative to have a closer look at the STSc methodology. As indicated above, the methodology is an extension of the application of the MLP from historical transitions to possible future ones. Hitherto, the MLP has been used for explanatory science; the STSc methodology extends it into the realm of the design sciences. This is reflected in the methodological design of this study (figure 2.9), which consists of two parts. The first part is an analysis of the current situation, involving the MLP (as in STSc step 2) as a method to explain recent and ongoing events. The second part concerns the future, and should answer to the requirements of design science.

Genus and Coles' critique concerns the MLP as a tool for analysis, and is therefore only relevant for the left-hand part of figure 2.9. Note that although their arguments are analytically separate, it is hard

to distinguish them practically. Case studies as a method inevitably entail substantial researcher discretion.
It cannot be avoided that other researchers apply the MLP in an unstructured way, as Genus and Coles assert. What can be the contribution of this work is to advance understanding on how the MLP can be made more robust to researcher subjectivity. The key is to increase the formality of the method. Ideally, for this one would like to use established methods, such as questionnaires that perhaps even allow statistical analysis (cf. Genus and Nor, 2007). Although this is valuable to gain formal insight in actor views and expectations, such methods necessarily omit a lot of information from the complex system the MLP is designed to study.
The approach here is different. The object under study is too encompassing to be captured by formal research methods, but that does not hold for its elements. These elements do lend themselves to accepted, formal research methods, research that in many cases has been carried out already. These results can aid the understanding of the dynamics between the various levels greatly. Specific examples that are used here are stated preference (SP) research to determine consumer preference in car purchasing, the Theory of Planned Behaviour (TPB) to explain why which factors influence consumers' intention to (not) purchase an alternative fuel vehicle (AFV), and the calculation of fuel price elasticities of car use and purchase. For parts not explored in this manner new research can be designed – although that is beyond the scope of this thesis.
Formal academic research is thus the first input for the analysis. The second is historical facts. Examples in this thesis are trends in various attributes of cars, in the distribution of car sales over various market segments, and in the number of car varieties.
This implies that actors' visions and expectations – which the MLP presumes shapes transition dynamics – are not measured directly, although they are approximated by the (secondary) sources used. The main advantage of this approach is well recognized: it removes researcher discretion to a certain level. That (historical) visions and expectations are not measured directly is, however, a major drawback. The data analyzed are arguably less rich. Keeping the limitations of a master's thesis in mind, this is how the balancing act between objectivity and providing a full account plays out.

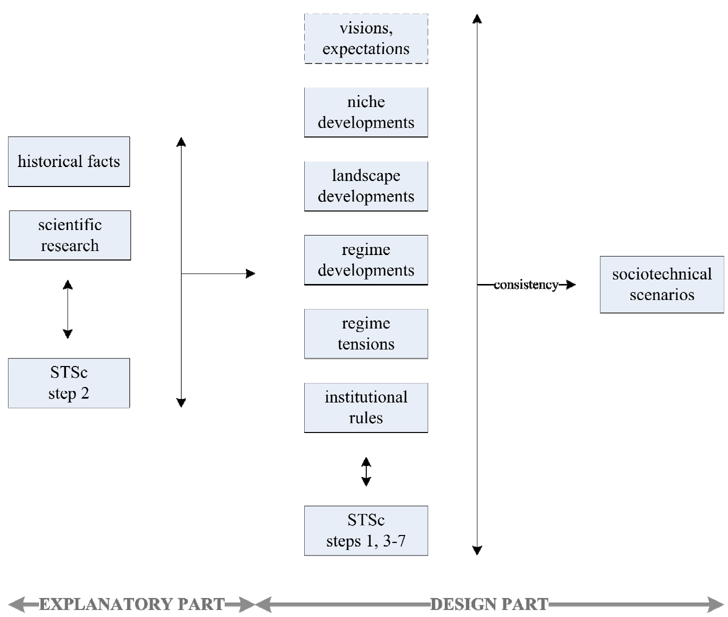

Figure 2.9 Methodological design.The MLP is only used as a tool for analysis during step 2 of the STSc methodology.

Then, the design part. The critique on the MLP is not relevant here. The MLP is still used, though, but now as a tool to construct the scenarios. It is the MLP that connects the two parts of the methodology by providing the design rules on which the scenarios are built. These rules are the institutional rules that follow from the analysis. It is these rules that shape the interactions between the various levels.

Furthermore, for each level a set of ongoing developments is formulated. At the regime level, this is complemented with a set of tensions, which explain why the regime runs into difficulties if it continues along the current trajectory.
The design of the scenarios follows from the interactions between all these developments in such a way to solve regime tensions. The institutional rules form the boundary conditions for the resulting transitions. Although institutional rules are not completely rigid – and may even change permanently during the transition – the assumption is that transitions that 'abide by' institutional rules are more likely to occur.
This procedure is open to one major improvement. As the MLP stipulates, visions and expectations of the actors involved are very influential in determining future developments. Unfortunately, these are not included formally in the methodology. Due to practical constraints, input on this part was restricted to feedback from THRIVE participants and one visit to an OEM[5].
The design part should be consistent. The condition for internal consistency is that all the building blocks of the scenarios are included. Although it must be that not all elements are equally emphasized in the various scenarios – that is exactly the point where they differ – all scenarios take place in the same world, implying that all developments must be present.
For external consistency, the test is more problematic. The progression of time only partly fulfils this role. Recall that the scenarios are not meant to foretell the future. Rather, they are meant to inform decision making. The test is thus that if the future brings more of a certain development, does the expected consequence happen as well? This is, however, theorizing without any practical value. Obviously, there is never a way to tell how externally consistent the design is at the time of designing itself.

The following chapters are an elaboration of the STSc methodology steps for the transition to hydrogen as an automotive fuel. Documenting each step in one chapter has proved next to impossible. The thesis is therefore divided into two parts: analysis and design. Table 2.2 provides an overview of which chapters belong to which part and how they relate to the steps in the STSc methodology. Note that the first step has already been completed in section 2.2.

	Chapter/Section			STSc step		
	2.2	-	Research setting and objectives	1	-	Specification of the scenario objectives
ANALYSIS	3	-	Analysis of the recent and ongoing dynamic	2	-	Analysis of recent and ongoing dynamic
	4	-	Relationship of consumers to OEMs			
	5	-	Relationship of OEMs to consumers			
	6	-	Regime tensions and conclusions			
	7	-	Analysis of niche development			
	8	-	Landscape developments			
DESIGN	9.1	-	Elaboration of potential linkages	3	-	Elaboration of potential linkages
	9.2	-	Design choices	4	-	Design choices
	9.3	-	Scenario architectures	5	-	Development of scenario architecture
	10	-	Scenario elaboration	6	-	Elaboration of scenarios
	11	-	Reflection and conclusions	7	-	Reflection and recommendation

Table 2.2 Mapping of steps in the STSc methodology onto the chapters and sections of this thesis. Based on Van Aken and Van der Bij (2000).

[5] Carmakers are often referred to as original equipment manufacturers (OEMs). This term is used to distinguish them from their suppliers, who produce and design more and more parts of the car. The car industry can be thought to comprise of both the OEMs and their suppliers.

3 Actor analysis, regime elements, and regime history

This chapter provides the basis for the analysis of the recent and ongoing dynamic in the regime (step 2 of the STSc methodology). Obviously, this requires the need to tell apart the regime from the other two MLP-levels. Landscape developments are rather easily identified. Geels (2004a, p. 913) states that they are “beyond the direct influence of actors, and cannot be changed at will”. Therefore, developments at the landscape level need (and will) be treated differently from development at the regime and niche levels. Regime and niche dynamics are driven by actors. Actors shape and are influenced by institutional rules, that form one of the conceptual links between the analysis and design part of the STSc methodology (see figure 2.9). Landscape developments differ because their influence is unidirectional. They can influence actors, but actors cannot influence the landscape developments.

The chapter starts with an analysis that determines who are actors in the current regime. Two reasons exist for first carrying out this analysis. First, since actors carry the institutional rules in regimes and niches, they must be identified before any rules can be formulated. Second, the actor analysis provides a means to operationalize the analytical distinction between MLP-levels as well as sharpen system boundaries.

Since the relationship between only two actors is part of the analysis, the next section shows which parts of the socio-technical system are in focus and which receive less or no attention. Finally, a short overview of regime history sets the stage for the next two chapters.

3.1 Actor analysis

Geels (2004a) identifies several social groups that carry and reproduce socio-technical systems, broadly defining them as belonging to either the production side or functional/user side. Based on that work, the groups (actors) that are relevant for the regime for personal transportation by road can be diagrammed as in figure 3.1.

The interactions between OEMs, the oil industry, and consumers can be considered to form the ‘core’ of the role of the car in the mobility regime. The interaction between OEMs and consumers is governed by the offering of products by OEMs, which are accepted to a certain degree by consumers. OEMs adapt their product offerings to consumer preferences, which they also attempt to influence. Similarly, consumers influence the car industry by expressing their preferences through (not) purchasing their vehicles. The interaction between consumers and the oil industry proceeds through the offering and purchase of fuel. There is a similar pattern of the oil industry and consumers influencing each other. In sum, OEMs and the oil industry are jointly the key enablers of the role of the car in the personal mobility regime. As such, they are also the major determinants of it, although heavily influenced by consumers.

There is also an interaction between the oil industry and the car industry. This interaction consists of monitoring each others’ activities, as well as coordination of technical issues such as specification of fuel and lubricants such that engine performance is optimized.

Figure 3.1 features two more actors, that are considered to have more of an influencing role rather than being at the core. The government exerts influence through policy. This includes measures such as tax (both on cars and fuel), subsidies, and regulations (e.g. emissions). Consumers influence the government by voicing their consent and/or dissent, which in most elemental form entails voting. Industry attempts to influence government through lobbying (e.g. the European Automobile Manufacturers’ Association, ACEA).

The final actor listed consists of non-governmental organization (NGOs), such as environmental organizations and support groups of certain technologies. These groups lobby to influence the other actors. Note that the goals of individual organizations within this groups of actors may be different and even conflict.

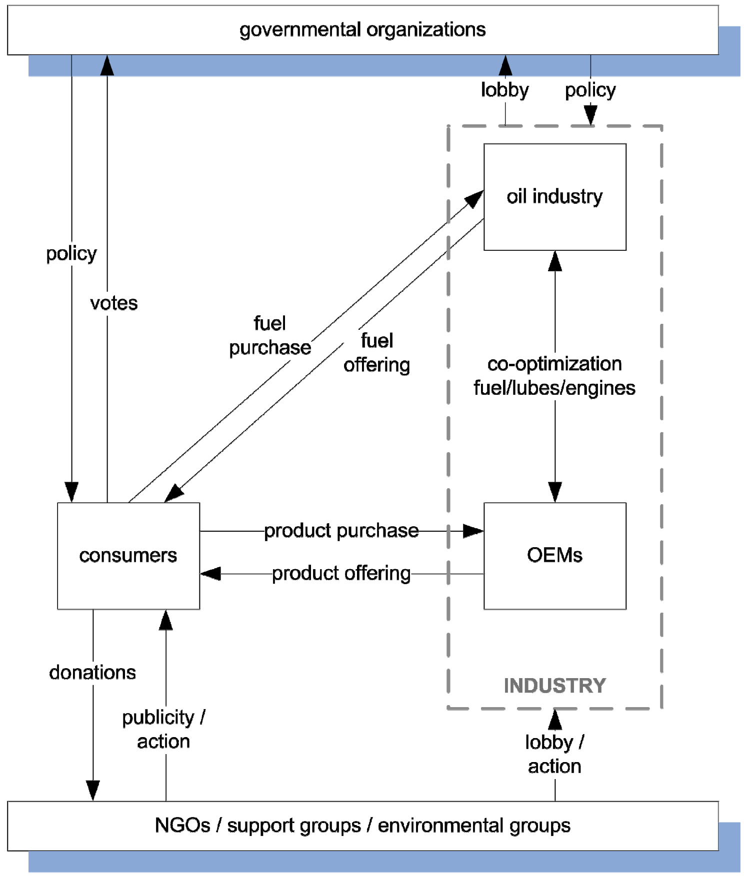

Figure 3.1 Actor analysis of the current regime situation.

This is a system that is stable and reproduces itself. There is a well-known phenomenon that blocks a transition to a different system which would require substantial infrastructure investment, such as one that uses hydrogen as a fuel: the chicken-and-egg problem (Yeh, 2007; Flynn, 2002). Such infrastructure investments are generally costly, but also risky if it is unsure if their use does not lead to a utilization rate that is high enough to recoup investment costs. A high utilization rate requires AFVs to be available to the consumer in sufficient numbers, which in turn requires investments in vehicle R&D and capital goods for mass production. All of these investments are equally risky if the fuel infrastructure that enables its use is not in place, so that no change can occur. Investments in vehicles *and* infrastructure supplying the new technology must be carried out simultaneously to eliminate risk as much as possible. A close cooperation between the oil industry and OEMs is therefore a necessary condition for a successful rollout.

Nonetheless, risk is always present, as it is uncertain whether the consumer will accept the new technology. Within the THRIVE consortium, there is ample knowledge about refuelling infrastructure in general (Linde and Shell) as well as the interaction with consumers in providing fuel (Shell). On the other hand, no OEM is part of the consortium, implying a lack of knowledge on the relationship between consumers and OEMs. Hence, the focus in this thesis will be on this relationship and the next two chapters will analyze it. It will be central to the socio-technical scenarios. That is not to say that infrastructural implications are considered out-of-scope – instead, they are a result of the analysis rather than an input.

3.2 The car in the socio-technical system for land-based road transportation

Geels (2005) identifies elements for the socio-technical system for land-based road transportation, of which the car is part (figure 3.2). Restricting the scope to the relationship between consumers and OEMs implies that culture and symbolic meaning of the car, the car itself, markets and user practices, and the production system and industry structure are focus of the analysis. The other elements are not studied, with the exception of regulations and policies, and the fuel infrastructure. However, they will only play a part in scenario design, rather than be extensively analyzed. Regulations are necessary to induce particular changes. Fuel infrastructure is a result rather than an input in the scenarios.

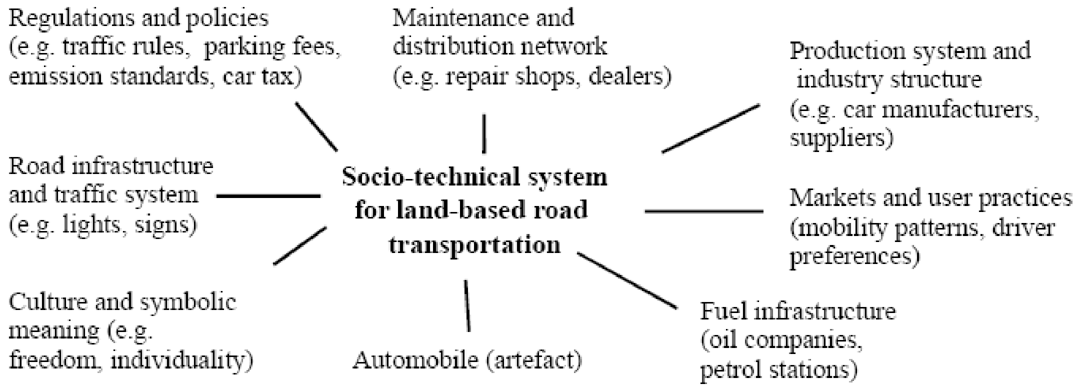

Figure 3.2 Elements of the socio-technical system of which the car is part. Source: Geels (2005).

3.3 Regime history[6]

This section is an introduction to recent and current developments in the regime. It forms the backdrop against which the next two chapters (on the interactions between consumers and OEMs) can be interpreted.

The automotive idea dates back centuries filled with experimentation on automobiles. Virtually no successes in the field are recorded until around the middle of the 19th century. Several experimenters build vehicles that achieve respectable performances. These were based on one of three types of power plants: steam engines, electric motors, and the ICE. The victory of the ICE over the other types would only become apparent during the second and third decades of the 20th century.
It would take to the last decades of the 19th century for these ventures to lead to commercially viable undertakings. The automobile industry was an entrepreneurial business at the time, with many small companies building cars to order. Each car was fitted exactly to the wishes of the customer, which required the craftsmanship of skilled workers.
All of this was bound to change with the introduction of the Ford Model T in 1908. Next to being a well-designed car, it came at a price that fell within the budget of the middle class. This was enabled by perhaps its most revolutionary aspect: mass production. The model T was designed to be built from standardized parts, so that customized fitting of the parts was no longer necessary. The new production system was pioneered by Ford. It featured the moving assembly line, enabled by vastly simplified manufacturing tasks so they could be carried out by unskilled workers. Consequently, the model T could be built very efficiently and at low unit costs. Hardly any firm in the US industry could follow, causing the number of players in industry to fall from 253 in 1908 to 108 in 1920 to 44 in 1929 (Flink, 1988; p. 70). This innovation put the US industry at a lead that manufacturers in other parts of the world would not catch up with until after World War II.
The era of cheaply built cars triggered an automobile boom during which the car in the US diffused rapidly among the middle class. Market saturation was achieved around 1925. Europe (including the Netherlands) lacked the US manufacturing capabilities, so that diffusion set in later – initially through import, later through local production as well. Nonetheless, significant numbers of car ownership would not be achieved in Europe until after the World War II (Mom, 2007).
Up until the 1930s, a number of important basic innovations were applied to the car: the self-starter (1912)[7], four-wheel hydraulic brakes (1920), the closed steel body (1921), low-pressure balloon tires

[6] This account draws heavily on three books: 'The Automobile Age' (Flink, 1988), 'Highways to Heaven' (Finch, 1992), and 'The machine that changed the world' (Womack, Jones, and Roos, 2007). To not litter the text with references, these works are only explicitly referenced where deemed appropriate.

(1923/24), more sensitive steering mechanisms (1925), and the addition of tetraethyl lead to petroleum to reduce engine knock (1926). These product innovations were accompanied by process innovations that improved efficiency and product quality.

Mechanical performance of the car had progressed to the point that not much improvements were deemed necessary. No major mechanical innovations other than the one-cast motor block (1932, greatly reducing manufacturing costs) and the introduction of the Diesel engine (by Mercedes-Benz of Germany) were witnessed until the 1950s.

The industry entered hard times. The market had saturated and basic product innovations to drive demand were more or less finished. Innovations turned to improvements of comfort, handling, and ease of operation. Nonetheless, other means to stimulate demand needed to be devised.

The major innovation came in the form of a new business model, introduced by Alfred Sloan. Marking a break with Ford's product philosophy, Sloan aimed to bring "a car for every purse and purpose" (Flink, 1988, p. 234) to the market. To achieve this objective, a range of different models was needed. Moreover, a new version of each model was introduced annually. The differences between a model and its successors were marginal and originated mainly in styling[8]. Each model carried 'planned obsolescence': it was aimed to become obsolete as the new version came out, so that consumers would replace their vehicles at a faster pace.

During World War II, the car industry turned to the production of war machinery. In the post-war age, diffusion of the car entered a second wave. Even so, problems loomed for American car makers. The cars of the 1950s are iconic. In this decade, styling turns non-functional and excessive. Contrary to the styling innovations of the 1930s, the new fashion compromises engineering, introducing safety hazards and terrible handling. Yet, the 'accelerated obsolescence' business model was continued (and would be continued to the 1970s). Hence, cars grow increasingly bigger, are disproportionately motorized, and fuel consumption and running costs escalate. A simple explanation for this seemingly irrational design philosophy is that large cars represent a more valuable proposition for the industry – called a 'truism' by Flink (1988).

The excessive styling elements and ever longer cars make them hard to park. And as the number of cars on the road increased, the regime ran into more problems. The 1950s mark the first incidence of visible air pollution in the form of smog over Los Angeles. Motorization reaches such levels in LA and New York that congestion starts being a problem. Consumers voice their complaints: dissatisfied with the offerings of the US industry, they turn to imports, culminating in an 8.1% of all sales being imported in 1958 (which marked a small recession).

Innovation in the 1950s comes from the Western European car makers. They experienced a post-war boom, quickly overtaking the leading positions of the US industry in Europe. While their American counterparts were fixed on producing larger, excessively styled cars, European carmakers sought to complete the car diffusion by producing people's cars such as the Volkswagen Beetle, the Fiat 500, and the Citroën 2CV. Moreover, European car makers developed innovative new technology to overcome differences in national tastes and regulation. By this standard, progress thus occurred in Western Europe in this decade.

The European industry would retain its technological lead all through the 1970s. Furthermore, despite US attempts to mimic the European small cars, the role of the US industry in global exports declined. The erosion of the position of US industry in global car manufacturing would continue to the 1990s (Womack, Jones, and Roos, 2007). As early as 1967 the US turned into a net importer of cars.

In the US market, three aspects of the car regime were to be addressed by regulation. In 1966, the first regulation setting safety standards came into force. Starting around 1965, emission regulations were put into place, with California taking a leading role. The third government intervention came during the 1970s, the decade of the oil price shocks. In 1975 the Corporate Average Fuel Efficiency (CAFE) standard is adopted, stipulating a minimum fuel efficiency for cars.

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[7] The numbers in parentheses mark the years of introduction of these innovations into models available to a large clientele according to Flink (1988).

[8] The altered styling of the cars of the time were by no means dysfunctional (as they would become in later times). The first cars had been modelled after (and often built like) carriages. As cars developed more power and speed, styling adaptations were necessary to e.g. lower the centre of gravity and thus improve handling.

The surge in fuel prices marks a dramatic shift in consumer preferences for small, fuel efficient cars. This opened a window of opportunity for Japanese car makers, who had successfully been making inroads into overseas markets since 1965. The 1980s mark the dominance of the Japanese industry, as fuel prices remained inflated during much of the decade. Consequently, the downsizing trend that had been established during the 1970s continues. Nonetheless, the major competitive advantage of the Japanese is the system of 'lean production', pioneered by Toyota during the 1960s. This system, focused on continuous quality improvements, produces cars more efficiently than the mass production system that had been in place since the beginning of the century.

During the 1980s, the car industry turns into a truly multinational enterprise. Manufacturers open plants outside of their home markets. On the product side, the 1980 Ford Escort is hailed as the first 'world car', a car that sells in markets over the world with minor local variations.

This trend continues into the 1990s as the industry becomes global[9]. During this time, oil prices come down and consumer preferences for larger cars return. This is especially true of the US, where light trucks and SUVs are exempt from the CAFE regulations, but such cars gain some popularity in other regions as well.

In recent years, producers from the US and Europe have adapted elements of the Japanese lean production system. Car design is modularizing, so that multiple models can be produced from one platform and adapted to local needs. OEMs focus on their core competences, so they can adapt to fast changing customer needs. The automotive production system is no longer owned by a single company, but has become a network of organizations (Wibbelink and Heng, 2000).

This is largely the state of the regime today. However, very recent events mark a break with some of these historic developments. A severe economic downturn has set in and no signs of quick recovery are visible at the time of writing. The car industry has been especially hard-hit, with car sales dropping 26% in Western Europe in the period January 2008 to January 2009. Globally, the picture is no different (European Parliament, 2009). This unprecedented slump in sales has its repercussions on industry. Although the full impact is by no means clear, an interesting development is ongoing in the US, where Chrysler and General Motors have received government support to avoid bankruptcy. Government aid has not come without conditions, however. Requirement is that the carmakers turn their efforts to producing fuel-efficient cars that appeal to consumers, so they can return to profitability. The US president, Barack Obama, has publicly endorsed plug-in hybrid vehicles (PHEVs). Whereas the history of regulation has been characterized by a reluctance to directly steer OEM product development, the current economic situation and subsequent government interventions seem to head in this direction ('Time for a new driver', 2009). General Motors seems to have lost its autonomy to a large extent. Yet, this development is largely restricted to the US for now.

A number of conclusions can be drawn from this historic overview:

- There is a need in the car industry to drive consumer demand. Although the total car stock is growing, the market situation in the developed world has been a saturated one for many decades now. The car industry actively stimulates demand via their model design and introduction strategy.
- The industry cannot proceed in this manner entirely autonomously. Regulation has been put in place to prevent excesses in three areas: emissions, safety, and fuel consumption. Currently, consumers require OEMs to produce safe and fuel efficient cars beyond government-imposed standards.
- Larger cars provide a larger margin. OEMs will therefore be inclined to influence consumer demand towards the purchase of larger vehicles.

This overview sets the backdrop for a possible transition to the use of other fuels in the mobility regime. The next two chapters will analyze the relationship between OEMs and consumers in more detail and will elaborate on the conclusions of this overview.

[9] This is true for the modularization trend. On some aspects, consumer preferences in the three major markets (US, Japan, and Europe) are growing apart. For instance, light trucks are only favoured in the US, minicars in Japan, and diesel-powered vehicles in Europe. These differences are mainly due to differences in the regulatory regime (Jürgens, 2003).

4 Relationship of consumers to OEMs

The most basic form of the relationship of consumers to OEMs is mirrored by the distribution of sales over the set of car models made available by OEMs. Differences between the models determine which models have a high representation in this distribution. This chapter explores consumer behaviour towards cars, notably purchasing behaviour. Consequently, it discusses how consumers value the various characteristics (also referred to as attributes) of vehicles.

The following section discusses trends in consumer preferences. It first explores the relative importance of the various attributes, and next discusses some important attributes in more detail. Research on conventional vehicles (CVs) as well as AFVs is included.

The next part investigates the relationship between consumer behaviour towards vehicles at a higher level. Rather than looking at individual attributes, it deals with motivations for car use and consumer attitudes towards cars.

The chapter ends with a conclusion in the form of a set of institutional rules for the relationship of consumers to OEMs.

4.1 Ranking consumer preferences: Conventional vehicles

Only a few studies on consumer preferences for car attributes are publicly available, although it can be expected that much research on this topic is carried out by private parties. Here, two studies are discussed that come from a review by the Low Carbon Vehicle Partnership (LowCVP, 2005). The first (table 4.1) is by the British Department for Transport, the second (table 4.2) by the Transport Research Institute (TRI) and the Environmental Change Institute (ECI)

	Primary	**Secondary**	**Tertiary**
DfT (2004a)	Price	Performance/Power	Depreciation
	MPG/Fuel consumption	Image/Style	Personal experience
	Size/Practicality	Brand name	Sales package
	Reliability	Insurance costs	Dealership
	Comfort	Engine size	Environment
	Safety	Equipment levels	Vehicle emissions
	Style/Appearance		Road tax
			Recommendation
			Alternative fuel
DfT (2004b)	Costs	Running costs	Emissions
	Brand loyalty	Size	Warranty
	Reliability	Performance	Tax
	Image	Colour	Number of doors
	Comfort	Safety	
		Petrol/diesel	

Table 4.1 Ranking of vehicle attributes by British car buyers (DfT 2004a and 2004b).

Cost, comfort, safety, and reliability seem to be the most important considerations among British car buyers. Running costs play a less important role, although fuel consumption is among the primary factors in the research of the Department for Transport (DfT, 2004a). Performance-related attributes are somewhat in the middle, whereas environmental concerns are among the least important factors.

Attribute	Rank
Reliability	1
Safety	2
Comfort	3
Price	4
Appearance	5
Fuel economy	6
Internal space	7
Physical size	8
Brand	9
Environmental impact	10
Engine size	11
Resale value	12
Fuel type	13
Financial package	14
Recommendation	15

Table 4.2 Ranking of vehicle attributes by British car buyers (TRI/ECI, 2000).

4.2 Ranking preferences: Alternative Fuel Vehicles

Research into consumer preferences for AFV attributes necessarily comes in the form of stated preference (SP) studies, amongst others for the simple reason that AFVs are not available to consumers in significant numbers (Hensher, Louviere, and Swait, 1989). Hence, the only option open to researchers is to have consumers state their preferences regarding AFVs.

First, discrete choice experiments will be considered. In this type of research, a respondent is presented with a description of a number of vehicles (usually three) by their attributes. He/she is asked to indicate a preference for one of the alternatives. By repeating this procedure while altering the attributes presented, the researcher is able to rank the preferences of each respondent and aggregate them. Statistical analysis can then be used to determine the significance, sign, and strength of the attribute influence on the purchase decision.

Appendix A lists the seven studies that are used here. A glance at this appendix quickly reveals some difficulties for aggregating the results. Firstly, a cultural bias may be present, since data collection has taken place among consumers in places that range from the United States to South Korea. Clearly, consumer preferences may be different for each place[10]. Secondly, every single has a different specification. An erroneous specification presents major problems in multivariate analysis (Hair, Black, Babin, Anderson, and Tatham, 2006). Determining a correct specification is especially difficult in research on AFVs, as it entails including attributes that are specific to AFVs (Ewing and Sarigöllü, 1998).

Moreover, a fundamental issue for this type of research is that consumers are unfamiliar with the alternatives that they are rating. Since they have never really experienced these novel characteristics, they cannot be expected to fully understand them (Brownstone, Bunch, and Train, 2000; Golob and Gould, 1998). Their judgment may thus be flawed, e.g. by incorrectly perceiving their risk or desirability.

The aggregation method that is used here comes at the expense of 'downgrading' the interval type of information that the discrete choice experiments yield. Translating this information into an (ordinal) ranking of coefficients per study allows comparison of attributes across studies, yielding an

[10] Although the 'world car' has arguably been a success, there remain differences in preferences depending on local circumstances. Rosa, Porac, and Runser-Spanjol (1999) demonstrate that the perception of a family car is different around the world. See also footnote 9.

impression of relative importance to consumers[11]. Due to the loss of information during the procedure and the resulting informal nature, it can be taken as an impression only!

	Vehicle attribute	Number of studies
1	Fuel efficiency	1
2	Purchase price	6
3	Variety	1
4	Range	4
5	Emission level	4
6	Maintenance cost	3
7	Fuel availability	4
8	Fuel cost	7
9	Refuelling time	1
10	Acceleration	4
11	Top speed	1
12	Engine displacement	1
	Total number of studies	7

Table 4.3 Ranking of consumer preferences based on the comparison of seven SP studies.

Table 4.3 presents the result, but must be interpreted with care. As indicated, the specification of every study is different[12]. Hence the different frequency of occurrence for the attributes. This has been (rudimentarily) compensated for in the comparison methodology, but care should be taken nonetheless. Attributes that feature a frequency of more than one can be considered more reliable. Detailed discussion of table 4.3 is postponed to section 4.4. First, a more detailed view of the car purchase process will put the ranking exercises in better perspective.

4.3 The car purchase process: Ranking reconsidered

Ranking provides some insight into the relative importance of vehicle attributes. However, a simple list, such as in tables 4.2 and 4.3, can be somewhat misleading. Purchasing a car tends to be a two-stage process (Lane & Potter, 2007; De Haan, Müller, Peters, and Hauser, 2007). Possibly because the cognitive burden is too large to trade off all options available (Ben-Akiva et al., 1997), consumers first focus on a limited number of ‘primary’ decision criteria. Having limited their choice set to a manageable number of options, a set of ‘secondary’ decision criteria is used to make a more detailed comparison of the options within this set. The DfT studies (2004a and 2004b) come to this conclusion as well and have ordered their rankings accordingly[13] (table 4.1). It is hard to generalize which criteria make up the two criteria sets. In the view of Blauw Research (2006), consumers try to attain goals by picking vehicles with certain attributes. Following this reasoning, the ranking of goals determines what characteristics end up in which choice sets. There will therefore always be individual differences. Nonetheless, a closer examination of consumer behaviour vis-à-vis car attributes illustrates that at least large groups of consumers make similar choices[14].

4.4 Consumer preferences for vehicle attributes in more detail

The econometric models and questionnaires discussed above are well suited to distil patterns and preferences for large groups of respondents, but they are necessarily restricted to producing

[11] The procedure is explained in more detail in appendix A.

[12] The implicit assumption is that differences in particular attributes between choices are captured by so-called alternative specific constants (ASCs).It is assumed that consumers are aware of attribute differences for different models. For instance, emission levels are left out of the model specification because consumers are assumed to be aware that an EV produces less emissions than a conventional vehicle. A dummy variable is then included in the model specification that captures all differences between EVs and other vehicles (including, in this example, emission levels).

[13] These studies also distinguish a set of even less important tertiary criteria.

[14] Despite regional differences as outlined in footnote 10.

importance rankings. Focus groups and individual interviews with car owners (both conventional and alternative-fuel), as well as preferences revealed through behaviour observable in real-life choices and statistics, provide additional insight into the trade-offs that pertain to the purchase of a particular vehicle. A number of relevant attributes will now be discussed in greater detail by incorporating these results.

Purchase price ranks as one of the top valuable attributes for consumers. There is evidence from the UK market that it, being the major source of fixed costs related to car ownership, is more important than variable costs: the price elasticity related to purchase price is higher (i.e. more negative) than that for running costs (Dargay and Vythoulkas, 1998). The AFV importance ranking (table 4.3) supports this notion. Elasticities with respect to purchase price are generally estimated to be below unity (Dargay and Gately, 1999), indicating that cars are a necessity good. This is more true of rural areas, where less alternatives to car travel are available.
Purchase price is frequently considered a 'primary' decision attribute, consumers use it to limit the total number of offerings to the choice set they consider for detailed analysis (LowCVP, 2005). For instance, the report by Blauw Research (2006) amongst Dutch car owners on purchasing criteria finds that 'budget management' translates into car category, i.e. consumers first choose a car category that fits their budget. As this choice satisfies their budget constraints, attention can be diverted to other criteria for trade-offs within the category.

Range barely enters into the consideration of purchasing a CV – it is not considered in any of the studies referenced in section 4.1. Yet, it is an important concern for buyers of AFVs, since some alternative technologies offer a significantly lower range than CVs[15].
Yet, the average daily travel distance of a car is often less than the maximum range. For instance, the average distance travelled by a car in the Netherlands equalled only 42 kilometres in 2004 (CBS, 2006). Such a distance can be covered by most EVs, and for such vehicles there is a convenient option to recharge them overnight at home[16]. A longer range is only necessary for trips to more distant destinations, which are likely to occur only infrequently. When nonetheless faced with the cover more distant trips, Golob and Gould (1998) find that consumers are willing to change behaviour by switching to other household vehicles for such trips. A logical hypothesis is therefore that limited-range vehicles could well serve as a second (or third, etc.) car. Kurani, Turrentine, and Sperling (1996) find support for this 'hybrid household hypothesis'. After they have primed consumers to make them aware of the distance they typically travel on a daily basis, they are more willing to consider purchasing an EV (with a limited range).
There is also evidence that consumers experience a range 'threshold'[17] (Golob and Gould, 1998), implying that they would only consider purchasing a vehicle provided it features a certain minimum range. As a result, range can be considered to be one of the primary decision criteria (Kurani, Turrentine, and Sperling, 1996). Vehicles below the threshold would not enter the choice set, while the marginal benefit of range beyond the threshold is virtually zero. Such nonlinearity is also apparent from econometric models (e.g. Ewing and Sarigöllü, 1998). Range does not play an important role as a secondary criterion – hence its absence as a criterion in the studies on CVs.

Maintenance costs are harder to interpret. The four SP studies that have incorporated it do not provide more information nor insight. The study by the EPRI (2001) measures maintenance costs along with personal time invested in maintenance, and consumers like to minimize both. Perhaps it is

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[15] An analysis of the range of the top-10 selling gasoline cars in the Netherlands in 2008 reveals an average range of 780 kilometres (OEM quotation). Recent prototypes of FCVs start to approach that range (e.g. 620 kilometres for the 2008 Honda Clarity FCX), but EVs lag behind (e.g. the Mini E prototype has a range of 240 kilometres).
[16] In a study by the EPRI (2001), consumers expressed a strong preference of home refuelling instead of going to a refuelling station. Kurani, Turrentine, and Sperling (1996, p. 147) find that home refuelling is 'probably the most valued novel attribute of EVs'.
[17] Such a threshold would be different for different consumers, depending on home refuelling options, commuting distance, frequency of longer trips, etc. The result would be a market that is segmented by ranges acceptable to different consumers (Kurani, Turrentine, and Sperling, 1996).

confounded with reliability – a study by Shell (2004) on consumer acceptance of alternative fuels and technology finds that reliability is highly relevant, while cost of maintenance is found to be relatively unimportant. In sum, results are inconclusive, which makes it hard to determine at what stage in the purchasing process maintenance costs play a role, and how large this role is.

Emission levels take a place in the middle in the ranking of SP studies (table 4.3). Interestingly, these are the only studies that lend so much importance to emission levels as a decision criterion in the car purchasing process. Those results must be interpreted with care, since it has been shown that responses in SP surveys and actual consumer behaviour (i.e. revealed preferences) can differ on this aspect (Bunch, Bradley, Golob, Kitamura, and Occhizzo, 1993). To add to the complexity, fuel efficiency tops table 4.3, and more fuel efficient cars emit less. A high valuation of fuel efficiency can thus indicate concern for the environment, but also concern over fuel costs (see below), or both.
The studies on the UK market in the LowCVP (2005) research do either not mention emission levels or rank them among the least important ones. For the Dutch situation, Blauw Research (2006) reports environmental care to be ‘hardly a goal people aim for when choosing a car’. Metrixlab (2004) finds that even drivers of hybrid cars, a key technology currently available to reduce emissions, have generally not purchased their car for environmental reasons. In a study among early adopters of the hybrid technology in California, Heffner, Kurani, and Turrentine (2007) identify environmental concern as only a partial driver for the purchase of a hybrid vehicle.
Figure 4.1 shows the development of emissions from the Dutch car fleet since 1980. It reveals that most kinds of emissions have been reduced significantly over the last decades. In accordance with the conclusion that environmental concerns are no determinant of vehicle choice, the reduction has been the result of incremental innovations (i.e. technological solutions) rather than behavioural change (Levy and Rothenberg, 2002). This has not been the case for CO_2 emissions, since no technological fix for reducing this type of emissions is available at present[18] (Zachariadis, 2008).
Emission levels seem to be particularly vulnerable to this attitude-action gap (Lane and Potter, 2007). It is true that consumers care about emissions. Hence, they will state so in surveys and some consumers even consider them when buying a car. However, other factors carry more weight. In sum, emission levels are definitely a secondary concern – if they enter the purchase decision at all.

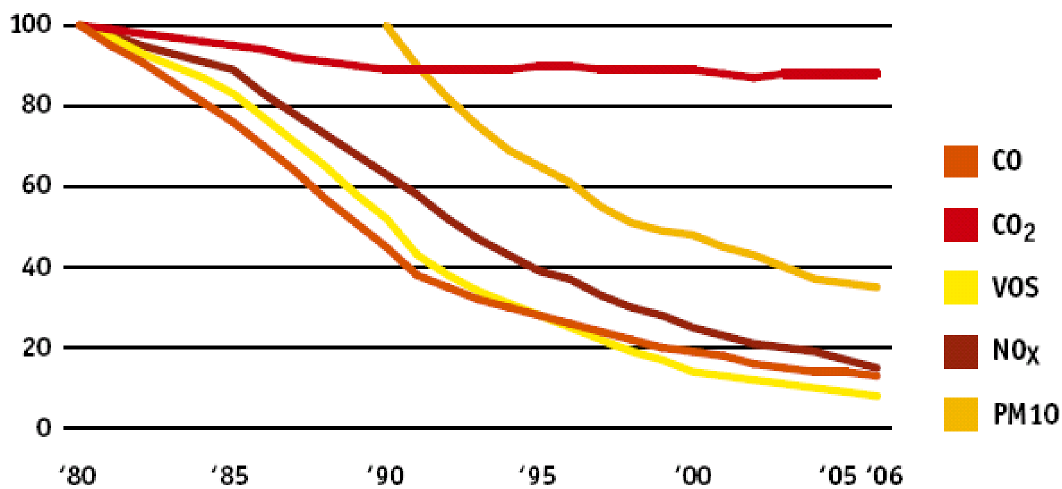

Figure 4.1 **Index of emissions from cars (1980 =100). ‘VOS’ = Volatile Organic Compounds, ‘PM10’= particulate matter with a diameter smaller than 10 micrometre. Source: BOVAG-RAI (2008).**

Fuel costs[19], **fuel efficiency**[20], and **fuel economy**[21] will be discussed together here. The concepts are related: the fuel economy (or mileage) of a vehicle will better when it is more (fuel) efficient, which

[18] As a result, all reduction in CO_2 emission must come from burning less fuel.
[19] Measured in monetary units per unit of time (e.g. euros/week).

implies that fuel costs will be lower (provided distance travelled as well as all vehicle attributes are constant). In table 4.3, fuel efficiency tops the list, whereas fuel costs take a position somewhere in the middle. In the study by Shell (2004), which also focuses on AFVs, fuel costs are among the four most important factors. Molin, Aouden, and Van Wee (2006), in an exploratory study among Dutch car owners, find that fuel price is the most important purchasing decision factor. Such mixed results make it hard to draw any conclusion on this issue.

Blauw Research (2006) provides some more detail on Dutch consumers' considerations surrounding 'fuel consumption' (i.e. fuel economy, which unfortunately they mix with fuel efficiency). It is termed a 'less prominent criterion', which is only important for consumers that try to reduce costs. That means people that drive a lot, but not lease drivers (since they do typically not pay for their own fuel). Yet, other attributes, such as tax, car category, and type of fuel are considered more important.

An intermediate conclusion – from SP research – is that fuel type could be a primary factor in the purchasing research. Fuel costs, efficiency, and economy are secondary criteria – other factors (such as purchase price, vehicle class) that are correlated ensure that the vehicles purchased feature a fuel economy/efficiency that leads to acceptable fuel costs. Indeed, consumers are confident that within-class fuel economy is similar (TRI/ECI, 2000).

The relationship that consumers have with fuel economy is barely based on rational decision making, at least in California (Turrentine and Kurani, 2006). Respondents have a hard time recalling the fuel economy of their vehicle, and they can only give a rough estimate on their fuel expenditures. Consequently, determining how much they are willing to spend extra on a more fuel efficient vehicle is too difficult a task. Not surprisingly, fuel economy has not been a major decision criterion for the purchase of the vehicles of the households interviewed.

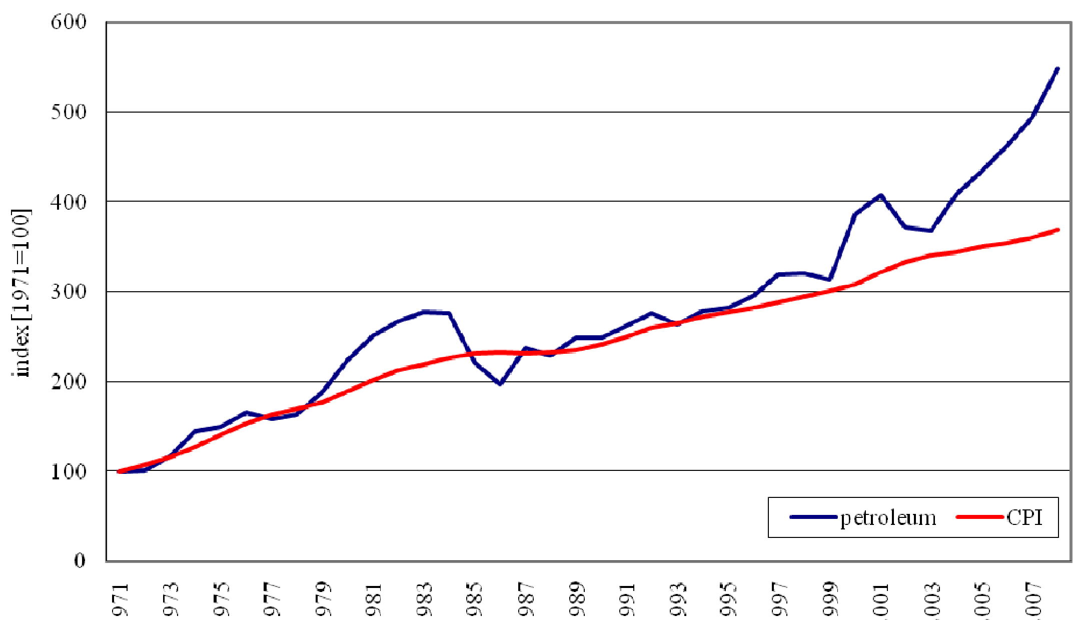

Figure 4.2 Index of petroleum prices and Consumer Price Index (1971 =100). Sources: BOVAG-RAI, 2008; CBS, 2008.

Two broad conclusions emerge from this study. First, fuel has hitherto been too cheap to enter any calculation on vehicle choice. Since prices in the Netherlands are much higher[22], it is plausible that

[20] The ratio of useful energy output to energy input.

[21] Measured as distance travelled per volume of fuel (e.g. miles per gallon) or volume of fuel used per unit (e.g. litres per 100 kilometres).

[22] On 26th January 2009, the average price for a litre of regular-grade petroleum was approximately 3.5 times higher in the Netherlands: € 0.366 for the US versus € 1.299 for the Netherlands. The US price is from the Energy Information Administration (EIA, http://tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp) , the Dutch price

calculative methods include fuel prices more regularly here. Yet, rising fuel prices will tend to make consumers more calculative in other places as well, including the United States.

Second, if consumers shift their preferences in the light of rising fuel prices, these are most likely not entirely attributable to economic considerations. Rather, the meanings that are attached to vehicles (e.g. 'gas guzzlers') will shift. Consumers adjust their purchasing behaviours such that they own a vehicle that reflects the meaning they appreciate – which may be a more fuel efficient vehicle.

Shifts of consumer preferences must be reflected in aggregate statistics. Fuel prices rather than costs will be considered, since costs are dependent on the choice of a particular vehicle (and factors such as driving style). Prices are a proxy for fuel costs – fuel costs increase for all potential vehicles as prices rise. As fuel costs increase, consumers may be led to choose other vehicles, typically those that have better fuel economy (because they are more efficient and/or have higher fuel economy).

Figure 4.2 displays the development of fuel prices and the Consumer Price Index (CPI) in the Netherlands since 1971. Three well-known price spikes are visible. The first two are the oil crises of the 1970s, the first due to the Organization of the Petroleum Exporting Countries' (OPEC) oil embargo, the second due to struggles between Iran and Iraq. The third sharp spike occurs in 2001, as prices are depressed following the terrorist attacks of 11 September. A gradual but steady increase in prices has marked recent years, although prices have collapsed at the end of 2008. Apart from these 'anomalies', the trend has been roughly the same as the overall price increase as expressed by the CPI.

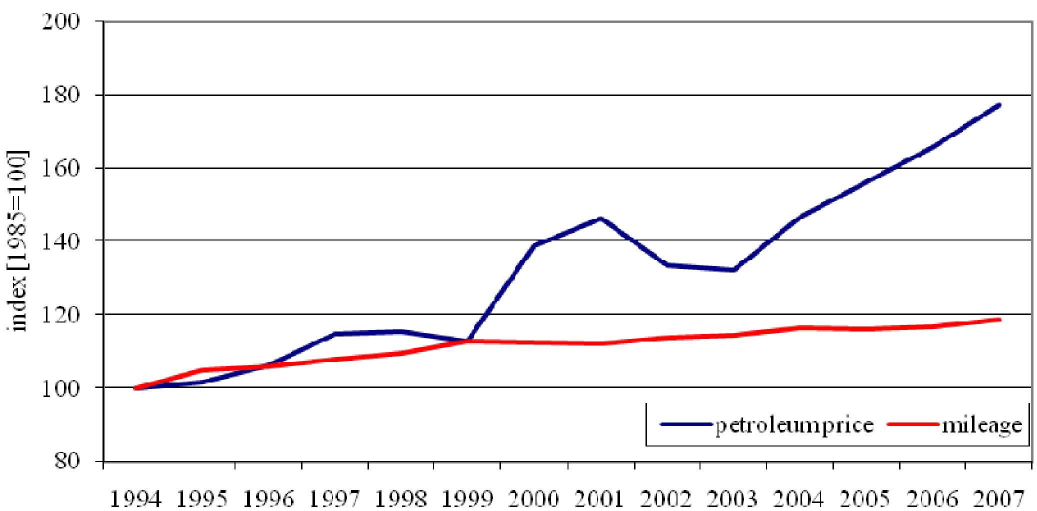

Figure 4.3 Index of fuel prices and daily distance covered by car per person (1994 =100). Sources: BOVAG-RAI (2008), CBS (2008).

Again adopting a rational perspective, consumers can be expected to respond to petroleum price changes by (i) reducing distance travelled by car or (ii) improving fuel economy (Puller and Greening, 1999). Figure 4.3 plots daily travel distance by car against fuel price. Unfortunately, data is only available for the period after 1994, i.e. during the gradual increase of prices. Distance covered does not increase as fast as fuel prices and seems to be especially flat during the peak up to 2001.

There are many factors that influence the fuel economy of a vehicle, such as vehicle weight, resistance coefficients, frontal area, vehicle weight, fuel type, engine type, engine displacement, and appliances in the car (Van den Brink and Van Wee, 2001; Turrentine and Kurani, 2007). Vehicle classes typically segment cars in ascending order according to all of these attributes. Figure 4.4 plots the market share of various vehicle classes against fuel price. Unfortunately, the data are only available since 1996, the period of gradually increasing fuel prices (except for the collapse of the price in 2001). Two trends become apparent. The first is that on the one hand midsize and large cars are losing market share, whilst classes small cars are maintaining and gaining market share, respectively. Furthermore, two new classes are introduced (multi-person vehicles, MPVs, and sports-utility

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is the National Recommended Price (http://www.nu.nl/brandstof/). Exchange rates taken from http://www.xe.com/.

vehicles, SUVs) that eventually capture market share, but whose growth is waning off towards the end of the period. Studying the figure more closely, there seems to be a slightly positive correlation between small car market share and fuel prices, whereas a slightly negative correlation can be thought to exist between fuel prices and large cars, SUVs and MPVs[23].

A more comprehensive method of studying consumer response to changes in fuel prices is to determine price elasticities of fuel. A meta-analysis of 43 studies finds a price elasticity of -0.53, which is typical for such studies (Brons, Nijkamp, Pels, and Rietveld, 2006). This implies that consumers' response to fuel price changes is inelastic, implying that they are not very sensitive to changes in price. This elasticity figure can be decomposed. Doing so reveals that consumers respond to price changes primarily by reducing car ownership and improving fuel efficiency (i.e. purchase a more economic vehicle). Reductions of mileage take a second place (Kayser, 2000). This result is in agreement with figures 4.3 and 4.4, which show adaptations of vehicle ownership, but not a reduction in mileage.

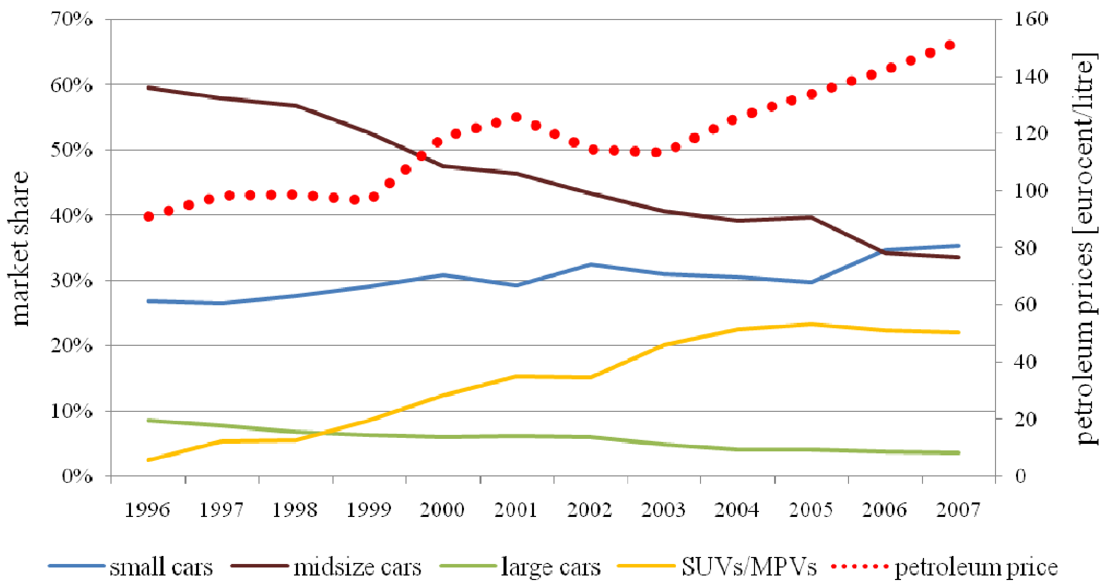


Figure 4.4 Share in total car sales of various vehicle classes. Source: BOVAG-RAI (2008).

Anecdotal evidence surrounding the oil price shock of 1973 illustrates this. In the early months of 1974, tens of thousands of workers were laid of at the large car manufacturers in the US because consumer preferences rapidly shifted towards smaller, fuel efficient cars. The US carmakers could not adapt their model ranges quickly enough, while Japanese were in an excellent position to deal with the preference shift (Finch, 1992).

In sum, fuel-related attributes present a complicated phenomenon. For now, it seems that they are not in the primary set of criteria that are considered in a car purchase. Rather, an affordable fuel economy is ensured by the choice of a vehicle within a certain class as illustrated by the study of revealed preferences. Due to the difficulty consumers have identifying fuel economy and costs, it is unlikely that these aspects enter the decision process in a rational way. Reviewing the above, however, it is likely that fuel costs, economy, and efficiency could start playing a more major role as prices increase.

Fuel availability is similar to range in the sense that it applies to AFVs only. Likewise, it does not show up influencing the purchasing process for CVs. It is an important item, though, and is at the core of the chicken-egg dilemma. Joint rollout of infrastructure and vehicles is paramount to a successful introduction of an AFV running on an alternative fuel (see e.g. Flynn, 2002; Yeh, 2007). Similar to range, it enters among the primary decision criteria. Marginal utility will probably decline rapidly

[23] Changing fuel prices need not be the only instigators of these shifts. Nonetheless, of all the significant attributes here, none have witnessed changes in the order of that of fuel prices.

after a certain coverage is attained, but until that level has been attained, only a small fraction of consumers will consider the purchase.

Closing the list in table 4.3 are three attributes that are related to **performance**. They apparently do not play a large role in the purchasing decision. Still, all three attributes have seen gradual improvements over time (BOVAG-RAI, 2008), necessitating an increases in output power of over a third (see figure 4.5). There is evidence that the relationship of acceleration is non-linear: marginal utility declines after a certain level of acceleration is attained (Ewing and Sarigöllü, 1998). Research on preferences in buying CVs confirm that performance is not among the primary decision factors (LowCVP, 2005). Therefore, performance improvements do not seem to be driven by consumer demand, but are implemented by OEMs in a rather autonomous fashion.

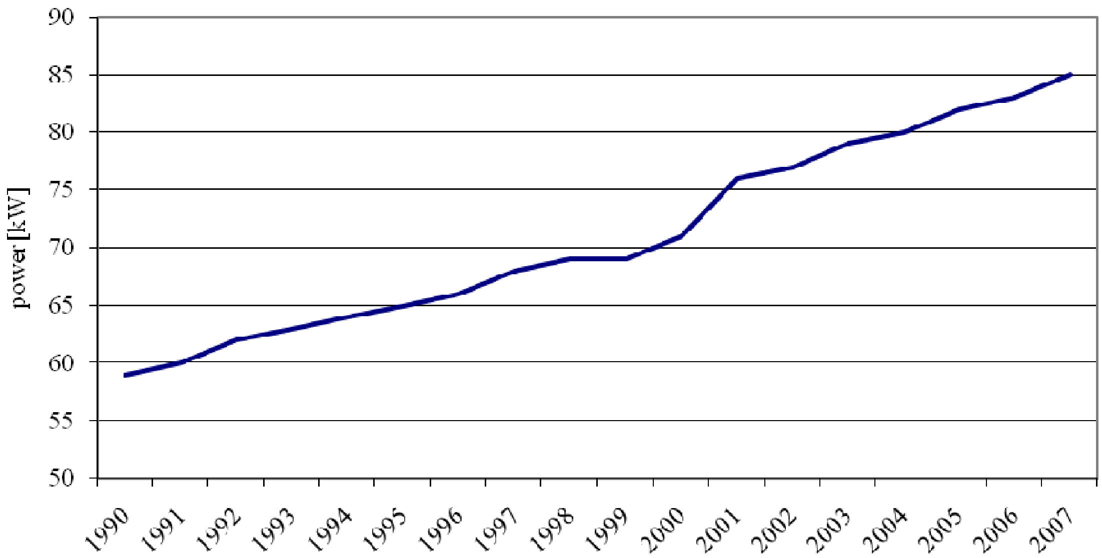


Figure 4.5 Development of the power of newly registered cars in the Netherlands. Source: ACEA (2008).

Finally, **comfort**, **safety**, and **reliability** are of paramount importance in purchase decisions.
The 2000 TCI/ECI study considers them to form the top three of most important vehicle characteristics, and a study by the British Department for Transport (2004) ranks all three of them among the primary decision variables.
Basically, the standard that consumers enjoy for these variables has been gradually increasing over the years. For comfort, cars have grown larger with every new model[24]. This partly explains the increase in weight over the recent years, but ever improving safety accounts for as much as a quarter of weight increase (Kågeson, 2000). See figure 4.6 for the recent development of size and weight in Dutch car registrations.

[24] Van den Brink and Van Wee (2001) nicely illustrate this point by noting that the 1997 Polo is larger and heavier than the 1981 Golf.

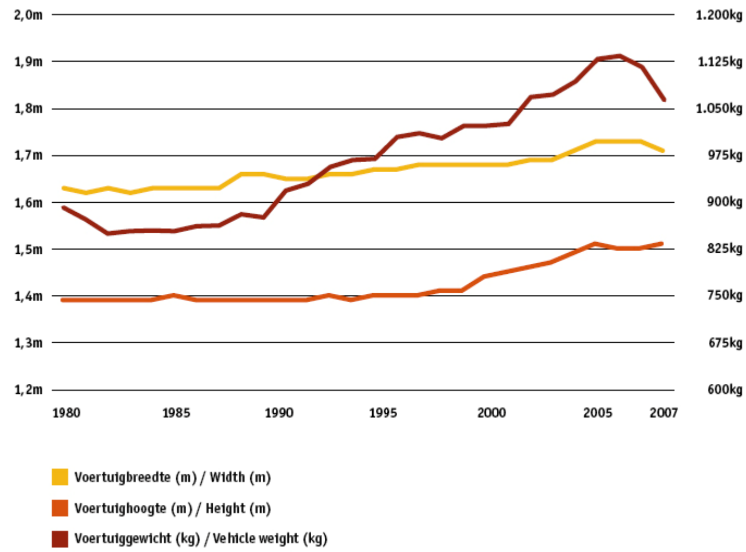


Figure 4.6 **Development of the size and weight of new car registrations in the Netherlands. The gradual increase in height is likely to be attributable to the increasing popularity of SUVs and MPVs. The drop in weight can be a combination of the application of lighter materials and increasing popularity of smaller cars. Source: BOVAG-RAI (2008).**

Reliability has improved dramatically as well. Figure 4.7 shows the (downward sloping) trend of the number of breakdowns that the ADAC (the German General Automobile Association) has recorded. The implicit assumption in SP research is that AFVs can match CVs in terms of comfort, safety, and reliability. It seems reasonable to assume that AFVs will have a hard time competing with CVs if they lag much on these attributes.

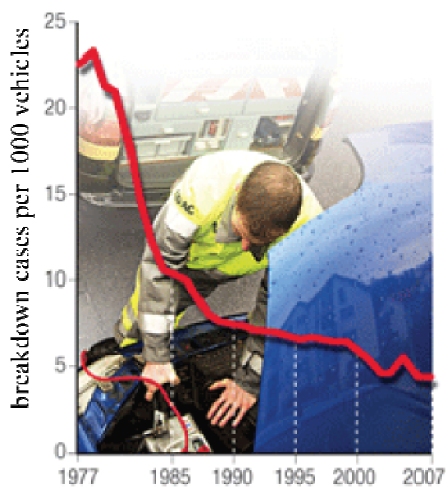


Figure 4.7 Number of breakdown cases per 1000 vehicles registered by the ADAC since 1977.

4.5 Diffusion process: The hybrid-electric vehicle

Just over a decade ago, hybrid-electric vehicles (HEVs) have entered the market. The purchase price for these vehicles is higher than for a CV, but they deliver substantial higher fuel economy and lower emissions. No fuel availability issues played a role in their introduction as they take regular petroleum. Their introduction provides an interesting case to study the diffusion of AFVs.

HEVs arguably do not represent an economically rational proposition (White, 2005). Yet, they have attained quite respectable market shares in various markets recently[25]. Reportedly, there are different reasons for adoption. Heffner, Kurani, and Turrentine (2007) have conducted in-depth interviews with early users of hybrids to study the reasons behind purchases of HEVs. They do indeed find that financial trade-offs are not at the basis of the decision to buy an HEV.

More interesting are their findings on how consumers define their vehicles. Instead of applying a particular vehicle class (compact, midsize, SUV, etc.) as an initial limiting criterion to narrow down their choices, they view their car as *hybrid* in the first place. Apparently, their first choice criterion was to have a hybrid drive train, after which they 'shopped' within this category. This is further illustrated by the fact that the vehicles the HEV drivers previously owned fall into various different categories (De Haan, Mueller, and Peters, 2006). It seems unlikely that so large a fraction of the sample would not stick to a certain vehicle class.

This is evidence that hybrids currently form an unstable product category (cf. Rosa, Porac, Runser-Spanjol, and Saxon, 1999). The question remains how developments will be in the future. Two competing hypotheses can be formulated: (1) HEVs keep forming a separate product category, which stabilizes eventually or (2) the HEV product category 'connects' with conventional car categories and disappears as a separate category.

The former case could lead to a limited diffusion of HEVs. Brand loyalty is typically identified as a primary decision criterion for a large group of consumers (see e.g. DfT 2004b). If certain brands decide not to enter the HEV market (which would exist as a largely separate market in that case), a sizeable part of their consumers would be ruled out as HEV adopters.

In the latter case, it is possible that hybrid technology would not become available in all classes. Consumers opting for a certain vehicle class in the first stage of the purchasing process would then rule the HEV option out.

4.6 Car use motivations

Car use and purchase are inextricably linked. Steg (2005) has studied motivations towards car use and found three: instrumental, symbolic, and affective. Instrumental motivations refer to the use of a car to fulfil its function as a means of transport, getting a person from A to B, although preferably as safely, reliably, etc. as possible. Yet, as the HEV case has shown, cars are more than just instruments. Their symbolic function allows drivers to express their self and their social status, representing a rather different motivation for car use. Similarly, the affective function fulfils deeper, non-instrumental needs, forming a third motivation.

The work of Steg suggests that symbolic-affective motives for car use are even stronger than instrumental ones. This implies that diffusion of AFVs is not only dependent on the relative performance of AFVs on the various attributes discussed above, but also their ability to fulfil various symbolic-affective functions. This has been acknowledged in other studies as well – see, e.g., the importance of 'image' in table 4.1. Some illustration of symbolic notions attached to AFVs can be derived from Heffner, Kurani, and Turrentine (2007). They find five symbolic meanings that are important to HEV buyers (see table 4.4). Note the possible bias due to the context of the early US market for HEVs.

[25] Hybrid cars represented 1.3% of all new car registrations in the Netherlands in the first half of 2008 (BOVAG-RAI, 2008, and autoweek.nl) and 2.4% of car sales in the US over 2008 (http://www.hybridcars.com/hybrid-sales-dashboard/december-2008-dashboard-focus-production-numbers-25416.html).

Meaning	Description
Preserve the environment	Most households interviewed had only a basic understanding of environmental issues. Yet, out of ethical concerns, concern for others, community orientation, or a perceived heightened awareness and/or intelligence to comprehend environmental problems, consumers have been moved to purchase an HEV.
Oppose war	Several interviewees connected the purchase of petroleum to wars, notably in the Middle East. Reducing fuel purchases through the use of an HEV symbolizes an opposition of this type of war.
Manage personal finances	Consumers do not use economically rational ways of calculating monetary benefits of HEVs, but do use the HEV to symbolize this rationality, i.e. signal that it is sensible to save on fuel costs as petroleum prices are high. Some use this apparent rationality to 'compensate' the environmental meaning of an HEV.
Reduce support for oil producers	Major and national oil companies have a negative image, and driving an HEV signals opposition to them. Connects with connotations of national and personal independence.
Embrace new technology	The new technology of hybrid vehicles distinguishes HEV owners from CV owners. Some buyers view their purchase as a support for OEMs that are innovative.

Table 4.4 Meanings conveyed by HEV owners (Heffner, Kurani, and Turrentine, 2007).

4.7 Early adopter profiles

Naturally, early adopters of AFVs are new car buyers. New car buyers form a subgroup of all car buyers, and are typically older, have higher purchasing power, and are less likely to have children under 18 years of age (De Haan, Müller, Peters, and Hauser, 2007). A study carried out for Shell (2004), referenced in LowCVP (2005) adds that early adopters have a higher than average education, are likely to be 'urban dwellers' and have an interest in technology and innovation.

Early adopters of AFVs must be willing to cope with their disadvantages compared to CVs (Spitzley, Brunetti, and Vigon, 2000)[26]. Not surprisingly, research on willingness to switch that focuses on material aspects finds that consumers are generally not very interested in adopting AFVs as they cannot meet CV performance across the board. Perhaps due to this observation, nonmaterial aspects have become a well established part of transportation policy research. Part of this work is to segment the market according to attitudes and/or behaviours (e.g. Jensen, 1999; Pas and Huber, 1992). Such categorization is valuable, since it helps to identify policy that addresses specific groups.

Some work has found the Theory of Planned Behaviour (TPB) useful to define segments (e.g. Harland and Wilke, 1999; Anable, 2005). TPB states that the intention to perform a given behaviour is determined by the intention to do so combined with perceived behavioural control (PBC) (Ajzen, 1991). PBC refers to the actual control a person has over performing the behaviour (e.g. requisite resources) plus the perception of control (i.e. how well one judges to be able to perform the behaviour). In turn, intention is directly determined by the interaction between attitudes, a subjective norm, and PBC. Attitudes towards behaviour refer to the evaluation a person has about the likely outcomes of the behaviour. Evidently, a positive attitude enhances the intention to perform the behaviour. The subjective norm refers to 'the perceived social pressure to perform or not to perform the behavior' (Ajzen, 1991, p. 188). The constructs that make up TPB and their interrelationships are summarized in figure 4.8.

Unfortunately, the work discussed above focuses almost exclusively on transport mode choice. Nonetheless, a private (and confidential) study commissioned by Shell has proven that it is possible to meaningfully segment the market based on the constructs of the TPB. Notably, there are segments that combine a positive attitude towards driving an AFV with a high PBC. Such segments are likely candidates for early adopters. In the socio-technical scenarios, different early adopter groups are characterized by making use of the TPB and car use motivations as defined by Steg.

[26] Further illustrated by chapter 7, table 7.4.

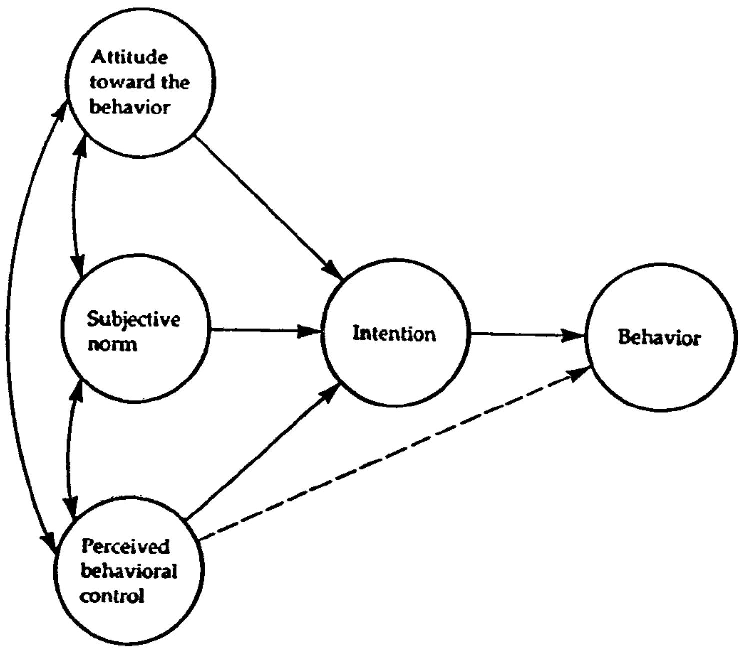


Figure 4.8 Schematic illustration of the Theory of Planned Behaviour (Ajzen, 1991).

4.8 Conclusion

This chapter has reviewed how consumers value various vehicle attributes. The main conclusion is shown graphically in figure 4.9. It features the two stages of the car purchase process. In this first step, two primary factors function to narrow down the overwhelming set of models that is available: it is assumed that consumers use a vehicle class as filter. Which particular class is determined by purchase price (linked to budget) and capability (i.e. the functions consumers want to fulfil with the vehicle). Range and fuel availability do not play a role in this stage, provided they do not interfere with the capability a consumer has in mind. The first stage enables the purchaser to limit the choice set to a handful of vehicles.

In the second stage, a more detailed trade-off is made based on secondary factors. Emission levels have been put in parentheses, because their influence is minor. The second stage ends with the choice for a single car.

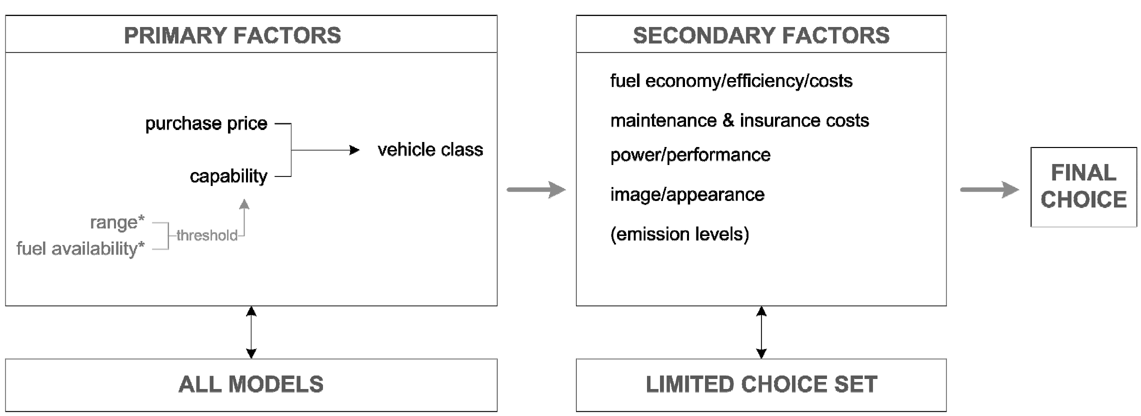


Figure 4.9 Schematic representation of the car purchase process.

Furthermore, the findings of this section can be formulated as a set of institutional rules that govern the relationship of consumers to OEMs. These rules are summarized in table 4.5. The rules are formulated to fit into the framework Geels (2004a, p. 906) lays out as much as possible.

	description	type	regime
C1	Any product offering (including radically new ones) must be able to address symbolic-affective motives for car use on top of instrumental ones.	cognitive	socio-cultural
C2	Sufficient variety (in terms of models, brands, etc.) must be available in the product offerings of a particular technology for it to grow into a mass market technology.	cognitive	socio-cultural
C3	Consumers expect new product offerings to improve (incrementally) over old ones, except on attributes that are above their 'threshold' of marginal utility.	normative	user/market
C4	The importance of attributes is (becomes) larger as their role in the trade-offs of the purchase process is (becomes) larger.	cognitive	user/market

Table 4.5 Institutional rules governing the relationship of consumers to OEMs.

The first two are cognitive rules in the socio-cultural regime. Consumers attach meanings to their car. Consumers express this meaning, hence the significance of the symbolic motivation to use a car (Steg, 2005). Any new product offering must address these use motivations to be successful (rule 1). Additionally, since groups of consumers (i.e. market segments) want to express different meanings, sufficient variety must be present in the cars offered of a particular technology for it to grow into a mass market technology (rule 2). Nonetheless, a smart choice of first group to address can simplify successful market introduction.

The third rule can be described as a normative rule in the user/market regime. Development of cars in recent history has shown that cars improve incrementally on a number of attributes (e.g. size, safety, comfort, etc.). Consumers have come to expect new product offerings to improve over the previous offering, albeit only slightly, and will be reluctant to settle for less than what they currently have (and value).

The fourth rule can be classified as cognitive in the user/market regime. It states that attributes become more important in the purchasing process as their impact on the trade-offs that the purchase process entails are larger. For instance, range and fuel availability are very important if they are below their threshold value as they then limit ease-of-use. If above, they are only of very minor importance. Fuel costs are currently not very important either as they are perceived to only be a small part of total costs. As fuel prices rise, they may (and do!) gain in importance as a decision criterion. Consequently, emission levels have little impact at all, as no trade-off is involved whatsoever.

This implies that alternative technologies must either bring their performance on these attributes to a level comparable to conventional technology or external developments must increase the trade-offs involved. This finding is of paramount importance for defining changes to the current system and opportunities for alternative technologies.

5 The relationship of OEMs to consumers

The OEM part of the OEM-consumer relationship consists of producing and marketing vehicles. This chapter analyzes how OEMs respond to the consumer preferences identified in the previous chapter.

5.1 Development trade-offs

Consumer preferences as identified in the previous chapter place conflicting demands on OEMs. Figure 5.1 illustrates this graphically. The figure shows a number of vehicle attributes that consumers prefer (cf. figure 4.9)[27]. The middle part of the figure relates to vehicle design – these are decisions on attributes that are up to the OEM. The outer (left- and right-hand) parts of the figure are preferences as expressed by consumers. The preferences on the left-hand side are in conflict with the preference for cars that are consume as little fuel as possible (right-hand side)[28].

The figure has been filled in using two papers that have studied these relationships. Van den Brink and Van Wee (2001, referenced as BW henceforth) have studied the trends for the Dutch car fleet in the period from 1985 to 1997 (figure 5.1a). Sprei, Karlsson, and Holmberg (2008, SKH) have done the same for the Swedish car fleet during the periods 1985-1995 (figure 5.1b) and 1995-2002 (figure 5.1c). The numbers deserve some explanation. Percentages reflect actual developments in attributes of new car offerings[29]. For instance, safety improvements in Dutch cars in the period 1985-1997 have led to a 5% increase in weight. The total weight increase during this period has been 20%.

The arrows that feed into 'fuel consumption' are *implied* fuel savings. They should be interpreted as follows: had attribute X (e.g. weight) not increased by y%, fuel consumption would have been lower by z%. The last figure (z%) derives from *calculations* by the authors of the studies.

A better **performance** in terms of faster acceleration and higher top speeds requires a car to have a bigger engine. The numbers differ somewhat for the studies. In the Netherlands, engine displacement has increased 13%, while displacement increased only 8% during the corresponding period in Sweden[30]. Surprisingly, the (direct) effects of this increase are more or less the same[31]. The discrepancy could be due to differences in the model describing the physical relationship between fuel economy and engine displacement in the two studies[32]. An alternative explanation is that the relationship depends on the absolute value of engine displacement, which is higher in Sweden than in the Netherlands.

Since SKH have studied two distinct time periods, longitudinal comparison is possible. The period 1995-2002 differs markedly from the previous period, because average cylinder capacity shows a downward sloping trend. This is popularly called 'downsizing' of engines, which is currently possible without sacrificing performance characteristics. It has a direct effect that brings fuel consumption down.

[27] Excluded from figure 5.1 are all attributes that relate to costs, reliability, and range. Costs are excluded because they trade off negatively to all of the other variables and therefore do not change the picture structurally. Reliability is left out because it is not thought to enter any of the trade-offs. Range relates to fuel economy – *ceteris paribus*, range is extended if fuel economy is higher. It is excluded from the figure because it is above its threshold value for conventional vehicles, so there is no need for OEMs to trade it off against other vehicle attributes.

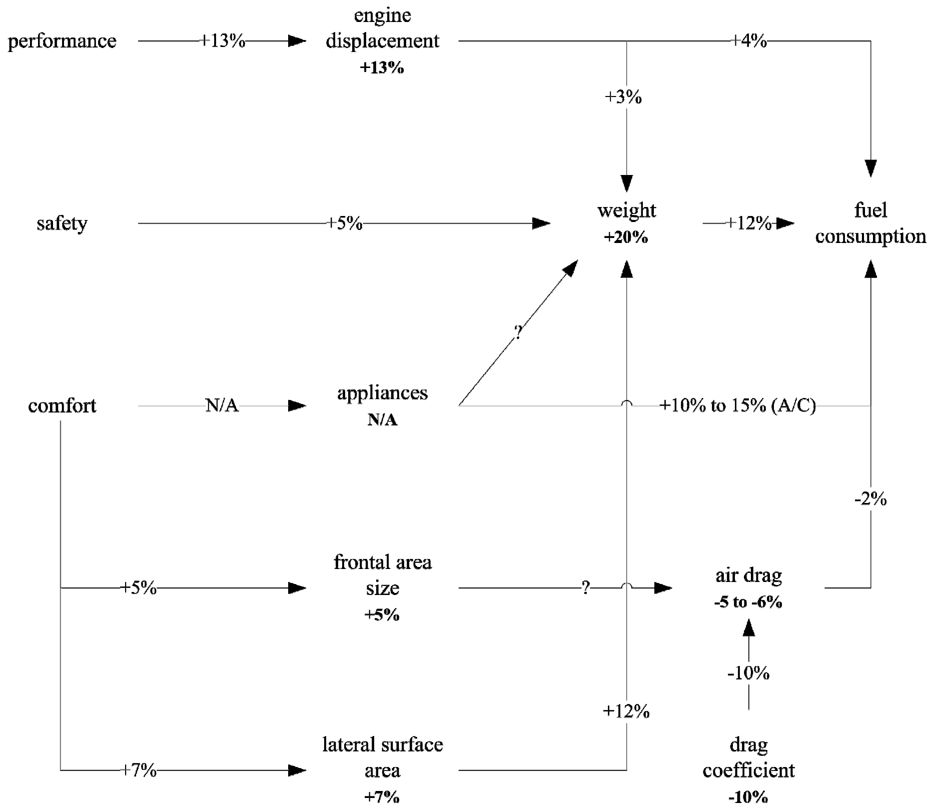
[28] In line with the convention in literature on this subject, the discussion in this section is based on fuel consumption, as measured in litres per kilometre. Please note that this is the inverse of fuel economy as defined previously (see footnote 21).

[29] An exception is the relationship of size to air drag, which is based on calculations by the authors of the respective studies instead.

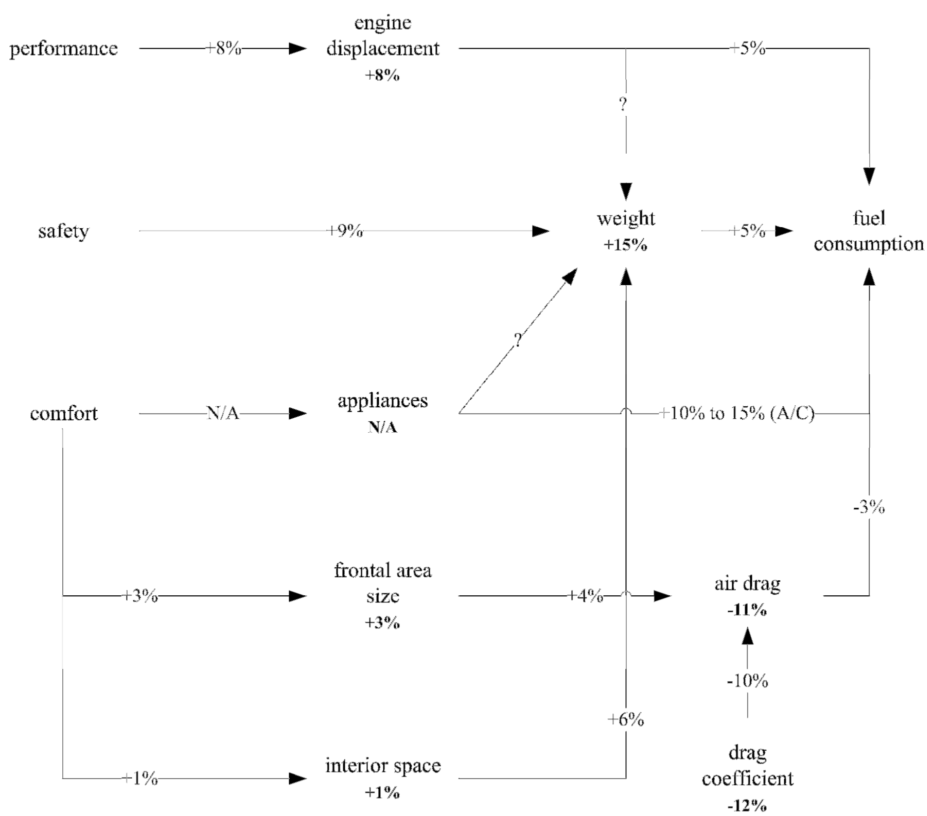
[30] As noted above, BW cover the period of 1985 to 1997, while SKH cover 1985-1995. These periods will be treated as equal in the remainder.

[31] These numbers exclude the indirect effect of a larger engine on fuel economy through increased weight.

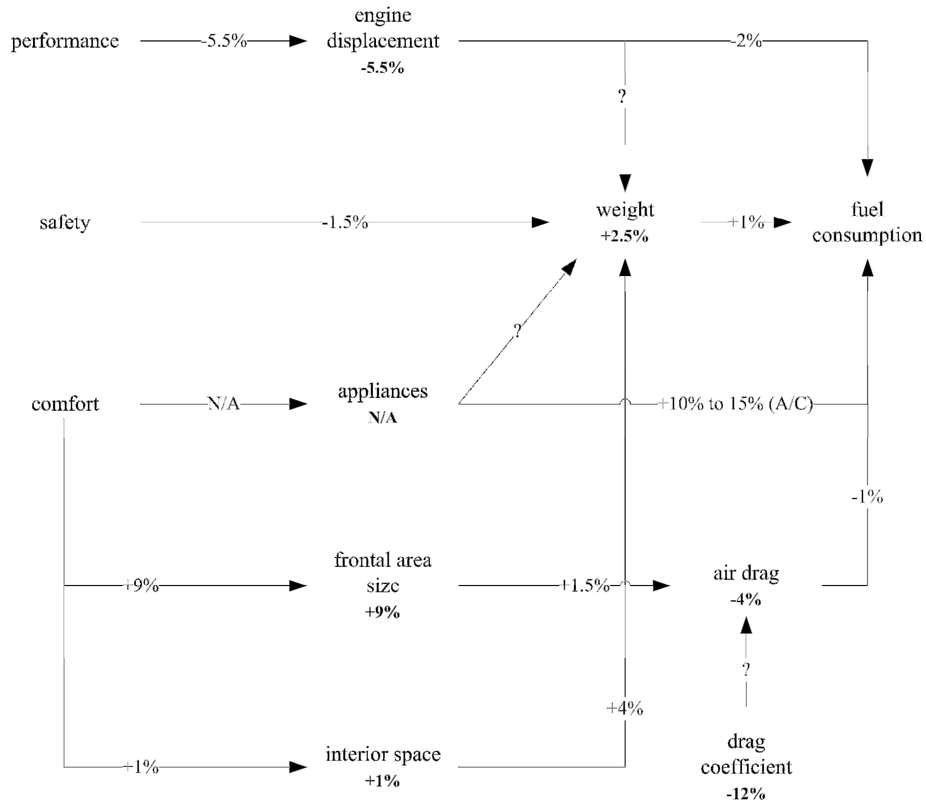
[32] Van den Brink and Van Wee (2001) base this relationship loosely on an examination of the development specific fuel consumption of a set of selected car models, while Sprei, Karlsson, and Holmberg (2008) develop a function for the relationship.



(5.1a) Based on Van den Berg and Van Wee (2001). Covers the period 1985-1997 in the Netherlands.



(5.1b) Based on Sprei, Karlsson, and Holmberg (2008). Covers the period 1985-1995 in Sweden.



(5.1c) Based on Sprei, Karlsson, and Holmberg (2008). Covers the period 1995-2002 in Sweden.

Figure 5.1 **Conflicting consumer requirements: performance, safety, and comfort are at odds with fuel consumption. Percentages indicate changes during a period, e.g. safety improvements in Dutch cars in the period 1985-1997 (figure 5.1a) have led to a 5% increase in weight. The total weight increase during this period has been 20%.**

Engine displacement indirectly affects fuel consumption through a weight increase. This increase not only involves the engine itself, but other elements – that need to become sturdier – as well (BW). Unfortunately, an estimate for this relationship is not available.

A design that improves **safety** generally requires a car to be heavier. Kågeson (2000) cites a report by the European Conference of Ministers of Transport (ECMT, 1995) that 'for an upper medium car model, only around a quarter of the weight increase has been due to safety features'. Taking this as a guideline, the total of 20% weight increase in BW translates into a component of 5% for safety. This compares to a 9% for the corresponding time period in SKH, although it must be noted that this amount includes everything besides engine displacement and enlargement of the car itself.
Interestingly, weight itself does not add significantly to safety (Khazzoom, 1994). At least, this seems to be the case nowadays. The 1995-2002 period in SKH reflects this by showing a weight decrease – although, again, not all of this should be attributed to safety. It seems that weight increases were beneficial for safety during the seventies and eighties, but are no longer now (Zachariadis, 2008).

A more **comfortable** car is fitted with more **appliances**, which results in an increase in weight. These two relationships have not been quantified, however. Intuitively, the weight increase of more appliances does not seem very significant. The fuel consumption due to appliances, on the contrary, is not insignificant. For instance, the air conditioner – having become more and more standard on new cars in Europe – can account for an estimated 10-15% increase in fuel consumption by itself (Kågeson, 2000).

A second way to make cars more **comfortable** is to increase their **size**. Size increases are of the same order of magnitude for the three studies, although the two time periods reveal a significant increase in the trend to make cars larger. A direct effect of a larger car is that it increases weight. BW relate the weight increase to the increase in lateral surface area. The weight increase thus implied is calculated by subtracting the weight increases due to engine enlargement (3%) and safety (5%) from the total weight increase (20%). SKH base their approximation of the increase in car size from an index based on nine measures of interior space. Due to these different methodological approaches, their estimates are much lower.
A second effect of size increase is a larger frontal area and thus a larger air drag. This can be offset by improving the aerodynamic characteristics of the car by minimizing the drag coefficient. Unfortunately, the two studies take a different approach to disentangling these effects. BW do not provide the direct effect of size on air drag, but do estimate the drag coefficient to have decreased by 10%. Conversely, SKH have a number for the direct effect of size on air drag, but only provide a number for the improvement of the drag coefficient for the period 1985-1995. Probably due to these differing approaches, the results on air drag change deviate quite a lot. Nonetheless, the estimates on the ultimate effect of air drag on fuel consumption are reasonably in check. They all show that aerodynamic properties have improved, so that fuel economy has increased over all periods. Aerodynamic improvements are becoming smaller, judging by the effect that a smaller increase in size leads to a relatively smaller improvement of air drag.

Preferences for improved performance, safety, and comfort thus all have direct and indirect positive effects on car **weight**. For all periods studied, weight increase is the most influential factor influencing fuel economy. As a rule of thumb, an increase in weight of 10% drives fuel consumption up by 6% (DeCicco and Ross, 1996)[33].

	Weight [kg]			Lateral surface area [m^2]		
	1981	1997	2008	1981	1997	2008
Golf	750	1104	1117	6.1	7.2	7.5
Polo	736	850	989	5.8	6.1	6.5
Lupo	-	856	-	-	5.8	-
Fox	-	-	973	-	-	6.4

Table 5.1 Weight and lateral surface area (approximated by width x length) of selected Volkswagen models. Data taken from http://www.autoweek.nl and retrieved on 19 February 2009.

The interesting question is what drives the weight increase. It can be observed that OEMs have been 'upgrading' their models. Table 5.1 is based on observations in BW. It lists part of Volkswagen's model range in descending order, Golf thus representing the highest class. A comparison of classes over time is interesting. The 1997 Polo weighs more than the 1981 Golf, and is of equal size. The same holds for the 1997 Lupo and the 1981 Polo. This implies that these models have been 'upgraded' a class, so that there was room for the introduction of 'new' classes: the Lupo basically filled the void created by upgrading the Polo, the Fox did the same for the Lupo[34].
Although this exercise is insightful, it does not explain why OEMs seek to upgrade their models. A plausible explanation is that OEMs have engaged in competition on attributes as safety, performance, and comfort, resulting in increasing car weight. Yet, such competition is only possible if fuelled by shifting consumer preferences – if there would not have been demand for such cars, it is unlikely that producers would have been able to sustain these trends autonomously. Nonetheless, some attributes, such as performance, size, and weight, seem to be pushed beyond a reasonable utility for consumers. These attributes have seen large increases while they do not show up as very important in consumer

[33] Hence the 12% decrease in fuel economy that BW find. SKH have apparently incorporated a slightly different assumption in their physical model.
[34] This situation was actually somewhat more complicated. The Lupo did not sell well in the (Western) markets it was intended to serve. Volkswagen then decided to introduce the Fox, produced in Brazil and originally aimed at industrializing countries, instead of the Lupo.

preference rankings. Larger, more powerful cars do generally have a higher profit margin, which means that upgrading beyond consumer need is a way for OEMs to increase profits.

Analysis by Kågeson (2000) shows that the weight increase is *not* due to a shift in consumer preferences for higher class models. In other words, consumers do not on average choose a car in a higher segment *on top of* the upgrading by OEMs. Upgrading seems to largely suffice to accommodate shifting consumer preferences. As BW note, the upgrading is in keeping with rising real income, so that consumers can afford to buy the upgraded models. Buying a vehicle in a more expensive class is only possible if an individual's income rises faster than average income.

As a side note, this simple analysis provides some additional evidence for a phenomenon noted by SKH: trends are slowing down (see figures 5.2 and 5.3). This is partly due to changing consumer preferences, perhaps because marginal utility of some attributes is declining. For instance, there is a limit to the benefit of again a larger car. Partly, the explanation is in technological progress, e.g. today's engines attain much higher power-to-volume ratios[35]. Interestingly, the advance in size and weight seems to be continuing for the smaller models, while it has stalled for the larger Golf.

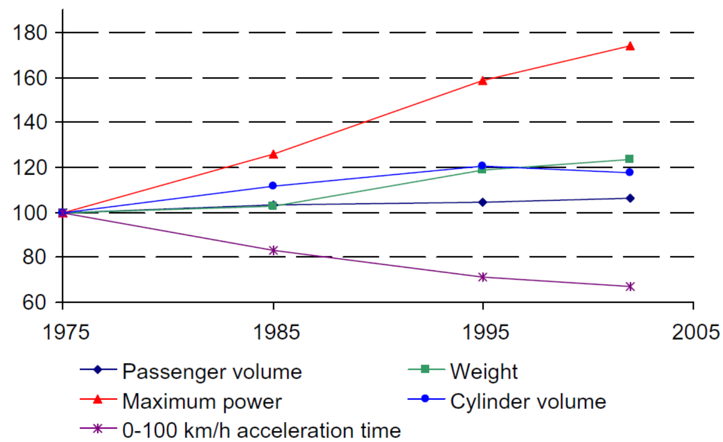


Figure 5.2 Developments of various vehicle attributes in Sweden (Sprei, Karlsson, and Holmberg, 2008).

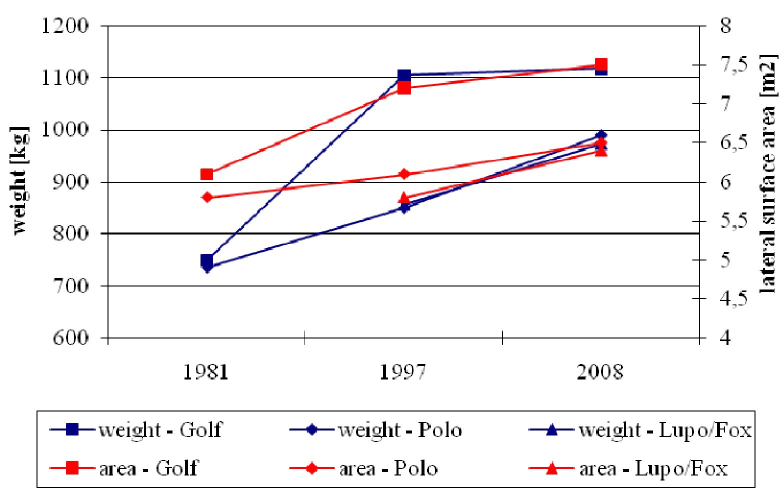


Figure 5.3 Based on table 5.1. Trends in increasing weight and size seem to be declining for the Volkswagen Golf, but not for the smaller Polo, Lupo, and Fox. Note that the Polo and Fox have been combined in one series, since the Fox has replaced the Polo.

[35] Engine displacement grew by a mere 7% for new cars in the Netherlands in the period from 1990 to 2007, while power output grew by an impressive 44%. This illustrates the engine downsizing trend referred to before.

5.2 Technological improvement

The previous section has shown that OEMs have made choices in developing their products that have tended to increase the fuel consumption of cars. Yet, consumption has stayed essentially flat in the Netherlands during the period studied in BW (figure 5.4) and has decreased in Sweden during the period studied in SKH (figure 5.5).

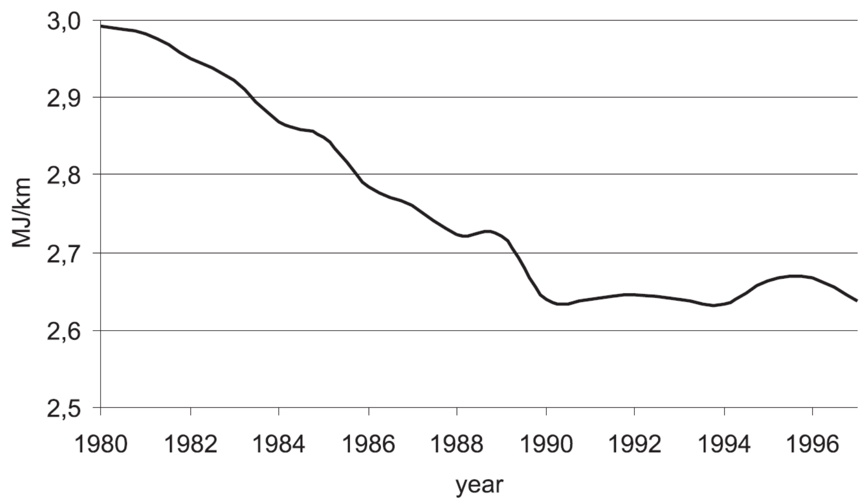


Figure 5.4 Car-fleet specific fuel consumption in the Netherlands (Van den Brink and Van Wee, 2001).

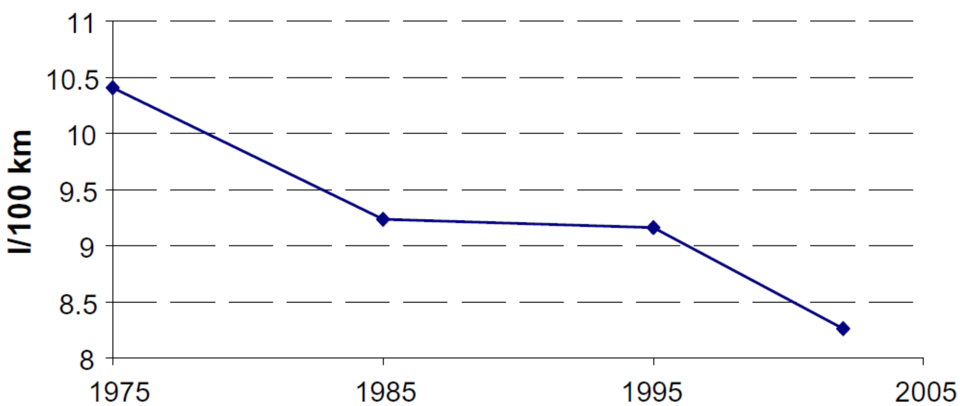


Figure 5.5 Car-fleet specific fuel consumption in Sweden (Sprei, Karlsson, Holmberg, 2008).

Obviously, technological progress has produced these relatively positive trends. The two studies nicely reflect how OEMs have allocated technological improvements. For the Dutch situation, technological improvements have prevented an increase in fuel consumption of 17%. In the Swedish situation, a raise of 23% has been offset, plus an improvement of 12.4% realized. This implies that 65% of progress has been attributed to offsetting more safety, performance, and comfort, while the rest has been used for reducing fuel consumption[36]. See figure 5.6 for a breakdown of technological improvements.

[36] Obviously, 100% of improvement has been attributed to offsetting increases in other attributes in the Dutch situation.

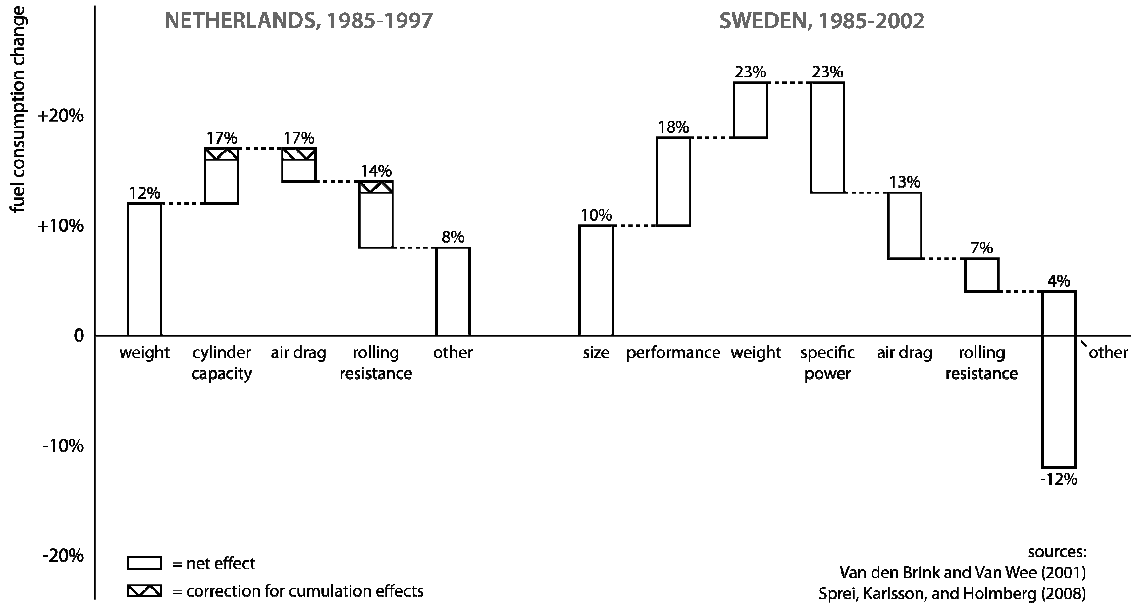


Figure 5.6 **Breakdown of fuel consumption according to attribute changes. Based on Van den Brink and Van Wee (2001) and Sprei, Karlsson, and Holmberg (2008).**

The trade-off between consumer convenience and fuel economy is also topic of a study of the UK situation by Kwon (2006), who quotes Rice and Parkin (1984) and Sorrell (1992) on the matter. Their results are summarized graphically in figure 5.7. It provides a nice longitudinal comparison and shows that consumer preferences actually shifted towards purchasing more fuel efficient cars during the oil crisis years in the period 1979-1983. A closer examination of the 1990-1997 period that is also covered by Kwon reveals a flattening trend similar to that in the Netherlands.

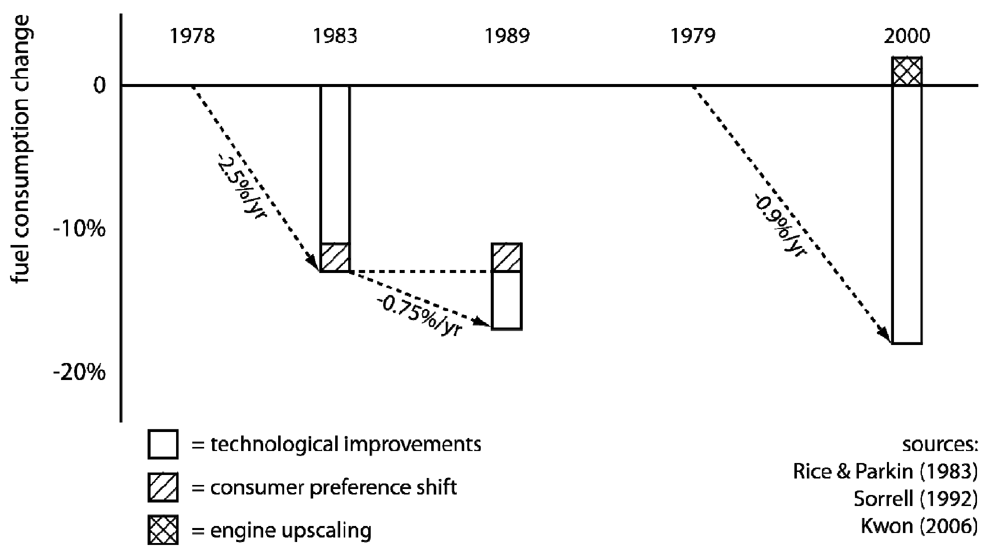


Figure 5.7 **Developments of fuel consumption in the UK. Based on Rice and Parkin (1983), Sorrell (1992), and Kwon (2006).**

Finally, Chen and Zhang (2009) provide a comparison with the situation in the US during the period 1985-2002. Their analysis focuses on the relationship between weight on the one hand and fuel economy on the other. For each year, they examine whether the big three OEMs in the US (General Motors, Ford, and Chrysler) decide to improve either weight or fuel economy, or develop new technology that enables simultaneous improvements in the two variables. The analysis of industry aggregate data reveals that statistically significant technological improvements have only been made in the period of 1995-2002. In the years leading up to 1995, the market seemed to move two ways: consumers demanding fuel economy were served by small and light cars, whereas consumers that put fuel economy low on their priority list were served by increasingly larger cars such as SUVs.

5.3 Product variety, life cycle, and modularity

Another consumer preference that was identified in chapter 4 is fondness of a larger variety of product offerings to choose from. It is possible to distinguish two different types of variety: fundamental and peripheral (MacDuffie, Sethuraman, and Fisher, 1996). Fundamental variety refers to the number of distinctly different model offerings that are introduced to the market. Peripheral variety refers to the number of variations that are available on each of these offerings.

Fundamental variety has increased for the US car market: the number of models offered increased from 84 in 1973 to 142 in 1989 (Womack, Jones, and Roos, 2007). Figure 5.8 offers a more recent, but similar, overview for the Western European car market. It shows almost a tripling of the number of models on offer, which plateaued during much of the 1990s. Volpato and Stocchetti (2008, p. 25), on which the figure is based, label the larger part of this period as ‘the years of increasing demand’, which fits nicely with the picture – if demand increases autonomously, there is no need to evoke additional competition by introducing product-line extensions.

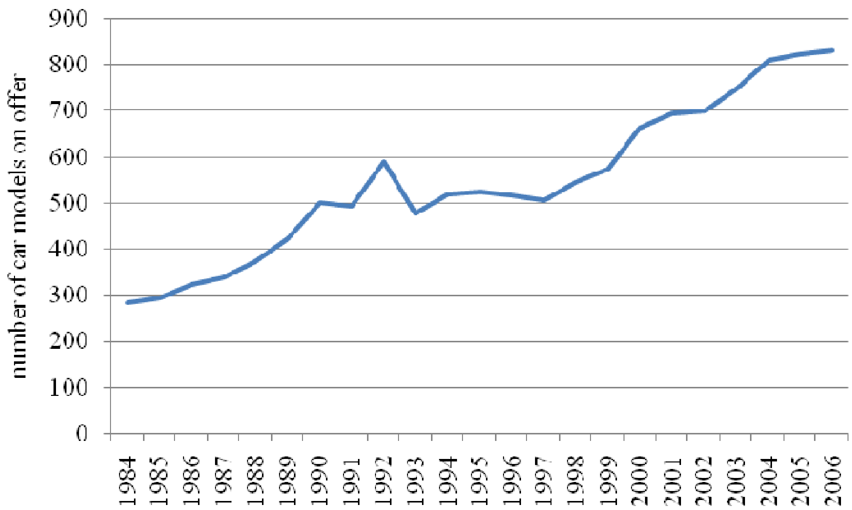


Figure 5.8 The average number of car models offered in Germany, Italy, and France. This is a measure of fundamental variety. According to these data, the number of models on offer peaked briefly in 1992, for which no other explanation than administrative error can be offered. Based on Volpato and Stocchetti (2008).

The same study conducts a more detailed analysis of the Italian market to uncover whether peripheral variety has increased as well. This is confirmed, as the average number of versions per model has increased from 4.1 in 1984 to 12.2 in 2006. Another bit of evidence is provided by an analysis of the number of powertrains on offer in a selection of product offerings in the UK market (figure 5.9).

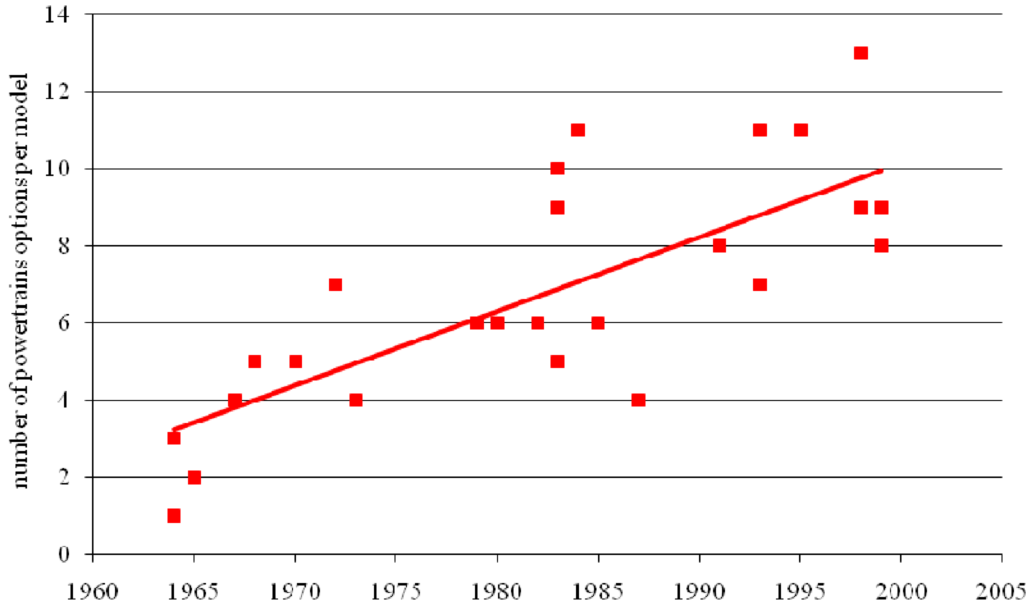


Figure 5.9 **Number of different powertrains (e.g. 1.9 litre Diesel engine) on offer in a selection of car models in the UK market. This is a measure of peripheral variety. Based on data in Holweg and Greenwood (2000).**

A related issue is the shortening product life cycle (PLC) of cars. Shortening the PLC provides consumers with more variety, as they can choose from other offers more frequently[37]. This has indeed happened, as the time between model introduction and discontinuation has declined from 10.7 years in the period 1970-1980 to 5.6 years in the period 2000-2006 (Volpato & Stocchetti, 2008). Note that shortening the PLC is tricky for OEMs, since they might risk cannibalizing sales of another model in their line-up.

Again, it is hard to tell whether these trends have been initiated by consumers or OEMs. And again, it seems plausible to think of it as an interaction. OEMs compete for a larger share of the market and discover that offering more variety is a successful strategy. Also, OEMs can now apply price differentiation instead of to 'pile them high and sell them cheap' (The Economist, 1992). Until now, consumers have not really objected to this trend. For OEMs, there are surely benefits, since they expended a lot of effort to adapt their production system to producing more variety.

5.4 Production system, modularity, outsourcing, and innovation

Increasing variety and shorter PLCs could not have been realized without changes to the carmakers' production system. Recall that Ford started the mass diffusion of the automobile by introducing a system of mass production in the early 20th century. This system represented the exact opposite of variety, since it offered literally only a single option. As early as the 1930s, this system revealed its limitations, when Alfred Sloan identified opportunities to increase sales volumes by extending product lines with more models. Nonetheless, mass production remained in place until approximately the 1980s.

By that time, the efforts that the Japanese carmakers had put into developing an alternative system started to bear fruit[38]. The Japanese had identified numerous opportunities to improve the system of mass production. The main change they applied was to eliminate unnecessary waste ('muda'). The objective was to increase the added value of the time spent by a worker in the factory as much as

[37] Although there is, strictly speaking, no net addition to the variety of the car fleet, new car models do 'update' the variety in the market.

[38] The following description of lean production is based on Womack, Jones, and Roos (2007).

possible. Notably, they strove for minimization of defective parts during production, so that the need for quality control and rework at the end of production lines was eliminated. A second change was to minimize inventories, by eliminating buffers between workstations and requiring suppliers to implement a just-in-time delivery system.

Further improvements to quality were deemed necessary. To this end, a different approach was taken to sourcing parts. Ford had been designing and manufacturing 100% of the required parts in-house, but in the light of cost savings the trend had been to outsource the production of a significant fraction of parts. However, since cost reductions were the major driver for outsourcing, there was fierce competition among suppliers and quality suffered as a result. Therefore, the Japanese took a different approach. They organized their suppliers into functional tiers. Suppliers in the first tier were given complete responsibility in designing and manufacturing components to specification. Furthermore, since they were each assigned a different functional area, they all competed in separate markets. This opened the opportunity to have suppliers jointly discuss process improvements.

The result of this system of 'lean production' was that quality indeed improved tremendously. This nicely coincided with a rising consumer need for reliability. By the 1960s, the complexity of cars had advanced beyond the level that a car could be easily repaired using tools from the backyard shed. To avoid frequent visits to the garage, a car needed to be reliable.

Not only the manufacturing system and supply chain configuration were altered, the design process was also improved. In Western carmakers, tasks in the design process were subdivided into very small functional areas, creating many interfaces and much slack. Japanese manufacturers took a project-oriented approach, again resulting in quality improvements but also a dramatic reduction of development lead times and associated cost.

The latter achievement complements the trend identified in the previous section: variety. Because the lean carmakers were able to develop products quicker and cheaper, they could introduce a larger variety of models and shorten the PLC of their offerings. Furthermore, the flexibility of the new manufacturing system allows production of low volumes at competing costs.

The advantages of lean production are clear. Western carmakers have been adopting elements of lean production since the 1980s, but it is hard to tell whether they have already fully caught up with the Japanese.

Lean production can produce more variety than mass production. The main advantage of lean production is in fundamental variety through reduced design lead times. Modularity, a more recent trend, allows peripheral variety to increase as well. More peripheral variety implies that products can be customized to – ideally – the individual level, resulting in mass customization. According to a large-scale survey among manufacturing managers and employees, modularity-based manufacturing practices enhance mass customization capabilities (Tu, Vonderembse, Ragu-Nathan, and Ragu-Nathan, 2004).

Three types of modularity can be distinguished (Pandremenos, Paralikas, Salonitis, and Chryssolouris, 2009): modularity in use, modularity in design, and modularity in production. Modularity in use relates to peripheral variety. It allows the consumer to define the modules that he/she would like, such as is the case with selecting car options. This is enabled by modularity in design, which tries to couple functional requirements to car elements in one-to-one relationships. This way, if a consumer demands a different functions, it can be achieved by replacing a module. Finally, modularity in production refers to subassembling modules that are assembled into the final product in the last step of the production process. Ideally, the modules of each type are identical.

There are two opposite trends in variety (Jiao, Simpson, and Siddique, 2007). First is an increase in functional variety, implicating an increasing number of modules in modularity in use. Increasing rates of modularity accommodate this trend by providing OEMs with more real options, so that complexity remains manageable and they can hedge against uncertainty of demand (Fisher, Jain, and MacDuffie, 1995).

On the other hand, cost advantages and operational complexity favour reduced *technical* variety. This is why many OEMs have pursued a strategy in which multiple models are produced from one common technical base, the product platform (Pandremenos, Paralikas, Salonitis, and Chryssolouris, 2009; Jiao, Simpson, and Siddique, 2007). Platforms are the basis of product families. Modules are built onto the platform to produce individual cars (see figure 5.10). Table 5.2 provides an illustration of the number of product families that can be derived from one platform (fourteen in this case). In this particular case, 65% of parts are shared across product families.

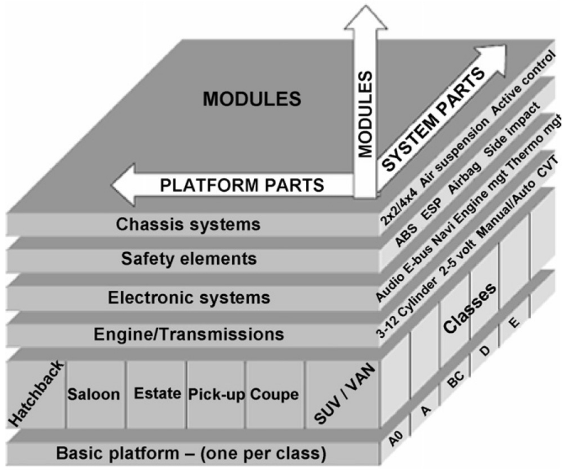


Figure 5.10 Illustration of the product platform concept. A platform is used for multiple models, which are customized by applying a variety of different modules. Source: Pandremenos, Paralikas, Salonitis, and Chryssolouris (2009).

Brand	Body style							Image		
	Hatchback	Sedan	Estate	Convertible	Coupe	Pick-up	Niche	Premium/mass	Quality/price	Sport/comfort
Audi	A3			TT	TT			Premium	Quality	Sport
VW	Golf	Bora	Golf	Golf		Caddy	Beetle	Mass	Quality	Comfort
Seat	Cordoba	Toledo						Mass	Price	Sport
Skoda	Octavia	Octavia	Octavia					Mass	Price	Comfort

Table 5.2 No less than 14 different models are built on the same platform, addressing a variety of markets. Source: Pandremenos, Paralikas, Salonitis, and Chryssolouris (2009).

Still, the carmakers are not in the most modular of industries. Modules are typically designed for individual models and no standards have been adopted that attempt to standardize interfaces across models and manufacturers (Takeishi and Fujimoto, 2001). The biggest issue in this respect is the difficulty of integrating the various modules into a workable final product (Pandremenos, Paralikas, Salonitis, and Chryssolouris, 2009).

There are regional differences in the adoption of modularity. In their terminology, Takeishi and Fujimoto (2001) observe that Western OEMs, notably the Europeans, focus on inter-firm modularization, meaning that they outsource relatively large parts of their production process. This is only possible if they also apply modularization in production. What they then struggle with it is to get modularization in product architecture (i.e. design) in line. Conversely, the Japanese keep more of their production in-house. This facilitates product integration, since they design and produce relatively more of their own modules. It thus seems that integration is the problem that keeps the three elements of modularization from being completely aligned.

Driven by a crisis in the 1990s and resulting cost focus, European carmakers have thus surpassed the Japanese in outsourcing design and manufacturing of modules (Takeishi and Fujimoto, 2001). For German manufacturers, as much as 77% of the frame and 63% of the drivetrain were outsourced to suppliers in 2002, numbers that are expected to grow in the coming decade (Roth, 2004). During the 1990s, the proportion of external R&D for European OEMs grew to 10-20% and as a consequence, value added is expected to shift from the OEMs to first-tier suppliers (Jürgens, 2003). In fact, industry structure changed into a network-like structure (Wibbelink and Heng, 2000). Simultaneously, OEMs attempt to reduce complexity in their supply chain. To this end, they strive for reducing their first-tier supply base.
It is an interesting question what the effect of modularization on innovation will be. Modular design reduces the complexity of (changes of) individual modules, so that the rate of incremental innovation

can be expected to be enhanced. Furthermore, replacing individual modules is easier, so that the rate of radical innovation can also be expected to be bigger (Pil and Cohen, 2006). Unfortunately, although a lot of researchers assert that modularity fosters innovation (e.g. Baldwin and Clark, 1997; Jain, Fisher, and MacDuffie, 1995), none of them provides empirical data for the automobile (or comparable) industry. Therefore, the only conclusion here can be that it seems likely that the modular route embarked on can spur innovation in the automobile industry – but proof still has to follow.

5.5 Model introduction strategy: The hybrid-electric vehicle case

In recent years, the car industry has witnessed one more radical innovation: the introduction of vehicles with petroleum-electric hybrid drivetrains. It is interesting to analyze how OEMs have proceeded in introducing these HEVs. Figure 5.11 illustrates the introduction strategy for hybrids into the Dutch market. The market segments into which hybrid models have been introduced represented less than 30% of sales in 2007. Furthermore, sales figures in absolute numbers are tiny: less than 1% of all cars sold in 2007 were HEVs.
The least the figure illustrates is that introducing a radical innovation such as the hybrid car takes a long time. There does not seem to be any considerable incentive for consumers to adopt the HEV[39].
The limited sales numbers imply that there is little motivation for OEMs to introduce more model variety. The situation is somewhat better in the United States, where the American carmakers have introduced some models as well and less alternatives in the form of diesel cars are available. Nonetheless, OEMs remain cautious as consumers are prudent in adopting this new technology.

		Model Year								
		2000	2001	2002	2003	2004	2005	2006	2007	2008
Toyota	Prius	22	383	63	18					
	Prius II					1060	2708	2375	2225	2799*
	Lexus RX 400h							331	296	155*
	Lexus GS 450h							34	n/a	37*
	Lexus LS 600h L								82**	30*
Honda	Civic II							415	808**	2905*

* = first half year of 2008
** = estimate

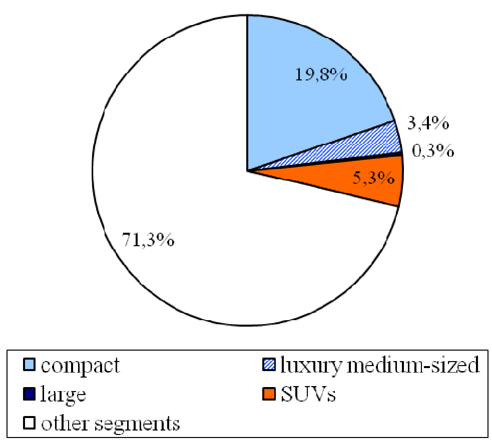


Figure 5.11 Introduction of hybrid vehicles in the Netherlands. Numbers in the table are numbers of cars registered in the respective years. The pie diagram lists sales percentages for each listed segment in 2007 (data from autoweek.nl).

5.6 Conclusion

This section has analyzed how OEMs have coped with consumer preferences for cars. Three conclusions can be drawn in the form of institutional rules, as summarized in table 5.3.

[39] The major incentive is for users of lease cars, that receive a substantial tax break.

	description	type	regime
O1	OEMs have a profit motive. They will continually update their product portfolio to offer the most profitable product mix.	cognitive	technological/product
O2	External pressure, such as government regulation and changing consumer preferences, is needed to alter R&D and product development search routines.	cognitive	technological/product
O3	The industry seeks to organize itself in the most profitable way, allocating design and production processes to the firms that can perform them most effectively.	normative	technological/product

Table 5.3 Institutional rules governing the relationship of OEMs to consumers.

The first rule states that OEMs will search for the most profitable composition of their product portfolio. They have an incentive to produce larger cars – the profit margin on these cars is larger, to some extent because consumers expect cars in a particular segment to be comparable, not in the least with respect to pricing (Flink, 1988; Ricardo, 2006). This partly explains the upgrading phenomenon. By gradually scaling up models (including their price!), OEMs increase profit margins. Consumers that nonetheless demand smaller cars are serviced by introducing a new, smaller model at some point. Furthermore, extending product lines and providing more options (i.e. increased variety) has proved a successful competitive strategy.

Note that in the upgrading process some attributes seem to be pushed beyond the point that they provide much added value to consumers. An example is performance, that has been shown to hardly influence the purchase process. Another result of the upgrading process has been increasing car weight over the last decades. This trend has slowed down in recent years, but now average car size is increasing, in part due to the introduction (in Europe) of new segments such as SUVs and MPVs.

For the rest, R&D and new product development are influenced by external pressure from consumers and government (rule 2). Government regulation seems only effective in areas that align with direct consumer interest or can be solved relatively easily by technological fixes (Zachariadis, 2006). Consequently, safety has been improved dramatically and a host of emission types have been curbed. Contrariwise, there has been no incentive to improve fuel economy or curb emissions of CO_2 beyond what consumers demand. Although there has been considerable technological progress, cars have only become more efficient to the point that they compensate for conflicting changes in other attributes. Consequently, fuel economy development of cars has been essentially flat during the 1990s, and CO_2 emissions are still at 1990 levels. Pure market mechanisms are unlikely to trigger substantial improvements in these areas (Levy and Rothenberg, 2002). Note, however, that consumer preferences shift to fuel efficient cars in times of high fuel prices, triggering OEMs to change their R&D search routines. Absent these pressures, gradual upgrading of models (rule 1) is the norm.

Finally, industry structure is organized in the most profitable way (rule 3). More variety and shortening PLCs require modular design, which triggers changes in industry structure. However, there seem to be limits to modular design as product integration becomes more complex. Still, it is reasonable to assume that larger parts of the value chain shift to suppliers as cars become more modular. In that case, increased (modular) innovation is to be expected.

6 Regime tensions and conclusions

The purpose of this chapter is to take stock. Based on chapters 4 and 5, three tensions internal to the regime are formulated in the first section. These render it problematic for the regime to continue on the current path. A set of developments in the regime, basis for the scenarios, concludes the chapter.

6.1 Regime tensions

The first two tensions are closely related and arise from the reconciliation of the demand for large, comfortable, and safe cars on the one hand, and controlling car fuel economy (and associated costs) as well as emissions on the other hand. The previous section has shown that consumers in general prefer larger cars because they are more comfortable and safe, while OEMs tend to produce larger cars because they generate a larger profit margin. The regime runs into problems as fuel prices rise, especially if they spike. OEMs cannot adjust their model ranges as quickly as fuel prices change. The option most readily available to consumers is to settle for smaller cars[40]. As a consequence, OEM margins decline. Incremental innovation holds the potential to ease the tension, but has not been able to solve it in the past decades.

This tension is closely related to the oil regime. The market situation in this regime determines the price of oil, and consequently the price of automotive fuel.

Tension #1: *Both consumers and OEMs have a preference for larger, safe, and comfortable cars. This puts a strain on the fuel economy of cars, which is exacerbated in times of inflated fuel prices. Shocks in fuel prices therefore imply difficult periods for the regime.*

The preference for larger, more comfortable, and safer cars is at odds with another vehicle attribute: emissions. Hence, the dynamic underlying the first and second tension is similar.

There is a difference as well. Although the second tension can also be traced back to the link with the oil regime, it is not so volatile. Consumers tend to prioritize fuel economy according to the rise and fall of fuel prices. However, curbing emissions is generally mandated by government, as opposed to consumers (Levy and Rothenberg, 2002). On the consumer side, emissions hardly play a role in the vehicle purchase process (Blauw Research, 2006; Metrixlab, 2004).

Emissions regulation has prompted OEMs to implement measures to reduce levels of various kinds of emissions. This has been successful for a number of different emission types, but not for CO_2. Hence the second tension.

Tension #2: *Both consumers and OEMs have a preference for larger, safe, and comfortable cars. This puts a strain on the emission levels of cars (notably CO_2) and meeting regulated emission levels is increasingly difficult.*

The third tension concerns the management of the PLC in the car industry. As is the trend in many other industries, new product development time is decreasing and PLCs are shortening. Additionally, OEMs are broadening their model range by offering an increasing number of product-line extensions (Volpato and Stocchetti, 2008). These developments are at odds with producing (radical) innovation that can solve the first two tensions. Rather, OEMs are focused on improving their current product portfolio and spread their R&D efforts across many options, not significantly pushing a single one (Van den Hoed, 2007; Oltra and Saint Jean, 2009).

This strategy works out successfully in the short term. However, innovation is needed to overcome the challenges and landscape pressures of the future.

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[40] Other ways for consumers to deal with high fuel prices and is to drive less. However, recall that it has been shown that consumers adapt their behaviour by purchasing less cars and more efficient cars instead (section 4.4).

Tension #3: *The PLC in the car industry is shortening. OEMs are focusing on product-line extensions instead of product innovation. This is a sound short-term strategy, but innovation is necessary to address the challenges of the long term.*

6.2 Conclusions

The relationship between consumers and OEMs in its most basic form consists of an exchange of product offerings and preferences. In stable times, OEMs engage in upgrading their models, gradually improving and enlarging their line-up. Often, this drives performance beyond what is necessary for consumers, but it allows OEMs to increase their profit margins. The upgrading process is interrupted by pressure from consumers or governments. For instance, if fuel prices rise, consumers acknowledge that they can do with a vehicle which performs less than their current one and choose their next vehicle from a lower segment. This hurts OEM profits. Similarly, governments can slow down the upgrading process by enforcing strict emission regulations.

Seven institutional rules have been found to govern the relationships, while the regime struggles with three internal tensions. Using the rules and tensions as a basis and in line with the STSc-methodology (Elzen and Hofman, 2007), table 6.1 lists a number of regime developments that will be used to form 'transition seeds' in chapter 9. Note that these developments assume a stable regime situation. These seeds are the building blocks for the socio-technical scenarios.

	Name	Description
R1	Consumer & OEM preference for larger cars	Consumers prefer cars that are larger (roomier), more comfortable, and safe. OEMs share this preference, as their margin on larger cars is higher.
R2	Incremental progress	New product offerings generally feature incremental improvements across the board of vehicle attributes. All new products - whether conventionally or alternatively fuelled - must live up to the promise to deliver slightly more than the previous generation of vehicles.
R3	Fuel price responsiveness	Vehicle attributes move up consumers' priority lists as they play a larger role in the trade-offs among attributes in the purchase process. For instance, consumers respond to rising fuel prices by increasing the priority they attach to fuel economy. For the case of fuel economy, OEMs lack the flexibility to match the speed of fuel price changes.
R4	Emissions curbing	Curbing emissions has been fairly successfully accomplished to date. It will become increasingly difficult and costly, although further efficiency improvements (of up to ~30%) are expected using ICE technology.
R5	Shortening PLC and increasing variety	The product life cycle (PLC) in the car industry is decreasing and OEMs are increasing the variety of models offered.
R6	Modularity	Design, manufacturing, and use of cars is becoming more and more modular. This allows OEMs to offer more variety on the same product platform.
R7	Changing industry structure	OEMs gradually increase the parts of the design and production process that are outsourced to their suppliers. The role of the first-tier suppliers grows and they add more value to the final product.
R8	No clear focus in R&D	OEMs spread their R&D efforts over many alternative propulsion technologies (electricity, hydrogen, hybrid forms), as well as improving current technology. A clear preference for any option cannot be discerned.

Table 6.1 Regime developments that are used as input for the transition seeds that are formulated in chapter 9.

7 Analysis of niche development

The analysis now moves to another level of the MLP. The first issue is to determine how niche developments can be separated from regime developments. Since regime actors can and do engage in developing niche technologies, it is not necessarily true that niche developments concern only 'niche actors'. Therefore, the criterion that is applied here is that niche technologies are those technologies that are not currently available for the majority of consumers. This may seem a rather vague definition, but easily identifies vehicles propelled by an ICE (and fuelled by petroleum, diesel, or liquefied petroleum gas) as 'regime technology'. Note that the currently available HEVs are also not considered to be niche technology – all other technologies are.

Several niche technologies are available that hold the potential of solving the regime tensions. Besides vehicles fuelled by hydrogen, EVs which use batteries as their energy are considered here. There are other alternatives (such as biofuels), but these are expected to influence the uptake of hydrogen- and battery-powered cars equally. The niches for EVs and HVs are expected to interact, hence the focus on these two technologies. Additionally, PHEVs are considered. These vehicles are a combination between CVs and EVs and succeed in taking away or mitigating some of the barriers that the other alternatives face.
For each niche technology, a description of the barriers to introduction, niche experiments, and actors involved are provided. Descriptions of niche technologies can be found in appendix B.

7.1 Hydrogen as automotive fuel

7.1.1 Barriers to introduction

The following barriers prevent the large-scale introduction of hydrogen as an automotive fuel:

1. *The chicken-egg problem*
   This has been illustrated before. Section 3.1 provides a discussion.
2. *Safety regulation*
   In Europe, there is no unified set of regulations that covers hydrogen safety. This complicates matters such as the design of hydrogen refuelling stations, spatial planning permitting procedures, etc. An industry grouping has prepared a handbook for approval of hydrogen refuelling stations that has been offered to local authorities (HyApproval, see www.hyapproval.org), but no official regulations have come into force yet.
3. *Mismatch with consumer preferences*
   Hydrogen technology cannot meet the performance of conventional cars on all aspects, which limits consumer adoption. Section 7.4 will further elaborate on the performance difference between electric, hydrogen, and CVs.
4. *High cost*
   Fuel cell production costs need to come down about an order of magnitude to be in the range of ICEs. Mass production is expected to contribute significantly towards this goal, but further improvement of fuel cell design is clearly required to get anywhere near the ICE production cost (IEA, 2005).

7.1.2 Niche experiments

An enormous amount of projects is taking place on hydrogen and fuel cells. A quick search on the website of the European Hydrogen and Fuel Cell Technology Platform[41] yields no less than 1147 projects. Projects that come closest to the actual introduction of hydrogen as an automotive fuel are the demonstration projects. A number of these are taking place around the world, a selection of which is presented in table 7.1. Unfortunately, there is no information source that lists all projects, so the table is not exhaustive. It can be considered representative, however. The thrust of the projects is similar: it is a collaboration between several partners, almost always including government agencies,

[41] https://www.hfpeurope.org/infotools/index.html

OEMs, and the oil industry. A number of vehicles (generally in the order of tens) is demonstrated, supported by the requisite infrastructure (in the order of about ten refuelling stations). Often, fleet operators such as public transport companies are involved, since they provide a controlled environment for refuelling and testing vehicles and refuelling practices. Apart from monetary support, governments see the projects as an opportunity to experiment locally with technology that holds the potential to realize their (environmental) policy agendas.

This size of experimentation is about the upper limit of what is practically possible in a demonstration project. The projects typically have a budget in the order of tens of millions of euros. Partners are only willing to spend more if there is a return to their investment, which is not the case in demonstration projects. Scaling up the projects is thought to lead to considerable losses as it takes quite long for investments to pay back. Rollout simulation has revealed that tens of thousands (preferably over a hundred thousand) of FC vehicles and tens of refuelling stations (preferably over one hundred) are required for a typical metropolitan area such as Washington, DC, to provide the system with the requisite critical mass (Meyer and Winebrake, 2009).

The demonstration projects have largely been paid for by the oil and automobile industries. For the European situation, large-scale demonstration projects (called 'Lighthouse projects') are thought to be the way forward. However, the oil and automobile industry are unwilling to bear the large investment costs associated with such projects that require production capacity and infrastructure to support thousands of HVs. A call on government to provide financial support has been made (HyWays, 2008). For now, the situation resembles that of a stalemate.

Indeed, the characterization of the niches as technological (Raven, 2005) still fits the current situation fairly well. Niches are protected by the demonstration project partners, e.g. by conducting them in controlled environments and through financial support. However, the niches have arguably stabilized somewhat as the more recent and larger scale projects have tended to work with a smaller scope of technical variation.

7.1.3 Actor locus

Actors that take part in the hydrogen demonstration projects almost exclusively include regime actors. This makes sense, since it is a way to protect prior investments. OEMs can preserve most of the design of current vehicles, whereas the oil industry is capable of producing and distributing hydrogen partly by using existing infrastructure.

Some actors that are outside of the traditional regime actors are involved. For instance, the HyNor and Hydrogen Link projects include Th!nk, a relative newcomer that is an offshoot of the Ford Motor Company. Originally, Th!nk produced EVs, but it has now ventured into producing a hybrid electric fuel cell car. However, Th!nk represents an exception as far as cars are concerned[42]. In the energy field, some non-regime actors get involved, such as parties that produce hydrogen and/or design hydrogen distribution and dispensing equipment (e.g. Linde, Air Products).

Indirectly, one could expect other non-regime actors to get involved. In essence, application of hydrogen in a car only requires the substitution of drivetrain components. OEMs can decide to

[42] Many projects do include parties that are not part of what is here considered the socio-technical regime, but these producers focus on other vehicles as buses, forklifts, etc. instead.

				participants						
project name	**location**	**start**	**end**	**government**	**public transport companies**	**OEMs**	**other automobile industry**	**oil industry**	**other energy industry**	**description**
CUTE	Various major European cities	2001	2006	x	x	x		x	x	Operation of 27 hydrogen-powered public transport buses to demonstrate feasibility.
HyFLEET:CUTE	Various major European cities + Perth + Beijing	2006	2009	x	x	x		x	x	Operation of 47 hydrogen-powered buses in regular public transport service in 10 cities on three continents.
HyCHAIN	Emscher-Lippe (D), Rhône-Alpes (F), Castilla y Léon (ES), Emilia Romagna (I)	2006	2010				x			Deployment of 158 small urban vehicles, including wheelchairs, scooters, cargobikes, Light Utility Vehicles and midibuses.
ZeroRegio	Lombardia (I), Rhein-Main (D)	2006	2008	x		x		x	x	The project consists of construction and demonstration of hydrogen infrastructure in two European regions for supplying hydrogen fuel to supply fuel cell passenger cars. The project aims at developing and demonstrating zero emission road transport systems in normal daily use for the European cities.
Clean Energy Partnership	Berlin (D)	2004	2016	x	x	x		x	x	A hydrogen and fuel cell vehicle demonstration project supported by the German federal government. It demonstrates a fleet of 17 hydrogen vehicles and two hydrogen filling stations to provide the necessary infrastructure.
HyNor	Oslo (N), Stavanger (N)	2003	2009	x	x	x	x	x	x	HyNor demonstrates real life implementation of various production technologies (electrolysis, biomass gasification, natural gas steam reforming with CO_2 treatment; industrial by-product hydrogen) and uses of hydrogen - buses, taxis, private cars; urban, regional and long transport. Infrastructure covers the 580 km corridor between Oslo and Stavanger.

ARGEMUC	München (D)	1999	2006	x	x	x	x	x	x	Demonstration of several production and dispensing methods of hydrogen for use in forklifts, buses, and cars on FCs and ICEs.
Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project	California, Michigan, Florida (US)	2003	2009	x		x	x	x		The project seeks validation of fuel cell vehicles and supporting infrastructure. 59 vehicles are tested along with 9 refuelling stations.
JHFC	Tokyo, Nagoya (J)	2003	2010	x		x	x	x	x	Demonstration of 59 fuel cell vehicles and 12 refuelling stations.
SINERGY	Singapore	2001	2008	x		x		x		Testing of 6 fuel cell vehicles and 2 refuelling stations.
Hydrogen Link	West Denmark	2006	?	x			x		x	Demonstration of several fuel cell vehicles (cars, forklifts, golf carts) and refuelling stations.
Althytude	Dunkerque, Toulouse (F)	2005	?				x		x	Objective is to test the operation of buses fuelled with a blend of natural gas and hydrogen and evaluate economic and technical feasibility.

Table 7.1 Selection of demonstration projects that involve HVs.

perform research and design of these components themselves, but can also opt for outside suppliers. This complements the tendency of OEMs to increasingly outsource design and production of modules. However, it seems that many OEMs consider research and design of fuel cell systems as strategic investments, as the larger OEMs either do their own research or form joint ventures (e.g. NuCellSys).

7.2 Electricity as automotive 'fuel'

7.2.1 Barriers to introduction

The following are major barriers for the mass market introduction of EVs.

1. *Mismatch with consumer preferences*
   EVs cannot match performance of CVs across the board. Most notably, the range of EVs is limited. Section 7.4 provides a comparison of performance of electric and CVs.
2. *High cost*
   Batteries represent the largest cost in the production of an EV and render them significantly more expensive than CVs. As is the case with fuel cell vehicles (FCVs), this cost needs to come down before the mass market can be addressed. It must be noted that the operating costs of EVs are significantly less than for a CV.
3. *Infrastructure*
   In principle, EVs can be recharged at home using standard outlets. However, given the limited range of EVs, it would be convenient to be able to charge them wherever possible. Therefore, most plans that aim at putting large numbers of EVs on the road include a network of charge spots in public places. Also, fast-charging capabilities would require installation of high-power chargers. Furthermore, even large numbers of PHEVs would require extensions of the current distribution grid (Kintner-Meyer, Schneider, Pratt, 2007), so that these can be deemed necessary for all-electric vehicles as well. Still, small numbers of EVs can be introduced with relatively moderate infrastructure investments.

7.2.2 Niche experiments

In niche experimentation for EVs the focus is on developing individual models rather than showcasing them in demonstration projects. A coordinated effort as in the case of hydrogen is less necessary from a technical viewpoint – major infrastructure investments for EVs are only necessary when sizeable numbers of vehicles enter the roads. Table 7.2 lists a selection of EVs in various states of development. This list is not exhaustive but fairly representative. There is a relatively large number of manufacturers that are not part of the regime. The 'traditional' OEMs do not have any EV on the market – BMW comes closest, currently offering electric Minis for testing by consumers on the basis of a limited lease contract. Interestingly, this is the road that a number of OEMs have gone in the late nineties to meet regulation of the California Air Resources Board (CARB) (Pilkington, Dyerson, and Tissier, 2002). The regulation required that 2% of car sales by 1998 represented zero-emission vehicles (ZEVs) that produce no tailpipe emissions at all. OEMs developed EV prototypes in response – with the EV-1 by General Motors as perhaps most (in)famous example. Some of these vehicles were reportedly a modest commercial success, but all were revoked at the end of the lease contract term. Ultimately, the regulation was relaxed and all vehicles scrapped.

Offerings from manufacturers external to the regime that are available or in advanced stages of development occupy market niches. Most of these focus on small cars, so that relatively small and light battery packs are sufficient. Such vehicles are offered in large cities where they offer the additional benefits of easy parking and (in some cases) the avoidance of traffic jams. The G-Wiz is an example that has been quite successful in London. Alternatively, manufacturers as Tesla Motors and the Lightning Car Company exploit characteristics of electric cars that outperform CVs, such as superior acceleration.

Hence, they choose to operate in the niche of sports cars. Disadvantages such as a limited range and high costs are of lesser importance in that particular niche.

manufacturer	model	model year	region	regime actor	status	description
ATT R&D	Parade	n/a	N-A		in development	Four-seater small car capable of highway travel.
BMW	Mini E	2009	N-A, EU	x	limited lease	Electric version of the Mini.
Build Your Dreams	E6	2009	China		prototype	Four-seater hatchback, capable of competing with conventional designs and offering up to 400 kilometres of electric drive.
Chrysler	Dodge Circuit	n/a	N-A	x	concept	Sports car built for high performance and upper market segment.
Commuter Car Company	Tango	2005	N-A		on market	Ultra-narrow but freeway capable one-seater, mainly aimed at commuters that want to circumvent traffic jams and parking problems.
Daimler	Mercedes-Benz BlueZero E-Cell	n/a	EU	x	concept	Modular concept that allows the application of different drivetrains, resulting in a set of models. The all-electric variant achieves 200 kilometres of electric drive.
Daimler	Smart ForTwo	2007	UK	x	demonstration	Two-seater cars currently tested by public authorities in London.
Electric City Motors	Current	2008	N-A		on market	Four-seater for urban passenger car usage, highway-capable.
GM	EV-1	1998	N-A	x	discontinued	Two-seater small car which had been on lease to a limited number of drivers in California.
Lightning Car Company	Lightning	n/a	EU		in development	Sports car built for high performance and upper market segment.
Miles Electric Vehicles	Highway Speed	2010	N-A		in development	Car with proportions and styling of a conventional sedan, addressed at mainstream (small/midsize) market segments.
Phoenix Motor Cars	SUT	2010	N-A		in development	Sports Utility Truck that is aims at the (large) American light-truck market.
Reva	G-Wiz	2004	mainly EU		on market	City commuter cars offering place for two adults and two children.
Tesla	Roadster	2006	N-A, EU		on market	Sports car built for high performance and upper market segment.
Th!nk	City	2008	EU		on market	Two-seater city car sold successfully in Norway and the UK, formerly backed by Ford. The company plans exports to the US.

Table 7.2 Selection of electric car models. Concepts are not intended to enter series production, prototypes are. 'N-A' = North America, 'EU' = European Union (Sources: evfinder.com, peswiki.com, various manufacturer websites).

Tesla plans to finance the development of its next model, a sedan, from the proceedings of its first model. This second model then enters more mainstream markets. There, it will face competition from manufacturers such as the Chinese Build Your Dreams and Miles Electric Vehicles, that are developing a similar offering. In sum, external actors are more active in this niche than for HVs.

Furthermore, CVs can be converted into electric cars. There are several firms that offer such conversion kits or carry out the conversions. This allows enthusiasts to create their own electric car, but the a

conversion involves significant costs and voids warranty, so that these kits remain restricted to a small market.
Not all are just individual developments, however. Essent, a Dutch utility company, plans a project called ZER-X ('Zero Emissie Rijden', Zero Emissions Driving, the X represents the many advantages of electric mobility, according to Essent) in which it will distribute several hundred EVs among its employees[43]. Part of the project is a concept called the 'Mobile Smart Grid', that allows users to specify how much electricity they want, when they want it, and against which price. This information enables Essent to use its production capacity and the distribution grid more efficiently.
A firm named Better Place[44] operates on a larger scale. Its vision comprises a total concept of electric mobility, including electric cars, batteries, battery exchange stations, charge spots, and renewable energy. It proposes an innovative business model, comparable to that of mobile telephony. In the model, cars will be sold at a loss, or even for free. Then, consumers pay for the distance they travel. This way, the high upfront costs of purchasing an EV are avoided. To circumvent the range limitations of EVs, Better Place intends to replace depleted batteries with charged ones in exchange stations. It also plans a network of charge spots in public places, so that batteries can be charged at all times. Better Place has signed agreements to start executing its plans with the governments of Israel, Denmark, Australia, California, Hawaii, and Canada.
Applying Raven's (2005) typology, EVs are in dedicated market niches. There is a low degree of niche protection (especially compared to hydrogen niches), but niche stability is quite low as well, since niche experiments have not significantly reduced uncertainty.

7.2.3 Actor locus

The most active players in this niche are outsiders to the regime. The models that are developed by OEMs are merely studies and not intended for series production. External actors do intend their models to enter series production, although for now they aim for non-mainstream markets. Yet, they are the ones closest to entering main markets. OEMs do make strategic investments in the industry. For instance, the Big Three in the US (Ford, Chrysler, and General Motors) have erected the US Advanced Battery Consortium (USABC) to this end in 1992, Toyota enlarged its minority stake in Panasonic EV Energy to 60% in 2005 (Nikkei, 2005), and Nissan and NEC have recently founded a joint venture for the production of lithium-ion batteries (Nissan, 2007).
Some actors are involved indirectly. Players such as Tesla Motors and ACP are delivering electric drivetrains to firms both internal (i.e. OEMs) and external to the regime. Sometimes they have a dual role: ACP does conversions of conventional cars to electric but supplies the drivetrain of the BMW Mini E as well.
Interestingly, non-regime actors from the energy field are showing interest. Utilities are entering the field and developing demonstration projects. Other outsiders are completely new actors such as Better Place.

7.3 Hybrid forms

As stated, petrol-electric hybrids as currently on the market are not considered niche technologies, since they are available as a competitive alternative in the mainstream market. PHEVs are not available commercially yet and consequently do qualify.

7.3.1 Barriers to introduction

The barriers of the hydrogen vehicle and all-electric vehicle are thus to a large extent eliminated by the PHEV, although infrastructure investments remain if PHEVs are deployed in large numbers (Kintner-Meyer, Schneider, Pratt, 2007). Yet, the largest barrier is the relatively high cost for the vehicle.

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[43] See http://www.essent.nl/content/overessent/maatschappij/elektrisch_rijden/index.jsp (in Dutch).
[44] See http://www.betterplace.com/

7.3.2 Niche experiments

Experimentation is about developing and testing models rather than large-scale demonstration projects. Table 7.3 lists a selection of PHEV models in development. No PHEV is currently commercially available. The players in this market seems to be mainly the traditional OEMs. Note that most of the developments are taking place in North America.

manufacturer	model	model year	region	regime actor	status	Description
Build Your Dreams	F3DM	2009	China		protoype	Midsize sedan offering up to 100 kilometres of electric drive. Matches conventional sedan offerings.
Chrysler	200C		N-A	x	concept	Sports sedan aimed at luxury midsize vehicle segment.
Chrysler	Town & Country		N-A	x	concept	Minivan with looks and options that match current minivan offerings.
Chrysler	Jeep Wrangler		N-A	x	concept	SUV with looks and options that match current minivan offerings.
Chrysler	Jeep Patriot		N-A	x	concept	SUV with looks and options that match current minivan offerings.
Daimler	Mercedes-Benz BlueZero E-Cell Plus		EU	x	concept	Modular concept that allows the application of different drivetrains, resulting in a set of models. The plug-in hybrid version achieves 100 kilometres of electric drive.
Fisker Automotive	Karma	2010	N-A		protoype	Luxury sedan aimed at the upper end of the market. Offers up to 50 miles of electric drive.
Ford	Edge HySeries		N-A	x	concept	Plug-in hybrid fuel cell vehicle offering 25 miles of electric drive on battery power, after which the fuel cell recharges the batteries.
General Motors	Chevrolet Volt	2010	N-A	x	concept	Sedan that offers 40 miles of electric travel.
Toyota	Prius PHEV		Japan	x	protoype	Modified version of the 'standard' hybrid Prius.
Volkswagen	Space up! Blue		EU	x	concept	Plug-in hybrid fuel cell MPV offering up to 100 kilometres electric drive.

Table 7.3 Selection of PHEV models. Concepts are not intended to enter series production, prototypes are. 'N-A' = North America, 'EU' = European Union. (Sources: calcars.org, various OEM websites)

Kits are offered to convert existing vehicles into PHEVs. Enthusiasts can have their current (non-plug-in) hybrid fitted with an extension cord.

Demonstration projects with PHEVs are comparable to those for all-electric vehicles. There does not currently seem to exist such a project in the Netherlands. A project is currently being planned by the Energy Technologies Institute (ETI) of the UK, a public-private partnership involving industrial partners from the energy sector and car industry. Its main aim is to validate the several assumptions (e.g. economical, technical) underlie the PHEV idea. It is infrastructure-centred, comprising the entire chain from generation to charging and billing. The project envisions to put a few hundred PHEVs on the road. In another example, 20 Volkswagen Golfs converted to PHEVs are tested in real-world conditions. Other partners in the project are government agencies, a utility, and various research institutes.

Raven's (2005) typology is hard to apply in the case of PHEVs, since experimentation is sparse. If anything, the projects can be characterized as technological niches, since there is little certainty (due to limited testing so far) and high protection (the projects that are planned are carried out in controlled environments).

7.3.3 Actor locus

OEMs are quite closely involved in developing PHEVs, and relatively little outside actors are active in this niche. No PHEVs are currently commercially available, so that they do not occupy niche markets as do all-electric vehicles. One type of non-regime actors is involved in niche experiments: utilities. This makes sense, as they are the obvious candidates for supplying the electricity to power PHEVs, as well as to provide infrastructure for (fast) charging.

7.4 Performance comparison

This section provides an analysis of the performance of the three niches on the attributes that were found to be important in the regime analysis (see chapter 4). The result can be found in table 7.4. Note that not all attributes relevant to consumers are part of the table. Some of these attributes are hard to measure objectively (e.g. comfort). The omissions are not too problematic; as they do not relate to the drivetrain, it can safely be assumed that performance differences are negligible.

Comparing the technologies is tricky, since no study exists that includes all alternatives considered here. Different assumptions underlie the calculations in the various sources, mainly on size and performance requirements of the vehicles. Comparison across technologies should only be taken as indicative!

First a remark on the PHEV values: these depend to a large extent on the exact PHEV configuration. A PHEV is a combination of a CV and an EV, hence its performance is expected to be in between those two, perhaps with an exception on the cost dimension. Combining two technologies raises costs because elements of both must be included and due to increased complexity. For a number of attributes, the PHEV performs as a CV. For the others, its performance depends on its position on the conventional-electric continuum.

Despite the difficulty of direct comparison, the table yields a good overall impression. The main difference in cost is that the alternatives have a higher vehicle cost, whereas their fuel costs are lower. Note that FCV costs are estimated to be significantly higher than EV costs.

Acceleration and top speeds are similar for all technologies. Top speeds of both fuel cell and EVs match that of CVs without severe compromise of other attributes.

FCVs can be quite easily designed to have ranges that match those of CVs. This is illustrated by the Honda Clarity FCX, furthest down the commercialization path, that features a 620 km range. Range, however, is the Achilles heel of the EV. The list of prototypes studied did include one vehicle with a reported 400 km range (the BYD E6), but this claim has not been verified in real-world driving.

A limited range would perhaps be a minor problem if not refuelling (or rather, recharging) would take so much time for EVs. FCVs can be refuelled in approximately the same time as a CV. Electric cars require several hours (the figure in the table is loosely based on the sample of electric car prototypes). Pinpointing a particular (average) recharging time is difficult, since it depends on the power of the charging device and on the state of charge that is required (which is a non-linear function of the charging time). There are some bold plans, such as for the Phoenix SUT that is designed to be charged in 10 minutes on a 250 kW charging station. Fast-charging plans such as these (but also less extreme) might be difficult to implement, since they require extensive infrastructure investments including upgrading of the electricity distribution grid. For comparison: refuelling a conventional car only takes two minutes, but involves an energy flow in the order of 20 MW.

Table 7.4 also includes some figures that are interesting from an environmental standpoint, even though their influence on consumer choice is limited. The alternatives represent a significant improvement of well-to-wheel efficiency over CVs. Consequently, their emissions on a well-to-wheel basis are lower as well, even though production paths involving fossil fuels are assumed[45]. There are no local (tank-to-wheel) emissions at all.

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[45] Assuming electricity production from renewable sources, EVs are by far superior with a well-to-wheel efficiency of over 60%.

Attribute	Unit	Conventional	Fuel cell vehicle[a]	Electric vehicle	Plug-in hybrid
Vehicle cost	[index]	100[b]	220[b]	151[c]	depends
Fuel cost	[eurocent/km]	9.4[d]	2.5[e]	2.4[f]	depends
Acceleration 0-100 km/h	[sec]	12[g]	12[h]	8.3[i]	as conventional
Top speed	[km/h]	181[g]	152[j]	155[k]	as conventional
Range	[km]	780[g]	359[l]	230[m]	as conventional
Refuelling time	[min]	2[n]	2[n]	240-480	as conventional
WTT efficiency	[%]	88[o]	43[p]	31[q]	depends
TTW efficiency	[%]	16[o]	55[p]	88[q]	depends
WTW efficiency	[%]	14[o]	23[p]	27[q]	depends
WTT emissions	[gram CO_2/km]	25[r]	90[r]	60[s]	depends
TTW emissions	[gram CO_2/km]	170[r]	-	-	depends
WTW emissions	[gram CO_2/km]	195[r]	90[r]	60[s]	depends

[a] Non-hybrid, compressed hydrogen.

[b] Based on the joint research study by CONCAWE, EUCAR, and JRC (2007), expectations for 2010.

[c] Assuming the relative price difference between FC and electric drivetrains as in Eaves and Eaves (2004).

[d] Based on fuel consumption of 50 best selling petrol cars in the Netherlands in 2007 and 2007 prices.

[e] Based on THRIVE assumptions (0.233 kWh/km and 33.33 kWh/kg H_2) and Kramer et al. ($4.5/kg H_2). Exchange rate at 9 March 2009 (0.79050 euro/$) taken from xe.com. Taxes not included.

[f] Based on Campanari et al. (230 Wh/km, assuming a range of 230 km) and gaslicht.com (10.48 eurocents/kWh).

[g] Based on a simple average of the top-10 selling petrol cars in the Netherlands in 2008, based on OEM statement.

[h] Based on the average of a selection of 17 prototypes after 2002. Minimum of this selection is 8.5 seconds.

[I] Based on the average of a selection of 5 prototypes. Minimum of this selection is 4 seconds.

[j] Based on the average of a selection of 24 prototypes after 2002. Maximum of this selection is 175 km/h.

[k] Based on the average of a selection of 7 prototypes. Maximum of this selection is 201 km/h.

[l] Based on the average of a selection of 27 prototypes after 2002. Maximum of this selection is 800 km.

[m] Based on the average of a selection of 7 prototypes. Maximum of this selection is 400 km.

[n] Benchmark used in the THRIVE project.

[o] Based on Campanari et al. (2009).

[p] Based Campanari et al. (2009) and on production from natural gas.

[q] Based on Campanari et al. (2009), assuming average Italian electricity mix.

[r] Based on the joint research study by CONCAWE, EUCAR, and JRC (2007), assumption compression 700 bars; gram CO_2-equivalent.

[s] Based on Svensson et al. (2007), assuming average EU electricity mix.

Table 7.4 Performance comparison of the niche technologies on selected attributes. ‘WTT’ = ‘well-to-tank’, ‘TTW’ = ‘tank-to-wheel’, ‘WTW’ = ‘well-to-wheel’.

7.5 Conclusion

There is a distinct difference in dynamics underlying EVs and PHEVs on the one hand and HVs on the other. HVs are nurtured by the current regime, but the niche experiments seem to have reached a stalemate. Technically, FCVs have proved themselves, but the actors involved seem to be hesitant to commit themselves to the investments that are required to take the technology to the next stage of commercialization. However, as one representative of the energy industry articulated, 'it is becoming increasingly hard to explain why we are still spending millions on demonstration projects'. HVs are in well-protected technology niches.

For electric cars, experimentation is more on the level of the development of individual models. This route has failed once before (in California) as the OEMs withdrew their support. However, outsiders are now showing that they can build a viable business with electric cars, albeit in niche markets. They are already planning to address more mainstream markets, although they still have to prove that they can be successful there, as 'traditional' OEMs have failed in that arena about a decade ago. In a different dynamic, small-scale experimentation projects are now being planned in which utilities take a prominent and sometimes leading role.

PHEVs represent a technology that holds the potential to fulfil a bridging function. It can help consumers to get accustomed to electric mobility while still offering the convenience of conventional technologies.

There is a widely held believe in the industry that changes are imminent. Given the activity in all niches, this does not seem unlikely. The niche dynamics discussed here will be used to design the architectures that underlie the socio-technical scenarios.

8 Landscape developments

Despite pressures and tensions in the past, the socio-technical regime has been able to maintain a state of dynamic equilibrium. This chapter will discuss three relevant landscape developments that might change that. Landscape developments have been defined in chapter 3 as beyond the direct influence of the five actor groups The focus in this thesis is on the relationship between OEMs and consumers. The test for the identification of landscape developments is thus that they are beyond the influence of these two actors. It will turn out that the landscape developments are to a large extent also outside the sphere of influence of the energy industry.

8.1 Fuel price development

Pressure on the regime through high fuel prices is not without precedent. The two oil crises in the 70s have had their repercussions on consumer preferences as fuel economy rapidly moved up the priority list (see section 4.4). In the short term, consumers adapt their behaviour by resorting to smaller and lighter cars. If a manufacturer does not offer such cars, there is immediate trouble. If a manufacturer does offer them, there is trouble as well, since the margin on such smaller cars is lower. Another precedent is the more gradual increase in fuel prices that initiated in 2004 and continued to late 2008. Over this time, preferences also shifted to cars consuming less fuel.

The breakdown of prices for the two main automotive fuels (petroleum and diesel) is displayed in figure 8.1. It follows from this breakdown that a significant part of the price is determined by production costs, which are obviously linked to the price of crude oil. Note that the other price components are either fixed (e.g. excise duties) or a surcharge dependent on the base that is determined by production costs (e.g. margins). Changes in fuel prices are thus almost entirely determined by changes in the price of crude oil.

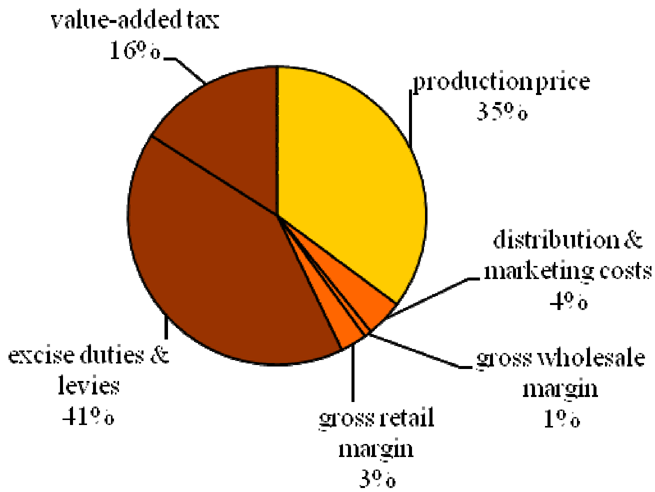
Few businesses are so speculative as the forecasting the price of crude oil. However, in an essay, Jesse and Van der Linde (2008)[46] provide an excellent overview of the current situation and the outlook for the next decade[47]. A few points are of interest here. First, they note that in circa 2004 the market situation has moved from being a "Oil Demand-led World" to an "Oil Supply-constrained World". In the former situation, demand basically determined the amount of oil that was extracted, and the oil price would be determined by the marginal cost of the last barrel needed to match demand. However, there are good reasons to believe that supply, relative to demand, will be more constrained in the future. Newly industrializing countries, notably China and India, are expected to contribute enormously to rising energy demand as their energy intensity keeps pace with their economic growth. They are expected to account for up to half of the growth of world primary energy demand until 2030 (IEA, 2008). This of course includes demand for oil. New fields need to be exploited to meet this demand, especially as decline rates from existing fields are accelerating at a faster pace than expected. According to the International Energy Agency (IEA), the majority of the required increase in production should come from members of the OPEC. This is only possible if OPEC is willing to undertake the requisite investments. Moreover, domestic provision of oil has been heavily subsidized in the OPEC region and consequently, a large portion of the production increase has been devoted to fulfilling domestic demand.

As constraints on supply increase, the role of marginal cost in price formation is likely to decrease. Instead, another building block assumes more importance: long-term scarcity. This block drives the price up to a point that Jesse and Van der Linde term the 'user value' of oil: the price consuming countries are willing to pay for oil, given the use that they have for it. As perhaps illustrated by the high prices in 2008,

[46] The discussion that follows mainly derives from this work and explicit references are therefore omitted. References to other work are made wherever appropriate.

[47] That developments can be fast, abrupt, and unexpected is nicely illustrated by the recent march of events. At the time of publication of their essay (June 2008), West Texas Intermediate (WTI) oil price had just peaked at $147/bbl, while at the time of writing of this thesis (March 2009), price had tumbled to $46/bbl (spot price taken from bloomberg.com). Nonetheless, the analysis they provide for the next decade remains largely valid.

the user value is thought to be much higher than the marginal cost of supply. Note, however, that marginal cost of supply still accounted for approximately 70% of these high prices.
In their latest outlook on the world energy supply, the IEA confirms this view of likely future oil price increases. They also acknowledge, and this is an important second point, that the market will become more volatile. As is illustrated by today's relatively low prices caused by the current economic crisis, swings in the oil price can be very substantial. Two reasons for this volatility can be provided here. First, spare production capacity is at historically low levels, which implies that any shift in demand (e.g. a cold winter) or unexpected blow to supply (e.g. a natural disaster) has an immediate effect on price. Second, as supply becomes more constrained, the amount of oil that is traded through bilateral agreements increases, so that price formation is less transparent and price swings happen as details of deals are leaked.



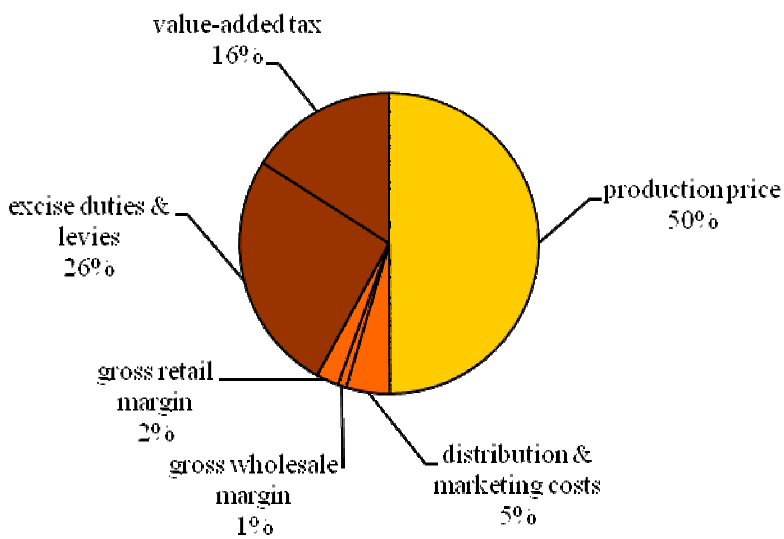


Figure 8.1 The breakdown of the price of petroleum (top) and diesel at a retail station in 2008. Source: BOVAG-RAI (2008).

As said, forecasting oil prices is speculative. The future image that is sketched here – a bumpy road towards high oil prices – can therefore only be taken as a view, and alternative views can be found. For instance, protagonists of the peak oil theory expect production to decline even more rapidly than described above, prompting perhaps even larger price increases or a collapse of supply. Alternatively, OPEC insists that investments in future production capacity are sufficient, which implies that they do not

expect dramatic price increases. For OPEC, the major uncertainty is not security of supply – as it is for consuming countries – but security of demand (OPEC, 2008).
Two factors threaten security of demand for OPEC. First is the development of alternative fuels, notably biofuels. However, it seems unlikely that these can make a serious dent in the demand for conventional fuels, since the projected demand increase is so large. Rather, biofuels are expected to account for accommodating only part of this rise at best. Second, efficiency improvements can lower demand. Yet, history tells that efficiency improvements come with a rebound effect, implying that they are (more than) offset by an increase in use of a product if its energy requirements decrease.
The objective here is not to refute other views. Future price increases form an important part of both socio-technical scenarios. Therefore, this section aims to provide arguments that such increases are indeed likely to happen, and thus lend more plausibility to the scenarios.
Fuel price changes are obviously outside the sphere of influence of both consumers and carmakers. It is interesting to note that there is little direct influence of international oil companies on oil price as well. The oil price is determined by trade on international commodity markets (such as the New York Mercantile Exchange, NYMEX). About four hundred players are active in this market. Traders are banks, countries, and some oil companies (but not all of them). None of them is able to exert so much influence as to significantly manipulate price. Fuel prices are thus a landscape factor for consumers, OEMs, and the actors in the energy industry.

8.2 Security of supply

As transportation is based on oil-derived fuels, security of supply of oil is an important concern for countries around the world. Not surprisingly, energy policy is for a large part directed at securing supply. Bilateral agreements are made to ensure steady streams of supply to individual countries. Yet, if supply will struggle to keep up with demand, as suggested above, securing the necessary inputs will become increasingly difficult.
For the longer term, diversifying sources is a means to provide more energy security. Therefore, it can be expected that policies are increasingly directed at stimulating fuels that do not derive from oil. Such initiatives can already be observed, as exemplified by the US and EU mandates for blending biofuels. It must be noted that energy security is considered a more important issue in US policy than in EU policy (Jesse and Van der Linde, 2008).
Energy policy is out of the direct sphere of influence of consumers and OEMs, and the same might be argued for energy companies. Note that this last group of actors does have an influence by lobbying, the effect of which is hard to establish. Similarly, consumers can influence policy during elections. However, there is generally only an opportunity to cast a vote once every four years, and even then voters can hardly be said to actually shape policy. Therefore, this landscape development can be assumed to be out of regime actors' influence for all practical purposes.

8.3 Increasing environmental stresses

The combustion of fossil fuels harms the environment, in two ways which are relevant in the context considered here. First, the local air quality deteriorates. The contribution of the ICE to this has been first acknowledged during the 1950s in California as smog formed over Los Angeles. Government regulation was required to force the OEMs to address this problem. Nonetheless, the problem of the deterioration of local air quality persists. In recent years, the increasing number of diesel cars in the Netherlands has added to the problem, as the amount of particle matter emitted by diesel cars is higher than that of petroleum cars. In 2005, this has led to the cancellation of a number of construction projects because they would involve placing buildings in areas with too much particulate matter or they would contribute to a (further) increase in local particulate matter concentrations[48]. There is a trend to change policy to improve

[48] More information on particulate matter in the Netherlands can be found on the website of the Netherlands Environmental Assessment Agency (www.pbl.nl).

local air quality. An example is the idea that was raised in Amsterdam to ban cars that are heavy polluters. Although the plan has been postponed, it is still being considered (Parool, 2009). In sum, there is an increasing pressure to reduce local emissions.
The second major environmental stress is global warming[49]. Average temperatures have risen over approximately the last six decades. This has been attributed to rising concentrations of anthropogenic greenhouse gases (GHGs) in the atmosphere. GHGs trap heat in the atmosphere and can be classified based on their radiative forcing, i.e. ability to trap heat. Such a classification shows that the contribution of CO_2 to global warming is greatest of all GHGs[50]. Converting amounts to CO_2-equivalent to account for differences in radiative forcing between individual GHGs, CO_2 from fossil fuel use accounted for 56.6% of all GHG emissions in 2004. Transport accounted for 13.1% of GHG emissions in the same year.
To combat these environmental stresses, emissions regulation is becoming more and more stringent. In the EU, the most relevant case for this thesis, the car industry committed itself voluntarily to achieving an average fleet emission of 140 grams of CO_2 per kilometre by 2008. This target was missed, and on 17 December 2008 the European Parliament voted in favour of regulation that proposes the fleet average of emissions to be 130 grams per kilometre, phased in from 2012 onwards and to be completed by 2015. Car sales by each OEM must match these goals; if not, they face substantial fines. A long term target of 95 grams/km has been defined for 2020[51].
These events illustrate that environmental stresses and related policy and regulation are out of the sphere of influence of OEMs. The same holds for consumers, although the argument that they can exert an influence through voting can be put forward here as well. The energy industry is heavily influenced by emissions regulation, but generally not in this context (i.e. car emissions). In any case, there seems to be little interaction between the energy companies in the regime on the one hand and environmental stresses and related policy in this context on the other.

8.4 Conclusion

Three landscape developments have been identified that hold the potential to exert future pressure on the regime. They are summarized in table 8.1. Each of these has been shown to be outside the sphere of influence of regime actors within the scope of this thesis, implying that they truly hold the potential to initiate change within the regime.

	landscape development	description
L1	fuel price development	Fuel prices are expected to become structurally higher during the next decades, due to rising demand and supply struggling to keep up. Prices will likely be volatile, implying that the price increase will not be smooth.
L2	supply security	Energy policy is increasingly motivated by security of supply issues. This provides an incentive for (petroleum) consuming countries to diversify their energy supply.
L3	increasing environmental stresses	Local air quality is harmed by automotive emissions. Furthermore, emissions from cars contribute to global warming. Both local and national policies are likely to be increasingly directed at reducing emissions.

Table 8.1 Landscape developments relevant for the role of the car in the mobility regime.

[49] The discussion of global warming is based on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007).
[50] Note that other GHGs have a larger global warming potential, implying that their radiative forcing is larger. The fact that the amount of CO_2 produced is larger than any other GHG renders it the largest contributor to global warming. A proper comparison converts emissions into CO_2-equivalent to correct for these individual differences.
[51] See http://ec.europa.eu/environment/air/transport/co2/co2_home.htm for more information on this regulation.

9 Linkages, design choices, and scenario architecture

To break the lock-in of the ICE in the current socio-technical regime is not trivial. Pressure on the regime is required that holds the potential to open up 'windows of opportunity' for niche technologies. This chapter defines how these windows come about. In the next section, the building blocks of the analysis part (regime and landscape developments) will be linked up to form 'transition seeds'. These are the foundation of the two socio-technical scenarios. By emphasizing particular regime developments, landscape developments, and seeds, two different scenarios are shaped in section 9.2. The final section lays down the basic characteristics of each of the scenarios.

9.1 Elaboration of potential linkages

Table 9.1 lists the various transition seeds that result from linking up the regime and landscape developments. The first (S1) derives from institutional rules defined in the OEM-consumer relationship. It states that fuel consumption moves up the priority list as fuel prices increase, because it takes on a more important role in the trade-off that consumers have to make among various vehicle attributes. It relates to the internal regime tension that the regime runs into problems as cars become larger and perform better while fuel prices rise.

The second seed (S2) is one of the prime reasons why niche technology might break through. It states that niche technologies hold the potential to resolve the tension that is outlined in S1.

S3 refers to the second tension, implying that more comfort and higher performance lead to increased stresses to the environment. Again, niche technologies provide a way to alleviate this pressure.

One of the ways that a transition could take place is explicitly alluded to by the next three seeds. All three identify modularity as a means for (gradual) changes. Incorporating additional or different modules in the car could lead to improvements in fuel economy (S4), emissions (S5), and performance (S6).

S7 links up the fact that emissions by cars are typically addressed by regulation (which is laid down in institutional rule O2) with the fact that environmental stresses are likely to increase. The result is that emissions regulation is likely to become more stringent. Policies are expected to be set up on local, regional, national, and supranational level. They will address local air quality and global issues, notably emissions of CO_2.

Curbing of emissions potentially aligns with security of supply (S8), given that the reduction is achieved through less burning of fuel. That will generally be the case, especially for CO_2. Naturally, niche technologies hold the potential to further reduce emissions, especially locally (S3, S5). Local, regional, and national availability of resources and technology can influence which solutions are preferred.

S9 holds that it is easier for suppliers to develop particular niche technologies than it is for OEMs. This is especially true for first-tier suppliers. Whereas the OEMs have a broad knowledge base (which might be not too deep in particular areas), suppliers are able to develop in-depth knowledge in their business area. First-tier suppliers are in better position to develop innovations than suppliers from other tiers, since the expertise of the latter may be too narrow. This transition seed builds on the expectation that outsourcing will be increasing (Roth, 2004) and that first-tier suppliers will capture a larger share of the automotive value chain (Jürgens, 2003).

S10 is related to the previous transition seed. OEMs do not take a clear focus, whereas a number of suppliers work on different technologies (notably batteries and fuel cells). Combined with the fact that different actors support different niche technologies, experimentation with a variety of technologies is happening (and likely to continue in the future).

Finally, S11 states that changes are not likely to occur to the entire regime at the same time. Pressure can work locally. This implies, for instance, that in part of the market, business-as-usual continues – cars grow incrementally larger, performance improves, the PLC shortens, and variety increases. It provides the backdrop against which a wider breakthrough of a niche technology must be achieved.

	cluster of drivers		transition seeds & linkages
S1	L1	Fuel price development	As fuel prices rise, fuel economy moves up the consumer preference priority list. In times of price shocks, this may occur in an abrupt way, favouring OEMs that have offerings with low fuel consumption.
	R3	Fuel price responsiveness	
S2	L1	Fuel price development	An increase in fuel prices conflicts with a preference for larger cars with incrementally increasing performance, since these consume more fuel. Technological improvements and the application of niche technologies can aid the reconciliation of this conflict.
	R1	Preference for larger cars	
	R2	Incremental progress	
S3	L3	Environmental stresses	Larger cars with incrementally improving performance contribute to environmental stresses. Technological improvements and the application of niche technologies can provide a way for performance improvement while mitigating environmental stresses.
	R1	Preference for larger cars	
	R2	Incremental progress	
S4	L1	Fuel price development	A modular vehicle structure allows the addition of modules that improve fuel economy. Examples are start-stop technology, regenerative breaking, and regenerating energy from the suspension.
	R3	Fuel price responsiveness	
	R6	Modularity	
S5	L3	Environmental stresses	A modular vehicle structure allows the addition of modules that reduce emissions. These additions can be stimulated by local and regional policy.
	R4	Emissions curbing	
	R6	Modularity	
S6	R2	Incremental progress	A modular vehicle structure allows the addition of modules that improve performance. An example is an electric motor that provides extra torque during acceleration.
	R6	Modularity	
S7	L3	Environmental stresses	As environmental stresses increase, emissions regulation will tighten. Regulation will focus on local air quality (enforced through local policies) as well as regional/national/supranational emissions (predominantly CO_2).
	R4	Emissions curbing	
S8	L2	Supply security	As fossil fuel supply further struggles to keep up with demand, policies will be put in place to make increased use of alternative energy sources. Such policies are likely to take into account local and regional availability of alternatives.
	R4	Emissions curbing	
S9	R7	Changing industry structure	OEMs do not show clear preferences for any particular niche technology. Suppliers, being smaller and focused on specific modules, have clearer preferences. They further develop these modules for application in future models.
	R8	No clear focus in R&D	
S10	L2	Supply security	Various actors do either not show a clear preference for a particular niche technology (OEMs, consumers, government). Others (oil industry, utilities) have a clear preference but are unable to push this sufficiently. The result is experimentation with several technologies in various niches.
	L3	Environmental stresses	
	R8	No clear focus in R&D	
S11	R1	Preference for larger cars	The regime needs pressure to initiate changes. Pressure, however, does not affect all elements of the regime equally. Therefore, some elements will carry through business as usual, implying gradual improvements in performance, size, and comfort, as well as more variety.
	R2	Incremental progress	
	R5	Shortening PLC and increasing variety	

Table 9.1 Linkages of developments at regime and landscape level that form seeds for transitions.

9.2 Design choices

The scenarios differ to the extent that the various regime developments, landscape developments, and transition seeds play a role. The objective of this section is to determine which developments and seeds are emphasized in which scenario.

The main criterion for determining the number of scenarios is how many can be meaningfully distinguished. This criterion leads to two scenarios, chiefly based on the two types of dynamic that are present in niche technology development. Recall that hydrogen experimentation has hitherto occurred mainly through demonstration projects that were supported by government agencies and regime insiders. EVs and PHEVs are developed through launching individual models, some even commercially. Actors outside the regime are involved as well. PHEVs build on current regime technology.

Building on these dynamics, two kinds of breakthroughs can be envisioned. The former case can be extended by large-scale experimentation, in a form like proposed as so-called ‘Lighthouse Projects’[52]. In the latter case, a breakthrough would come more gradually and uses synergies between current and niche technologies. The PHEV is a case in point. The PHEV is often viewed as a transition technology, but the end state of this transition is not clear-cut. It could very well involve hydrogen. By emphasizing one of the dynamics in each of the scenarios, they both get a distinctive character. Building on these dynamics, the two scenarios will be labelled ‘Large-Scale Experimentation’ and ‘Gradual Breakthrough’.

Taking this as a point of departure, it is natural that landscape developments play out differently as well (table 9.2). Large-scale experimentation has currently reached a stalemate in which the industry actors involved call on the government to help them finance the costly rollout of larger-scale projects. Further recall that emissions have been reduced chiefly by government intervention, not by consumer preferences. This scenario is thus likely to be chiefly government driven, and therefore increasing environmental stresses (L3) has the largest influence. This is followed by supply security (L2), which is also a government concern. The influence of supply security is judged to be somewhat less than environmental stresses, as it has traditionally been in EU (and Dutch) policy[53].

		Large-Scale Experimentation	Gradual Breakthrough
L1	Fuel price development	+/-	++
L2	Supply security	+	+/-
L3	Increasing environmental stresses	++	+/-

Table 9.2 Emphasis on various landscape developments in the two scenarios.
++ = very large influence, + = large influence, +/- = medium influence.

By contrast, a gradual breakthrough along the path that EVs and PHEVs are now being experimented with requires less government incentives. Therefore, it will be driven by the interactions between consumers and OEMs. Of the landscape factors, only fuel prices (L1) seem to directly influence consumer choice. Consequently, fuel prices take the most important role in this scenario.

It must be noted that all three landscape developments play a role in each of the scenarios – it is just their importance that differs. Although emissions regulation and local availability of resources play the most important part in large-scale experimentation, the uptake of alternatives can be expected to be accelerated by high fuel prices in this scenario as well. The same holds for limited supplies of fossil fuels and more stringent emissions regulation in the other scenario. It is exactly the differences in emphasis that allow a clear description of how the two dynamics play out.

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[52] See for examples www.hylights.eu.

[53] As Jesse and Van der Linde (2008) argue, supply security may become more important in the EU as the supply situation tightens.

		Large-Scale Experimentation	Gradual Breakthrough
R1	Consumer & OEM preference for larger cars	+	++
R2	Incremental progress	+	++
R3	Fuel price responsiveness	+/-	++
R4	Emissions curbing	++	+/-
R5	Shortening PLC and increasing variety	+/-	++
R6	Modularity	+/-	++
R7	Changing industry structure	+/-	++
R8	No clear focus in R&D	++	+/-

Table 9.3 Emphasis on various regime developments in the two scenarios. ++ = very large influence, + = large influence, +/- = medium influence.

Similarly, there are differences in the emphasis on the various regime developments in each of the scenarios (table 9.3). The two most important regime developments in the Large-Scale Experimentation scenario are emissions curbing (R4) and no clear focus in R&D (R8). Emissions curbing is important because of the role the government plays in this scenario. The lack of focus in R&D takes a large emphasis because this leads to the experimentation in multiple niches that characterizes this scenario. Furthermore, consumer and OEM preference for larger cars remain important (R1), as well as incremental progress (R2). The other regime developments play a smaller role. Fuel price responsiveness (R3) relates to consumer preferences, which is why it takes on a smaller role. The shorter PLC and increasing variety (R5) play a smaller role as well, as they actually play a blocking role in this scenario. Experimentation takes place in niches, therefore modular innovation (R6) and the related changing industry structure (R7) are less important as well.

Again, more or less the mirror image shows up in the other scenario. Perhaps the most relevant observation is that the consumer-OEM relationship is central to this scenario. Therefore, the preference for larger cars remains (R1), as does the desire to improve a new offering slightly over the previous one (R2). Consumers are responsive to fuel price changes (R3). The modularization trend carries on (R6), enabling more variety and a shorter PLC (R5), and the associated change in industry structure (R7). Emissions curbing (R4) only plays a minor role in the OEM-consumer relationship. The unclear focus in R&D is not so important as well – it is assumed that as fuel prices rise, R&D will be focused on reducing fuel consumption in the first place, largely irrespective of which technology is involved.

Lastly, table 9.4 presents an overview of the importance of the various transition seeds in each of the scenarios. In the Large-Scale Experimentation scenario, the perhaps most important seeds are the fact that emission regulations become more stringent (S7) and that emissions can be mitigated through niche technology (S3). Note that it is not expected that this will happen through the replacement or addition of modules (S5) to a large extent[54]. Niche technologies also offer the opportunity to alleviate pressure from supply constraints (S8). The dynamic through which the scenario operates is experimentation in several niches (S10). Finally, it is important to note that 'business-as-usual' continues to a certain extent, making it harder for niche technologies to break through (S11).

Elements that govern the consumer-OEM relationship receive less emphasis. Fuel economy (S1) does not have as much importance, at least initially. Consequently, niche technologies are primarily judged by

[54] Addition of modules to mitigate emissions is not unlikely. Perhaps the best example is the three-way catalytic converter. More recently, particulate filters are considered to be one of the key technologies for meeting the Euro 5 emission standards that will come into force September 2009 (European Commission, 2008). Nonetheless, such measures are not applicable for CO_2 emissions and typically lead to higher fuel consumption.

their ability to curb emissions (S3) and alleviate supply problems (S8) rather than accommodating high fuel prices (S2). Note that these goals do align, however. Since experimentation takes place in distinct niches, modularity plays a smaller role (S4, S6) as does the associated restructuring of industry (S9).
Central to a gradual breakthrough is the consumer-OEM relationship. Therefore, the way consumers evaluate fuel economy (S1) and the ability of technology to improve this as fuel prices rise are important (S2). It is important to both consumers and OEMs that current trends in car performance and size continue (S11). The basic car outline should therefore remain the same and improvements will come through the adoption of modules to fuel economy (S4) and performance (S6). Development of modules takes place at suppliers, since they are able to focus their R&D (S9). Emission regulations (S7) and the role of technology to counter emissions (S3) are less important, as are security of supply constraints (S8). Modules may be used to reduce emissions (S5), especially if this coincides with a reduction in fuel consumption. Finally, experimentation in protected niches (S10) is not the main dynamic of the breakthrough. Rather, it is a gradual reconfiguration of the car (S4 and S6).

		Large-Scale Experimentation	**Gradual Breakthrough**
S1	Fuel economy moves up the consumer preference priority list.	+	++
S2	Technology accommodates fuel economy importance.	+	++
S3	Technology mitigates otherwise increasing emissions.	++	+/-
S4	Modules are added to improve fuel economy.	+/-	++
S5	Modules are added to reduce emissions.	+	+
S6	Modules are added to improve performance.	+/-	++
S7	Emission regulations become more stringent.	++	+/-
S8	Niche technology provides an opportunity to ease supply constraints.	++	+/-
S9	Suppliers perform focused R&D activities.	+/-	++
S10	Experimentation with various technologies in several niches.	++	+/-
S11	Incremental improvements in segments unaffected by landscape pressure.	+	++

Table 9.4 Emphasis on various transition seeds in the two scenarios.
++ = very large influence, + = large influence, +/- = medium influence.

9.3 Scenario architectures

Two distinct scenarios have emerged from the previous sections. It has been made clear which regime and landscape developments are at the basis of the breakthrough of niche technologies. This section marries the scenarios to two of the transition pathways as defined by Geels and Schot (2007) and discussed in section 2.3.2.

Large-Scale Experimentation matches best with the transformation pathway. In this pathway, niche-innovations have not yet fully developed. However, landscape pressure builds beyond the level that the regime can handle with the current configuration. The regime survives by adopting symbiotic niche innovations.
Niche technologies have currently indeed not yet fully developed, perhaps best characterized by the discrepancies in performance between CVs on the one hand, and fuel cell and electric vehicles on the other (see section 7.4). In this scenario, it is assumed that there is quite severe pressure to reduce emissions and alleviate supply constraints, so that niche-innovations indeed do not have the time to fully develop. The pressure leads to increased experimentation with each of the alternatives. By adopting elements of the technologies deployed in niches, the regime is able to withstand landscape pressure. It is typically regime actors who are involved in the development of the alternatives, so that the regime is able to survive with minor adaptations.

The Gradual Breakthrough scenario also starts out along the transformation pathway – the regime adopts elements of the not yet developed niche-innovations. However, subsequent adoption of symbiotic innovations does not fully relieve landscape pressure. This situation is therefore more prolonged than in the Large-Scale Experimentation scenario. In the mean time, niche-innovations have the opportunity to develop fully.
As more innovations get adopted, the configuration of the car changes in such a way that it requires changes in institutional rules. The dynamics of the scenario change into that of the reconfiguration pathway. The end result is a vehicle that has changed consumer preferences and market dynamics. Additionally, the roles of some (regime) actors shift.

This implies that two of the pathways are not used. For the technological substitution pathway, this is indeed the case. In this pathway, niche-innovations have fully developed but are countered by a very strong regime. A large landscape pressure is required to fully overthrow the regime, after which a niche-innovation takes over. This pathway does not follow logically from the analysis part, because it requires sudden and diverse landscape pressure. The landscape developments that have been identified as relevant have been present for quite a while and although they are expected to increase in the next decades, it seems unlikely that this will be in the sudden way that the technological substitution pathway presumes. Rather, they are of a type that Geels and Schot (2007) characterize as 'disruptive change'.
The de-alignment and re-alignment pathway is not entirely left out, but is partly included the Large-Scale Experimentation scenario. This scenario features a competition between hydrogen and electricity that is characteristic of the de-alignment and re-alignment pathway. However, the fact that regime actors survive to a large extent and that there are no significant rule changes make that the scenario comes closer to the transformation pathway. Section 11.1.4 explains how the de-alignment and re-alignment pathway is related to the two scenarios in more detail. A summary of the main characteristics of each scenario is presented in table 9.5.

	LARGE-SCALE EXPERIMENTATION	GRADUAL BREAKTHROUGH
Main characteristics	Pressure on the regime comes primarily from emissions regulation and fuel supply constraints. Public-private cooperation allows for the creation of regional scale networks that diminish infrastructural barriers for niche technologies.	Pressure on the regime derives from increasing fuel prices. Fuel economy moves up the consumer priority list. OEMs that are able to develop cars that meet current needs while improving fuel efficiency perform best. Innovations in the form of changing and adding modules.
Primary transition seeds	S3, S5, S7, S8, S10	S1, S2, S4, S5, S6, S9, S11
Rules	Emissions regulation presses OEMs to change their R&D search routines. Adoption of niche technology by consumers requires temporary changes in the way they value product attributes.	Fuel economy moves up the priority list. Since changes are done in a modular fashion, sufficient variety remains. However, changing user preference and behaviour shape the regime configuration.
Dynamic	Political dynamics call for stringent emissions regulation on local and (supra)national level. Local policies stimulate experimentation.	Market dynamics. Reconfigurations are induced by interactions between consumers and OEMs.
Multi-regime interactions	Mobility with electricity and oil regime.	Idem, oil regime enters later with hydrogen.
	LANDSCAPE FACTORS	
Fuel price increases	Moderate influence as technological changes pushed by the other factors align with rising fuel prices.	Strong influence as consumers increasingly base their purchasing decisions on fuel consumption.
Supply security	Moderate to strong influence as governments will seek to diversify away from oil-derived fuels.	Minor influence as governments limit their active role in securing supply.
Increasing environmental stresses	Strong influence as emissions regulation is sharpened and policies to improve local air quality are put in place.	Moderate influence as regime actors succeed in fending off stringent emissions regulation.
	REGIME FACTORS	
Infrastructure aspects	Joint infrastructure investments in (large-scale) experiments. Cooperation essential to overcome the associated investment costs.	No need for infrastructure investment as cars incorporate more and more electric drive elements. As the fuel cell gets introduced, corridors of hydrogen stations are built along highways.
Principal actors	Government agencies, OEMs, and the oil industry.	Consumers and OEMs, as well as utilities and the oil industry.
Role of outsiders	Outsiders get involved in experimentation, but regime actors retain their positions.	Collaboration between regime actors and (relative) outsiders (suppliers).
Niche development	Niche technologies develop in (large-scale) demonstration projects. The first implementations are in products that are regarded as distinctly different by the market. Further development by project partners brings technology performance in line with that of CVs.	Niche technologies develop mainly by efforts put in by (first-tier) suppliers. OEMs take a coordinating role. Subsequent adoption of modular innovation transforms the CV into a plug-in hybrid with a fuel cell as range extender.

Table 9.5 Main characteristics of the two scenarios.

10 Scenario elaboration

This chapter represents step 6 in the STSc methodology. The two scenarios outlined in the previous chapter will be elaborated into two narratives. Each narrative is divided into three episodes[55]. In the first episode, links emerge between the regime and niche developments. Then, during the second episode, there are significant changes in the regime to accommodate the linkages. In the final episode, the regime stabilizes into its new configuration.

Some details are highlighted for each episode:

- types of vehicles introduced;
- which consumers are adopters;
- which are the (other) key actors, and how their role changes;
- the response of the regime (except in the last episode, where it is no longer relevant);
- infrastructural requirements[56];
- what can be achieved in the timeframe considered;
- how institutional rules change, or hold.

10.1 Large-Scale Experimentation

In this scenario, emissions regulation and security of supplies issues put pressure on the regime. Niche technologies compete to replace the ICE.

10.1.1 First episode [0-10 years after introduction]

The key landscape pressure in this scenario is emissions regulation. For the Dutch situation, this partly derives from the European level. The trend that has recently been adopted by setting the Euro 5 and Euro 6 targets, coupled with fines for OEMs if they do not meet them, is continued. At the same time, local governments implement policies to combat local emissions. An example could be a ban on (very) polluting cars in regions such as city centres. This is again required to meet European (air quality) rules. These rules spill over to other sectors, e.g. as construction projects get delayed.

These policy measures motivate regime actors to continue and expand their experimentation with niche technologies. On the one hand, this is a way to show goodwill and so weaken and/or delay future regulation. On the other hand, the need to experiment is more obvious and pressing as expectations are that emissions are to become even more stringent in the future.

The nature of experimentation is dependent on a number of factors. First, the fit between a niche technology and local needs. Smaller-scale projects in city centres favour EVs: smaller vehicles are easier to handle in city traffic, easier to park, and a limited range is less problematic as driving distances are shorter. Similarly, HVs and PHEVs are favoured in projects that require larger vehicles and ranges.

Second, local availability of resources has influence. Projects involving hydrogen are best located where (excess) hydrogen is already available, in the Dutch case for instance near the refineries in the Rotterdam-Rijnmond region. Although the requirements for EVs are best for city traffic, the recharging infrastructure might be largely absent for inhabitants of apartments lacking a carport or garage. PHEVs are less bound to the local availability of resources, as they do not have special requirements.

Third, the support of government actors. Such support may be different for actors at different levels, local and (supra)national. Local policy will be aimed at improving local air quality and optimal utilization of local resources. (Supra)national policy is directed primarily at reducing CO_2 emissions. In this episode, support is divided over all options.

[55] These three episodes coincide with the linking, transformation, and evolution episodes that Elzen and Hofman (2007) describe. To avoid confusion, these terms are not used here, because ‘transformation’ is also the term used for one of the transition pathways.

[56] Although this thesis does not focus on infrastructural requirements, they do have a large influence. It is therefore instructive to compare infrastructural developments with (modelling) findings in this area.

Experimentation with hydrogen starts to go beyond the projects that are currently in place to reach a scale that aligns with the ambition of 'Lighthouse Projects' as defined by the current regime actors in the project HyWays (2008). These projects involve rolling out a few thousand HVs and the supporting infrastructure. Their main aim is to establish a broad acceptance of hydrogen and to accelerate technology development. They are backed by public-private partnerships at European level, such that the costs invested in vehicles and infrastructure are fairly shared among partners, including the governments involved. Specific policy support for hydrogen is put in place.

Experimentation with electric cars mainly takes place on a local level. Entrepreneurial start-ups and established OEMs cooperate with local governments and utilities to experiment on a smaller scale in limited areas, typically involving tens to hundreds of cars. Infrastructure investments comprise charge points for those who do not have the facilities to charge their vehicle at their disposal. At this point, the costs of these investments are limited compared to those of a hydrogen infrastructure. Additionally, EVs occupy some market niches in which their advantages offset their drawbacks, such as the sports car niche and two-seaters for local use (comparable to the current Smart).

The development of PHEVs is different from the experimental character of EV and HV experimentation. Except for costs, the barriers for introduction that exist for electric and HVs are not present for PHEVs. Therefore, PHEVs go through more or less the same development and launch process as a conventional car. The OEMs involved do remain cautious as they acknowledge the risks involved with introducing this new technology. As with (conventional) HEVs, they do not strive for immediate market penetration at a large scale, but market the car in such a way that it is attractive to a limited part of the market initially. Attempts to increase market share are only undertaken if the technology proves a success. The main causes for a limited market share, however, are the limited variety of models available and the high costs – despite government subsidies.

Type of vehicles

Fairly large numbers of consumers get involved, especially towards the end of the episode as the projects involving electric and HVs scale up and PHEVs gain market share. Still, none of the alternatives reaches a fleet penetration that exceeds 10%, if only because even a very aggressive scenario without competition between alternatives is unlikely to reach those numbers (illustrated in appendix C).

All of alternatives involve risk for the partners involved. OEMs try to limit this risk by carefully managing the link that the alternative models have with their established model range. Especially for the PHEV, which is launched on a commercial basis in this episode, a separate model range is created (e.g. Chevrolet Volt), models are varieties that are only available in the plug-in hybrid versions (cf. current Lexus hybrids), or are presented as varieties of current hybrid models (e.g. a plug-in Toyota Prius). Additionally, the variety of models that is introduced is limited. Typically, the experimental projects (electric and hydrogen vehicles) only involve a few models, whereas for PHEVs there are only a few first movers as well, that typically launch one model.

Adopter profile

This causes adoption to be limited. As with current HEVs, only consumers that specifically prefer an alternative technology qualify as first adopters. There are two typical adopter profiles. The first group scores high on a symbolic-affective motivation for car use – they like to show that they are different by driving an AFV. Although they are perhaps rather indifferent about the environment, they have a strong perceived behavioural control (PBC) that causes them to dismiss potential practical difficulties.

The other group concerns users that primarily use their vehicle out of an instrumental motivation. This implies that practicalities are important to them. However, they also feature a strong concern about the environment and have a very positive attitude towards environmentally friendly behaviour. Finally, they have a strong PBC. This combination of factors implies that they are willing to change their behaviour despite the practical difficulties that they see.

Emission regulations that tie up excessive emissions with fines will increase the cost of driving a car in general. As chapter 4 has shown, price is one of the primary factors determining the choice of vehicle for consumers. The typical reaction of consumers that do not fit the above two profiles is to switch to vehicle classes that fit their budget.

Key actors

Table 10.1 presents an overview of the key actors besides consumers. The hydrogen experimentation niche carries all regime actors. This reflects the fact that hydrogen fits best with their current activities. By contrast, the electric experimentation niche involves outside actors as well. The most important are the utilities, that see an opportunity of greatly expanding the demand for electricity. Furthermore, OEMs are joined by companies that focus exclusively on electric cars. The PHEV market introduction involves a smaller number of actors, primarily because it requires less investment in infrastructure. It is mainly (electric) car manufacturers that were not part of the regime that exploit market niches for electric cars, similar to the current situation.

Governments of various levels are involved in the experimentation projects. All levels are involved in the hydrogen experimentation. This is required as the lighthouse projects entail large numbers of vehicles and infrastructure investments, affecting many regions. Experimentation with EVs is typically restricted to smaller regions and hence involve only regional and local governments. The market introduction of PHEVs and EVs (in niches) is subsidized by measures such as tax breaks and subsidies, arranged at the national level.

In sum, regime actors are involved with HVs and PHEVs. Regime actors are less prominent participants in EV experimentation, although notably a number of OEMs do get involved.

Development	Key actors involved
Hydrogen experimentation	Governments (local, regional, (supra)national), OEMs, oil industry
Electric experimentation	Governments (local, regional), (traditional) OEMs, electric car manufacturers, utilities
Electric niche exploitation	Electric car manufacturers, (national governments)
PHEV market introduction	OEMs, (national governments)

Table 10.1 Key actors involved in the first episode.

Regime response

Although regime actors are heavily involved in developing the niche technologies, they continue to invest in conventional technology. As currently, about half of their R&D efforts is geared towards improving the ICE. Such improvements are expected to lead to a reduction of fuel consumption (and related emissions), although it requires expensive modifications. Alternatively, OEMs can incorporate modules such as particulate filters and catalytic converters[57] that reduce emissions, although these may reduce fuel economy as well. Modifications and additions are warranted as the costs of driving in general rise. Of course, if modifications reduce fuel consumption, such pressures are alleviated by reducing operating costs. The improvements represent a sailing ship effect.

Infrastructural developments

PHEVs and EVs launched in market niches do not require significant infrastructure investment in this episode. For experimentation with more mainstream electric cars, no upgrades to the grid are needed, although there is need for some charge points.

For hydrogen, the development of infrastructure is quite in line as modelled in the THRIVE project. The project assumes seeding in a number of cities, upon which demand for HVs is generated in those areas.

[57] New developments are underway in catalytic converters. An example is the addition of a solution of urea in water to exhaust gases, where the urea reacts with NO_x to form harmless N_2 (Kašpar, Fornasiero, and Hickey, 2003).

The scenarios that are considered do not differ during the timeframe considered here, and result in a fleet of several thousands of HVs. Assuming that the seeding takes place in regions where local circumstances favour hydrogen, this is a nice quantitative illustration of the qualitative work in this thesis (cf. section 2.2).

Timeframe

This episode is estimated to take about ten years. Although the number is indicative, it has some implications. First, ten years is about the time that commercialization of the Prius to significant numbers took. This gives a good indication of the potential sales of PHEVs in this period. Ten years suffices to develop the electric and HVs to a point that commercialization is possible. The expectation in HyWays (2008) is that lighthouse projects take approximately five years to materialize, but a longer time period is required to further reduce costs. Perhaps experiments with EVs require less time to set up due to limited infrastructure requirements, but comprehensive projects involving impact on (local) distribution grids are not as far down the learning curve yet. In sum, the end situation in this episode is limited commercialization for PHEVs and such improvements in HVs and EVs that they are ready for the commercialization phase.

Institutional rules

There are not really changes in any of the institutional rules. Rather, the regime responds largely in accordance with the rules. Low variety and the associated impossibility to address all motivations for car use limit the penetration of niche technologies (C1, C2). This is amplified by the fact that alternatives do not (yet) outperform the niche technology, while the ICE keeps improving (C3). Furthermore, consumers do still not buy cars because of lower emissions, although emissions are indirectly moving up the priority list by increasing the cost of driving a car (C4).
Perhaps the most important rule in this episode is that external pressure is needed to influence OEM development routines (O2). Environmental stresses are the cause of pressure and – in line with historical precedent – governments are the actors that press the OEMs for change. Governments are also the ones that stimulate the OEMs to update their product portfolios with innovative products to safeguard future profits (O1). Finally, there is one rule that only influences dynamics to a very minor extent. The automotive industry changes very little, because OEMs maintain the status quo in vehicle design and production (O3).

10.1.2 Second episode [10-30 years after introduction]

The most important characteristic of this episode is that regime actors lose faith in regime technology. They start to realize that tightening regulation can no longer be addressed by pushing the limits of the ICE. Moreover, their margins are falling as consumers shift to smaller cars.
In the previous episode, experiments have basically been kept alive through government backing. These experiments have moved niche technologies to the point that they are fit for commercialization. Now the point that private parties take over has been reached. The government's role is restricted to maintaining pressure on the regime through increasingly stringent emission regulations.
In the R&D portfolios of OEMs resources are shifted from improving the ICE towards niche technologies. It now becomes clearer which technologies take the upper hand, so that R&D budgets can be allocated with more certainty. As will follow from the remainder, it is mainly an OEM's market position that will determine what technologies to invest in.
The storyline now comes to a crossroads and can continue along two lines. Some assumptions are necessary to set it off on one of these roads. The matter is that each of the niche technologies requires significant investments in infrastructure to grow beyond the stage they have reached during the previous episode. These investments are in the same order of magnitude for either option. Furthermore, there are

major returns to scale[58], so that a dominant position is only in store for one. Hence, the one storyline implies investment in an electric infrastructure, from which PHEVs and EVs benefit. The other story is a major extension of the hydrogen infrastructure, such that its supply reaches the standards that currently apply for conventional fuels.
A clear, coherent story can be formulated for each alternative. It is far less clear-cut which is more likely. Most informative, at this point, is to define the matters that are relevant in deciding which technology takes the upper hand. This first and foremost depends on the relative strengths of the coalitions that have assembled in each camp. This strength is determined by the number and kind of actors in each camp. Note that oil companies are in the hydrogen camp, whereas utilities are in the electric camp. Second, it depends on how technology has evolved in the previous episode. For fuel cells, it is of chief importance that costs have come down to the range of the ICE (which has increased in cost!) and it meets criteria for durability. For batteries, advances in specific energy, cost, and durability are important. Third, it matters to what extent consumers have adapted their threshold values for critical vehicle attributes such as range and fuel availability. To provide an example: if consumers have shown in experimentation with EVs to adapt their behaviour to incorporate overnight charging and switching to other modes of transport to cover distances that are beyond the range of their EVs, such behaviour obviously favours the electric camp.
Unfortunately, making assumptions on any of these issues separately involves peering into a crystal ball and adds little to the discussion. It is here therefore assumed that a combination of circumstances arises that favours the hydrogen pathway. This implies that the hydrogen coalition finds itself in a more powerful position, the development of batteries misses its targets while fuel cell development progresses according to plan or better, or consumers are reluctant to deviate too much from current practices. A mix of these three circumstances provides the conditions that push hydrogen into a dominant position.

OEMs and the oil industry are now keen to move the rollout forward. They set out to lower barriers to introduction as much as possible. This implies introducing more models to increase variety and so address a larger part of the market. Perhaps the quickest way to do this is to integrate models into the current range. This can be done through designing platforms for future models to incorporate a number of drivetrains, including one or more based on fuel cells. That way, consumers can buy the same vehicle they possessed already, only changing the fuel.
All parties have an interest in rolling out the infrastructure as quickly as possible. This diminishes consumer perception that fuel availability is low, so that uptake of HVs is accelerated. This, in turn, minimizes underutilization of stations, so that return on investment is realized sooner[59]. Strategic placement of stations allows access to fuel for a large number of consumers while keeping investment costs to a minimum (Melaina and Bremson, 2008; Lin, Ogden, Fan, and Chen, 2008). Investment costs are distributed over partners in a way that is considered fair by all involved.

Type of vehicles

OEMs introduce hydrogen in the midsize and large vehicles segment first. Due to higher fuel consumption, it is harder for these vehicles to comply with regulation. Moreover, to protect their margins, OEMs will try to prevent consumers to switch to smaller cars.
EVs dominate in the lower segments. Smaller and lighter cars achieve fairly acceptable ranges on electricity. Moreover, they are often not driven so far, implying that they can do with only a battery.

[58] This must be interpreted carefully. For OEMs, there are economies of scale in the traditional sense – as more vehicles are produced, costs per vehicle fall. The benefit of scale is different in the case of energy companies. For them, returns to scale come from network effects. The infrastructure they build becomes more valuable to consumers as it is larger, speeding up adoption and minimizing underutilization.
[59] This is one of the outcomes of the THRIVE allocation model.

Adopter profile

The introduction of more models and the incorporation of hydrogen drivetrains for current models provides more groups with the possibility to switch to AFVs. In the previous episode, only two adopter groups could be typified, largely because those were the only consumers that were willing to cope with some of the drawbacks of AFVs. These formed barriers for other groups, which are now to a large extent removed. As the variety of hydrogen-powered models on offer broadens, more and more groups of consumers find that their barriers to switch have been removed. This implies that they experience a higher PBC to change their behaviour towards driving an AFV. Moreover, driving a conventional car has become more expensive, and switching to a smaller car to compensate means doing away with a certain comfort. AFVs have reached the phase in which they are able to compete with CVs across the board.

Driving has become more expensive, regardless of which technology is involved. Therefore, groups on a tight budget are forced to choose smaller vehicles. Because HVs are primarily introduced in midsized and larger vehicles in first instance, these groups might be one of the last groups to switch. Their adoption is strongly motivated by which technology offers the cheapest way to drive.

In all cases, the two-stage purchase process still holds. The difference is that adopters of AFVs no longer make the decision to purchase an AFV in the first stage. Rather, as prior to the transition, the result of the first stage in the process is again a vehicle class and perhaps a brand. The choice for a drivetrain is made in the second phase, albeit that the proportion of consumers that opts for a hydrogen-powered vehicle increases throughout the episode.

Key actors

There are basically no changes in the actors involved in each of the developments (see table 10.1). It is possible that some OEMs stick to the development of PHEVs and EVs. They may gain a market share in the (niche) markets in which EVs become the norm. In those markets, they compete with specialized producers that were previously external to the regime. However, some OEMs that have put their cards on these technologies and try to compete in the midsize and larger vehicle segments may lose the battle, mainly due to a lack of supporting infrastructure. Those OEMs may find themselves in so much trouble they can no longer survive.

In general, the time and extent of use of hydrogen as a fuel depends on the market position of OEMs. Larger vehicles are expected to be the first to be fitted with fuel cells on a large scale, and consequently OEMs whose product portfolio consists of these vehicles for the larger part are wise to be the first to switch. OEMs with a cost focus strategy and primarily small vehicles in their model range can profit from consumers switching to smaller vehicles as driving becomes more expensive. They will implement fuel cells at a later moment and perhaps not across their entire model range, but opt to fit some cars with batteries to power the electric drivetrain instead.

Utilities find that their adventure in electric cars has been very costly but did not yield a satisfactory return. Nonetheless, demand for electricity does increase through the niche markets in which electric cars have found a place.

Regime response

As has been indicated above, regime actors have lost faith in the ICE. As they shift resources from developing the ICE to the new technology, the sailing ship effect wanes off. However, as the previous section has illustrated, the regime actors survive. They can use the main skill they have developed since the inception of their industry – efficient mass production – to outperform the newcomers, although some of those are successful in niches such as sports cars.

Infrastructural developments

The development continues along the lines modelled in THRIVE to a reasonable extent. In that model, the rationale underlying the introduction of models is of a quadratic nature[60]. The introduction process sketched here is slightly different. During the first episode, a limited number of models is available for a prolonged period. It is only in the current (second) episode that models become available in large quantities.

This difference must be taken into account when interpreting the results from the model used in THRIVE. It only simulates growth during the first fifteen years after introduction. Taking into account that the introduction of models probably occurs less rapidly than the model assumes, a rough estimate is that the end of the simulation period coincides with about midway the second episode. By that time, the infrastructure has expanded to cover most of the Netherlands. Depending on other assumptions in the model, it is possible that the infrastructure does not reach less densely populated areas such as the northern part of the country.

Timeframe

This episode spans twenty years. In line with the THRIVE modelling results, this time period suffices for the expansion of the range of models that include hydrogen to cover the entire market. However, the fact that the models are offered does not mean that the adoption of HVs is completed during this episode. The allocation model reports that fleet penetration levels vary between only 1% and 5% at the end of the simulation period. By the end of the episode (which is roughly ten years later), this can be expected to be significantly higher as the model shows that penetration rates are growing fast towards the end of the simulation.

Institutional rules

There are some changes to institutional rules in this episode and they are due to a dilemma that the OEMs face. Furnishing their current models with a hydrogen drivetrain is an enormous operation. It should be carried out carefully, as new models potentially cannibalize sales of existing models[61].

Until this process is complete, some institutional rules are violated. First, OEMs have lost faith in the ICE and consequently stopped investing in it. Their profit motive is no longer best served by the upgrading their current range of models. Instead, they invest in carefully selecting models to update with hydrogen. This breaks with the upgrading of models that was the standard prior to the transition. There is thus a change in rule O1. Interestingly, this change comes from the OEMs themselves – as in the previous episode, regulation is a strong driver, but governments do not interfere directly with the rollout anymore. This marks a change in rule O2. Structural changes in the industry do not happen; rule O3 is therefore not relevant in this scenario.

The changes have their repercussions for consumers and can only be successful if they alter some of their rules as well. They must be willing to accept less variety (C1, C2). More importantly, they can no longer expect the same incremental improvements as they have been used to prior to the transition (C3). It is an not entirely unrealistic assumption that they are content to settle with this change – after all, it remains questionable how much value some of the elements of the upgrading by OEMs added anyway. Selecting a vehicle from the reduced set on offer proceeds much along the same lines as before (C4).

Prior to the transition, OEMs often offered the argument that technological changes to the car were only possible to the extent that consumers would accept them. It is impossible to establish whether this is

[60] The assumption is that n manufacturers introduce 5 models at $t = 0$, and keep a regular cycle of introducing 5 new models with an interval Δt. These first movers are joined by n additional manufacturers at each cycle. The cumulative number of models thus follows a quadratic pattern. This reasoning gives a number of discrete points, the first few of which are fitted by a logistic curve. In the end, this curve is the input for the model.

[61] During the previous episode, this was only a minor issue. In that episode, adopters were represented by two groups of atypical consumers.

indeed the truth now. In any case, during the transition in this scenario the OEMs assume more power by offering those products that they expect to best serve their long-term goals, in the first place survival.

10.1.3 Final episode [30-50 years after introduction]

During this episode, the replacement of the ICE by alternatives is completed. FCVs are now the most common propulsion system. The fuel cell has proven a symbiotic niche-innovation that has served to alleviate landscape pressure and preserve the position of the regime actors. It is possible, however, that consumers have developed a liking for the situation during the prior episode that permanently changes the socio-technical regime.

Type of vehicles

OEMs have started dropping the ICE from their model ranges, so that most models only come equipped with a fuel cell. A (niche) market has emerged for EVs for use on trips with a limited range, typically in urban areas.

Adopter profile

Almost all groups in the market have adopted AFVs. Urban cars have been adopted by a group of consumers willing to change their behaviour to charging overnight and switching to other means of transportation for longer trips. They save on the fuel cell, which they do not require. This group has a high PBC. Note that they do not belong to this niche for environmental reasons, since the mainstream HV does not produce (local) emissions either. For this reason, it is likely that their main motivation for car use is instrumental. EVs have also attained reasonable shares in niches such as sports cars.

Key actors

The regime actors remain the key players in the regime. The attack on the regime that has been staged by the utilities, electric car manufacturers external to the regime, and a number of OEMs has been successfully withstood.

Infrastructural developments

Competition in the oil industry to provide good service to their customers drives the density of infrastructure higher than strictly necessary from a consumer point of view, as was the case prior to the transition. However, the trend of network optimization, i.e. closing smaller stations and scaling larger ones up, is sped up during the transition.

Timeframe

This episode again takes 20 years, making the total for the transition 50 years. The episode carries on beyond the timeframe that is used in THRIVE. As another means of comparison, the project HyWays assumes that 80% of all vehicles are fuelled by hydrogen 35 years into the rollout. Based on this number, 50 years seems a good indication for the transition to complete, although the HyWays results are more optimistic than THRIVE during the part of the timeframe that allows comparison.

Institutional rules

During this episode, the institutional rules more or less return to their status prior to the transition. The introduction of HVs in the segments where they can be successfully introduced has been completed. Now, OEMs will again try to increase profits by returning to the upgrading ‘trick’, basically restoring O1. Only external pressure can change this dynamic.
Consumer rules are likely to return to a form much like prior to the transition – unless consumers have been content with the institutional situation during the previous episode. They might be able to restore the OEM-consumer power balance, if they show they can settle with lower variety (C2) and are content with

the performance they currently get (C3). To attain this situation, a shift towards a car as an instrument instead of a symbol (C1), is also required. If such changes are the case, the regime has permanently changed.

As a conclusion, figure 10.1 provides a graphical illustration of the Large-Scale Experimentation scenario.

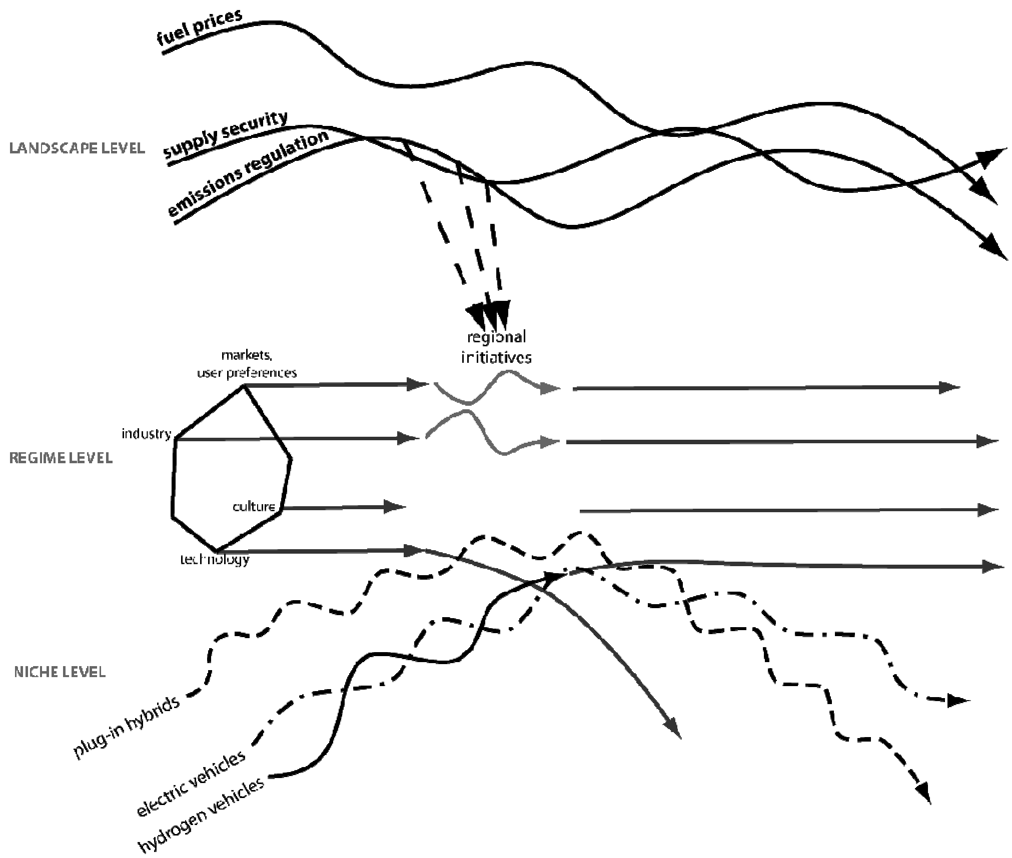

Figure 10.1 Graphical illustration of the Large-Scale Experimentation scenario. Policy and science are part of the regime, but are beyond the scope of this thesis.

10.2 Gradual Breakthrough

In this scenario, fuel prices increase dramatically and put pressure on the regime. Regime actors respond by reducing fuel consumption of the conventional car as much as possible. In doing so, they gradually transform it into a HV.

10.2.1 First episode [0-15 years after introduction]

OEMs and the oil industry form a strong coalition in this scenario. Therefore, they are able – as in the recent past – to fend off strict regulations by governments at various levels. Fuel prices, on the other hand, are beyond their influence. This exacerbates the tension between preferences for larger cars that both consumers and OEMs prefer and the increasingly pressing need to reduce fuel consumption as fuel prices rise.

Fuel prices will increase continuously, while the market for crude oil becomes increasingly volatile. As a result, the frequency of price shocks will increase. During shocks, consumers respond as they have done before: they quickly turn to cars with good fuel economy. In the short term, the only option available is to revert to smaller cars. Additionally, as the recent gradual increase in oil prices has shown, even during times of gradual price increases consumer preferences shift to cars consuming less fuel.

This hurts OEMs' interest[62]. In their view, the best way to solve the tension is by improving the current technology. Partly, they can realize this themselves by improving the ICE, e.g. by fine-tuning the combustion process itself[63]. Partly, they will have to revert to other methods, mainly replacing or adding modules to the car design. For instance, start-stop technology allows engines to be shut off automatically when they are idling, as during traffic jams or while waiting in front of traffic lights. The system is able to restart the engine in a time well under a second (Karden, Ploumen, Fricke, Miller, and Snyder, 2007). This happens when the driver touches the accelerator, so that there is no change to the normal driving routine.

Start-stop technology comes in the form of a module that can be added to a current vehicle. It is easy to implement and can be developed by suppliers that have specialized in it. There are more, but similar ways to save fuel. Regenerative breaking, already incorporated on current HEVs, captures energy during braking and stores it in batteries or (super)capacitors. The shock absorbers can be connected to a generator to capture energy from friction while absorbing shocks (Chandler, 2009).

Most of these additions involve components that work with electricity. Regenerative braking and capturing energy from shock absorbers involve adding or expanding generators and increasing battery capacity. The stored energy can be used for functions that are traditionally powered by electricity (e.g. starting, lights, ignition), but the amount of energy that is stored exceeds the requirements of these functions. Instead, it makes sense to fit the car with a (small) electric motor that assists during acceleration. This is especially relevant in market segments that focus on high-performance cars.

Gradually, the size of the battery that is incorporated in cars increases. Although this helps bring down fuel costs, both OEMs and consumers realize that driving by using electricity alone provides even larger cost savings. That is why some OEMs fit models that are equipped with large batteries with the option to recharge the batteries from the electricity grid. Since the aim is a limited electric range initially, no major expansion of infrastructure is required. It is an addition to current models, and since they are sold widely, the number of consumers that is willing to adopt these PHEVs and possesses the means for recharging is large enough. In some cases the battery does not allow the typical daily commute to be made on a single charge – this is not too problematic as the ICE is still large enough to comfortably finish the trip.

Type of vehicles

Different modules are applied in different segments. Most additions will take place in the midsize segments. A large part of OEM sales comes from these segments, and OEMs want to prevent consumers from switching to segments featuring smaller cars. Fuel savings in absolute terms are larger in the midsize segments than in the small cars segments, while most modules probably cost more or less the same for both segments. Additional and/or different modules are therefore most cost-effectively applied in the midsize segments. Series-parallel drivetrains are the system of choice, since it offers the best options for fuel savings.

For the smaller cars, not many differences are expected. Additional modules will drive up the purchase price, to which consumers in this segment are typically quite sensitive.

In other segments, additional modules are applied in a different way. Sports cars, for instance, can enhance their acceleration capabilities through the application of electric motors, that deliver a lot of torque over almost their entire rpm range. The same holds for SUVs, the heavy weight of which requires large engine power to achieve an acceleration figure that is acceptable to its buyers. In these segments, the transformation into hybrids is thus motivated by a performance rationale rather than a fuel saving one. The focus on performance favours the choice for a parallel-hybrid drivetrain configuration.

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[62] But not necessarily that of consumers. By shifting to smaller cars they signify that larger, luxurious cars are not really a necessity, although some consumers may regret that they have to make this move.

[63] An example is homogeneous compression combustion ignition in petrol engines, which involves ignition by compression rather than spark. This allows up to 50% fuel saving, although many technical difficulties have to be overcome before this number can be realized (Taylor, 2008).

Following this logic, PHEVs are first introduced in the midsize segments. As batteries increase in size and the all-electric range increases, more models are fitted with the simpler series configuration.

Adopter profile

Since innovations come in the form of additions and updates to existing products, it is hard to pinpoint specific adopter groups. Groups differ according to the modules that are included in models. For instance, regenerative braking may appeal to a group of consumers with a strong instrumental motivation for car use, with a positive attitude towards cost savings but a low PBC for switching to a smaller vehicle. Alternatively, consumers with a highly symbolic-affective motivation for car use and a positive attitude towards performance-oriented cars might be inclined to add electric motors for increased acceleration to their model of choice.

Perhaps the most important point is that consumers need not change their current behaviour and model choice. Rather, OEMs update their current model range to tailor to consumer's needs. This implies that consumers can stick with their vehicle of choice while still benefiting from improvements on those attributes that they value.

This also implies that the car purchase process remains largely the same. The main difference over time is that many consumers will lend higher priority to fuel consumption. For the rest, adopter groups of certain modules may differ in the way they prioritize their preferences, including the factors they consider primary and secondary.

Key actors

Regime actors succeed in withstanding the pressure from increasing fuel prices by innovating. However, not all innovation comes from the OEMs themselves. Continuing a trend that has been initiated during the 1990s, the role of first-tier suppliers increases. They are often the ones pioneering innovative modules[64]. Thus, although all actors involved are part of the regime, the role of the automotive suppliers relative to the OEMs increases.

Regime response

Obviously, the regime defends ICE technology. In a sense, this can be labelled a sailing ship effect, but there is a key difference. The sailing ship effect presumes that the regime technology is threatened by niche-innovations. This is not the case – niche-technologies are no direct threat in this scenario, but provide symbiotic additions. Instead, the increase in performance of regime technology (in casu: fuel economy) is induced by rising fuel prices – a landscape development.

This does not imply that alternatives such as hydrogen and all-electric drivetrains are abandoned. Experimentation with these technologies is kept alive for two reasons. First, government regulation on emissions is continuously pending. One of the means regime actors use to fend off the regulation is continuing experimentation with alternatives on a small scale. Second, regime actors expect that fossil fuels will be replaced eventually. Although they feel that the transition should be postponed until it can be executed in an economically viable way, development of alternatives continues, albeit at a modest rate. In terms of R&D portfolios, not much changes – OEMs invest heavily in improvement of the ICE while spreading their remaining efforts over a range of alternatives.

[64] A cooperation between Valeo and Michelin, two component suppliers, provides an example of how the activities of suppliers evolve beyond their traditional role of designing and manufacturing. These two companies join efforts to design an electric powertrain system. The electric motor of the system is placed inside the wheel. The development is not related to a specific order of an OEM. This way, suppliers innovate beyond what an OEM would deem necessary. See http://www.autobloggreen.com/2009/02/14/ze-ev-valeo-michelin-team-up-for-french-electric-car-champion/ for more information.

Infrastructural developments

There are no significant infrastructural developments in this episode. Possibly, some charge points are installed to accommodate consumers who do not have a convenient option to recharge their PHEVs at home. However, this is likely to be a minor fraction.

Timeframe

This episode spans fifteen years. The uptake of all kinds of modifications to improve fuel economy is quite fast, especially since many modifications are only minor. Yet, the evolution into PHEVs is not a minor step. It takes to roughly halfway the episode before PHEVs are offered on a significant scale, i.e. a considerable portion of (midsize) models comes with a plug-in option. An estimate roughly based on the calculations carried out in appendix C is that PHEVs have captured 15% to 20% fleet penetration by the end of the episode.

Institutional rules

There are no significant changes in institutional rules – rather, the landscape developments set in motion changes that are laid down in the rules. The rule that plays the most prominent part is that the importance of attributes becomes larger as they play a larger role in the trade-offs of the purchase process (C4). Practically, this implies that consumers are on the lookout for cars with low fuel consumption. The guiding principles that OEMs use in product design change in this direction (O2). Other than blindly following consumer preferences, OEMs act in this way because they want to protect their margins (O1).
The scenario allows this to happen without sacrificing the amount of variety that is on offer (C1, C2). In fact, variety only increases by the application of various modules. This also prompts the structural changes in the industry that had been set in motion to continue (O3). Especially first-tier suppliers add an increasing amount of value to the end product.
The only rule that possibly sees a minor change is that future models do not improve incrementally over previous ones (C3). This is not to say that there is no improvement – rather, the way improvement is measured shifts in some segments. For instance, as fuel economy moves up on the priority list, fuel consumption ratings become a more important yardstick for measuring improvement. Note that the meaning of improvement can be different across segments, depending on preferences in those segments.

10.2.2 Second episode [15-30 years after introduction]

This episode sees the success of the PHEV spread. As time progresses, CVs are gradually replaced by plug-in versions. At the same time, the size of the battery increases so that a larger part of trips can be covered using electricity, and the function of the ICE is restricted to that of a 'range extender'.
Yet, there are limits to these trends. It does not make sense to fit cars with batteries that have capacities beyond the typical daily trip distance[65]. This implies that the part of battery capacity that is left unused[66] basically represents dead weight being carted around most of the time.
This could be an end point, at which the transformation of the car so far proves sufficient to withstand further landscape forces, and the regime reaches a dynamic equilibrium. Note that this assumes that consumers have adapted to recharging their vehicles at night to reduce their dependence on conventional fuels.
Although this is a plausible storyline, it is not the end situation considered here. There is a number of reasons that render it likely that consumer will be provided with cars that are able to operate in electric

[65] This is assuming that there is no major breakthrough in battery specific energy. Even so, the theoretical energy densities for battery chemistries that are closest to commercial application are one to two orders of magnitude smaller than that of fossil fuels (Zheng, Liang, Hnedrickson, and Plichta, 2008). It is safe to assume batteries will remain too heavy to practically approximate the typical range of a conventional car.
[66] Capacity that is referred to here excludes that part of the battery that is not used due to technical reasons. Power management ensures that batteries are never depleted entirely, which would have detrimental effects for their life span.

drive mode only. First, consumer attitudes have changed in favour of electric drive during the previous episode. It offers them protection from shocks in fuel prices, which lends driving on electricity an air of rationality[67]. There are other benefits, such as reduced maintenance. Perceived benefits can also arise from intangible notions such as 'liking' the handling of a car driven by an electric motor. Second, governments are keen to eliminate the use of fossil fuels in cars altogether. This would provide them with the opportunity to better control emissions[68]. Also, in a supply-constrained world, eliminating the use of oil is a major step towards energy independence.

Finally, utilities and oil companies both have a stake in the game. Utilities have witnessed demand for electricity soar in the last years, and they are keen to sustain this growth. The oil industry, on the other hand, has been following the trends with mixed feelings. Their position is still fairly good. Prices have risen sharply, but so have the marginal costs of production. Fuel demand has weakened due to the electrification of driving, but a growing world population and motorization in developing countries have balanced the trend. However, the industry realizes that the trend to provide consumers with a larger electric range cannot be reversed and is keen to claim a share of this new market.

This leads to the options that are available to extend the electric range of cars. Having dismissed further enlarging the battery, two alternatives remain, each of which require the rollout of extensive infrastructure. Interestingly, each of the options has its own champions. The first is the installation of fast-charging stations. Apart from the investment in these stations, this requires significant upgrades to the electricity production and distribution infrastructure. This option is favoured by utilities. The second option is substituting a fuel cell for the ICE range extender. This way, refuelling practices are also comparable to the current standards. This options is preferred by the oil industry, since it allows for utilization of their existing retail network.

This is where this scenario comes to a crossroads. Again, returns to scale prohibit the breakthrough of both options. The matters that determine which alternative emerges as the winning proposition are similar to those in the other scenario – coalition strength, consumer preference, and technological advances. Coalition strength boils down to the conflicting interests of utilities and the oil industry. Consumer preference for either option constitutes the second issue. This includes issues such as perception of safety and valuation of refuelling time (which is likely to be shorter in the case of hydrogen). Technological advances mainly refer to fuel cells, as batteries have proved that they are suited for the application in cars.

A combination of circumstances arises that favours the fuel cell. Costs of fuel cells have come down to a range comparable to that of the ICE, and durability has also risen to an acceptable level[69]. Consumers appreciate the quick refilling times that can be achieved with hydrogen and judge it to be safe. And perhaps most importantly, the old cooperation between OEMs and the oil industry proves more powerful than the lobby started by the utilities.

A hydrogen infrastructure is rolled out in close coordination between OEMs and energy companies. The introduction of fuel-cell vehicles proceeds in much the same manner as was the case with the PHEV: existing product lines are extended with a version featuring a fuel cell. Note that the infrastructure primarily needs to be rolled out along highways, since that is where the need for refuelling for range-extending purposes takes place.

The birth of the fuel cell hybrid electric vehicle marks the end of this episode. The rollout of the hydrogen infrastructure is started during this episode, but will not be completed until the next episode.

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[67] Comparable to the meanings buyers of hybrid vehicles currently want to convey (see table 4.4). Note that a larger battery need not *actually* provide financial benefits if calculated by conventional financial calculations (e.g. based on net present value).

[68] Tailpipe emissions from cars are very much geographically dispersed. If these sources of emissions are eliminated, it is easier to use mitigating techniques such as carbon capture and sequestration (CCS) can be applied to tackle the remaining sources.

[69] Note that fuel cells need only be used to provide extra range. This implies that a limited number of operational hours is sufficient to achieve a decent life span.

Type of vehicles

All of the changes described above will first take place in the midsize vehicle segment, later to be followed by segments such as SUVs and other large cars. These latter segments switch later because focus is primarily on performance.

The typical daily distance covered by a car differs. As OEMs expand the range that PHEVs can travel by electricity alone, groups of consumers turn out to be satisfied with their typical daily driving range. This implies that a market segmentation based on electric driving range will emerge (Kurani, Turrentine, and Sperling, 1996). The segmentation is loosely based on actual daily travel – individual consumers can be expected to have individual preferences regarding the 'range buffer' that they consider acceptable.

A niche evolves for cars that require a limited range. These cars can be offered at lower prices by eliminating the range extender. The size of the niche is related to the number of consumers that permanently change their behaviour to never use this vehicle to travel much further than roughly their daily average.

Adopter profile

Again, there is not really a typical adopter profile. The introduction of fuel cells proceeds – like with the PHEV – across existing model ranges. Consumers that previously purchased a car in a certain segments are the largely same ones that now adopt a FCV. The main difference between the first adopters and other groups is perhaps that the former experience a lower threshold as to what is acceptable with regards availability of hydrogen. This will play out in the two-stage purchasing process – for those consumers that consider fuel availability to be too low, the PHEV is eliminated in the first stage.

Key actors

The role that utilities play increases during this episode. They benefit from the PHEV and promote its development into an EV. As an outsider, their importance grows at the expense of the oil industry.

The importance of first-tier suppliers increased during the previous episode. This trend continues during this episode. Also, suppliers that are outsiders to the regime, e.g. producers of electric drivetrains, enlarge their influence. These suppliers capture a larger part of the value chain at the expense of OEMs.

Fuel cell production has been kept in-house by OEMs, however, since they considered it to be a strategic investment. Rolling out a fast-charging infrastructure by utilities would have rendered this investment largely worthless – hence the close cooperation between OEMs and the oil industry to push the fuel cell.

Regime response

As this episode progresses, regime actors gradually lose faith in the regime technology. Its role is marginalized, and the technology is abandoned altogether in the end. Once it is clear which niche technology is the winner – fast charging or hydrogen – R&D investments are channelled from the ICE into that technology. Nonetheless, abandoning the ICE has proceeded in a controlled manner, and all involved have optimally retrieved their investments in it.

Infrastructural developments

Two major infrastructural developments occur during this episode. First, electricity production and distribution is upgraded to accommodate the growing numbers of PHEVs. How much upgrading is required depends on consumer behaviour. In the most optimal situation, consumers only recharge their vehicles at night, when the demand for electricity is traditionally far below capacity. In that case, a large number of vehicles can be sustained by existing infrastructure. If a significant number of consumer decides to recharge during peak hours, capacity has to be expanded dramatically. In either situation, the system will be operating at near-capacity rates for longer periods than is currently the case. It is unclear how this will affect the reliability of electricity supply (Kintner, Meyer, Schneider, and Pratt, 2007).

Second, investments in a hydrogen infrastructure will be undertaken. The nature of this rollout has currently not yet been simulated by the THRIVE allocation model. In terms of the model, it requires the refuelling stations on which hydrogen is allowed to be rather exclusively restricted to stations along highways and other high-traffic roads. This brings the costs for deployment down significantly. In part, this is because its size is smaller, but also because the stations that are put in place can be made bigger, exploiting economies of scale. On the other hand, the sales of hydrogen are limited, as it is only used as a fuel to extend the range of a vehicle that is expected to use electricity from the distribution grid for the bulk of the trips.

Timeframe

The time covered in this episode allows PHEVs to reach their full market penetration. However, it takes to the end of the episode for the fuel cell to be implemented and the deployment of the hydrogen infrastructure to start.

Institutional rules

During this episode, there are some fundamental changes in the rule that consumers expect incremental improvements of new product offerings (C3). The most fundamental change is that consumers accept a vehicle that has a limited electric range, which requires a behavioural change to recharging the vehicle overnight. It is this change that allows a breakthrough of the PHEV as standard for most vehicles. Furthermore, this change paves the way for the emergence of a market segmentation based on EV range. Consequently, meeting the demand for making longer trips is not met by enlarging the battery – which would go against the now established market segmentation – but by fitting a fuel cell.

This change occurs gradually and is the process of the reconfiguration dynamic that has set in. Such gradual change is possible because OEMs provide enough variety, hence comply with rules C1 and C2. The main driver is rising fuel prices, that move the importance of reducing (fossil) fuel consumption up the priority list (C4).

This change has its repercussions on the upgrading process that OEMs like to engage in (O1). Fitting cars with a battery that provides a range beyond a range that is strictly necessary seems a logical way to upgrade a model in this new context. However, the strict market segmentation that consumers settle with prevents this. Basically, the OEM-consumer balance shifts towards consumers and OEMs miss an important instrument for the upgrading process. The importance of rule O1 diminishes.

The other OEM rules remain largely intact. It is indeed changing consumer preferences that lead OEMs to change their search routines, in this case to provide a solution to do away with conventional fuel use altogether (O2). The restructuring of industry continues as suppliers that are involved in hydrogen technologies assume more importance (O3).

10.2.3 Final episode [30-50 years after introduction]

The changes that have been set in motion at the end of the previous episode are completed in this episode. The hydrogen production and distribution infrastructure expands and becomes denser as vehicles fitted with a fuel cell capture a larger fraction of sales. As the network nears completion, the old infrastructure is dismantled, urging any laggards to adopt as well.

Type of vehicles

The fuel cell spreads to all vehicle segments for which travelling beyond the all-electric range is required. Some niches remain for vehicles that have no need to travel beyond ‘battery distance’.The market segmentation based on all-electric range is a permanent feature of the new regime.

Adopter profile

Any remaining laggards adopt during this episode. Note that there is a group of consumers that saves costs by purchasing EVs that satisfy their daily travel need. Any travel beyond this vehicle range they do by reverting to other means of transportation.

Key actors

There are changes with respect to the situation prior to the transition. Utilities are now one of the most influential players in the regime, because electricity from the grid powers cars for the larger part of the distance they cover. This brings benefits, but also shifts much of the burden of reducing emissions in the personal mobility sector to them. In turn, the oil industry has become less influential. It has been able to maintain a foothold, but the hydrogen it now supplies only accounts for the smaller part of energy supply. Finally, first-tier suppliers have captured a larger part of the value that is created in the automotive value chain. Some were previously external to the regime, especially those specializing in electric drive components and hydrogen technology. Their increased importance comes at the expense of the OEMs.

Infrastructural developments

The hydrogen infrastructure is completed. Competition between hydrogen providers results in a more dense refuelling station network than would be strictly necessary from a consumer point of view.

Timeframe

The calculations of appendix C provide a rough indication that full diffusion of the fuel cell is feasible within the timeframe of the episode. The transition is fully complete in this fifty-year time period.

Institutional rules

This scenario sees a permanent change of regime rules. Consumers have shown that they are willing to change their behaviour and do away with incremental improvements to cope with landscape pressure. Rule C3 has permanently changed. As a consequence, the power balance in the relationship between consumers and OEMs has shifted towards the consumers. This implies that the OEMs are now seriously limited in their ability to raise profits through ‘upgrading’ in their new product development process – rule O1 has permanently changed as well.

As a summary, figure 10.2 provides a graphical illustration of the Gradual Breakthrough scenario.

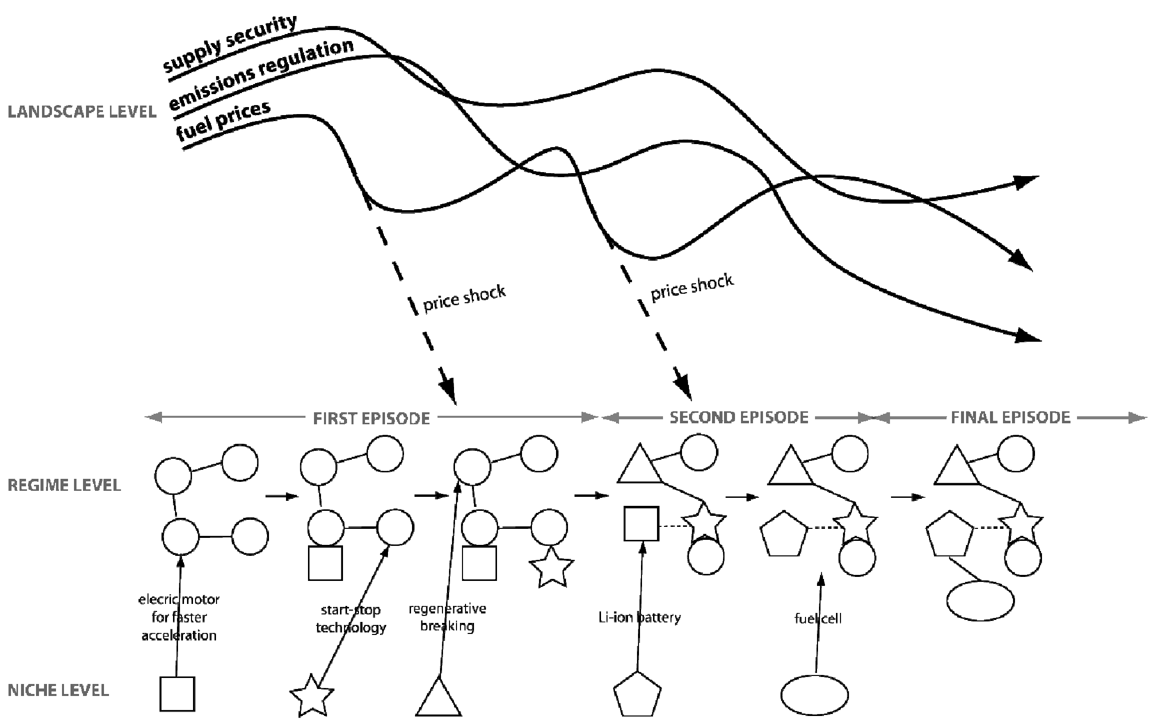

Figure 10.2 Graphical illustration of the Gradual Breakthrough scenario.

11 Reflection and conclusions

This section reflects on the scenarios and the process by which they came about. Two sets of conclusions are thus presented, that each end with a set of recommendations.

11.1 Conclusions on the socio-technical scenarios

11.1.1 Regime tensions

Three regime tensions have been identified in chapter 6. In the Gradual Breakthrough scenario, the emphasis is on the first tension (larger, more comfortable cars versus reducing fuel consumption), whereas the second tension (larger, more comfortable cars versus curbing emissions) is emphasized in the Large-Scale Experimentation scenario. The two tensions align, implying that both tensions are eventually solved in both of the scenarios with a single (technological) solution, despite the difference in emphasis.

The third tension (product-line extensions versus radical innovation) is handled differently in the scenarios. In the Large-Scale Experimentation scenario, increasing landscape pressure forces the regime actors to focus on long-term, radical innovation. Notably, tightening regulation works to break the short-term, incremental innovation focus. In the Gradual Breakthrough scenario, the focus remains on the short term during much of the transition. Here, the balancing act between short-term improvements and long-term research is solved by the increasing importance of suppliers. They are able to concentrate research on a limited set of technologies in a demarcated area and need to make less choices on what to pursue.

11.1.2 Agency and institutional rules

Geels and Schot (2007) define two change processes for institutional rules: evolutionary-economic and social-institutional. It is instructive to see how these two processes are at work in the two scenarios. In general, the Gradual Breakthrough scenario most prominently features evolutionary-economic processes. The product variations that are possible by incorporating various modules into the existing configurations are subject to a market selection process, especially because the most influential contextual factor is formed by rising fuel prices. These processes eventually trigger the change that consumers no longer accept upgrades of new models. On the other hand, the experimentation that is the core of the Large-Scale Experimentation scenario leads to social-instructional change. It is the shared vision that the participants in the projects build that determines how their success is evaluated and with what technology to go forward. It (temporarily) changes the rule that variety is a necessary condition for new offerings.

In reality, things are not this clear. In the Gradual Breakthrough scenario, there is also competition between alternatives, and the shared interpretation of technology is a determinant for which technology will eventually win. Note that it is consumer preference for electric drive that pushes the storyline beyond the PHEV as an end state. On the other hand, a technology is unlikely to win in the Large-Scale Experimentation scenario if its business case is far behind the alternatives.

For both scenarios, an important function of institutional rules is to form the boundary conditions within which transitions take place. In that sense, the two scenarios represent transitions that choose the line of least resistance. As mentioned in chapter 2, it is assumed that the odds are better for transitions that respect institutional rules as much as possible. Nonetheless, there are some permanent rule changes, especially in the Gradual Breakthrough scenario. The role of agency is to shape the dynamics of each scenario within the bounds of the ‘steady’ institutional rules.

11.1.3 Scenarios versus ideal-type pathways

The transition pathways as defined by Geels and Schot (2007), that are the basis for the scenarios, are ideal types. This section examines some similarities and differences between these ideal types and the scenarios.

The Large-Scale Experimentation scenario indeed shares similarities with the transformation pathway. Landscape pressure is addressed by adopting hydrogen as a fuel. Hydrogen technology represents a symbiotic niche-innovation, following the transformation pathway dynamic. This adoption is accompanied by adjustment of regime rules, notably during the second episode of the scenario. In that episode, consumers are satisfied with less variety and settle for less performance improvements as OEMs stop investment in the ICE. Regime actors survive, implying that hydrogen technology represents a way to preserve the current regime configuration.

As in the ideal type, there are institutional power struggles. This is most obvious in the competition between the oil industry on the one hand and utilities on the other, the former promoting HVs and the latter EVs. Yet, the struggle has more aspects than just a clash of actors. It is also about the extent consumers are willing to change institutionalized habits. For instance, are consumers willing to change their behaviour, settle for a limited range and charge their EVs overnight? In this scenario, they do not, and institutional rules do not change in this respect – but there is also a scenario in which they do (see the next section).

Finally, there is a difference as well. In the ideal-type pathway, criticism is voiced by outsiders. In the Large-Scale Experimentation scenario, the criticism comes from governments. Strictly speaking, governments are internal to the regime, although their relationship with the regime was not included in the analysis part. On the other hand, it is reasonable to state that local governments are not part of the regime, while they do play an important part in voicing criticism in the Large-Scale Experimentation scenario.

The Gradual Breakthrough scenario also starts out along the transformation pathway. Regime pressure is addressed by using symbiotic niche-innovations, which come in modular form and focus on reducing fuel consumption while retaining ICE technology. Rules start shifting under these changes, as consumers demand additional range while they are not willing to invest in more battery capacity – effectively segmenting the market by range. Institutional power struggles are between component suppliers during this episode, as first-tier suppliers strive to enlarge their influence. Suppliers external to the regime, such as battery manufacturers, get involved.

The subsequent additions and substitutions of components trigger behavioural changes. This is the point where elements of the reconfiguration pathway enter. Consumer interpretations change and they adopt new practices. They are happy to recharge their vehicles overnight. Moreover, they settle for vehicles with a limited range from batteries, which leads to changes in institutional rules. That modular technological changes influence consumer behaviour is a characteristic of the reconfiguration pathway.

Yet, there is an essential difference. The reconfiguration pathway stipulates that the subsequent adoptions of symbiotic niche-innovations lead to architectural innovation, but the adoptions in the Gradual Breakthrough scenario bear more resemblance of modular innovation (Henderson and Clark, 1990). This does not mean that architectural innovation is unthinkable in this scenario. An innovation such as the hub motor, an electric motor integrated in a wheel, greatly reduces the space required for the propulsion system. This offers the opportunity to enhance passenger interior space, potentially opening up the car to functions such as working. Alternatively, a module can be fitted to control two-way electricity flows: from and to the distribution grid. This essentially turns a vehicle into an extension of the grid (Tomić and Kempton, 2007). It can function as energy storage and backup device, again expanding the functionality of the car.

Although possible, such radical changes are not necessary to achieve the scenario objectives (see section 2.2). Recall that these are formulated to support for the THRIVE project, that studies the transition to hydrogen. As architectural innovation is not required to achieve this goal, it is not included in the scenario.

11.1.4 Timing and alternative paths

A key difference between the two scenarios is timing. As is apparent from the scenario descriptions in the previous chapters, it is not clear-cut *that* hydrogen enters as the technology that emerges during the transition, although it can be clearly articulated *how* the transition would take place. A these points in the scenarios, there are alternative routes. An overview of all possible scenarios is diagrammed in figure 11.1.

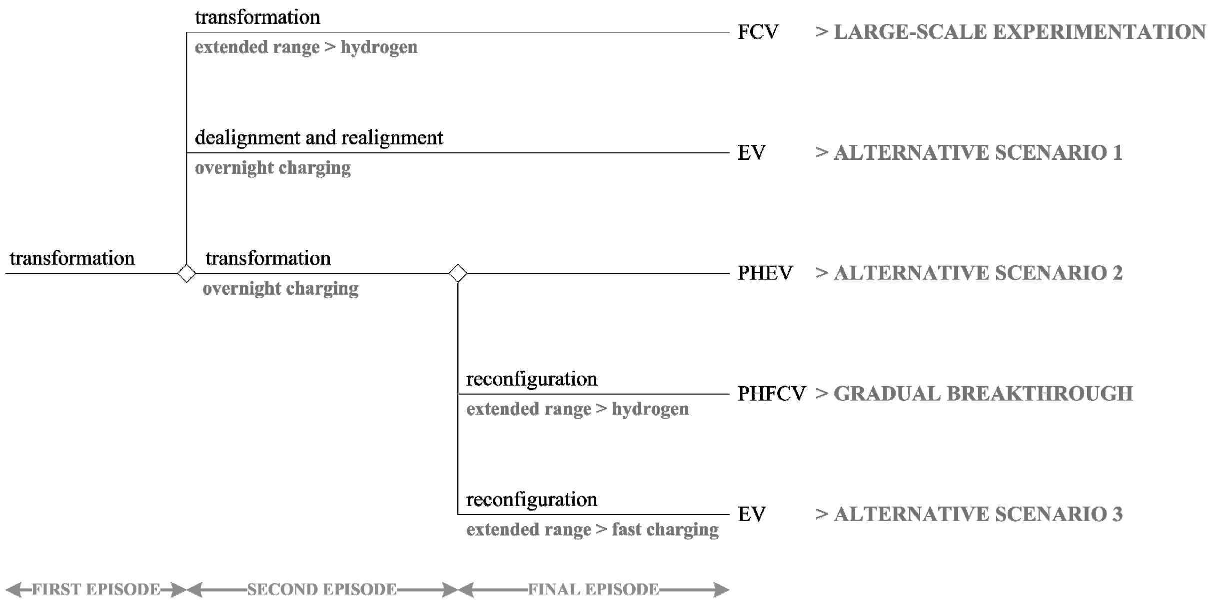

Figure 11.1 All possible scenarios, including those without hydrogen as end state.

Figure 11.1 illustrates the sequence of pathways that Geels and Schot (2007) find likely to happen under 'disruptive change'. Disruptive change occurs at slow speed, so that actors only slowly change their behaviour. As pressure builds, however, they are forced to react more dramatically.

The dynamics of the first response resemble that of the transformation pathway. The regime changes the direction of its activities to address the pressure. This is the basis of all the scenarios of figure 11.1. In the Large-Scale Experimentation scenario, the change of direction comes from the application of fuel cells. This solution emerges from an institutional power struggle. It solves tensions, which implies that regime actors survive and institutional rules return to their state prior to the transition.

Alternatively, EVs can emerge from the power struggle. This is the case in alternative scenario 1, the dynamics of which change into that of the de-alignment and re-alignment pathway. The regime players lose faith in the regime technology, but no alternative has sufficiently developed to take over. This could happen if OEMs fail to meet emissions regulation. National governments feel that OEMs have not expended enough effort to meet regulation. Local governments prefer to engage in experimentation with outsiders, that they feel offer better perspectives to meet their (emissions) goals. Regime actors are largely excluded from demonstration projects. Key actors are external producers of EVs (e.g. Th!nk of Norway and Tesla Motors) as well as utilities. Consumers experience the drawbacks of owning a CV as local and national governments discourage their use. At the same time, they experience the benefits of using the new vehicles.

EVs as a niche innovation have not yet fully developed, in the sense that they cannot match CVs on various vehicle attributes (notably range). However, consumers abandon the notion that matching such performance is necessary. Hence, some institutional rules change permanently. First, they do away with the expectation that new product offerings must be better than previous ones. The main change is that they are willing to settle for a shorter range. Rule C3 changes, undermining the upgrading process that OEMs was part of the OEM-consumer interaction. It also means that consumers are happy to do away with the need for variety (C2). Most notably, the upgrading process is no longer part of the rules (O1). New product development is no longer aimed at improving the products towards particular 'traditional' performance measures, such as acceleration and top speed (O2). Finally, a new industry implies a new structure, making O3 obsolete. In the end state of this scenario, consumer perception of cars has changed radically. Its function has changed to local transportation, car use motivation is mainly instrumental, and it is commonsense to resort to other forms of transportation for long-distance travel.

In the other three scenarios, the transformation pathway continues for a longer period of time. Alternative scenario 2 presumes that consumers are only willing to change their behaviour to a limited extent. Regime players offer PHEVs to deal with landscape pressure. Consumers accept PHEVs as a solution and are stimulated to change their behaviour to overnight charging. No major institutional rule changes are necessary – although PHEV performance might lag that of CVs slightly, a minor violation of C3. Landscape pressure remains at a moderate level, so that the PHEV is the end state of this scenario.

In the remaining two scenarios, consumers no longer accept the upgrading process that has been at work up to this point. Rather than accepting continuous incremental improvements (as in rule C3), they expect cars that provide them an extended electric range, while they are not willing to pay for larger battery capacity that they do not use. This stance deprives OEMs of an important instrument in the upgrading process. Two alternative, modular solutions emerge. One is to fit cars with fuel cells and rolling out the accompanying infrastructure. This represents the Gradual Breakthrough scenario. The other alternative is to roll out a fast-charging infrastructure, leading to alternative scenario 3. The latter case implies that the role of the oil industry is marginalized – utilities have become the main energy provider for the transport sector.

11.1.5 Practical implications and recommendations

Both of the scenarios mark a break with business-as-usual, the dynamic stability that has characterized the regime for most of the past century. If the changes described in the scenarios materialize, there is a number of practical implications for the actors involved. First, infrastructure investments. These are significantly smaller in the Gradual Breakthrough scenario, at least in the case of hydrogen. This implies that the chicken-and-egg problem, one of the major barriers for the introduction of hydrogen, is significantly reduced as well.

Second, and related, is the market size for hydrogen. If a plug-in hybrid FCV is the end-state, as in the Gradual Breakthrough scenario, hydrogen is only sold on a minor number of trips. It is very well possible that the market for hydrogen in that scenario is significantly smaller than the current market for petroleum and diesel. On the other hand, major opportunities will open up in the electricity sector.

Finally, in both scenarios at some point a competition between electricity and hydrogen arises[70]. There are three important determinants for which alternative emerges as a winner from this competition. First are consumer preferences. It is imperative for all involved to closely monitor how consumer preferences evolve, both in the marketplace and in experiments with alternatives. Second, technological progress. If proponents of an alternative fail to invest in development sufficiently, the other alternative may win the technology race. Third, and perhaps most important to monitor, is coalition strength. Both alternatives will be supported by a coalition of like-minded, that for some reason prefers either EVs or HVs. It is reasonable to assume that utilities are part of the supporters of EVs, whereas the oil industry favours HVs. Judging by the way they spread their resources, OEMs are distributed over the two camps, but what the distribution exactly looks like (and how it evolves) is unclear. The same holds for government actors.

The main contribution of the scenarios is offering a way to interpret current and future events. The recent developments in the US industry are a case in point. Recall from section 3.3 that these events may have a profound effect of the role governments play. Traditionally, governments have refrained from expressing preferences for particular technologies. In the current US situation, the government is perhaps in a more influential position than it has ever been. Furthermore, it is no secret that it aims to do away with the use of fossil fuels in cars as soon as possible. The option that is nearest to commercialization is the PHEV. Specifically, General Motors is developing the Chevrolet Volt, and the US government has strict control

[70] Note that this is the main dynamic of the Large-Scale Experimentation scenario, but that it is also present in the Gradual Breakthrough scenario. In both scenarios, it drives the choice between electricity or hydrogen.

over General Motors' intentions through the conditions that it ties to state aid. It is plausible that General Motors will push the Chevrolet Volt onto the market as soon as possible under government pressure.

This introduction strategy – one model, separate from current model range – would fit the top two scenarios of figure 11.1. Yet, which scenario will materialize is highly dependent on the success of the Volt. If the Volt meets with limited success, competitors are not likely to follow General Motors' lead. Variety in the PHEV market is low and the top two scenarios of figure 11.1 are likely to materialize. Experimentation remains necessary because landscape pressures are not alleviated yet.

If the Volt is a success and competitors respond, variety increases. The other three scenarios, featuring market dynamics, are likely to materialize. The need for experimentation with alternatives is virtually gone, because landscape pressures are met by PHEVs for the time being.

11.1.5.1 Recommendations for the oil industry

Since this study has been carried out at Shell, this section provides some recommendations for the oil industry based on the pathways laid down in figure 11.1. First of all, the alternative scenarios 1 and 3, that have the EV as end state, are decidedly unattractive outcomes. The role of the oil industry as a fuel provider has been marginalized in these scenarios. Alternative scenario 2 is more attractive, but it is questionable how likely it is given the increasing pressure to reduce CO_2-emissions significantly. Moreover, the bulk of travel in this scenario is powered by electricity.

The end situation of the Large-Scale Experimentation scenario is most attractive. This scenario, resulting from the transformation pathway, comes closest to preserving the status quo. In the Gradual Breakthrough scenario, sales of hydrogen are restricted to a minor fraction of trips, meaning that the position of the oil industry has eroded at the expense of the electricity sector.

There is a tension, however. In the Gradual Breakthrough scenario, hydrogen is an even more long-term option than in the Large-Scale Experimentation scenario. That implies that investments in current oil production infrastructure yield returns for a longer time. If future signs show up that the Gradual Breakthrough scenario is materializing, players in the oil industry might do well to consider moving into electricity production to capture a piece of the growing pie in that sector. These investments should not be carried out prematurely – they will prove costly if the Gradual Breakthrough scenario emerges in the end.

In any case, figure 11.1 can guide decision-making. The most appropriate strategy seems to monitor activities to determine which of the pathways are most prominent. For instance, the success of the PHEV is an important issue. If this is well received by consumers and governments, alternative scenario 1 and the Large-Scale Experimentation scenario become quite unlikely. In that case, it might pay to start investing in the electricity sector and build coalitions to eventually introduce the fuel cell as range extender, thus pushing the plug-in FCV.

If the PHEV fails or EV experiments become increasingly successful, the need to push the FCV becomes more imminent. In that case, a viable strategy is to team with OEMs to quickly scale up hydrogen demonstration projects and offer significant incentives to consumers to switch to FCVs. This way, developments might be steered towards the Large-Scale Experimentation scenario and alternative scenario 1 prevented. Of course, this is a strategy that may be pursued anyway, but it may be a quite costly way of introducing hydrogen, since enough incentives must be provided to 'push' the FCV onto the market.

11.1.5.2 Recommendations for THRIVE

The THRIVE model can be used to quantitatively support the findings of this thesis. Although its specification is already quite fit for such an analysis, there is room for some refinements, depending on which scenario is under consideration. The HV introduction parameter is currently based on a 5-year vehicle introduction cycle. Upon consultation, two major OEMs have confirmed that this strategy represents a realistic assumption, at least for the time period in which the rollout of hydrogen is well underway. In that period, a 5-year cycle represents standard industry practice. The initial period is more uncertain, however. It is recommended that this period, for which the Large-Scale Experimentation

scenario predicts a low number of HVs on the market, is modelled differently. The early adopters during this period are likely to be those consumers that have a high intention to switch to HVs, as predicted by e.g. the TPB. Research by Shell has shown that market segmentation on this basis is possible. This different approach, based on early adopters rather than market shares in the current, steady-state situation is more appropriate for this period. This approach is not necessarily easier or simpler, but the analysis of this study shows that it might be more realistic. It does require additional empirical research. Note that these adaptations are not necessary for modelling the Gradual Breakthrough scenario, because this scenario assumes plenty availability of hydrogen models, which is reflected in current assumptions of HV uptake.
For modelling the Gradual Breakthrough scenario, other issues need to be taken into account. The model includes parameters that reflect the willingness of consumers to switch as a function of the local and global availability of hydrogen. The shape of these parameters is based on current refuelling behaviour[71]. This is not a realistic reflection of the dynamics of the Gradual Breakthrough scenario. It is reasonable to assume that the role of local availability is minor in this scenario. Consumers have changed their behaviour to recharging their vehicles at home most of the time. Their primary concern is to be able to refuel for longer trips, i.e. global availability.

With or without these refinements, THRIVE modelling work presents a nice quantitative illustration of the work in this thesis. Specifically, it can show how a hydrogen infrastructure would spread throughout the country, providing insight in how fast the rollout takes place, whether the whole country would be covered, and how many refuelling stations are required. Coupling these results with cost data provides insight into economic feasibility. This opens up the possibility to refine the socio-technical scenarios. Many assumptions in the scenarios could not be supported quantitatively, which could mean that, e.g., a scenario is not financially viable. It has been acknowledged that sales of hydrogen are less in the Gradual Breakthrough scenario – the THRIVE model can provide insight into how much less exactly.

Additional, quantitative research – for which the THRIVE model is perhaps suited, but in a less straightforward way – can be used to further evaluate this study's results. In section 11.1.4 it was argued that timing has a substantial influence on how scenarios play out. At two points in time, a competition between an electric and hydrogen infrastructure is assumed. It would be interesting to quantify some elements of this competition. For instance, it has been argued that the reason that only one alternative can become dominant in the end is because of returns to scale. Quantification of these scale effects can provide insight whether one of these technologies benefits more, or whether there are temporal differences. Furthermore, it is interesting to quantify the cost details of a rollout of both infrastructures. For instance, differences in the ratios of capital to operating expenditures of both infrastructures might lead to different rollout dynamics. It also provides insight into how prolonged a competition might be. Further research of this type can refine the scenarios, providing more detail and identifying (im)possibilities.

11.2 Conclusions on the STSc methodology

This section readdresses some critique on the MLP that was voiced in section 2.3.4. It also reflects on the methodological framework as defined in section 2.3.5.

11.2.1 Case study methodology/Researcher discretion

By relying on historical facts and accepted academic studies this research has attempted to keep the analysis part as formal as possible. This approach has worked in a satisfactory manner, but has drawbacks. Although many of the interesting links in the socio-technical regime have been part of other

[71] At the time of writing, this was actually not entirely the case yet. It is planned that the parameters will be based on a survey on refuelling behaviour among approximately 3000 Dutch drivers.

studies, there are some gaps. For instance, no market research study has been found that focuses on AFVs and is based on an accepted theory such as the TPB. The constructs that the TPB describes are nonetheless considered relevant to identify early adopters of HVs, especially in the Large-Scale Experimentation scenario. Ideally, these gaps need to be filled. Unfortunately, this leads to the standard call for more research. The added value of the MLP in this sense is that it provides a means to identify and prioritize useful additional research.

11.2.2 Agency and institutional rules

The application of the MLP in this study has identified actor analysis as a requirement for the formulation of institutional rules. As actors carry and (re)produce the rules, an actor analysis is a first requirement for formulating institutional rules.

Formulating rules has proved problematic. Some rules (such as the one stipulating that OEMs respond to external pressure to change their product development search routines, O2) are formulated in such a general way that they are very unlikely to change during a transition. Nonetheless, it is exactly rule changes that are characteristic of transitions. Formulating institutional rules is therefore delicate business, and, it must be admitted, very much up to researcher discretion.

The researcher is not completely lost, however. Reflecting on the process by which the scenarios came about, a guideline can be established here. Some institutional rules relate to how the regime responds to pressures induced by developments on other (landscape, niche) levels. Again, rule O2 is an excellent example: it states that the regime will only change under pressure from the government or consumers. Such a rule is unlikely to change during a transition, because it exactly describes how the regime changes under the conditions that stipulate change in the MLP framework[72].

On the other hand, there are rules that describe internal regime dynamics. Rule C3 is a good example: consumers expect new product offerings to improve (incrementally) over old ones, except if they are above a threshold value. This rule changes as landscape pressures lead to a reconfiguration of the car. Such 'internal' regime rules are more subject to change during transitions than 'linking' rules.[73]

'Linking' institutional rules are useful to restrict the use of a 'deus ex machina' to induce a turn in a scenario. It is tempting to introduce an arbitrary external influence to bring about such change. It is the virtue of the STSc methodology that such unexpected turns are kept to a minimum.

This is not to say that such a sudden turn is unrealistic. To provide an example: it has been found that the attitude of the general public towards hydrogen is positive, but unstable, implying that it is easily influenced by both positive and negative information on hydrogen (Molin, 2005). A dramatic event, such as an accident at a hydrogen refuelling station in a demonstration project, holds the potential to alter trajectories. Negative publicity can potentially kill the future of hydrogen as an automotive fuel, or at least significantly postpone it.

11.2.3 Unit of analysis

The choice of empirical level of analysis is at the basis of defining the scope of a transition. Geels and Schot (2007) propose organizational fields as a level of analysis. This level has proven useful for the analysis in this thesis. Furthermore, multiple organizational fields (e.g. car industry, oil industry) are involved *and* user practices, policies etc. change, so that a system change as Geels and Schot define it is in order.

This unit of analysis provides the basis for the actor analysis, which at the same time reveals a problem. Technically, suppliers are part of the organizational field of the car industry. However, in the Gradual

[72] Note that the level of generality at which institutional rules are formulated here is important. A rule might also be formulated that OEMs change their routines about emissions under government pressure. Such a rule is much more easily changed in a transition, e.g. because it is assumed that consumers start to care more about their (future) vehicle's emissions.

[73] The level of generality at which the rule is formulated is still important. Making the 'threshold value' for attributes in this rule explicit would decrease generality, and render a rule change (even) more likely.

Breakthrough scenario, there are shifts *inside* this organizational field, that give rise to broader changes in the regime. A closer look to this dynamic and the unit of organizational fields is in order.

The actor analysis provides a means to tell regime and landscape developments apart. As landscape developments are defined to be beyond actors' influence, there is a hard criterion to tell landscape from regime developments. Niche developments are harder to distinguish. They cannot be ascribed to actors outside the regime, as niche-innovations can also be developed by regime insiders. Here, an ad-hoc definition was adopted: technologies not currently available for the majority of consumers. This has served well in this study, but does not necessarily generalize to any setting.

11.2.4 Consistency

The test for the design part of the STSc methodology is consistency. As indicated in section 2.3.5, only internal consistency can be tested for. It is ensured by linking regime and landscape developments into transition seeds. This works well to formulate the building blocks of the scenarios. The implicit assumption is that the transition seeds open 'windows of opportunity' that allow niche-innovations to permeate the regime.

This procedure only partially ensures consistency. The method remains rather vague on the way *how* niche-innovations diffuse into the regime. Of course, the transition pathways form the basis for the dynamics of the transitions. What the method lacks is a way to devise scenario architectures and marry them to the transition pathways. Elzen and Hofman (2007) propose to use the pathways as blueprints for the scenarios. Although the pathways provide a valuable framework for the scenario architectures, it is important to recognize recent and ongoing developments in niches. That is how the scenario architectures have been designed here. The dynamics of the developments in niches are matched with the transition pathways. The transition seeds have then been used to create the circumstances that allow the niche-innovations to interact with the regime in ways stipulated by the pathways. Note that this method can lead to a combination of pathways in the scenarios, as is particularly illustrated by figure 11.1.

11.2.5 Scientific contribution of the MLP

Genus and Coles (2008) pose the question what the role of the MLP is – a heuristic device for organizing sets of data or a robust method to study transitions. That the MLP can attain the former status is beyond doubt. That the latter application is extremely ambitious shall be equally clear – it requires an absolutely objective stance on the part of the researcher, which is virtually impossible. Nonetheless, this study has tried to contribute to improving the role of the MLP as a formal research method by using sources that are as objective as possible. Turning the MLP itself into a research method to directly study transitions (as Genus and Nor (2007) attempt) seems a mission impossible. Nonetheless, it has proved very well possible to move it to a robust method as much as possible.

11.2.6 Recommendations for future applications of the STSc methodology

A number of recommendations follow from the experience gained in the application of the STSc methodology in this thesis. First, this research has shown that studies and methods from a variety of academic disciplines can be used to operationalize the MLP framework. To move this approach beyond the ad-hoc application in this study, it would be useful to develop an inventory of research methods that can be used to study the interrelationships between the various levels of the MLP and the relationships between the various elements of a socio-technical regime. Such an inventory simplifies the search for information on particular linkages, and can provide guidelines to study linkages that have not been studied before in a particular setting.

Second, it seems useful to distinguish between 'linking' and 'regime-internal' institutional rules. The former category provide guidelines on how a transition can take place. The latter category is likely to change during transitions. Further applications of the STSc are required to determine how clear-cut this distinction is and whether unique properties can be assigned to each class of rules. If the existence of two types of rules can be confirmed, they provide guidance on how scenario architectures can be designed.

This step of the methodology (number 5) requires further formalization anyhow. The approach that Elzen and Hofman (2007) describe is too limited. The transition seeds that provide the linkages between the landscape and regime level only provide 'windows of opportunity' for niches to break through. They are no guide on how to design the dynamics of the scenario. Moreover, there is also a need to link regime and niche developments. The work in this thesis suggests that these linkages can be matched with one or multiple transition pathways to define scenario architectures, given the windows of opportunity that are created by transition seeds. Formalization of this procedure – including the distinction between 'linking' and 'regime-internal' rules – can help the STSc methodology forward.
Furthermore, niche technologies require a proper definition. The actor analysis has proved insufficient to distinguish between niche and regime technology. A definition need not be complicated. Here, a definition of niche technology as 'not available to the majority of consumers' worked perfectly fine. Future applications of the methodology should show whether this definition is works in other settings as well.
The last point is not a novel recommendation and serves to point out a limitation of this thesis. The nature of writing a master's thesis is by definition individual. Although many conversations with experts in the field, including all regime actors, have taken place, the *neue Kombinationen* in this study are in the end all products of the author's mind – although it is very likely that they can all be found somewhere in the library of works that has been written on this topic. An indispensable element of any application of the STSc methodology is to collect visions and expectations of parties involved. Formalizing the exposure to experts in the field by means of (for instance) a workshop improves scenario architectures and consistency.

The STSc methodology, as well as the MLP that is an essential part of it, is work-in-progress. Nonetheless, the stage it is currently in makes it a powerful tool to analyze recent and ongoing developments and construct consistent and interesting images about the future. In many discussions with experts in the field it has already proved its ability to stretch mental maps and elicit intelligent discussion.

Epilogue

The preface opened with the question what ‘strategic niche management’, or more precisely the Multi-Level Perspective, brings at the end of the day. I think I am now equipped to offer an answer. What is in this thesis is to a large extent not new. The contribution, then, is a new perspective, a way to interpret the data. That is the use of the MLP.

At the end of the day, the future is still unknown, and only time will tell how consistent with the future the scenarios truly are. Yet, irrespective of whether scenario becomes reality, what happens in the present can now be translated into what might be in the future. As has been illustrated, the recent events in the US car industry are a case in point. And perhaps another student will write a different set of scenarios a few years from now, based on the course of events in the coming years.

For me, the result is that my ‘mental map’ has been stretched beyond the factual knowledge that I acquired during the research. Specifically, I learned there is more to a phenomenon than all involved can separately tell you. And although more abstract, this insight is presumably the most important result.

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A Analysis of stated preference studies

In chapter 4 seven SP studies are aggregated to determine consumer preferences for AFVs. Table A.1 prevents an overview of the studies involved. Note that it involves six publications, that are counted as seven studies: the paper by Mau et al. actually concerns two studies, one on HEVs and one on FCVs. That all studies have a different specification is illustrated by the last column in the table, which shows that the number of attributes considered in the studies ranges from four to ten.

First author	Year	Vehicles	Location	Number of respondents	Number of attributes	Attributes used
Ewing	1998	AFV, EV	Montreal	1500	10	8
Brownstone	2000	CNG, methanol, EV	California	874	10	8
Molin	2007	FCV	Netherlands	75	7	6
Potoglou	2007	HEV, AFV	Canada	482	6	6
Ahn	2008	CNG, LPG, HEV	South Korea	280	7	3
Mau	2008	HEV	Canada	916	4	3
		FCV	Canada	1019	4	3

Table A.1 Overview of the studies that are aggregated. Note that not all attributes considered for each study are used. Primary reason is that these often concern ASCs, which express an autonomous preference for a particular alternative fuel. These cannot be compared across studies.

Each study uses a form of logistic regression for data analysis. This analysis results in a set of coefficients that are a measure for how strongly the various attributes affect the odds of purchasing an AFV. Direct comparison of these coefficients within studies requires standardization by dividing them by the standard deviation of respondent answers on a particular attribute. Unfortunately, these data were not available for most studies. Standardization was therefore done using the interquartile range (IQR), which was available or could be estimated for all studies. Multiplying the coefficients with the IQR yielded a coefficient that could be used to rank the importance of attributes within each study:

$$C_{i,j} = IQR_{i,j} * B_{i,j}$$

where

$C_{i,j}$: comparison coefficient for attribute i in study j (A.1)

$IQR_{i,j}$: interquartile range for attribute i in study j

$B_{i,j}$: coefficient for attribute i in study j

This ranking is the basis for a rough comparison of attributes across studies. A comparison across studies requires that differences between studies are taken into account as much as possible. Therefore, rankings are normalized by dividing by the number of attributes considered in a particular study:

$$NR_{i,j} = \frac{R_{i,j}}{n_j}$$

where

$NR_{i,j}$: normalized ranking score of attribute i in study j (A.2)

$R_{i,j}$: rank of attribute i in study j

n_j : number of attributes in study j

Adding the normalized rankings and compensating for the number of studies that take a particular attribute into account produces aggregated ranking scores for each attribute:

$$AR_i = \frac{\sum_j NR_{i,j}}{m_i}$$

where

AR_i : aggregate ranking score for attribute i (A.3)

$NR_{i,j}$: normalized ranking score of attribute i in study j

m_i : number of studies containing attribute i

Ranking AR_j finally produces the overview of which attributes are most important in AFV adoption. These are the results published in table 4.2. Table A.2 reproduces this table, along with some additional information. Table A.3 on the next page lists the intermediate steps (equations A.2 and A.3) in the procedure. Note that the entire procedure has been followed for only six of the seven studies. The study by Molin et al. already included a ranking of attributes, so that the calculation of a comparison index was not required.

	ΣNR	m	AR	final ranking
Fuel efficiency	.25	1	.25	1
Purchase price	1.58	6	.26	2
Variety	.38	1	.38	3
Range	1.63	4	.41	4
Emission level	1.83	4	.46	5
Maintenance cost	1.42	3	.47	6
Fuel availability	1.92	4	.48	7
Fuel cost	4.00	7	.57	8
Refuelling time	.63	1	.63	9
Acceleration	3.17	4	.79	10
Top speed	.88	1	.88	11
Engine displacement	1.00	1	1.00	12

Table A.2 **Result of the aggregation procedure. Dividing the summed normalized ranking scores by the number of studies containing a particular attribute yields the aggregate ranking score. The final ranks are based on this score.**

	Ewing					Brownstone					Ahn				
	IQR	B	C	R	NR	IQR	B	C	R	NR	IQR	B	C	R	NR
Purchase price	2272.6	.0002	.499972	1	.13	22.45	.289	6.48805	1	.13					
Fuel efficiency	1	.4200	.42	2	.25										
Fuel availability						.45	.526	.2367	6	.75					
Variety						1.8	.718	1.2924	3	.38					
Range	100	.0039	.39	3	.38	2.6	.998	2.5948	2	.25					
Maintenance cost	175	.0010	.182	6	.75						10	4.6977	46.977	2	.67
Emission level	.425	.7128	.30294	4	.50	2.55	.388	.9894	4	.50					
Fuel cost	12	.0150	.18	7	.88	5.5	.131	.7205	5	.63	45.00	9.6012	432.54	1	.33
Refuelling time	147.5	.0014	.2065	5	.63										
Acceleration	.25	.0130	.00325	8	1.00	2.1	.09	.189	8	1.00					
Top speed						.5	.385	.1925	7	.88					
Engine displacement											.85	1.1835	1.005975	3	1.00
	n = 8					n = 8					n = 3				

	Mau (HEV)					Mau (FCV)					Potoglou					Molin	
	IQR	B	C	R	NR	IQR	B	C	R	NR	IQR	B	C	R	NR	R	NR
Purchase price	6357.75	.000195	1.23976125	1	.33	6357.75	.000147	.93458925	1	.33	3814.7	.9	3299.1	1	.17	4	.67
Fuel efficiency																	
Fuel availability																	
Variety						.075	.904	.0678	2	.67	32.5	.6	18.4	4	.67	3	.50
Range	120	.00791	.9492	2	.67											2	.33
Maintenance cost											262.5	6.5	1711.5	2	.33		
Emission level											32.5	.0	.9	5	.83	5	.83
Fuel cost	39	.00412	.16068	3	1.00	2.8125	.0196	.055125	3	1.00	32.5	2.9	942.6	3	.50	1	.17
Refuelling time																	
Acceleration											4.5	.1	.3	6	1.00	7	1.17
Top speed																	
Engine displacement																	
	n = 3					n = 3					n = 6					n = 6	

Table A.3 **Intermediate steps in the aggregation procedure. Multiplying the interquartile range (IQR) with the coefficients from the studies (B) yields a comparison index (C). These are ranked per study (R), and this rank is normalized (NR) using the number of attributes per study (n). Summing the normalized ranks per attribute provides the input for table A.2.**

B Description of niche technologies

B.1 Hydrogen as automotive fuel

There are two ways in which hydrogen can be used as automotive fuel. One is combustion in an ICE, directly generating kinetic energy that is transferred to the wheels. The other is feeding the hydrogen into a fuel cell where it combines with oxygen to generate electricity, which is transformed into kinetic energy driving the wheels in an electric motor.

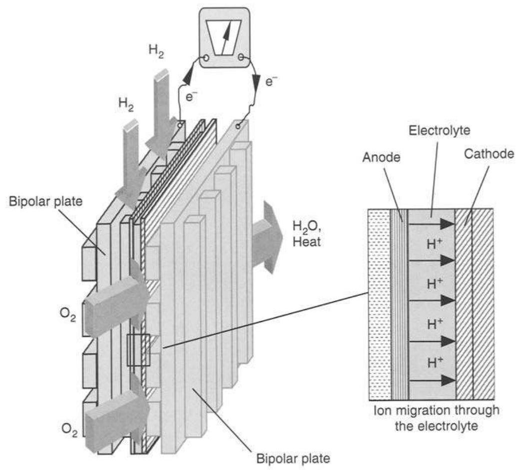

Figure B.1 Illustration of a fuel cell. Hydrogen is split into protons (H^+) and electrons at the anode. The protons migrate through the membrane, whereas the electrons are forced through an external circuit, where they can do work. At the cathode, electrons and protons recombine and form water (H_2O) with oxygen (O_2). Source: Brandon (2004).

The operation of a (polymer electrolyte membrane) fuel cell is illustrated in figure B.1. Currently, nearly all research and experimentation is directed at the use of hydrogen in fuel cells. Hence, the rest of this section will focus on the application of hydrogen in fuel cells.

Production of hydrogen can proceed via a number of routes (figure B.2)[74]. Hydrogen is an energy carrier, which implies that energy derived from primary sources is (temporarily) stored in hydrogen. The primary sources can be nuclear or solar. An array of mechanisms is available to convert the primary sources into secondary sources. These are then used to convert water (H_2O) into hydrogen using thermal, electric, or chemical conversion[75]. There are five methods available for the actual production of hydrogen. Currently, steam methane reforming, which uses methane (CH_4) to produce hydrogen from water, is the method most widely used. This is followed by production via electrolysis. This latter method has the advantage that it offers a 'carbon-neutral' path if electricity from renewable sources is used (Berry, 2004)[76].

[74] There are more routes for the production of hydrogen than illustrated in the figure (e.g. biomass gasification, biological, photobiological, photochemical). However, these are likely to have only a limited application (Berry, 2004).

[75] An exception is photoelectrolysis using photovoltaic conversion, which does not involve a secondary energy source.

[76] Steam methane reforming could be combined with carbon capture and storage to prevent that the CO_2 produced in the process ends up in the atmosphere.

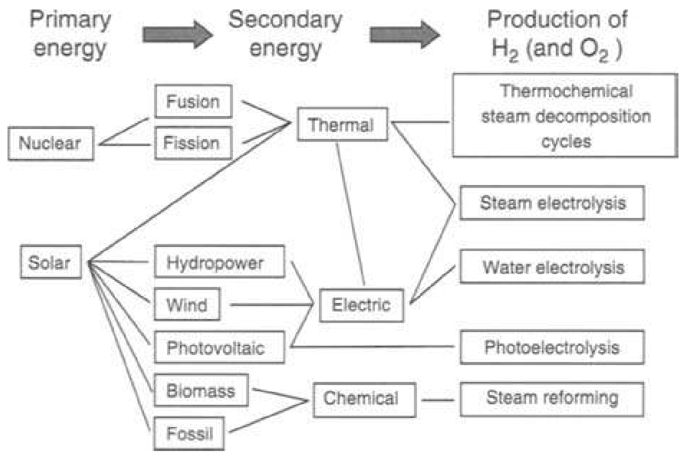

Figure B.2 Hydrogen production routes. Source: Berry (2004).

After production, hydrogen needs to be distributed and stored for use in vehicles. Figure B.3 shows the production, distribution, and storage chains that are considered viable options for the near term (Ogden, Steinbugler, and Kreutz, 1999). Centralized production will most likely be based on (gasification and) reforming of fossil fuels, although centralized electrolysis is also possible. Centralized production pathways require distribution. At ambient conditions, hydrogen is a gas with a very low density (0.0818 kg/m^3, Berry, Martinez-Frias, Espinosa-Loza, Aceves, 2004). Before storing or transporting hydrogen, it is therefore either compressed or liquefied. Then, distribution takes place via pipeline (gaseous hydrogen) or truck (mainly liquefied hydrogen, compressed hydrogen is still rather too bulky to be practically transported by trailer). This is typically also the form in which the hydrogen is stored at refuelling stations. In vehicles, hydrogen is stored either in liquefied or in compressed gaseous form, although on-board liquid storage has in recent years been abandoned in almost all prototypes.

Alternatively, hydrogen can be produced on-site. In that case, the two options available are again reforming and electrolysis. Reforming is steam methane reforming using natural gas supplied by pipeline. The high capital expenditures and energy penalty associated with liquefaction do not make that a practical option in on-site production. Storage and delivery will therefore be in compressed gaseous form.

A variety of technologies is thus available. It is important to note that the number of alternatives that is considered viable is decreasing. Perhaps counterintuitive, this signals progress, since it can be taken as a sign that the industry is moving towards a dominant design. For instance, almost all prototypes now use a proton-exchange membrane (PEM) fuel cell as opposed to a variety of other types of fuel cells that have been used before. Furthermore, there is agreement within the THRIVE consortium that one particular production, distribution and storage pathway is preferable over the other ones as regards costs and practical considerations. Such consensus allows research and development to focus on these options, thus spurring incremental innovation.

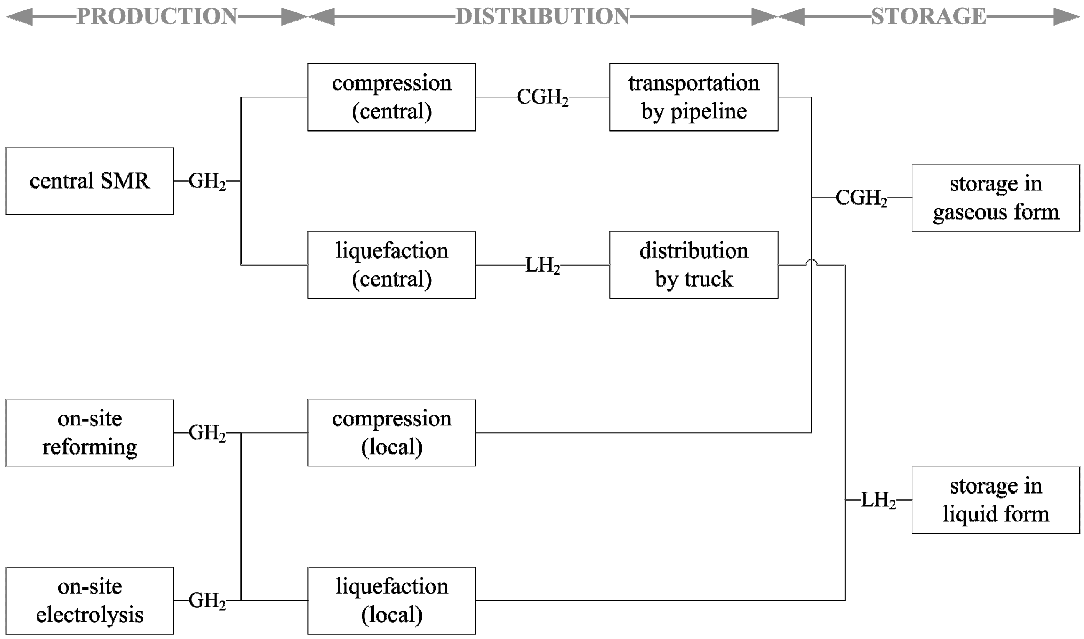

Figure B.3 **Hydrogen production, distribution, and storage pathways. Note that many more paths are possible (e.g. gaseous local storage from liquid hydrogen), but only the ones deemed most feasible are pictured here. 'GH_2' = Gaseous Hydrogen, 'CGH_2' = Compressed Gaseous Hydrogen, 'LH_2' = Liquid Hydrogen.**

B.2 Electricity as automotive fuel

Like hydrogen, electricity is a carrier rather than a source of energy. And like hydrogen, there are many pathways for the production and distribution of electricity. Note that, strictly speaking, electricity is what drives a FCV more than hydrogen – a fuel cell generates electricity that is converted into kinetic energy in an electric motor. Not surprisingly then, the latter part – the motor driving the wheels – is identical for hydrogen and electric vehicles. The difference is in production, distribution, and storage. Three different routes exist for electricity generation. Fossil-fuelled electricity generation represents the majority of electricity production. These fuels are combusted and the resulting heat is used to convert water into steam. The steam drives turbines which generate electricity. Nuclear power generation (the second route) is similar, except that nuclear fission (and possibly fusion in a remote future) are used to generate the heat required to produce the steam.

The third route is renewable sources. Here, a variety of methods is available to obtain forms of energy that are capable of driving a generator. Wind turbines capture the kinetic energy of the wind to directly drive generators, while hydropower does the same with the kinetic energy of flowing water. There are numerous other options that all essentially succeed in converting energy so that it can be used to drive generators. A noteworthy exception is photovoltaic conversion of sunlight, that uses semiconductor material to directly generate an electric current.

Irrespective of which method is used to generate electricity, it is eventually fed into the distribution grid. Appliances can be plugged into the grid to obtain power, but mobile applications (such as vehicles) require storage in batteries. Batteries are the essential difference between EVs and FCVs (which feature compressed or liquid storage and a fuel cell). There are several types of batteries, categorized by their chemistry (Thackeray, 2004). Lead-acid batteries are widely used to power appliances in cars. They are relatively cheap, but suffer from drawbacks such as relatively low specific energy and decay during long-time storage in discharged state. Most (hybrid) electric cars currently in operation use batteries with chemistries based on nickel (notably nickel-metal hydride, NiMH). NiMH batteries are the current choice in the best-selling hybrid car, the Toyota Prius. These batteries provide a significant improvement over lead-acid batteries in terms of specific weight, so that they provide an enhanced driving range in EVs.

The third battery type is fitted with a lithium-based chemistry. This type is currently widely applied in mobile electronic devices such as laptops and mobile phones. Its major advantage is again an improvement in specific energy. Lithium-ion batteries are still under heavy development and further improvements in energy density and power are expected. Perhaps the drawback that has hitherto most withheld lithium-ion batteries from mass application in EVs is safety concerns – the chemistry is particularly vulnerable to thermal runaway and the build-up of gas pressure, resulting in overheating and possibly fire. Laptop and mobile phone batteries have been recorded to catch fire and explode in recent years, arguably making OEMs even more hesitant to apply lithium-ion batteries prior to more extensive R&D and testing.

A comparison with hydrogen-powered vehicles reveals less variety in technical options for battery vehicles. On the other hand, prototypes and demonstration projects show less convergence towards a dominant design as prototypes are based on a multitude of chemistries. A dominant design is by no means apparent yet, although there is a fairly broad consensus that lithium-ion batteries will be the ultimate choice.

B.3 Hybrid forms

Hybrid forms are combinations of multiple technologies. Combinations enable all technologies to operate closer to their theoretical efficiencies (Rajashekara, 2005). Strictly speaking, most FCVs are hybrids. Fuel cell systems cannot adapt their output quickly enough to respond to the sudden changes in load that driving requires. Batteries are thus needed to perform a buffer function in the system. Batteries are also used to capture energy from braking (Emadi, Rajashekara, Williamson, and Lukic, 2005).

Petrol-electric hybrids can be categorized into three different configurations. In a series hybrid (figure B.4), only the electric motor drives the wheels. At slow speeds, the battery suffices to provide the motor with energy. At higher speeds and during acceleration, additional power is delivered by a generator driven by the ICE. At cruising speeds, the generator serves to charge the battery. Energy recovered from braking is also used to recharge the battery. The major advantage of this configuration is that the ICE can be relatively small and it can be run efficiently within a small load bandwidth. Drawback is that the battery needs to be relatively large, which drives weight and costs up.

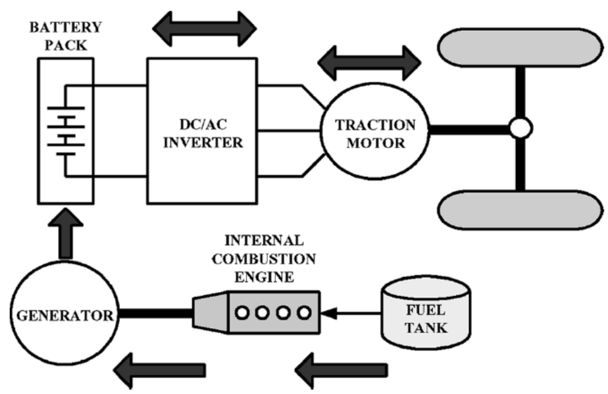

Figure B.4 The series hybrid drivetrain configuration. Source: Emadi, Rajashekara, Williamson, and Lukic, 2005.

The second configuration is parallel (figure B.5). In this setup, both the ICE and the electric motor deliver power directly to the wheels. In practice, the ICE will provide most of the power with the electric motor producing extra power when necessary. At cruising speeds, the ICE can deliver extra energy to charge the battery pack, and energy is stored in the battery pack during braking. The configuration is sometimes called a 'mild hybrid'. Honda calls it 'Integrated Motor Assist' and applies it in the Civic Hybrid that is available on the Dutch market. The major advantage of this configuration is its moderate cost – the battery pack can be of modest size because the ICE delivers the bulk of the power.

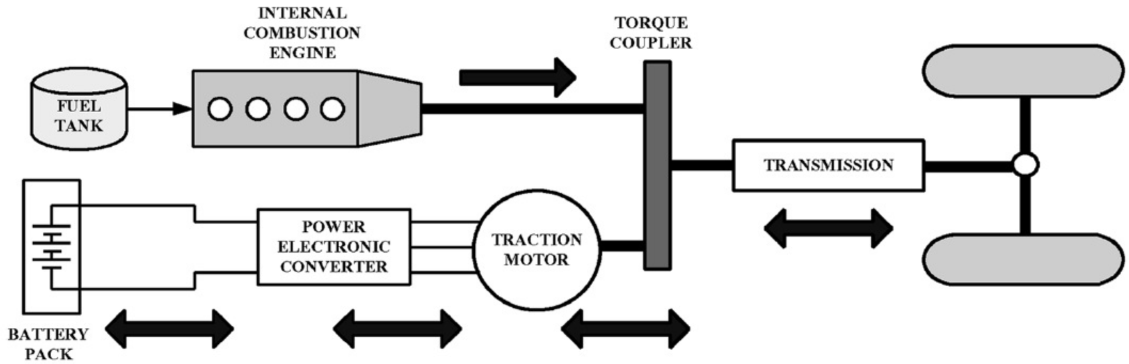

Figure B.5 The parallel hybrid drivetrain configuration. Source: Emadi, Rajashekara, Williamson, and Lukic, 2005.

The third configuration is a combination of the series and parallel systems (figure B.6). This system combines the benefits of the other two. The topology is essentially that of the parallel system with a separate generator providing an extra mechanical link to the electric motor (instead of the motor doubling as generator). The best of two worlds, but also more complicated and therefore more costly. This is the system of choice in the Toyota Prius.

A PHEV basically only adds an extension cord, i.e. it allows the battery to be charged from the distribution grid as in an all-electric vehicle. This reduces fuel use further, since less charging needs to come from the ICE. PHEVs thus offer a certain range that can be covered using only the electric motor, after which the ICE has to provide power for the rest, charging the battery or driving the wheels, or both, depending on the configuration. The technical difficulties are again with the batteries. However, thanks to the ICE the PHEV offers a range similar to CVs – and like CVs, they can be refuelled at a conventional refuelling station.

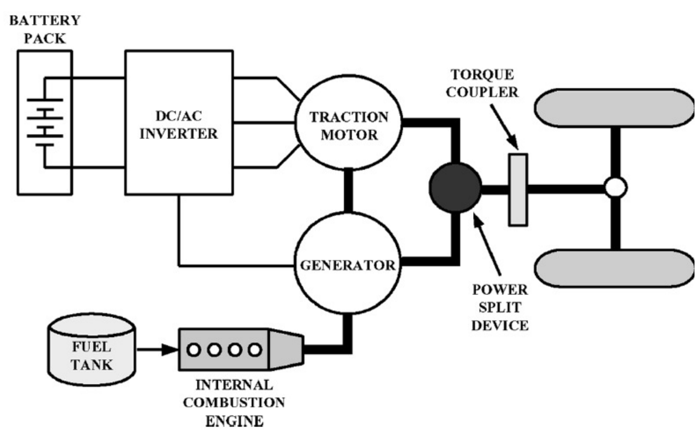

Figure B.6 The series-parallel hybrid drivetrain configuration. Source: Emadi, Rajashekara, Williamson, and Lukic, 2005.

C Time-scale required for significant market penetration

This appendix serves to provide an indication of the lower boundary on the time that is required for an alternative technology to reach significant penetration of the car fleet. The calculation is based on assumptions in the allocation model developed in the THRIVE consortium (Ajah, 2008). The uptake of HVs in this model is based on supply-side logic, assuming that an increasing number of OEMs will introduce subsequent HV models over time until HV models cover the entire market (i.e. there is an HV alternative to each CV). The resulting diffusion of HVs takes the form of a sigmoid curve, typical for many diffusion processes.

Here, this approach will be used to represent the introduction of any AFV, not necessarily HVs. The equation underlying the diffusion process is slightly altered, so that it has the following form:

$$\phi(t) = \frac{\rho}{1 + \exp\{-\delta(t-\beta)\}} \tag{C.1}$$

with

δ = scale parameter

t = year after introduction ($t = 0$ marks the year of introduction)

β = year after introduction in which growth reaches its maximum

$\phi(t)$ = fraction of car market covered by AFVs in year t

The introduction scheme of table C.1 is assumed. This implies that five OEMs each introduce 1 model at $t = 0$. After 5 years, these models are complemented by another 5, and at the same time another 5 OEMs each introduce a model, so that the cumulative amount of models is 15 at $t = 5$. Each model is assumed to capture a market share of 1.5%, which is the market share an average model attains. Fitting equation C.1 to the data points thus obtained yields $\delta = 0.261$ and $\beta = 14$.

Years	Cumulative number of AFV models	Average share per model (%)	Total share of AFV models (%)
0	5	1.5	7.5
5	15	1.5	22.5
10	35	1.5	52.5

Table C.1 Introduction scheme used in the THRIVE model.

About 7% of the Dutch car fleet is replaced with new vehicles on an annual basis (BOVAG-RAI, 2008). Assuming that the share of AFVs in these replacements in any year t is equal to the share of the market that is covered by AFVs in t makes it possible to calculate the share of AFVs in the car fleet (figure C.1).

In this simple model, it takes 23 years for AFVs to replace half of the CVs. Since the assumption that AFVs will replace CVs proportional to the fraction of the market that they cover at that moment is rather optimistic, there is reason to assume that AFV penetration might even be slower. More than three decades thus seems a suitable time scale for this thesis.

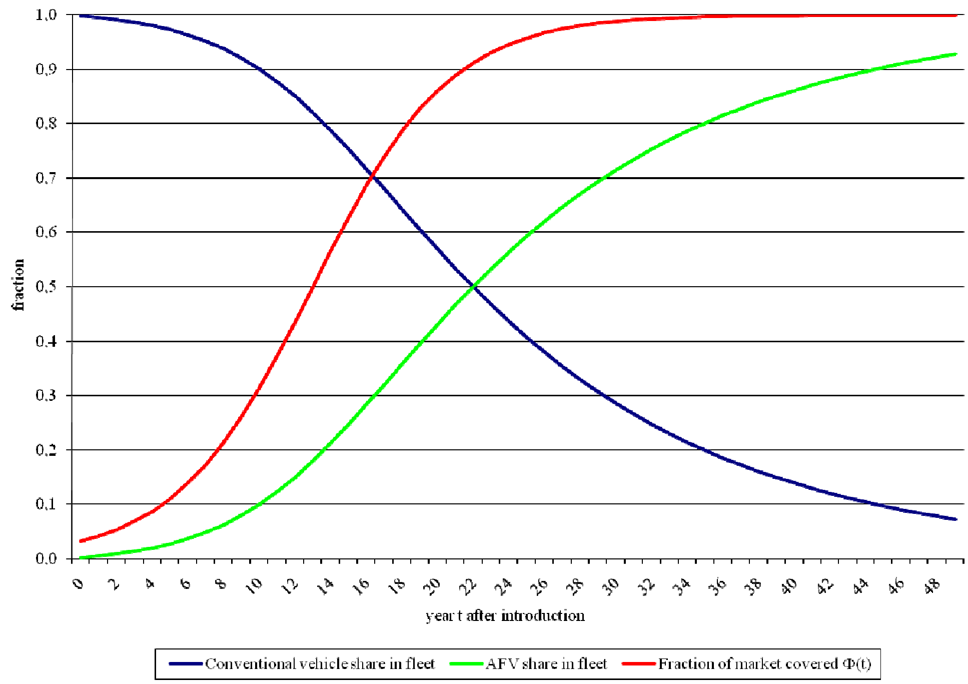

Figure C.1 Market shares resulting from the simple diffusion model for AFVs.