Accelerating Technological Change

Towards a more sustainable transport system

ISBN 978 90 6266 351 4

Cover: sjaakvandervooren.nl
Printing: GVO drukkers & vormgevers B.V.

Accelerating Technological Change

Towards a more sustainable transport system

Het versnellen van technologische verandering

Op naar een duurzamer transportsysteem

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht
op gezag van de rector magnificus, prof.dr. G.J. van der Zwaan,
ingevolge het besluit van het college voor promoties
in het openbaar te verdedigen

op vrijdag 7 maart 2014 des middags te 4.15 uur

door

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geboren op 4 december 1985 te Utrecht

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Funding for this research project was provided by the Advanced Chemical Technologies for Sustainability (ACTS) programme of the Netherlands Organisation for Scientific Research (NWO).

Dankwoord

Net als technologische verandering gaat ook het schrijven van een proefschrift niet vanzelf. Bij deze processen zijn vele factoren en mensen van onschatbare waarde. Ik heb dan ook veel te danken aan iedereen die mij heeft geholpen.

In de eerste plaats mijn co-promotor, dr. Floortje Alkemade, en promotoren, prof.dr. Marko Hekkert en prof.dr. Hans Amman, hartelijk dank voor jullie enthousiaste begeleiding en voor jullie vertrouwen in mij. Floortje, je hebt me met enorme toewijding laten kennismaken met alle aspecten van de wetenschap. Een betere co-promotor had ik me niet kunnen wensen. Marko, je hebt mij steeds weer laten zien hoe ik de essentiële vertaalslag kan maken van complexe simulatiemodellen naar een boodschap die voor iedereen begrijpelijk is. Hans, je hebt niet alleen de grote lijn van mijn proefschrift bewaakt, maar me ook scherp gehouden door je vragen tijdens onze bijeenkomsten.

Mijn dank gaat ook uit naar de leden van de beoordelingscommissie: prof.dr. J.C.J.M van den Bergh, prof.dr. K. Frenken, prof.dr. C.J.M. Kool, prof.dr. G.P. van Wee en prof.dr. M.P.C. Weijnen.

En plus, je tiens explicitement à exprimer ma reconnaissance envers Eric Brouillat. Travailler avec lui a sans doute augmenter la qualité de ma dissertation, et de toute façon cela m'a fourni beaucoup de joie.

Ook alle collega's van de innovatie studies groep wil ik graag hartelijk danken voor de getoonde interesse, de goede werksfeer en de opbouwende kritiek. Joyce, het was een groot plezier om je kamergenoot te zijn, ik heb genoten van de talloze gesprekken over ons onderzoek en van de gezellige tijd samen.

Mijn geweldige vrienden, al sinds de lagere school, Frans, Jens, Jens, Sam en Tim. Als ware vrienden hebben jullie me altijd gesteund bij alles wat ik doe, zelfs in het afgelopen jaar waarin ik zo weinig aandacht voor jullie had. Dank jullie wel.

Mijn familie ben ik bijzonder dankbaar. Mijn ouders Ashley en Sjaak, altijd behulpzaam, inspirerend en liefdevol; dank jullie wel voor de raad en daad bij het schrijven van mijn proefschrift. Rozemarijn, Jasper en Eva, heel veel dank voor jullie aanmoedigingen en interesse in het onderzoek van jullie serieuze broertje.

Onze lieve kleine Thijmen heeft me dit laatste, zijn eerste, jaar enorm geholpen door me zoveel energie en vreugde te geven tijdens het afronden van mijn

proefschrift. Mijn dank gaat bovenal uit naar mijn Rianne, maar die telt op dit moment dan ook voor twee. Rianne, dank je wel dat je me begrijpt en onvoorwaardelijk achter me staat. Wat heerlijk dat we alle uitdagingen samen en sommige allemaal tegelijk durven aan te gaan. Ik kijk uit naar onze volgende...

Contents

1 An overview

1.1 Introduction

The increasing concentration of greenhouse gasses such as carbon dioxide (CO_2) in the atmosphere (IPCC, 2007) is the widely accepted explanation of climate change. The second largest source of greenhouse gas emissions is fossil-fuel-based road transport, as the burning of fossil fuels produces CO_2 and other greenhouse gasses. Road transport is responsible for about 20% of the EU's total CO_2 emissions (Hill et al., 2012). Passenger cars alone are responsible for about 12% of EU CO_2 emissions. The current fossil-fuel-based transportation system, then, causes environmental problems such as air pollution and climate change.

This thesis addresses the transition towards a more sustainable transport system. More specifically, the greening of passenger cars is studied. Improvements in the sustainability of passenger cars have a significant impact on greenhouse gas emissions. In order to realise this transition, technological change is necessary. New, more environmentally friendly vehicle technologies are needed to replace the current ones.

Many actors are involved in this technological substitution process: technology providers developing and producing new vehicle technologies, consumers adopting these vehicle technologies, and governments that may implement policy instruments in order to stimulate the diffusion of more environmentally friendly technologies (eco-innovation). There are several reasons why policy is necessary to stimulate the diffusion of such technologies (Del Rio Gonzalez, 2009; Kemp, 1997). First, because negative externalities inherent to environmental problems are not sufficiently internalised in the costs of technologies (Horbach, 2008; Rennings, 2000). This is a disadvantage for the competitive position of more environmental friendly technologies. Second, uncertainties about what the vehicle technology of the future will be is high, which makes the returns on research and development (R&D) investments also uncertain (Jaffe et al., 2002), causing insufficient investments to be made in these new technologies. Third, most environmental technologies still need substantial R&D investments before being competitive (Cantono and Silverberg, 2009); it is therefore a long term process before any positive returns on this R&D can be expected. All this means that there are sufficient reasons for government intervention, but policymakers face a difficult task in facilitating the process of technological change. Uncertainties exist about which and how many new technologies to support, and how consumers and technology providers may respond to policy instruments and new technologies.

To study the potential for accelerating and facilitating the diffusion of more environmentally friendly technologies, it is necessary to understand the mechanisms of technological change in the transitions towards a more sustainable transportation system. On the one hand, empirical studies have contributed significantly to our understanding of technological change and provide many stylised facts that shape our thinking of technological change (e.g., David, 1985, 1989; Grübler, 1990; Hughes, 1983; Rogers, 1962). However, insights from empirical studies that address technological change are often difficult to generalise, as they mostly focus on a specific case. Analytical models of technological change, on the other hand, are generalizable (e.g., Bass, 1969; Fisher and Pry, 1971; Mansfield, 1961) and provide insights into the underlying conditions of technological change (e.g., Dalle, 1997; Frenken et al., 2013; Huétink et al., 2010; Malerba et al., 2007; Safarzynska and van den Bergh, 2010; Schwoon, 2006; Shy, 1996; Silverberg et al., 1988; Windrum and Birchenhall, 2005), but they insufficiently address the real world complexity of the transportation sector in their models, such as the emergence of multiple new vehicle technologies and their dependency on physical infrastructure. A prominent example is the emergence of plug-in hybrids, battery electric vehicles and hydrogen fuel cell vehicles that all depends on refuelling and recharging stations. The aim of this thesis, therefore, is to contribute to our understanding of the mechanisms of technological change by addressing real world phenomena of the transportation sector in models of technological change.

The research is presented in seven chapters that together make up this thesis. Chapters two through six each address specific real world phenomena in order to understand the mechanism of technological change in the transition towards a more sustainable transportation system. The concluding chapter seven provides the policy implications for facilitating and accelerating the diffusion of more environmentally friendly technologies, taking into account the real world complexity in our models of technological change.

This first chapter will proceed as follows. Section 1.2 discusses the theoretical concepts of technological change. Section 1.3 presents the conceptual model of technological change that I use in this thesis. In Section 1.4 I address the specific research questions of each chapter that guide this thesis. Section 1.5 describes the methodology used to study technological change. The chapter ends with an overview of the main findings of the chapters two through six.

1.2 Technological change as an evolutionary process

The transition towards a more sustainable transport system requires technological change. In this thesis technological change necessary for this transition is seen as an evolutionary process (Nelson and Winter, 1982; Dosi and Nelson, 1994) in which new technological systems needs to replace an existing dominant technological system. The term technological system is often used in the literature to emphasise that technology only works well when it is embedded in networks of interrelated components, infrastructures and artefacts (Frankel, 1955; Markard and Truffer, 2006; Unruh, 2000). The transport system is a typical example of a technological system: as the use of the vehicle technologies requires a network of physical infrastructure such as refuelling stations.

Evolutionary economists study dynamic processes that change the economy, of which technological change is an important one. It builds on insights from evolutionary biology, but uses the biological analogies only as a metaphor. An important principle for example is the *"survival of the fittest"*. The emergence of new technologies (innovation) creates technological variety. When these new technologies are small improvements of existing technologies (incremental innovations (Henderson and Clark, 1990)) this might be referred to as retention, while more radical innovations (Henderson and Clark, 1990) are coined as discontinuous shocks. Technologies compete for demand-side and supply-side adoption in order to survive this selection process. Technologies that have a high *fitness*, i.e., a high degree of adaptation with their selection environment (Saviotti, 1996, p.114), will have better chances to survive this selection process. The notion of selection environment comprises all factors that affect the competition process such as consumer demand, governmental policy and availability of resources (Lambooy, 2002; Nelson and Winter, 1982). Evolutionary economics emphasises that changes in the selection environment often go hand in hand with technological change, which is referred to as co-evolution or co-dynamics (Safarzynska et al., 2012).

Evolutionary economics differs from traditional economics in some core concepts to explain technological change and to create a more realistic representation of the world. Evolutionary economists agree that demand and supply-side actors try to optimise, as in traditional economics, but state that they are not able to collect and analyse all information to make optimal choices (Boschma et al., 2002). Rather, they are *'rationally bounded'*, the concept introduced by Simon (1955, 1969), which may lead to *suboptimal choices*. Contrary to traditional economics, in which agents often are assumed to be *homogeneous*, evolutionary economics assumes, in analogy with evolutionary biology, that agents are *heterogeneous*. In combination with bounded rationality this means that actors each have different information and differ in the ability to analyse this information. Besides, actors vary in their preferences for a technology's performance. So, actors make different choices, some of which will be suboptimal.

Another important concept in evolutionary economics is path dependence (David, 1985). The dominance of a technology can be explained for a large part by a cumulative process of historic events, meaning that a small initial advantage for one technology or certain minor random shocks can alter the course of history (Page, 2006). So, path-dependent processes may give rise to the emergence of one dominant technology. When the market gets locked in or stuck with this dominant technology, this can hinder the diffusion of newer, possibly superior technologies (Arthur, 1988; Unruh, 2000; Boschma et al., 2002; David, 1985; Frenken et al., 2004; Utterback, 1994). Increasing returns to adoption and network effects are examples of path-dependent processes causing the dominant technology to continue to be chosen by both demand-side and supply-side actors, and to be improved further (Arthur, 1988). For example, a user of electric cars benefits when the number of users increases over a large geographical area, as the network of recharging stations is likely to increase as well.

An evolutionary process of technological change can be driven by market-pull as well as technology-push mechanisms (Dosi, 1982). Market-pull refers to demand forces as the principal drivers of innovation, such as the increased demand for cleaner technologies. Besides environmental concerns, other developments can also create pressure on the existing technological system, such as oil prices and economic recession (Verbong and Geels, 2007). In technology-push processes technological change is driven by scientific research and development. It is recognised, however, that a combination of technology-push and market-pull is necessary for technological change, as they interact closely (Di Stefano et al., 2012; Mowery and Rosenberg, 1979; Peters et al., 2012).

The emergence of new technologies (variety), either driven by technology-push or market-pull mechanisms (or both) often involves competition between an existing locked-in technology and these emerging technologies. Lock-in into the existing technology is the reason why technological change is so difficult to bring about (Unruh, 2002). It is assumed that the more radical and new a technology is, the more difficult and time consuming it becomes to implement (Grübler et al., 1999). When technological change involves replacing technological systems in which technologies depend on a physical infrastructure, escaping lock-in may be difficult due to several reasons. First, a dominant design establishes a standard by which the new innovation is 'measured', while new performance characteristics are valued less; more specifically, consumers require the performance of the emerging technology to be at least comparable to the performance of the already existing technology. For example, most people expect similar price, driving range, speed and safety of new vehicle technologies, which is not always the case in an early stage, while for example the environmental performance is considered less important. Second, users have high switching costs because they benefit from the networks effects established by the dominant design. Third, technological systems that have gained momentum are difficult to change, because infrastructure components are capital intensive and characterised by enormous sunk costs, which makes switching to new technological systems unattractive for firms with interests in the existing system.

Earlier work has significantly contributed to our understanding of the diffusion and substitution of technologies. For example, empirical case studies show that the diffusion of technologies, which is an integral part of technological change, tends to follow an *s*-shaped curve. Diffusion is slow at the start, becomes more rapid as adoption increases, and finally levels off (Rogers, 1962). Historical studies about the diffusion of computers and dynamos (David, 1989) and electricity systems (Hughes, 1983), for example, show that innovations start of slowly because in the initial stage many uncertainties exist about unsolved technological and market problems. The limited capacity of batteries for electric vehicles might be such a unsolved technical problem for the diffusion of battery electric vehicles. Moreover, uncertainties exist about unknown responses of the diverse actors involved in technological change such as consumers and technology providers (Carlsson and Stankiewicz, 1991). Also, the diffusion of new technologies depends on the diffusion of other competing technologies, as the emergence of new technologies tends to cluster in time and space (Freeman and Louçã, 2001).

The availability of infrastructure is an additional condition for the diffusion of new technologies within the transport system (Bunch et al., 1993; O'Garra et al., 2005). Grübler (1990) studied the technological change of several technologies that depend heavily on the availability of infrastructure. He shows that the diffusion of technological components and infrastructure components are interdependent but have different development patterns in time. The diffusion of the infrastructure precedes that of the technology, whereby the rate of diffusion of technologies is somewhat lower. As mentioned before new infrastructures in the transport sector often require significant capital-intensive investments (Gómez-Ibáñez, 2003; Markard, 2011). Due to these particular characteristics of technologies in the transport sector and the public character of infrastructure, governments often intervene in technological substitution processes in this domain.

Technological change is highly context specific, as new technologies often evolve from existing designs, and conform to standards imposed by complementary technologies and infrastructure. Therefore a major limitation of a case study approach is its limited generalizability. The stylised facts of technological change presented above are the result of many case studies, which is necessary in order to make such general claims.

The use of formal models to study technological change is an approach that is less sensitive to these issues. Early models of technological change are able to capture the general observations of technological change by using only a few parameters and equations (Bass, 1969; Fisher and Pry, 1971; Mansfield, 1961). In the Fisher and Pry (1971) model the diffusion of the new technology depends on the remaining market share of the old technology that is left to be substituted. This model requires that no more than two technologies, one old and one new, compete, and builds on the assumption that the new technology completely replaces the old technologies. Once the substitution process in this model has started it continues until the new technology has taken over the market completely. The model is appropriate to represent the growth of new technologies if only positive feedback mechanisms are present. Mansfield's (1961) model explains technological change by a mechanism in which the probability that a firm will adopt a technology is an increasing function of the proportion of firms that have already adopted it and the profitability of doing so, but a decreasing function of the size of the investment required for adopting the technology. In the Bass (1969) model imitation is the key mechanism as well. Here diffusion takes place through innovators who are not influenced by others and imitators whose decision is based upon the number of customers that have adopted the innovation.

The number of innovators decreases and the number of imitators increase, as the installed base increases. These formal models have been very influential, as they show stylised mechanisms but lack some sense of the complexity of the real world. Moreover, models such as the Fisher and Pry (1971) model that fit the data well have limited explanatory power, as the underlying model is not always behaviourally verified.

More recent models of technological change add some of this real world complexity and variety, and thereby seek to increase the explanatory power of formal model in this area (e.g., Dalle, 1997; Frenken et al., 2013; Huétink et al., 2010; Malerba et al., 2007; Safarzynska and van den Bergh, 2010; Schwoon, 2006; Shy, 1996; Silverberg et al., 1988; Windrum and Birchenhall, 2005). They illustrate that conditions in favour of technological change are: 1) consumer heterogeneity such as varying consumer preferences, different consumer groups and experimental users; 2) early competitiveness of alternative technologies; 3) the valuation of technological characteristics of new technologies (preference changes); 4) backward compatibility of new technologies; 5) local network externalities for the new technology; 6) recombinant innovations that build on at least two existing technologies. These conditions enable the early adoption necessary for the diffusion of new technologies. They can be influenced by policy instruments to some extent.

Models like the ones highlighted in the previous paragraph provide important insights into the aim of this thesis: understanding the mechanisms that facilitate and accelerate the transition towards a more sustainable transportation system. However, most of these models do not address the specific complexity crucial for the diffusion of more sustainable vehicle technologies. Complexities that need to be addressed more extensively in current models of technological change are: 1) the dependency on a physical infrastructure; 2) the emergence of multiple new technologies; 3) compatibility between different old and/or new technological systems; 4) technologies that emerge at different moments in time; 5) significant incremental improvements in the existing technologies; 6) the co-existence of multiple technologies in a firm's portfolio; 7) imperfect substitution. In the next section I will present an evolutionary model of technological change that takes into account this real world complexity, which is necessary to understand the mechanisms of technological change in the transportation system.

1.3 An evolutionary model of technological change

A model is a simplification of real world phenomena in which essential elements and interactions are present. It is like a map of a country on which only “big“ cities and the highways between these cities are present. It is not the aim of this map to replicate the real world with all its detail. The same holds for models. Unnecessary complexity should be avoided, because it might disguise the underlying mechanism that explains the outcomes of the model. An evolutionary model allows for the presence of the core concepts of evolutionary economics, such as heterogeneity (variety), suboptimality and path dependence.

The conceptual model I have developed for this study is presented in Figure 1.1. It represents the key actors and core components that constitute the transport system studied in this thesis. It shows a dominant vehicle technology and its infrastructure, meaning that most technology providers[1] develop and produce this vehicle technology and infrastructure and most consumers use it. However, a number of new vehicle technologies emerges in an attempt to replace the dominant vehicle technology. Initially, these emerging technologies are adopted by only a few technology providers and consumers. Policymakers may influence changes in the current transport system by implementing policy instruments to stimulate the diffusion of the new technologies.

The interactions between model components and actors represent the evolutionary character of this model, such as changes in the selection environment that co-evolve with changes in vehicle technologies. In this model it is the consumer who select the vehicles technologies. Vehicle technologies change as consumer demand changes, but consumer demand in turn changes as new vehicle technologies become available. In other words, technology providers develop and produce more sustainable vehicle technologies as consumers prefer more sustainable vehicles. This is called co-evolution. Moreover, vehicle technologies and their necessary infrastructure co-develop. In the following section the core components are described and the role of the key actors is discussed.

Vehicle technologies and their **infrastructures** represent technological systems that consist of a broad range of technical components that are interrelated (Frankel,

[1] Throughout this thesis technology providers are also referred to as firms, suppliers, producers or car manufacturers.

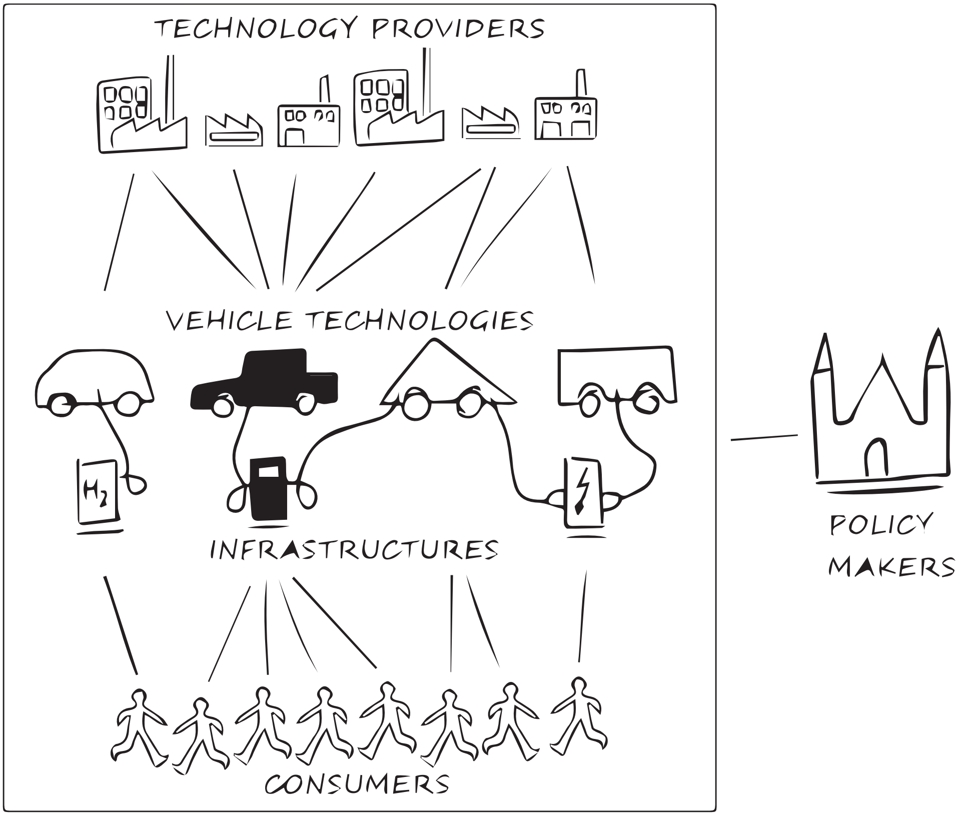


Figure 1.1: Model of technological change in the transport sector.

1955; Henderson and Clark, 1990; Markard and Truffer, 2006; Unruh, 2000). Physical infrastructure such as recharging and refuelling stations are pivotal for the use of vehicle technologies, but as Figure 1.1 shows there is not always a one-on-one relationship between vehicle technologies and infrastructures as some vehicle technologies are compatible with multiple infrastructures.

Vehicle technologies such as passenger cars are used to drive from A to B. Vehicle technologies differ in their performance on a number of product characteristics, such as acceleration, driving range, fuel consumption, etc. The characteristics approach describes technologies by a number of product characteristics (Hotelling, 1929; Lancaster, 1966; Saviotti and Metcalfe, 1984). In this approach consumers have preferences for the characteristics of the technology and not for the technology as such. According to Anderson et al. (1992) the characteristics approach provides an adequate representation of technological competition. Saviotti and Metcalfe (1984) extended the characteristics approach by representing a technology by its performance on two sets of characteristics: the internal structure of the product's technology and the services provided by the product technology to consumers, these are labelled the technological characteristics and the service characteristics, respectively. The services performed for its consumers follow from the technological characteristics of the product technology. The consumer thus selects a technology based on the alignment of his preferences with the service characteristic of the technology. In this thesis I consider the environmental performance of a technology as such a service characteristic.

Many different vehicle technologies are announced as the green technology of the future (or one of these) (Offer et al., 2010; Ogden and Anderson, 2011; European Expert Group on Future Transport Fuels, 2011; Bakker and van der Vooren, 2012). The most prominent alternatives for the currently dominant internal combustion engine vehicle (ICEV) are the plug-in hybrid vehicle (PHEV), the battery electric vehicle (BEV) and the hydrogen fuel cell vehicle (HFCV) (Ogden and Anderson, 2011; Oltra and Saint Jean, 2009; Thiel et al., 2010). These alternative technologies differ from the existing ICEV technology and from each other with respect to driving range and environmental performance as well as other characteristics. Moreover their dependence on existing or new infrastructure differs. For example, plug-in hybrids are partly dependent on existing fossil-fuel-based refuelling stations. Plug-in hybrids and electric vehicles are compatible with each other, as they both require the roll-out of a recharging infrastructure. Fuel cell vehicles on the other hand would need their own (hydrogen) infrastructure.

Consumers have an important role in this complex system as they eventually determine the success of a technology, which is usually measured by its market share in terms of consumers. Consumers adopt vehicle technologies that meet their requirements and preferences. An important requirement is that a sufficient number of refuelling stations is available such that the consumer can make use of his vehicle in actual practice (Bunch et al., 1993; O'Garra et al., 2005). A vehicle will emit a particular amount of CO_2 depending on its vehicle technology and the driving habits of its driver. As this thesis is about technological change to more environmentally friendly vehicle technologies, it emphasises the former.

According to the characteristics approach, discussed above, consumers have preferences for the characteristics of a technology and not for the technology as such. As consumers are heterogeneous in their preferences different consumers might prefer different vehicle technologies. In this thesis I assume that these preferences of consumers co-evolve with the performance characteristics of technologies. For example, when vehicles' acceleration becomes faster over time, the average consumer tends to want a vehicle with ever faster acceleration.

Technology providers develop and produce vehicle technologies. They compete with each other by offering different vehicles to consumers. Innovation provides technology providers with the possibility to (temporally) escape the competition (Saviotti and Pyka, 2004; Swann, 2009). A large body of literature shows that incumbent firms are the main source of incremental innovations, while new entrants are responsible for more radical innovations (Acemoglu and Cao, 2010; Jiang et al., 2010). Sierzchula et al. (2012) show however that within the automobile industry incumbent technology providers are important developers of radical new technologies. Incumbent firms develop radical innovations and incremental innovations simultaneously (Sierzchula et al., 2012; Jiang et al., 2010). They therefore have portfolios of different vehicle technologies, in order to optimise their market share of heterogeneous consumers. Another advantage of a portfolio of multiple vehicle technologies is that it increases the probability of offering the vehicle technology of the future. A disadvantage is that maintaining such a portfolio is expensive.

Policymakers may influence the transport system by implementing policy. Such government intervention is particularly necessary to stimulate the diffusion of eco-innovations. Policy instruments can be directed at different actors and elements in the system. Policy instruments that stimulate the consumer demand and preferences for more environmentally friendly technologies are referred to as demand-pull policies (Peters et al., 2012). Typical examples of demand-pull instruments are awarding a rebate (subsidy) for purchasing more environmentally friendly technologies or imposing a carbon (CO_2) sales tax. Stimulating the development of new vehicle technologies, for example by awarding subsidies to technology providers for innovative efforts, is referred to as a technology-push instrument (Peters et al., 2012). These instruments can either be generic, i.e., aimed at all vehicle technologies, or technology specific. For example, government investments in initial infrastructure, such as recharging points, is a rather specific policy instrument to stimulate the diffusion of electric cars.

1.4 Research questions

The key objective of this thesis is to create insights into the mechanisms of technological change in the transition towards a more sustainable transportation system based on an evolutionary perspective (see also Sections 1.1 and 1.2). Understanding these mechanisms is useful for designing government intervention to accelerate the diffusion of more environmentally friendly technologies. This thesis contributes to existing models of technological change by addressing the real world complexity that characterises this transition. Chapters two through six each capture part of the real world phenomena identified in the last paragraph of Sections 1.2. The following aims and research questions guide the thesis:

In Chapter 2 of this thesis I study the probability that technological substitution takes place when multiple radically new technologies that depend on the availability of a physical infrastructure compete to replace an existing locked-in technology. If this dominant technology is considered undesirable for society, governments may implement policy measures to facilitate an escape from the existing lock-in. Allocation of financial resources to support research, development and demonstration (RD&D) increases variety, while technology-specific support for initial infrastructure development in a later stage may decrease technological variety. So, policymakers that implement instruments to stimulate technological change influence which and how many technological options compete, though the optimal level of variety is uncertain and their budget is limited. Technological variety is a necessary condition to escape lock-in, but too much variety may lead to increased consumer uncertainty and reduces the benefits of increasing returns to scale for technology providers. This evolutionary process of variety creation and selection to stimulate the escape of lock-in is the topic of this chapter. The key research question addressed in this chapter is: **How does the allocation of public financial resources to RD&D and infrastructure development affect the technological substitution of infrastructure-dependent vehicle technologies?**

In Chapter 3 I deepen the study of multiple infrastructure-dependent vehicle technologies that compete to replace the currently dominant technology. The competing technological options are described by several emerging and market-ready vehicle technologies that can (partially) substitute fossil-fuel-based mobility options, such as PHEVs, BEVs and HFCVs. So, in this chapter the vehicle technologies not only differ in technological performance, but also in their degree of compatibility to the existing system and to each other, as well as their time of emergence. Technology providers have to determine their strategy in an environment of co-evolving consumer preferences, technology characteristics and green technology policies. This provides a complex task, as different policy instruments require different strategic responses from suppliers. In Chapter 3 the effect of different policy instruments on the speed and direction of technological change is analysed and the implications for technology providers are discussed. The key research question addressed in this chapter is: **What are the strategic implications for technology providers given different policy conditions to stimulate the diffusion of low emission vehicles?**

In Chapter 4 of this thesis technology providers can have multiple technologies in their portfolio, which reflects the idea that technology providers can invest in incremental and radical innovation simultaneously. I elaborate on the research question in Chapter 3 by studying the impact of policy instruments aiming at the reduction CO_2 emissions in the use of passenger cars. In this chapter I am particularly interested in the impact of policy instruments when they are combined in a policy mix. Several studies support the use of a policy mix to stimulate the development and diffusion of clean technologies (Acemoglu et al., 2012; van den Bergh, 2013), but it remains a challenge to predict the interactions between the different instruments of a policy mix (Veugelers, 2012). I study complementary, synergetic and contrasting effects between different policy instruments, which, according to Borras and Edquist (2013), require more attention. The effects of policy mixes on other economic aspects of technological change are taken into account as well. The key research question addressed in this chapter is: **What is the impact of mixes of heterogeneous policy instruments on technological decisions of firms, consumer choice, CO_2 emissions and public finance?**

In Chapter 5 of this thesis I focus on improvements in environmental performance of the existing ICEV technology. The emphasis is therefore on incremental innovations. I explore the consequences of emission reduction incentives such as energy-labelling schemes on car manufacturers' portfolios of car versions. The key research question this chapter is: **How did the portfolios of car manufacturers change with the introduction of energy labels?**

In Chapter 6 I continue the research on incremental innovations. I study technological change in product markets that vary in their level of competition intensity. I analyse the contribution of market-pull and technology-push incentives on accelerating the transition towards a more sustainable product market, such as the car market. The impact of these different types of policy incentives can differ as product markets vary in their level of competition intensity. The key research question addressed in this chapter is therefore: **What is the effectiveness of market-pull and technology-push instruments for accelerating the transition to more sustainable product markets?**

1.5 Methodology

While formal models of technological change may have mathematical solutions, this in not the case for models that capture more real world complexity and may have multiple outcomes. Agent-based modelling (ABM) is an increasingly popular tool for simulating the actions and interactions of autonomous agents over time in order to study how micro mechanisms lead to the emergence of macro outcomes (Epstein and Axtell, 1996; Holland, 1995; Miller and Page, 2007; Rand and Rust, 2011). Using ABM as a computational laboratory enables systematic testing of patterns that help to understand how attributes of agents and components, their behavioural rules and interactions affect macro level stylised facts of technological change (Janssen, 2005).

The basic concept of agent-based modelling is that researchers describe simple rules of behaviour for individual agents, their properties, and the way the agent interacts with other agents and the environment (Rand and Rust, 2011). When aggregating the micro level rules of each individual agent, such as consumers and technology providers, this creates macro level dynamics of a model, such as the transportation system. By assigning individual rules to the autonomous agents, all concepts of evolutionary economics, such as heterogeneity, bounded rationality, sub optimality and path dependence can be incorporated in agent-based models (Rand and Rust, 2011).

The agent-based models of the transport system that I have developed in the thesis vary in their emphasis on different components and actors described in Figure 1.1. Moreover, the models in the different chapters differ in their level of abstraction. In Chapters 2 and 3 the focus is on the interaction between infrastructure-dependent vehicle technologies and consumers. In these chapters policy instruments are implemented as exogenous mechanisms that affect the behaviour of consumers and availability of vehicles technologies and their infrastructure. Technology providers are ignored in order to reduce the complexity of these models. In Chapter 2 the technologies in the model are abstract and have a randomly assigned performance on each characteristic, while in Chapter 3 the technologies represent several emerging and market-ready vehicle technologies that exist in the real world. In Chapters 4 through 6 technology providers are an important decision-making actor in the model. However, technology providers and consumers in Chapter 4 have complex decision-making rules, while in Chapter 6 the decision making rules are extremely simple. The model in Chapter 6 builds on the results of Chapter 5, in which I empirically analyse the evolution of environmental performance of the portfolios of firms in the Dutch automotive sector.

1.6 Synopsis of study results

In the following I briefly present the key insights in Chapter 2 through 6 into the mechanisms of technological change in the transition towards a more sustainable transportation system. Chapter 7 of this thesis presents the concluding remarks and the main implications for policymakers who intend to accelerate technological change.

Chapter 2, which was published as van der Vooren et al. (2012), presents a model of technological substitution in order to study escaping lock-in with multiple alternative technologies competing. The simulation results show that there is a trade-off between the allocation of financial resources to support for RD&D and to support for infrastructure development. While escaping lock-in requires support for diverse technological options, this diversity should be limited, as the chances of success of one of the options are reduced when too many alternatives are competing. The model illustrates that if policymakers support RD&D to increase technological variety, this is most rewarding when all created technologies are also substantially supported for infrastructure development in a later stage, as policymakers are not able to pick winners on beforehand. However, when each supported vehicle technology receives only modest support for infrastructure development, it is difficult for any of those technologies to realise sufficient increasing returns to scale. So, to increase the probability of technological substitution when there is a strict dependency on a physical infrastructure, the created variety should be limited. Moreover, this approach is only beneficial when policymakers reserve financial resources to support the vehicle technologies in later stages of development.

In Chapter 3, published as van der Vooren and Alkemade (2012), the competition between three potential technological options for the future (PHEV, BEV, and HFCV) and the existing technology (ICEV) is studied. The results of model simulations show that different vehicle technologies might be preferred under different policy conditions. In an early stage the levying of a carbon tax is mostly in favour of ICEV, as the alternative options are insufficiently aligned with consumer preferences. Later introduction of a carbon tax creates opportunities for PHEVs and BEVs. Moreover, technological change is facilitated when new technological options make use of common infrastructures, such as PHEV and ICEV and PHEV and BEV, as compatibility of different vehicle technologies lead to stepping-stone effects. For example, the PHEV technology serves as a stepping-stone technology for the diffusion of BEVs. The model simulations illustrate that when a portfolio of compatible vehicle technologies exist, it is possible to provide technology-specific support for one technology (PHEV) without locking out the other compatible alternatives (BEV).

Chapter 4, accepted for publication as van der Vooren and Brouillat (in press), presents a model of technological change in which technology providers can produce and develop the old technology and new technologies simultaneously. I study the contribution of combining policy instruments in a policy mix on technological change. Simulation results show that policy mixes can be effective to generate additional pressure to accelerate technological change. But mixing policies might also increase the burden on public finance, even without any positive additional effect for technological change. For example, setting standards for the maximum amount of CO_2 emissions and simultaneously introducing a feebate system[2] (the Dutch bonus-malus system) creates significant pressure to improve the environmental performance of the incumbent technology. This results in many small incremental improvements in the incumbent technology, such that the radically new technology has no chance. Only in some cases where policy instruments are combined that focus on the radical as well as the existing technology do policy mixes lead to synergies that are desirable. An example is awarding a rebate for radical new technologies and imposing carbon tax. The carbon tax not only stimulates incremental innovation in the existing technology,

[2] A feebate system intended as a self-financing system of fees and rebates that are used to provide carrot-and-stick incentives to change the behaviour of consumers.

but also increases the competitive position of zero emission vehicles. Clearly, careful design of policy mixes is important.

Chapter 5, which appeared as van der Vooren et al. (2013), empirically identifies incremental improvements and portfolio strategies of car manufacturers after the introduction of energy labels. All car manufacturers significantly reduced the CO_2 emissions of their portfolio. But the key finding is that frontrunners in CO_2 reduction experienced the highest relative increase in sales, while manufacturers lagging behind with CO_2 reduction performed weak. So, tight environmental regulation like in the Netherlands is effective, as it rewards innovative behaviour of firms.

In Chapter 6 a competition model is presented to study technological change in product markets that vary in their level of competition intensity. Simulation results illustrate that in accordance with the theory an inverted u-shaped curve exists between environmental improvements and the intensity of competition. For technological change incentives and opportunities to offer more environmentally friendly products need to be present, which can be stimulated with technology-push and demand-pull policy instruments. To accelerate the transition towards a more sustainable product market policymakers must take into account that the effectiveness of policy instruments to stimulate environmental performance depends on the market structure of a sector.

2 Escaping lock-in with multiple competing technologies*

2.1 Introduction

The lock-in of society into a dominant technology is one of the main barriers to the diffusion of new technologies (Unruh, 2000, 2002). This risk of lock-in is particularly high for infrastructure-dependent vehicle technologies, which are characterised by high infrastructure investment costs and the presence of network externalities, two mechanisms that make it difficult to escape lock-in (Gómez-Ibáñez, 2003; Azar and Sandén, 2011). When the currently dominant technology is considered undesirable for society, governments may implement policy measures to facilitate the escape from the existing lock-in and the transition towards a more sustainable technology.

The substitution of a dominant, locked-in vehicle technology by a new vehicle technology can be seen as an evolutionary process characterised by creation and selection of variety (Nelson and Winter, 1982; Dosi and Nelson, 1994). Policymakers that seek to influence technological change can apply a wide range of instruments. These may stimulate investments in RD&D, for example, which lead to increased variety. Other measures such as favourable tax regimes, investment in new infrastructure and carbon pricing target the selection and diffusion process (van der Vooren and Alkemade, 2012). The government or public regulator has to decide how to stimulate the different processes.

This problem is similar to the exploration versus exploitation dilemma in studies on organisational strategy (March, 1991): first, the public budget for government intervention is limited. Second, the technological substitution process is characterised by feedback mechanisms, and intervention in one part of the process influences the success of intervention in other parts. Third, the optimal level of technological variety is unknown. The literature indicates that the existence of technological diversity is a prerequisite for the escape of lock-in (Arthur, 1989; van den Bergh, 2008; Metcalfe, 1994). However, while

* This chapter is published as: van der Vooren, A., Alkemade, F. and Hekkert, M.P.: 2012, Effective public resource allocation to escape lock-in: The case of infrastructure-dependent vehicle technologies, *Environmental Innovation and Societal Transitions* 2, 98 - 117.

variety is necessary to escape lock-in, too much variety may lead to increased consumer uncertainty and delayed adoption by end consumers. Furthermore, too much variety reduces the benefits of increasing returns to scale for technology suppliers (Geroski, 2000). It is thus difficult to decide upon an adequate level of variety, especially in situations where a limited budget for the creation and (long term) support of technological options is available (van den Bergh et al., 2011). Fourth, although innovations do tend to cluster in time and space (Freeman and Louçã, 2001), different technological alternatives may enter the market at different moments, which makes it difficult to evaluate the technological options.

The main research question that we will address in this chapter is therefore: how does the allocation of public financial resources to RD&D and infrastructure development affect the technological substitution process of infrastructure-dependent vehicle technologies?

We address this question by building an agent-based simulation model in which alternative vehicle technologies emerge that may replace the dominant, unsustainable technology. The model allows us to compare and analyse the effects of different public resource allocations to low emission vehicle RD&D (variety creation) and infrastructure development (selection). The allocation of financial resources to variety creation, for example, through RD&D investments, may lead to the emergence of new technological options. Financial resource allocation to infrastructure development, such as the development of refuelling or recharging infrastructure in the case of vehicle technologies, is needed to support the market introduction of some of the new technological options.

The remainder of this chapter is structured as follows: Section 2.2 provides a brief overview of the relevant literature, and the agent-based model of technological substitution of infrastructure-dependent vehicle technologies is presented in Section 2.3. Next, Section 2.4 presents and interprets the results of numerical simulations with the model. Section 2.5 offers an interpretation of the results in the context of sustainability transitions. Finally, Section 2.6 concludes and provides policy implications.

2.2 Theoretical framework

The substitution process of infrastructure-dependent vehicle technologies is a multi-stage process (Knudsen and Levinthal, 2007). The process starts from a situation of lock-in and in the first stage the creation of alternatives (technological variety) to the dominant design is supported with financial support for RD&D. In the second stage some of the new technologies receive government support for infrastructure development before being subjected to market forces in the third stage, the stage of consumer adoption. Below, we will discuss the three stages of this technological substitution process in more detail, but we will start with a discussion of lock-in.

2.2.1 Lock-in

A 'dominant design' is a technology that is the most successful on the market and becomes the standard for future designs. The emergence of a dominant design is the result of the interplay between technical and market choices (Utterback, 1994). Often, dominant technologies emerge from the competition between a number of alternative technologies (Abernathy and Utterback, 1978; Anderson and Tushman, 1990). For example, today's dominant internal combustion engine vehicles competed with electric and steam-powered cars to succeed the old technology of horse-drawn carriages.

The determinants of lock-in can be found in path-dependent processes (David, 1985), which are the results of increasing returns to adoption (Unruh, 2000; Arthur, 1988), such as learning by using (Rosenberg, 1982), scale economies, informational increasing returns, technological interrelatedness (Frankel, 1955) and network externalities (Katz and Shapiro, 1985). The effects of these determinants are even stronger when a technology depends on the availability of physical infrastructure. Infrastructure-dependent vehicle technologies can be subject to both direct and indirect network externalities (Katz and Shapiro, 1985; Koski and Kretschmer, 2004). Direct network externalities occur when a technology is valued more highly when the number of adopters increases. Indirect network externalities occur when the availability of complementary goods increases with an increased number of users, thereby indirectly increasing the value of the technology. This is the case for cars that depend on the availability of fuel stations. Increasing returns to adoption of the old technology can hinder the diffusion of newer, possibly superior technologies (Arthur, 1988; Frenken et al., 2004).

A dominant technology forms the selection environment for the new technology. New technologies initially often show higher prices and poor performance in comparison to the incumbent technology (Rosenberg, 1976), and when these new technologies depend on the availability of a physical infrastructure (that is incompatible with the existing infrastructure), overcoming lock-in is even more difficult.

2.2.2 Stage 1: public support for RD&D

Although difficult to overcome, history shows that lock-in is often a temporary phenomenon from which escape is possible. Technology-push and demand-pull processes can give rise to new options or inventions that replace existing technologies (Dosi, 1982). Demand-pull processes occur when consumer preferences regarding technological performance change in response to dissatisfaction with the current (unsustainable) technological paradigm. Technology-push processes occur when, for example, the government supports a new technological option through adapted regulation or financial support for RD&D.

Although it is very difficult to determine *ex ante* which of the newly created technologies will succeed in replacing the incumbent technology (Kemp et al., 1999), stimulating variety is often part of policy schemes that aim to replace the current dominant technology by a preferred alternative, like in the Dutch energy transition program (Smith and Kern, 2009; Kern and Howlett, 2009; Stirling, 2010).

Public RD&D support in this first, pre-market, stage offer actors a financial compensation for their exploratory efforts. Although such support schemes sometimes already involve elements of selection, this chapter considers public RD&D support as a contribution to technological variety (see for example, IEA (2007), on pre-award/*ex-ante* selection and Knudsen and Levinthal (2007) on alternative generation). For policymakers, the question at this stage is what part of their total budget should be spent on public RD&D support in order to escape the existing lock-in (Stirling, 2010).

2.2.3 Stage 2: public support for infrastructure development

The government can influence the rate and direction of technological change before infrastructure-dependent vehicle technologies actually compete on the market. It is especially this stage between the invention of a new technology and its deployment in large scale pilot projects where many innovations fail.

This phase is therefore sometimes called the ‘valley of death’ of technology development.

For infrastructure-dependent vehicle technologies, support often takes the form of subsidies for installing (refuelling) infrastructure or the implementation of a price subsidy in order to decrease the distance-to-market for the respective technologies. Given the inherent uncertainty of the innovation process, it is difficult to evaluate the different alternatives and to decide which and how many technological options to support.

2.2.4 Stage 3: consumer adoption

The adoption of a technology by consumers is the final stage of the technological substitution process because consumers eventually determine which technology is diffused throughout the population. In this third stage, the different alternative options for the dominant design compete with each other and with the current locked-in dominant design (Arthur, 1988). On the market the main selection criteria are the price of the technology and the degree to which the technological characteristics of the new technology fit consumer preferences (including preferences for sustainability) (Lancaster, 1971). For infrastructure-dependent vehicle technologies, the availability of infrastructure is an important factor in user preferences (Bunch et al., 1993; O’Garra et al., 2005).

This market selection environment is not static as consumer preferences evolve due to the availability of new technologies or due to exogenous forces that stress technological and service characteristics that differ from the characteristics of the current dominant design. Consumers might, for example, develop preferences for more sustainable vehicles or for vehicles with air-conditioning. Both the incumbent technology and the new technological options may benefit from this changing selection environment. When the incumbent technology successfully adapts to the changing environment this is called the ‘sailing ship’ effect (Harley, 1973; Geels, 2002).

2.2.5 The allocation problem

When designing a policy scheme to support low emission vehicles policymakers have to decide how to allocate public financial resources to the development of new technologies (RD&D: stage 1) and infrastructure development (stage 2) in order to stimulate the adoption of a more sustainable technology by consumers (stage 3). The literature indicates that this allocation decision is not trivial.

Regarding the first stage, the literature suggests that more variety creation is better because subsequent support leads to better outcomes when there is greater variety, as more variety leaves more future options open and leads to an increased probability of successful recombination and spillovers (Fisher, 1930; Metcalfe, 1994; van den Bergh, 2008; Zeppini and van den Bergh, 2011). The effects of increased variety in the next stage, where some technologies receive support for infrastructure development, are less clear. On the one hand, variety compensates for the uncertainty associated with the (future) performance of each technological option (Alkemade et al., 2009). On the other hand, as infrastructure-dependent vehicle technologies are characterised by increasing returns to scale, there are costs associated with maintaining diversity in this stage. In a model of optimising the benefits and costs of diversity, van den Bergh (2008) finds that under increasing returns to scale, diversity is only attractive when the payoffs of diversity are sufficiently large, i.e., they have to exceed a certain threshold. Other arguments on why increased variety in this stage might decrease the probability of overcoming lock-in can be found in the increased level of competition between the alternative technological options, the increased level of uncertainty for consumers and the decreased probability of establishing a new technological standard. With regard to the level of competition, moderate competition is considered to improve the chances of overcoming lock-in as rivalry among technologies gives incentives to further improve the technology (Gruber and Verboven, 2001; Koski and Kretschmer, 2004, 2005). Fierce competition among a large number of competing alternatives can slow consumer adoption of the new technology as it leads to increased consumer uncertainty. This uncertainty may cause consumers to postpone their adoption decision because of the risk of selecting a technology that will fail to generate network externalities and lose the competition (Geroski, 2000).

While moderate variety thus seems beneficial in the first stage, the adequate level of variety is less clear in subsequent stages. As public financial resources are limited and the uncertainty regarding future technological performance is high, deciding on how to allocate resources between the different stages is complex. In the next section we present a model that allows us to explore this resource allocation problem.

2.3 A model of technological substitution

The general structure of the model in Figure 2.1 shows that policymakers intervene by allocating financial resources to stage 1 and stage 2. Budget allocation to public support for RD&D (B_1) results in the creation of technological variety. The technological options differ in initial price and performance on the characteristics. Budget allocation to stage 2 (B_2) leads to technology-specific infrastructure development for the newly created technological options. In stage 3 consumer adoption determines if the locked-in technology will be replaced by one of the new technologies, that is if technological substitution occurs at all. Below a more elaborate description of the model is given.

The model starts from a situation of lock-in into a single technological option, labelled as the incumbent technology. We define lock-in as the situation where the incumbent technology is adopted by 90% of the consumers. We run the model to analyse the effects of different allocations of financial resources to stage 1 and stage 2. The budget allocated to the first stage (B_1) depends on the technological variety, that is the number of technological options (I_1) that receive RD&D support, times the costs of RD&D support per technological option (c). The budget allocation $B_2 = B - B_1$ to the second stage determines how much support for infrastructure development is received by the technological options (I_2) that are selected for infrastructure support. The I_2 technological options that receive infrastructure support are selected randomly, reflecting that it is difficult for policymakers to evaluate the performance of each technological option before it is actually on the market. Vehicle technologies that do not receive support will not enter the market and are therefore not available for consumer adoption in stage 3.

In the third and final stage, the infrastructure-dependent vehicle technologies compete for a market share with the incumbent and locked-in technology as well as with each other. The number of consumers that adopt a certain technology determines the market share of that technology. Consumers base their adoption de-

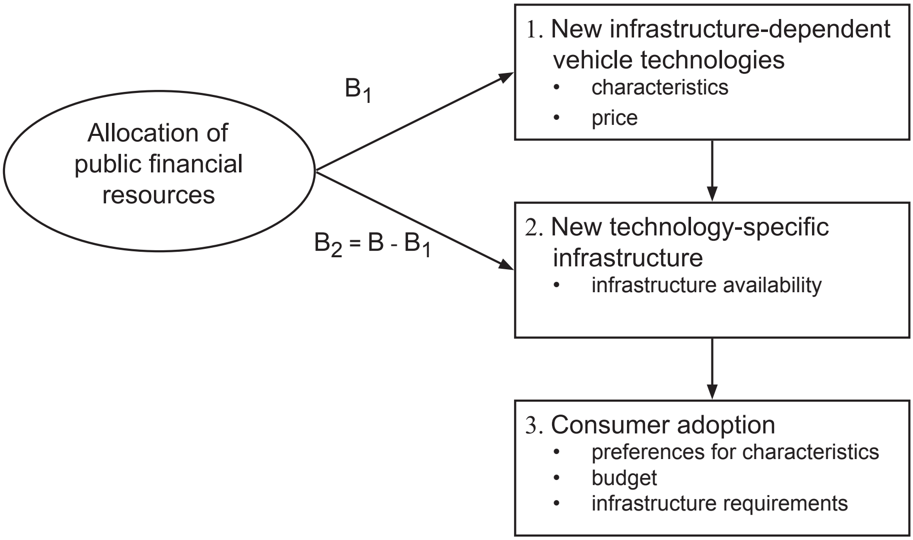


Figure 2.1: Structure of the model.

cision on the availability of infrastructure and on the degree to which a technology fits their individual preferences and budget. The remainder of this section gives a detailed description of the model components (technologies, infrastructure and consumers) and their interactions.

2.3.1 Technologies

In the model, a technology i is described by its performance on a set of characteristics $X_i \in [0, 1]$, as in Lancaster (1971) and Saviotti (1996), and by its price P. Not all characteristics are considered equally important and the way the different characteristics are valued can change over time. Furthermore new characteristics such as environmental performance can become important. These changes in the selection environment are an important driver of technological change (Dosi, 1982).

The current dominant design shows a high performance on the characteristics that are 'traditionally' considered important by consumers as it has co-evolved with, and thus become adapted to, its selection environment. Fossil-fuel-based internal combustion engine vehicles, for example, show a high performance on 'traditional' characteristics such as driving range and maximum speed. When technology-push or demand-pull factors change the selection environment, consumers may take into account a different set of characteristics in their adoption decision. In the case of vehicle technologies environmental performance characteristics like fuel consumption and CO_2 emissions have recently gained importance due to concerns about climate change. New technological options, such as electric vehicles, perform better on these newly evaluated environmental performance characteristics than the incumbent technology, possibly leading to an increase of consumer adoption of the new technologies. This is not necessarily the case however, as incremental innovation may also improve the environmental performance of the incumbent technology.

We model this process in the following way: we assume that the emergence of new technological options in stage 1 expands the set of characteristics that consumers consider in their adoption decision. Thus consumers do not only evaluate the traditional performance characteristics but also take into account the environmental performance characteristics of a technology, although not all consumers will consider environmental performance characteristics important in comparison with the traditional characteristics. On average, new technologies are assumed to initially show a better performance on these newly considered environmental performance characteristics than the incumbent one, but a worse performance on the traditional characteristics.

Figure 2.2 shows the initial performance of vehicle technologies in two performance dimensions, a 'traditional' and an 'environmental' dimension. The performance of technologies on each of the characteristics is valued between 0 and 1. The incumbent technology performs high on the 'traditional' characteristic but low on the 'environmental' characteristic. On average, the emerging technologies perform higher on the 'environmental' characteristic but lower on the 'traditional' characteristic than the incumbent technology. The initial performance is drawn randomly from a normal distribution with mean t or e. For incumbent technologies $t = t_2$ on the traditional characteristic and $e = e_2$ on the environmental characteristic. For the new technologies $t = t_1$ on traditional characteristics and $e = e_1$ on the environmental characteristic. As can be seen in Figure 2.2 technologies are initialised with $t_1 < t_2$ and $e_2 < e_1$. The emerging technologies do not have the same performance on the different characteristics, because technological diversity is broader than just variety. Stirling (2007; 2011) identifies balance and disparity as important aspects of diversity in addition to variety. Variety refers to

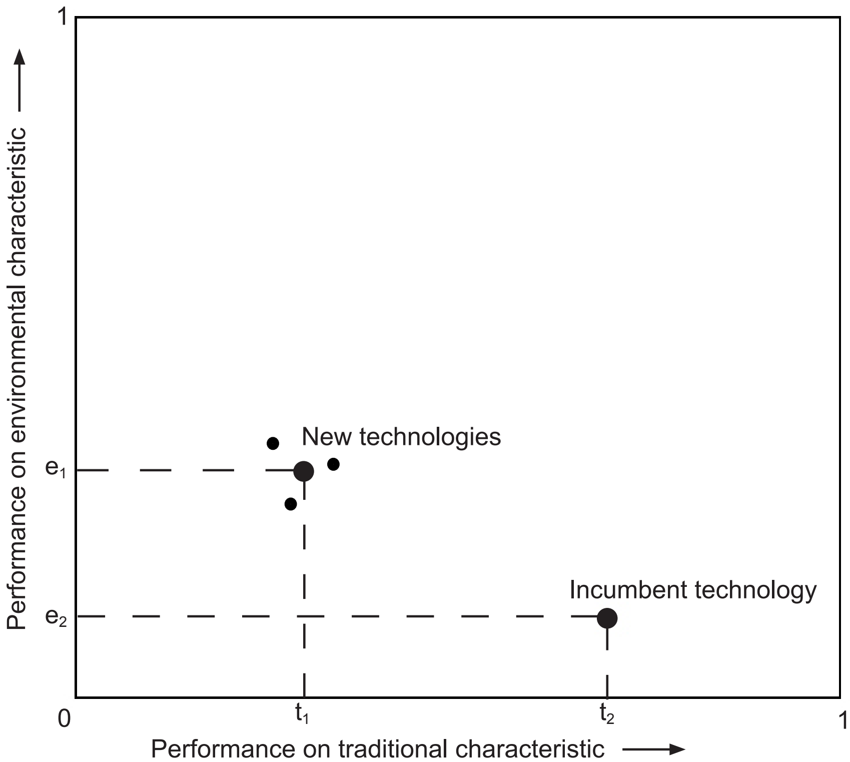


Figure 2.2: The initial performance of technologies in a traditional and a environmental performance dimension.

the number of different technological options, while balance describes the relative shares of each of the technological options. Disparity denotes how different the options are from each other. The average technological distance between the emerging technologies is higher for a higher disparity, which is modelled as the variance of t_1 and e_1.

Upon market entry, the price of newly created technologies is assumed to be higher than the price of the incumbent technology. The initial price of new technologies P_{i0} is equal to the initial price of the incumbent technology plus a random premium ϵ.[1]

[1] For the initial price of the incumbent technology, see Appendix A.

2.3.2 Infrastructures

Infrastructure-dependent vehicle technologies depend on the availability of a specific infrastructure, such as a refuelling or recharging infrastructure, and consumers consider the availability of this infrastructure in their adoption decision. Infrastructure is technology-specific in the model presented here, meaning that there is no compatibility between technology x and the infrastructure for technology y. The initial infrastructure availability for a technology is determined by the budget allocated by the policymaker to infrastructure development (B_2). This budget is equally divided among the selected technologies I_2. The initial infrastructure availability $A_{i(0)}$ of technology i is given by the following equation where κ represents the factor between financial resources and infrastructure availability and ρ represents initial investments in infrastructure availability by private firms:

$$A_{i(0)} = \kappa \cdot \left(\frac{B_2}{I_2} \right) + \rho \tag{2.1}$$

2.3.3 Consumers

The consumers in the model will adopt a technology that meets all their requirements. Consumers are myopic in that they do not take into account the positive and negative consequences of their behaviour, but base their decisions solely on past events and have no expectations about the future (Arthur, 1989). Consumers are characterised by fixed budget constraints m and infrastructure availability requirements a. Furthermore, consumers are heterogeneous and have different weights for the performance of the characteristics of a technology $x \in X$. A consumer's budget constraint m and infrastructure availability requirements a are drawn randomly from a normal distribution. The performance of a technology is valued in relation to the technological frontier. The maximum observed performance x_{max} on a characteristic x, over all technologies, is taken as a benchmark for that characteristic. The individual consumer weights φ for each characteristic x are drawn from a normal distribution with a mean equal to this benchmark x_{max}: $\varphi \sim N\left(x_{max}, \sigma^2\right)$. When the performance of the available technologies on a certain characteristic increases, the consumer weights for the performance on that characteristic increase as well, representing a technology-push mechanism. Consumer choice depends on how a consumer weighs the performance and the price of the technologies, and on the infrastructure availability for that technology. The decision-making process is described in more detail below:

1. *Adoption decision:* The probability that a consumer reconsiders his previous adoption decision and seeks to purchase a new vehicle is ω in each time step, where ω is the average replacement rate. When the consumer adopts a new vehicle, his current vehicle is replaced by either a new vehicle technology or the same vehicle technology as before, which might have improved on some characteristics.
2. *Determine weights for characteristics:* The consumer updates his weights for the technology characteristics given the current state of the technological frontier as described above.
3. *Identify affordable technologies:* A consumer only considers adopting a technology when the current price of that technology is below his budget constraint.
4. *Assess infrastructure availability:* A consumer only considers adopting a technology when the current availability of infrastructure for that technology satisfies his infrastructure requirements.
5. *Determine utility:* For those technologies that fulfil all requirements, the utility derived by the consumer from the performance characteristics of that technology is calculated. Utility U_i is the utility of consuming the set of characteristics X_i of a technology i (Windrum and Birchenhall, 2005; Lancaster, 1971). A simple Cobb-Douglas utility function determines the utility of each technology for an individual consumer:

$$U = x_1^{\varphi_1} x_2^{\varphi_2} \tag{2.2}$$

6. *Select and adopt technology:* Finally, the consumer weighs the utility and price of the technologies taken into consideration. When multiple options are considered the consumer adopts the technology with the highest utility/price ratio: $U_i / P_i^{(\varphi_1 + \varphi_2)}$. The adoption decision of a consumer thus consists of both hard constraints (1, 3 and 4) and soft constraints (2, 5 and 6).

The interactions of the different model components determine the dynamics of the model. They are discussed below. The characteristics, prices and infrastructure availability of infrastructure-dependent vehicle technologies change over time.

2.3.4 Technology dynamics

When new technologies such as low emission vehicles enter the market this can be considered a radical innovation. After market introduction these new technologies continue to evolve due to incremental innovation and learning effects. Incremental innovation in a technology occurs when the performance of that technology on one of its technological characteristics increases. This improves the competitive position of that technology and results in an increase in the number of adopters when the direction of technological change aligns with consumer preferences. Technological progress due to incremental innovation is modelled as a stochastic process in order to capture the inherent uncertainty of R&D as in Aghion and Howitt (1992) and Malerba and Orsenigo (2002). Each time step of the model innovation can only occur in one characteristic of a technology, representing a focus of the firm's innovation efforts (Moore, 1965; Nagy et al., 2011). Furthermore, innovation is path-dependent (David, 1985); once a firm has built up substantial technological capabilities in engine efficiency, additional R&D efforts in this area are more likely to lead to successful innovation than R&D efforts in areas where the firm has no prior experience. Performance increases in a certain characteristic are thus more likely if the firm's previous innovation efforts have focused on this characteristic.

This is modelled as follows: the probability that characteristic $x \in X_i$ of technology i is selected for innovation is equal to the cumulative number of innovations in characteristic x of technology i (Cum_{xi}), divided by the cumulative number of innovations in all characteristics of the technology i (Cum_i). The state of a characteristic after incremental innovation is given by Equation 2.3, where γ is the incremental innovation rate.[2] The effects of incremental innovation are large at first, but the effects of subsequent incremental innovations in a characteristic diminish over time as in a standard learning curve (Junginger et al., 2005, 2006).

$$x_{i(t+1)} = x_{i(t)}^{\gamma} \tag{2.3}$$

Besides changes in the characteristics of a technology, the price of a technology can also change over time. The price of a technology decreases over time due to economies of scale, learning by doing and R&D (Wright, 1936; Ferioli et al.,

[2] Incremental innovation can be unsuccessful if ($\gamma > 1$). In this case the incremental change is not adopted and the state of the characteristic remains unaltered.

2009). An increase in the consumer adoption of a technology causes a decline in a technology's purchase price (Mansfield, 1988; Arrow, 1962). The effects of a price decrease on consumer adoption are twofold: first, a price decrease makes the technology affordable to a larger group of consumers. Second, it increases the utility/price ratio of that technology. Both effects may lead to increased adoption. This relationship between price and the number of adopters is given by a standard learning curve as in Cantono and Silverberg (2009):

$$P_{i(t)} = P_{i(0)} \cdot \left(\frac{c_{i(0)}}{c_{i(t)}} \right)^{\alpha}, \tag{2.4}$$

where $P_{i(t)}$ is the price of technology i at time t, $P_{i(0)}$ the initial price of the technology, $c_{i(0)}$ the initial number of consumers, $c_{i(t)}$ the cumulative number of consumers of a technology and α the learning ability of a technology.

2.3.5 Infrastructure dynamics

Infrastructure co-develops with the size of the adopter group, due to indirect network externalities. On the one hand, an increase in infrastructure availability can enlarge the group of potential adopters, because more consumers will take the technology into consideration. On the other hand, an increase in the number of adopters of a technology leads to a higher availability of the infrastructure(s) for that technology because this attracts investors (Grübler, 1990). For example, low emission vehicles, such as battery electric vehicles, become more attractive when the availability of recharging points increase and an increase in battery electric vehicles will attract more investors in recharging points. Infrastructure availability A_i is described by Equation 2.5:

$$A_{i(t)} = \max\left(A_{i(t-1)}, A_{i(0)} + S_{i(t)}\right), \tag{2.5}$$

where $A_{i(0)}$ is the infrastructure availability at the time of emergence, $S_{i(t)}$ is the market share of technology i which is equal to the number of consumers that possess technology i at time t divided by the total number of consumers N.

2.4 Simulation settings and results

The simulation model is used to analyse how the allocation of public budget to the stages of public RD&D support and support for infrastructure development affects the technological substitution process. The model is run for different conditions, by varying three independent parameters: *total budget*, *RD&D costs per technological option*, and *disparity*. The total budget B that can be allocated to public RD&D support and infrastructure development is fixed at 1 in the simulations. Thus, an increase in budget allocated to public RD&D support ($B1$) corresponds with a decrease of the budget that is available to support the infrastructure development ($B2$) of the emerging technologies. Since the balance between costs of RD&D and infrastructure development is not trivial, this section presents the probability of technological substitution for different RD&D costs per technological option: zero (0), low (1/30), medium (1/15) or high (1/10). These different cost levels allow us to explore scenarios where the relative balance between the costs of RD&D and infrastructure development differs. Moreover, these parameter settings allow both for conditions where there is ample support for RD&D and infrastructure development and for conditions where the budget is limited due to high costs of RD&D per technological option. When the RD&D costs per technological option are high (1/10), allocating the complete budget to public RD&D support results in the creation of ten technological options; however, no budget will be left to support the infrastructure development of these ten technological options. Allocating the complete budget towards the infrastructure development of a single technological option results in the development of around 30% of the infrastructure for that technological option (see Equation 2.1). The literature suggests that an initial infrastructure availability between 15 and 20% is sufficient for the widespread diffusion of vehicle technologies (Melaina, 2003; Melaina and Bremson, 2003; Huétink et al., 2010). The exact level of infrastructure development that is sufficient for consumer adoption also depends on the technological characteristics of the vehicle, such as the range, and may thus be different for different technological options. More empirical research is needed here.

Disparity refers to the initial technological distance between the new technological options (see Section 2.3). Disparity is modelled by changing the variance σ^2 of the normal distribution function that sets the initial performance of the emerging technologies; it can be zero (0), low (0.02), medium (0.04) or high (0.06).

The average technological distance between the emerging technologies is higher for a higher disparity. The probability of technological substitution is expected to increase for a higher disparity, because in this case the technologies cover a wider area of the so-called search space (Frenken, 2006a; Silverberg and Verspagen, 2007).

Table 2.1 gives an overview of all possible allocations of public budget to RD&D support and infrastructure development up to ten technological options for the case of high RD&D costs per technological option (1/10). As an example, the table shows that RD&D support for two technologies leaves a budget of 0.8 ($= 1 - 2 \cdot 1/10$) to support the infrastructure development of these technologies. Policymakers can spend this budget either on the infrastructure development of both technologies (0.4 support per technology) or on the infrastructure development of one of these technologies (0.8 support). 100 model runs are simulated for each of the 55 possible allocations for 16 different conditions formed by the different disparity levels and RD&D costs per technological option.[3]

For each allocation the probability of technological substitution is calculated,

Number of technologies with RD&D support (stage 1)	Number of technologies with infrastructure development support (stage 2): 1	2	3	4	5	6	7	8	9	10
1	0.90									
2	0.80	0.40								
3	0.70	0.35	0.23							
4	0.60	0.30	0.20	0.15						
5	0.50	0.25	0.17	0.13	0.10					
6	0.40	0.20	0.13	0.10	0.08	0.07				
7	0.30	0.15	0.10	0.08	0.06	0.05	0.04			
8	0.20	0.10	0.07	0.05	0.04	0.03	0.03	0.03		
9	0.10	0.05	0.03	0.03	0.02	0.02	0.01	0.01	0.01	
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2.1: Overview of all possible allocations of budget to RD&D support and infrastructure development up to ten technological options for the case of high RD&D costs per technological option (1/10). The table shows the support for infrastructure development that each selected technology receives.

[3] The total number of simulation runs is 88.000 (55 possible allocations x 16 (4x4) different conditions x 100 runs.

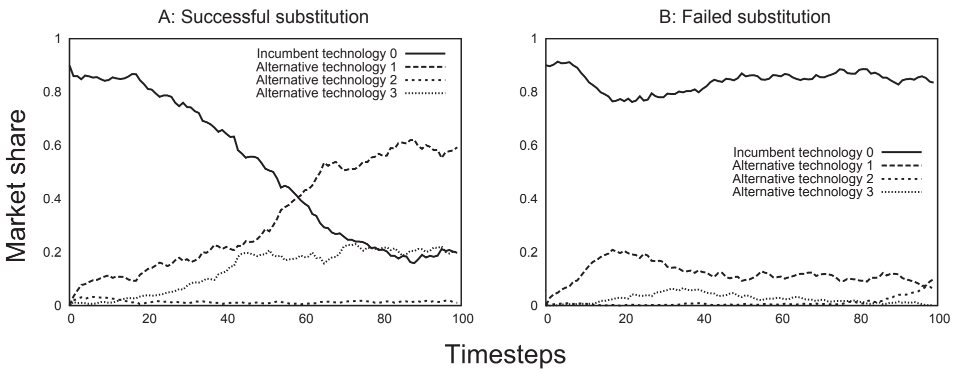


Figure 2.3: Typical runs of successful technological substitution (left) and failed technological substitution (right).

i.e., the percentage of simulation runs in which substitution of the incumbent technology by a new technology took place within 100 time steps. More specifically, technological substitution occurs when one of the new technologies obtains a higher market share than the incumbent technology at that time. So, if the incumbent technology is replaced by an alternative technology in 10 out of the 100 simulation runs for a particular allocation, the probability of technological substitution is 0.10. Figure 2.3 shows two typical runs, of a successful and a failed technological substitution process respectively.

Figure 2.3 shows the emergence of three alternative technologies at time step zero, when there is lock-in into the incumbent technology. The graph on the left of Figure 2.3 illustrates a simulation run where one of the alternatives becomes the dominant technology after 59 time steps, indicating successful technological substitution. The graph on the right of Figure 2.3 illustrates a simulation run where none of the alternatives succeeded in replacing the incumbent technology as the dominant technology. Failed technological substitution may be due to, for example, sailing-ship effects of the incumbent technology, bad technological performance and development of the alternative technologies, insufficient support for infrastructure development of these alternatives, or too much competition among the alternatives. A more elaborate analysis of the simulation outcomes at the level of single simulation runs in the context of sustainability transitions is presented in Section 2.5. This section proceeds with presenting the aggregate outcomes of the simulations.

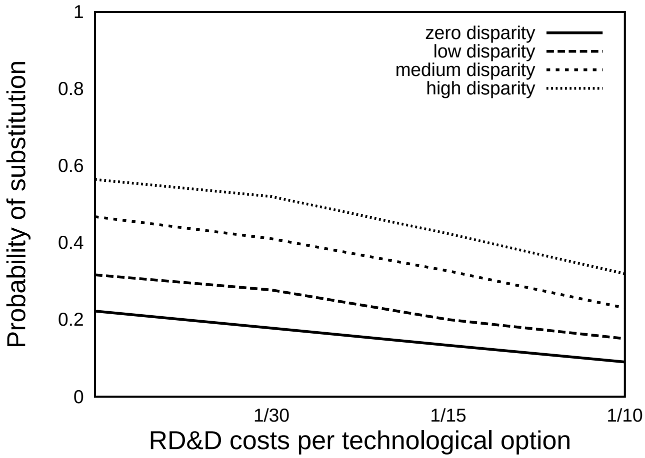


Figure 2.4: The relationship between the RD&D costs per technological option and the probability of technological substitution for different levels of disparity.

Figure 2.4 first shows the effects of the different parameters on the technological substitution process. The figure illustrates the relation between the RD&D costs per technological option and the probability of technological substitution for different levels of disparity. As expected, the figure shows a negative relation between the RD&D costs per technological option and the probability of technological substitution, because less budget is available to support the infrastructure development when the RD&D costs increase. The effects are highest for a high disparity level. Moreover, an increase in disparity results in a higher probability of technological substitution, as the technologies cover a wider area of the search space and the probability that one of the new options show high performance increases.

In summary, the highest probability of technological substitution occurs under conditions of low RD&D costs per technological option and high disparity. The effects of different allocations of public financial resources on the probability of technological substitution are analysed below. First, the effects of resource allocation to public support for RD&D is presented, followed by analyses of the effects of resource allocation to public support for infrastructure development, and the trade-off between the allocation of financial resources to support for RD&D and infrastructure development.

2.4.1 The effects of public support for RD&D

Figure 2.5 shows the relationship between public support for RD&D and the probability of technological substitution for the different disparity levels. The RD&D costs per technological option increase from zero (graph A) to high (graph D). The x-axis indicates the number of technologies with RD&D support in this first stage. For each number of technological options with RD&D support, the average probability of technological substitution is calculated over all possible allocations.[4]

Figure 2.5 illustrates the trade-off for the policymaker related to the optimal level of RD&D support. First, when RD&D comes at no costs (graph A), there is a positive relation between the number of technologies with RD&D support and the probability of technological substitution for medium and high disparity levels, but not for lower disparity levels. When more technologies receive RD&D support the probability that a high performing technology is among them increases immediately and in the long run. These positive effects of public RD&D support are largest when disparity is high. When disparity is zero, the supported technological options initially perform similar on the technological characteristics, therefore the benefits of supporting an extra technology with infrastructure development are small.

Second, when the RD&D costs per technological options are greater than zero there are decreasing returns of public support for RD&D, illustrated in graphs B (low costs), C (medium costs) and D (high costs). Graph D illustrates that support of technological options for RD&D only leads to a high probability of technological substitution when enough budget remains to support the infrastructure development of these technological options in stage 2 as well (e.g., at low levels of public support for RD&D). From graph B to graph D the optimal number of technologies with RD&D support shifts to the left for all disparity levels due to the increase in RD&D costs. Moreover, the decreasing returns of public support for RD&D are higher when the RD&D costs increase. This indicates that in domains that need large infrastructural investments, such as mobility technologies, public support for RD&D by itself is not sufficient to realise a

[4] For example, when three technological options receive RD&D support it is possible to support one, two or three of these technologies for infrastructure development. In this case averages are calculated over these three allocation possibilities.

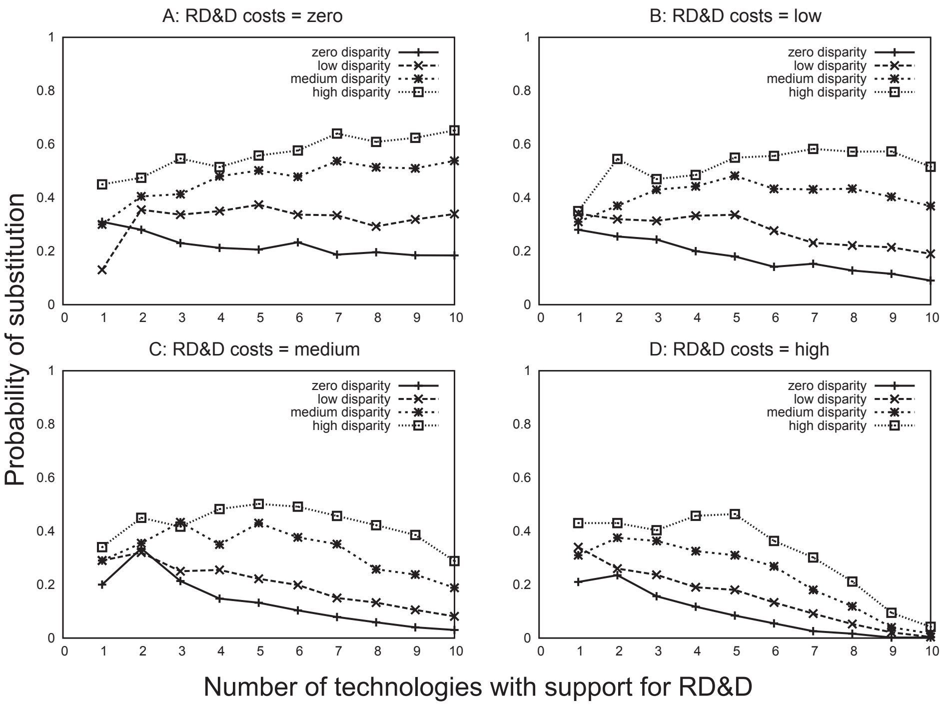


Figure 2.5: The relation between public support for RD&D and the probability of technological substitution for the different disparity levels. The RD&D costs per technological option are zero (graph A), low (graph B), medium (graph C) and high (graph D).

transition. In the model, the best balance between public support for RD&D and infrastructure development is found at low levels of public support for RD&D.

A final outcome of the simulations is that public support for RD&D is more beneficial if the new technologies are sufficiently different (high disparity). Graph B illustrates that the optimal number of technologies with RD&D support decreases for lower levels of disparity. Similar patterns are observed in graphs C and D. This indicates that the policymaker should take into account the technological characteristics of the different alternatives, adding a technology-specific element to the decision. For example, support of fuel cell vehicles and vehicles on biogas is expected to be more beneficial than support of vehicles on natural gas and vehicles on biogas, because the technological difference between fuel cell vehicles and biogas is higher than the technological difference between vehicles on biogas and natural gas.

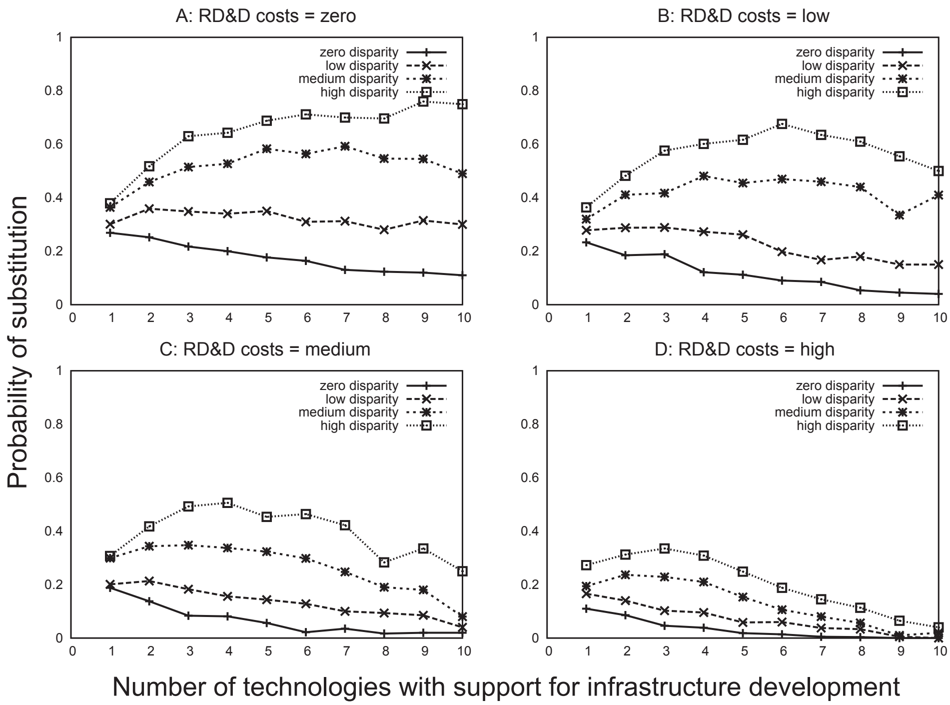


Figure 2.6: The relation between public support for infrastructure development and the probability of technological substitution for the different disparity levels. The RD&D costs per technological option are zero (graph A), low (graph B), medium (graph C) and high (graph D).

2.4.2 The effects of public support for infrastructure development

Figure 2.6 shows the relationship between public support for infrastructure development and the probability of technological substitution for the different disparity levels. Similar to Figure 2.5 the RD&D costs per technological option increase from zero to high for graphs A to D. The x-axis indicates the number of technologies that also receive support for infrastructure development. For each level of support for infrastructure development, the average probability of technological substitution is calculated over all possible allocations.

Figure 2.6 illustrates several trade-offs that the policymaker is faced with. First, when disparity is zero, a negative relation is observed between the number of technologies with support for infrastructure development and the probability of technological substitution. Since the initial technological performance of the different technological options is equal when disparity is zero, the benefits of supporting multiple technologies are low. In this case the highest probability of technological substitution occurs when the complete budget is allocated to the support of a single technological option. This negative relation between the number of technologies with support for infrastructure development and the probability of technological substitution holds for all cases where disparity is zero, independent of the RD&D costs per technological option (see graphs B, C and D).

Second, when disparity is medium or high it is beneficial to support different technological options. However, there is a minimum size of the support that is required for that support to have an effect. At some point the probability of technological substitution decreases again when more technologies are supported due to the division of the budget over more technologies. When more technologies are supported it is more difficult for each individual technology to realise increasing returns to adoption. The figure illustrates that the optimal number of technologies with support for infrastructure development also depends on the RD&D costs. For example, when disparity is high and support for RD&D comes at no costs, the optimal number of technologies with support for infrastructure development is at least ten (graph A). The optimal level decreases when the RD&D costs increase. The optimal level occurs at six supported technologies for low RD&D costs (graph B), four supported technologies for medium RD&D costs (graph C), and three supported technologies for high RD&D costs (graph D). In summary, when the RD&D costs per technological option increase this decreases the optimal number of technologies with support for infrastructure development.

2.4.3 Trade-off between support for RD&D and infrastructure development

Figure 2.7 illustrates the trade-off between public support for RD&D and infrastructure development and provides insight into the effects of resource allocation. At the top row of Figure 2.7, the disparity level is low, whereas the bottom row shows the probability of technological substitution for medium disparity. The graphs on the left show the probability of technological substitution for low RD&D costs per technological option, while the RD&D costs are medium for the graphs on the right-hand side. Each graph presents the probability of technological substitution for both the number of technologies with support

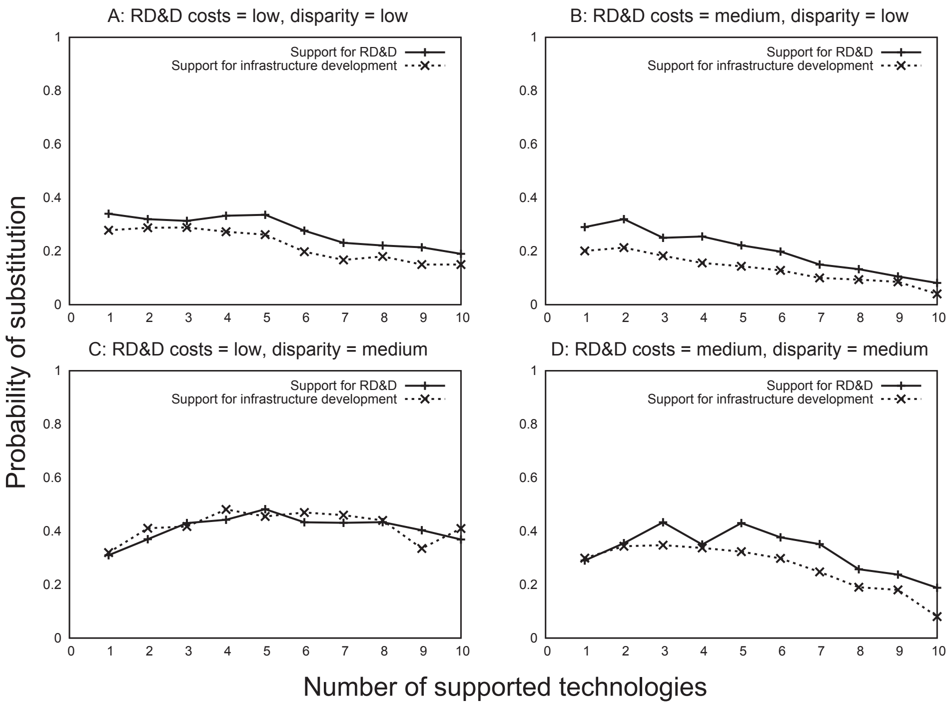


Figure 2.7: The relation between the number of supported technologies and the probability of technological substitution in stage 1 and stage 2. For different RD&D costs and different disparity levels: low RD&D costs and low disparity (top left), medium RD&D costs and low disparity (top right), low RD&D costs and medium disparity (bottom left) and medium RD&D costs and medium disparity (bottom right).

for RD&D and the number of technologies with support for infrastructure development.

The effects of RD&D costs per technological option and disparity on the optimal number of technologies with RD&D and infrastructure development support have been discussed above. Figure 2.7 shows that in our simulations the optimal number of technologies with RD&D support is similar to the optimal number of technologies with infrastructure support. This means that it is optimal to support also the infrastructure development of the technologies that received RD&D support. In other words, a policymaker should not support more technological options with RD&D than can be supported for infrastructure development. This observation seems to be independent of the RD&D costs and the disparity level.

The explanation for these results can be found in the decision-making process of the policymaker. It is assumed in this chapter that policymakers are not capable of picking winners, it is very difficult to determine *ex-ante* which technologies will be most successful. This is modelled as a random selection of the technologies that are supported with infrastructure development. This decision-making process is further explored below.

2.4.4 Informed decision making

Figure 2.8 presents the trade-off between public support for RD&D and infrastructure development for the case that policymakers do have the capability to assess the performance of the new technological options. Here it is assumed that policymakers can perfectly assess the initial performance of the technologies that received support for RD&D in stage 1, that is, they can adequately observe and interpret the outcomes of RD&D and pilot projects when deciding upon large scale support for infrastructure development in stage 2. This is modelled by supporting the infrastructure development of those technologies with the highest initial quality/price ratio[5].

A comparison of Figure 2.8 with Figure 2.7 illustrates the effects when the policymaker is capable of choosing the most promising technological options. The optimal number of technologies with RD&D support shift to the right when policymakers can make an informed rather than random decision over which technologies to support. So, it is beneficial to support more technological options for RD&D when a policymaker can evaluate the performance of these options. Informed decision making thus increases the benefits of allocating financial resources to RD&D support. Furthermore, the relation between the number of technologies with support for infrastructure development and the probability of technological substitution is negative, so that supporting one technological option for infrastructure development is most beneficial. Since a policymaker can pick the most promising option it pays to invest in this option. However, when the disparity level increases (from low disparity in Figures 2.8A and B to medium disparity in Figures 2.8C and D), it becomes more attractive to support

[5] $(x_1 x_2)/P$

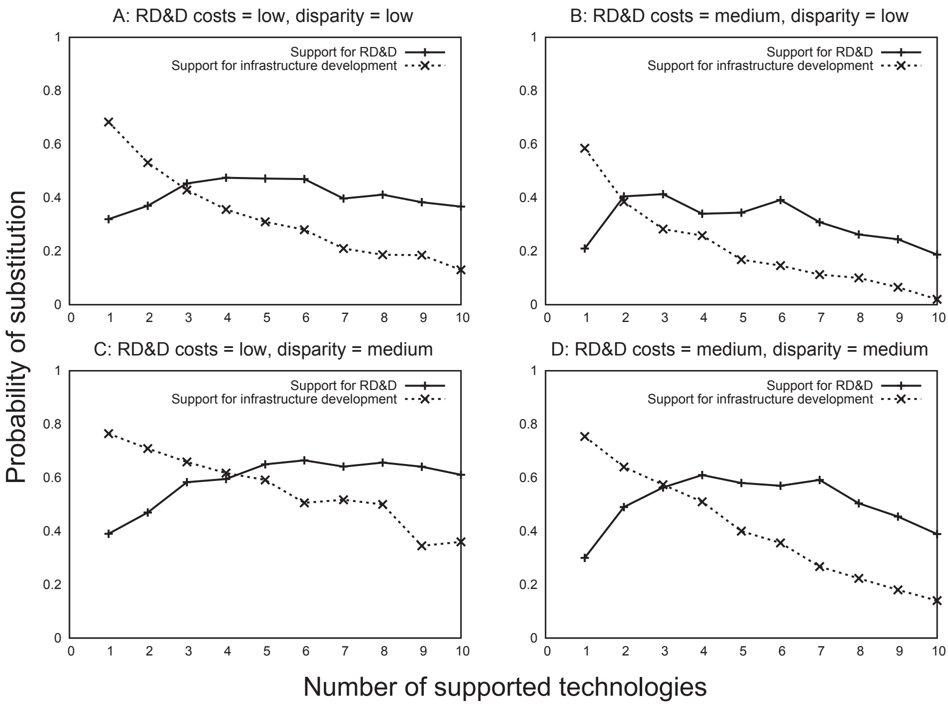


Figure 2.8: The relation between the number of supported technologies and the probability of technological substitution in stage 1 and stage 2 with informed decision making. For different RD&D costs and different disparity levels: low RD&D costs and low disparity (top left), medium RD&D costs and low disparity (top right), low RD&D costs and medium disparity (bottom left) and medium RD&D costs and medium disparity (bottom right).

the second and third most promising options as well. There is thus a clear benefit from increased information regarding the technological characteristics and performance of the different technological options.

In sum, for an informed policymaker the best allocation saves a budget for infrastructure development for the most promising technology while the remainder of the budget is spent on the creation of technological alternatives (RD&D support).

2.5 Analysis of results in a sustainability transitions context

From the perspective of sustainability transitions, technological substitution is neither a sufficient nor a necessary condition for a transition to occur, as new technologies might perform worse in terms of environmental indicators than the incumbent technology. Furthermore a sustainability transition can also occur when the incumbent remains dominant but becomes more sustainable. A sustainability transition can thus be realised in different ways. Geels and Schot (2007) have provided a typology of so-called transition pathways, distinguishing four different pathways: transformation, de-alignment/re-alignment, technological substitution and reconfiguration. These pathways differ with respect to the timing and the nature of the interactions between the different actors involved.

The model simulations presented in this chapter started from a situation of lock-in into an incumbent technology. At time 0, the time of emergence of different alternatives, consumers start taking the environmental performance characteristic into account. The incumbent technology scores better on the traditional characteristic whereas the emerging technologies score better on the environmental performance characteristic. A sample of all simulations runs is taken to study the development of the technological characteristics.[6]

Figure 2.9 illustrates three typical patterns. In each graph the solid line depicts the market share of the incumbent technology. The dashed lines depict the average performance on the different characteristics weighted by the numbers of adopters of each technology. At the start of the simulations the incumbent technology dominates the market, which causes the average performance, weighted over all technologies, on the environmental characteristic to be very low in comparison to the average performance, weighted over all technologies, on the traditional characteristic.

Figure 2.9A presents the case where no technological substitution and no transition takes place. This pathway, in which the incumbent technology does not lose any market share and shows accumulated incremental innovations in the traditional characteristic, is observed in 37.6% of the sample simulation runs and corresponds to what Geels and Schot (2007) label as the *reproduction process*.

Figure 2.9B represents the case with both technological substitution and a tran-

[6] For each of the 880 experiments (55 allocations, 16 different parameter settings) a single run was randomly selected (out of the 100 simulation runs).

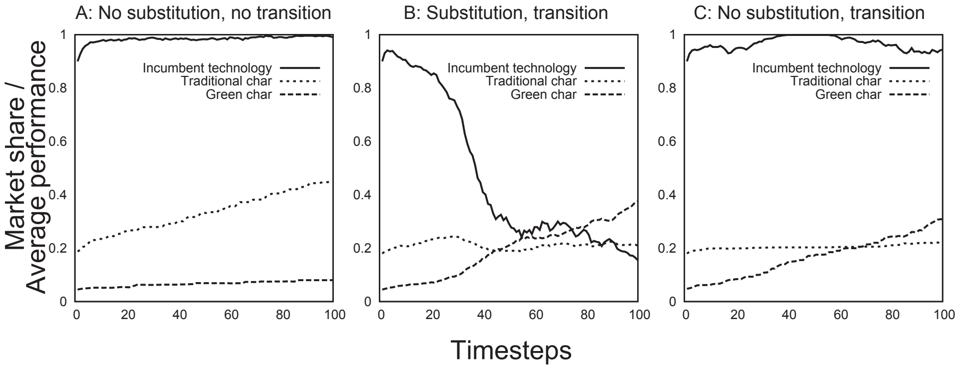


Figure 2.9: Transition pathways: The solid line in each graph presents the market share of the incumbent technology over time, which determines whether or not technological substitution occurred. The dashed lines show the average performance on the traditional and environmental characteristic weighted over all adopted technologies, which determines whether or not a sustainability transition occurred.

sition. The model outcome is considered a sustainability transition when the average performance on the environmental characteristic improves substantially and is at least as good as the initial performance of the incumbent technology on the traditional characteristic (see Appendix A). Technological substitution is observed in 36.3% of the sample simulation runs, and in 64.9% of these it is accompanied with a transition. The performance on the environmental characteristic improves over time and the new dominant technology is more sustainable than the previous incumbent technology. At the same time, a slight decline of the performance on traditional characteristics is observed, as the substituting technology is not yet completely developed on these characteristics. Geels and Schot (2007) label this type of transition pathway *de-alignment and re-alignment* followed by *technological substitution*.

Figure 2.9C again shows an example of a simulation where no technological substitution takes place. Nevertheless, it shows a considerable improvement in the environmental performance characteristic. This pathway is observed in 26.1% of the sample simulation runs and corresponds to the *transformation pathway*, in which *"the regime actors respond to landscape pressure by modifying the direction of development and innovation activities"* (Geels and Schot, 2007). The alternative technologies cannot take advantage of this pressure because they are not yet sufficiently developed. One might also link such a transition to the *reconfiguration pathway*, in which the new regime also grows out of the old regime, only here the regime's basic architecture changes as is often the case for sociotechnical systems.

2.6 Conclusions and policy implications

In this chapter we have presented a model of technological substitution focused on infrastructure-dependent vehicle technologies. The focus was on how the allocation of public financial resources to public support for RD&D and infrastructure development affects the replacement of a locked-in technology by a new technology. Although consumers in our model eventually determine which technology will be successful, policymakers can affect the probability (and speed) of the technological substitution process. We have analysed the effects of resource allocation to these stages by performing numerical simulations with our model. More specifically, the simulations provided insight into the trade-off between the allocation of a limited budget towards the creation of new technological options by supporting RD&D on the one hand, and the support for infrastructure development of these technologies on the other hand.

The results of our model indicate that for infrastructure-dependent vehicle technologies, an increase in public support for RD&D does not necessarily lead to a higher probability of technological substitution (or a transition). Supporting the RD&D for different technological options is usually costly, and these costs should only be made under conditions where it is possible to benefit from the increased technological variety. According to the model analysis, support for RD&D of different technologies is most useful when it meets three conditions: first, the supported technological options should be sufficiently different with respect to their technological performance in order to cover a wider area of the so-called search space. The analysis of the results show that such disparity increases the probability that a technological option will be developed that successfully competes with the incumbent technology.

A second finding is that policymakers should allocate substantial financial resources to the public support for infrastructure development of the infrastructure-dependent vehicle technologies. So, public support for RD&D in stage 1 is only rewarding when each of the created technologies is also substantially supported for infrastructure development in stage 2. The results illustrate that supporting many different technologies, each with a modest support for infrastructure development makes it difficult for any individual vehicle technology to realise increasing returns to scale.

A third important insight is that if policymakers are able to adequately evaluate the different technological options supported in stage 1, and because of that are able to pick the most promising options for support of their infrastructure development, the policymaker can reduce the number of technological options with support for infrastructure development and increase the number of options with RD&D support. As uncertainty is inherent to the development of new technologies, this knowledge is usually not available.

The foregoing conclusions only hold when there is a strict dependency of vehicle technologies on the availability of a particular physical infrastructure. Policies aiming at the technological substitution of infrastructure-dependent vehicle technologies should include all stages of the technological substitution process as well as a clear prescription of how results from early stages feed forward into later stages.

3 Competing technological options for the future*

3.1 Introduction

Environmental and societal concerns have led to a search for more sustainable alternatives to the current fossil-fuel-based mobility system. Several technological options for low emission vehicles have emerged in recent years, among which are hydrogen, electric and hybrid cars, alongside cleaner, less polluting versions of the incumbent fossil-fuel-based technology (OECD, 2011). These technological options differ with respect to their economic and environmental performance, their stage of development, and the extent to which they rely on the build-up of new infrastructure, but have in common that they compete to replace the current internal combustion engine as the dominant design for transport. Different types of actors attempt to influence these new technological trajectories: government actors are involved as they seek to reach sustainability targets and can provide the large investments needed for the build-up of new infrastructures; supply-side actors strategically compete and cooperate to stimulate the different technological options. For example, Budde et al. (2012) found that Daimler followed a more cooperative strategy for the development of its hydrogen technology than for the development of its hybrid electric vehicles, as the build-up of a hydrogen infrastructure requires the cooperation of a wider set of actors.

Firm actors involved in green technology management and investment have to determine their strategy in an environment of co-evolving consumer preferences, technology characteristics and green technology policies. This provides a complex task. Several authors have studied this complex setting, mostly focusing on the supply-side (technology providers) or on how policy instruments affect the conditions for technological change (Safarzynska and van den Bergh, 2010; van der Vooren et al., 2012; Schwoon, 2006; Huétink et al., 2010). In addition, several demand-side models study the conditions under which a single new technology succeeds in replacing a dominant and locked-in technology (Dalle, 1997; Malerba et al., 2007; Shy, 1996; Windrum and Birchenhall, 2005). These

* This chapter is published as: van der Vooren, A. and Alkemade, F.: 2012, Managing the diffusion of low emission vehicles, *IEEE Transactions on Engineering Management* 59(4), 728 - 740.

models demonstrate that conditions in favour of technological change are:

1. consumer heterogeneity such as varying consumer preferences, different consumer groups and experimental users;
2. early competitiveness of alternative technologies;
3. the valuation of technology characteristics of new technologies (preference changes);
4. backward compatibility of new technologies; and
5. local network externalities for the new technology.

These conditions enable the early adoption necessary for the diffusion of new technologies and can be influenced by supply-side and government actors to some extent.

Whereas theory thus emphasises the role of consumers (adopters) in processes of technological change, many scenario studies and earlier models focus on the supply side, using highly stylised aggregated models of consumer behaviour (Martin and Johnston, 1999; Dunn, 2002; Phaal et al., 2004; HyWays, 2008). However, for firms that seek to bring new technologies to the market it is pivotal to take into account consumer heterogeneity, as this influences the particular market niches that are most attractive for the firm. In order to gain better insight into the strategic considerations involved in the transition towards a more sustainable mobility system, it is therefore important to take both demand-side and supply-side as well as technological characteristics into account. The method of agent-based modelling (Holland, 1992; Epstein and Axtell, 1996; Axelrod, 1997; Bonabeau, 2002) makes it possible to study such systems consisting of heterogeneous interacting agents, which are difficult to treat analytically.

This chapter therefore analyses the competition between several new and market-ready technologies and an incumbent technology in an agent-based simulation model. This model is applied in a simulation of currently available sustainable mobility technologies in order to study the influence of different demand-side (market-pull) policy instruments on consumer adoption. The chapter thereby focuses on the strategic implications for supply-side actors, as model results indicate that different policies require different strategic responses from suppliers.

The remainder of this chapter is structured as follows: first, the theoretical framework is presented in Section 3.2. Section 3.3 then describes the agent-based model that simulates consumer adoption and the policy instruments that will be tested. Section 3.4 analyses and discusses the simulation results, and finally Section 3.5 concludes.

3.2 Theoretical framework

Vehicles on fossil fuels are currently the dominant mobility technology; they are widely adopted, proven, relatively cheap, have sufficient supportive infrastructure and benefit from different types of increasing returns (Arthur, 1989). A dominant technology is the one that wins marketplace allegiance, and the emergence of a dominant design is the result of the interplay between technical and market choices (Utterback, 1994). Often dominant technologies emerge from the competition between a number of alternative technologies (Abernathy and Utterback, 1978; Anderson and Tushman, 1990). For example, today's dominant internal combustion engine vehicles (ICEVs) competed with electric- and steam-powered vehicles to succeed the old technology of horse carriages. The outcome of such a competition depends on the cumulation of small 'historical' events and is therefore highly uncertain and unpredictable until a technology becomes dominant and gets locked in (Arthur, 1988).

The determinants for lock-in can be found in path dependent processes (David, 1985) and increasing returns to adoption (Unruh, 2000; Weisbuch et al., 2008) such as learning by using (Rosenberg, 1982), scale economies, informational increasing returns, technological interrelatedness (Frankel, 1955) and network externalities (Katz and Shapiro, 1985). Because of these sources of increasing returns to adoption, the dominant technology continues to be chosen by both the demand-side and supply-side actors and will improve further (Arthur, 1988), thereby hindering the diffusion of alternative, possibly superior, technologies (Frenken et al., 2004; Unruh, 2002).

As soon as society is locked-in into a dominant technology, it becomes difficult to achieve technological substitution, which is the replacement of a dominant technology by a new technology. A dominant technology establishes standards in terms of price and quality of the technological characteristics by which the new technology is evaluated. In other words, the dominant technology forms the selection environment for the new technology. This hinders substitution, since new technologies initially often show higher prices and poor performance in comparison to the incumbent technology (Rosenberg, 1976). When these new technologies depend on the availability of a physical infrastructure (that is incompatible with the existing infrastructure) overcoming lock-in is even more difficult. New technologies in the domain of energy and transport often require significant capital-intensive investments in infrastructure such as the construction of fuel stations or electricity grids (Gómez-Ibáñez, 2003; Markard, 2011). Due to these particular characteristics of technologies in the energy and transport sector and its public character, governments often intervene in technological substitution processes in this domain.

Although difficult to overcome, lock-in is nevertheless a temporary phenomenon from which escape is possible. Technology-push, market-pull or a combination of both mechanisms can give rise to new options or inventions that might replace existing technologies (Dosi, 1982). Market-pull processes can either originate from consumers due to evolving preferences or dissatisfaction with the current (unsustainable) technological paradigm or from government stimulation (adapted regulation or subsidies available to develop new technological options). However, it is very difficult to determine *ex-ante* which invention will lead to the replacement of the incumbent technology by a new technology (Kemp et al., 1999).

Currently, several technological options exist that can (partially) substitute fossil-fuel-based mobility options (OECD, 2011). This chapter considers three types of low emission vehicles: plug-in hybrid electric vehicles (PHEV); battery electric vehicles (BEV); and hydrogen fuel cell vehicles (HFCV). These technologies compete with each other and with the currently dominant fossil-fuel-based technology used in ICEVs. The degree of adaptation of a technology to its selection environment determines how successful a technology is in this competition (Saviotti, 1996). A good fit between an option and the requirements of the environment, which could for example focus on sustainability, costs or flexibility, makes a technological option promising. The selection environment comprises all factors that affect the competition process (Nelson and Winter, 1982) such as institutions, spatial structure and markets (Lambooy, 2002). Favourable institutions such as rules, regulations, subsidies, social norms, agreements and quality and safety norms can increase the probability of survival for an emerging technological system, i.e., for a specific low emission vehicle technology (Boschma et al., 2002).

Given the inherent uncertainty of the innovation process, it is difficult to evaluate the different alternatives, complicating the decision about which and how many technological options to support. For vehicle technologies support often takes the form of subsidies to install initial infrastructure or of purchase price subsidies decreasing the distance-to-market for the new technology.

Once technological alternatives to the dominant design become market ready (targeting either mass or niche markets), the market forms the main selection environment, where the price of the technology and the degree to which the technological characteristics of the new technology fit consumer preferences become the main selection criteria (Lancaster, 1971). Adoption of a technology by consumers is the final stage of the substitution process, as consumers eventually determine which technology is diffused through widespread adoption.

The selection environment is not static in this phase as consumer preferences evolve due to the availability of new technologies or due to exogenous forces that stress technological and service characteristics that differ from the characteristics of the current dominant design. Not only the new technological options benefit from this changing selection environment, the incumbent technology might also adapt to the changing environment (for a discussion of this so-called sailing-ship effect see Harley (1973); Geels (2002)). For infrastructure-dependent technologies the availability of an infrastructure is an important determinant of user preferences (Bunch et al., 1993; O'Garra et al., 2005), which indicates that this problem of technological substitution is characterised by indirect network effects (Katz and Shapiro, 1985; Koski and Kretschmer, 2004), increasing the probability of lock-in. Establishing refuelling standards for the new technologies is therefore a pivotal aspect of infrastructure development and the lack of standards might make it even more difficult to escape lock-in. When one of the alternative vehicle technologies succeeds in gaining a substantial market share or in replacing the dominant technology, the lock-in is overcome and the substitution process is complete.

3.2.1 The trade-offs for decision-makers

There is significant uncertainty among governments, technology providers and consumers about which low emission vehicle technology will be dominant in the future. Governments try to stimulate the transition to sustainable mobility with diverse policy instruments such as subsidies for the purchase of cleaner vehicle technologies. Policy intervention can reduce uncertainty and resistance among consumers, which slow down the transition. However, the precise effect of such support instruments on the speed of the transition are unclear since different low emission vehicle technologies might be preferred under different policy conditions. Decision-makers, such as firm actors involved in green technology management, are thus strongly dependent on government policy when making investment decisions. For these firm actors, determining their strategy in an environment of co-evolving consumer preferences, technology characteristics and green technology policies is a complex task involving several trade-offs.

Different alternative low emission vehicle technologies such as the PHEV, the BEV and the HFCV technology compete with the dominant ICEV technology to become the new dominant design in the future. Furthermore, these alternatives compete with each other for consumer adoption as well as for resources such as subsidies. Since it is difficult to escape lock-in, these technologies might benefit from collaboration. According to van de Ven (2005) stakeholders of competing alternative sustainable technologies must "run in packs" (cooperate with each other) as they seldom have the resources, power, and legitimacy to go at it alone. Standardisation is one of the most important cooperative strategies in the mobility sector as it creates network externalities and might lower the costs of escaping lock-in. For example, the standardisation of charging infrastructures for electric vehicles could attract early adopters and create economies of scale. Conformation to standards can thus be beneficial for technological change, but for each individual firm it is most beneficial if its own technology becomes the standard which often leads to so-called standard wars that cause delay in adoption and uncertainty among all actors involved.

Running in packs can also increase the success of lobbying activities for generic support policies. Generic support policies, such as a carbon tax, stimulate the adoption of more sustainable alternatives. Such generic policies avoid picking winners and the risk of early lock-in. In addition to joint lobbying for generic support, firms can also lobby for technology-specific support. Specific support policies such as the construction of infrastructure and purchase price subsidies for one of the vehicle technologies can assist early adopters in overcoming barriers and can create a competitive advantage for that technology. According to Azar and Sandén (2011) such specific-support policies are needed for the mobility system in order to reduce uncertainty for private investors and to bridge the gap between invention and large-scale diffusion.

Moreover, specific support can accelerate the transition towards a more sustainable society when the supported technology is a so-called "stepping stone" towards other preferred technologies. A stepping-stone vehicle technology is one that is more sustainable than the currently dominant technology but that is not considered a desirable end-state for sustainable mobility (Farla et al., 2009). Therefore, investing in a stepping stone technology creates the risk of undesired lock-in into this technology. For example, hybrid vehicles and vehicles running on natural or biogas were seen by the Dutch Transition Platform as a stepping stone towards a hydrogen-based mobility system. More recently hybridisation is seen as a stepping-stone technology towards all-electric vehicles (Farla et al., 2009). A common infrastructure, standardisation and other factors such as co-evolving consumer preferences can create synergies for the benefit of several technological options. This has strategic implications for decision makers concerning the question whether to support competing technologies that can function as a stepping stone technology.

Another strategic concern for decision makers is the timing of investments and other activities such as lobbying. Firm actors are competing to be the first with a market-ready technology. First-mover advantages arise when the new technology determines industry standards, raises expectations and generates funds (Bakker et al., 2013; Alkemade and Suurs, 2011). As discussed above another important source of first-mover advantages arises from the increasing returns to adoption that characterise infrastructure-dependent technologies.

Summarising, the trade-offs for managers relate to the extent to which infrastructure is shared; the presence of a stepping-stone technology, the presence of competing technologies, and the timing of possible strategic actions. Furthermore, these strategic considerations also depend on the presence of generic or specific policy measures for technology support. The model presented in the next section provides insights into these trade-offs for different policy environments.

3.3 The model

This section describes a model of the competition for consumer adoption between different alternative vehicle technologies and the incumbent locked-in vehicle technology. Each vehicle technology is characterised by different characteristics that describe its performance, a different price, and a different level of infrastructure availability. Consumers repeatedly make adoption decisions based on infrastructure availability and on the degree to which an affordable technology fits their preferences. Figure 3.1 gives an overview of the different model components (vehicle technologies, infrastructures and consumers) and their interactions. Each model component can be influenced by policy instruments, thereby eventually affecting the adoption decisions of consumers. In the following, a more detailed description of the model components and their interactions is given.

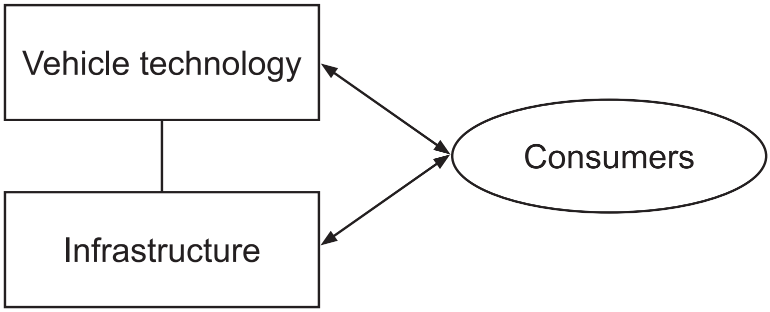


Figure 3.1: Overview of the main model components (vehicle technologies, infrastructures and consumers) and their interactions.

3.3.1 Vehicle technologies

In the model a vehicle technology i is described by its performance on a set of service characteristics $X_i \in [0,1]$, as by Lancaster (1971) and Saviotti (1996), and by its price P. Examples of service characteristics $x_i \in X$ of a vehicle technology are its driving range, acceleration, and emissions. Not all characteristics are considered equally important, and changes in the characteristics that are valued by consumers, i.e., changes in the selection environment, are an important driver of technological change (Dosi, 1982).

The current dominant design shows high performance on the characteristics that are currently considered important by consumers as it has co-evolved with and is adapted to its selection environment. When the selection environment changes (due to, for example, technology-push or market-pull factors), consumers may take into account a different set of technological characteristics when making their adoption decision. New technological options may perform better on these newly evaluated service characteristics than the incumbent technology, leading to an increase of consumer adoption of the new technologies. This is not necessarily the case however, as incremental innovation may also improve incumbent performance in the new direction. This model of co-evolving preferences and technologies is described the following.

The different vehicle technologies studied in the model (ICEV, PHEV, BEV, and HFCV) can each be described by four service characteristics. At the time of market introduction, the initial performance of the technologies on these performance characteristics differs. The four characteristics are: 1) functionality, including the driving range and refuelling time of the vehicle performance; 2) performance, including acceleration and top speed of the vehicle; 3) fuel consumption; and 4) emissions. Functionality and performance are characteristics that are traditionally focused upon by both consumers and producers; these characteristics are labelled as traditional characteristic T1 and T2. Fuel consumption and carbon emissions, labelled as sustainability characteristics S1 and S2, describe the environmental performance of the vehicles and have become increasingly important over the last decades.

ICEVs show high performance on the traditional characteristics that consumers perceive as important such as range and top speed and also on the price of the vehicle (Dijk, 2010), but relatively poor performance on characteristics such as fuel consumption and local emissions. BEVs do perform well on fuel consumption and emissions, but not so well on the traditional characteristics. The model starts from the assumption that the emergence of new technological options such as BEVs expands the set of service characteristics that consumers consider in their adoption decision. On average, emerging low emission vehicle technologies are assumed to outperform the incumbent technology on these newly considered sustainability characteristics but not on the traditional characteristics at the time of market entry.

Besides performance on service characteristics, vehicle purchase price also influences consumer decisions. The price of the alternative low emission vehicle technologies is assumed to be higher than the current purchase price of the ICEV technology whereby hydrogen vehicles (HFCV) have the highest purchase price. Table 3.1 illustrates the initial performance and price of the vehicle technologies considered in the chapter (OECD, 2011).[1] The initial performance level on each of the characteristics was chosen so as to reflect the current relative performance levels of the different technological options. The vehicle technologies are presented in rank order of their initial performance on the sustainability characteristics: initially ICEV is the least sustainable and BEV the most sustainable technology.

[1] The performance levels are implemented as follows: very poor (0.1); below average (0.2); average (0.3); above average (0.4); excellent (0.5). The initial price is either low (0.2), high (0.4) or very high (0.45).

Table 3.1: Initial performance: service characteristics and price.

		ICEV	*PHEV*	*HFCV*	*BEV*
T1:	**Functionality**	excellent	average	average	very poor
T2:	**Performance**	excellent	above average	below average	average
S1:	**Fuel consumption**	below average	average	above average	excellent
S2:	**Emissions**	very poor	below average	above average	excellent
$\mathbf{P_{(0)}}$**:**	**Purchase price**	low	high	very high	high

3.3.2 Infrastructures

Vehicle technologies depend on the availability of a specific refuelling (or recharging) infrastructure, and consumers consider the availability of this infrastructure in their adoption decision. There exist interdependencies between the infrastructures of different vehicle technologies. For example, the PHEV technology is compatible with both the fossil-fuel-based infrastructure and the energy infrastructure (electricity grid), as illustrated in Figure 3.2. ICEVs depend on the availability of fossil-fuel-based infrastructure only. HFCVs are compatible with hydrogen infrastructure only. PHEV technology thus benefits from improved availability of both fossil-fuel-based and electric infrastructure. The infrastructure availability $A_{i(t)}$ for a specific vehicle technology i at time t is given by the following equation:

$$A_{i(t)} = \sum_{g=1}^{G} A_{g(t)} \cdot \kappa_{i-g}, \qquad (3.1)$$

where $A_{g(t)}$ is the availability of infrastructure g at time t, G is the number of different infrastructures, and κ_{i-g} is the compatibility factor of technology i with infrastructure g. For example, when the PHEV technology depends for 25% on the fossil fuel infrastructure ($\kappa_{PHEV,fossilfuel} = 0.25$), 75% on the electric infrastructure ($\kappa_{PHEV,electric} = 0.75$), and 0% on the hydrogen infrastructure ($\kappa_{PHEV,hydrogen} = 0$), and the current availability of these three infrastructures is 1 (fossil-fuel-based), 0.3 (electric) and 0.45 (hydrogen) respectively, the infrastructure available for the PHEV technology is $A_{PHEV(t)} = 1 \cdot 0.25 + 0.3 \cdot 0.75 + 0.4 \cdot 0 = 0.475$. The development of an infrastructure g over time is further explained below in Subsection 3.3.5.

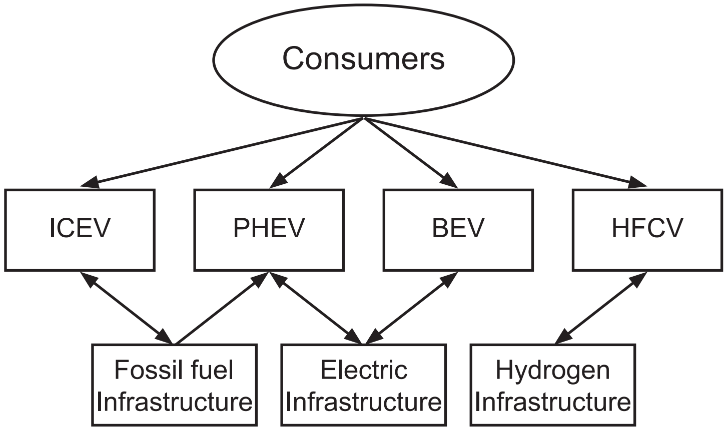


Figure 3.2: Infrastructure dependence of vehicle technologies. ICEVs depend on the availability of fossil-fuel-based infrastructure only. PHEVs are compatible with both fossil-fuel-based and electric infrastructure. BEVs depend on the availability of electric infrastructure for recharging. HFCVs are compatible with hydrogen infrastructure only.

3.3.3 Consumers

The consumer part of this model is based on the model that is presented in the Chapter 2. The consumers in the model are seeking to buy a vehicle and will adopt a vehicle technology when there is a vehicle on the market that meets all their requirements. Consumers are myopic in that they do not take into account the positive and negative consequences of their behaviour, but base their decisions solely on past events and have no expectations about the future (Arthur, 1989). Consumers are characterised by individual preferences Φ for the service characteristics of a vehicle technology $x \in X$, a budget constraint m and infrastructure availability requirements a. Consumers form their preferences by observing the performance of all available technologies. The maximum observed performance x_{max} on a characteristic x over all technologies is taken as a benchmark to evaluate that characteristic. Preferences for each characteristic x are drawn from a normal distribution with a mean equal to this reference point x_{max} ($\Phi \sim N\left(x_{max}, \sigma^2\right)$). Each period consumers thus define their preferences in relation to the current technological frontier and as a consequence they may thus have preferences that are not satisfied by the currently available technologies.

Consumer preferences co-evolve with technological performance thereby allowing for both technology-push and market-pull mechanisms in the model. When the performance of the available technologies on a certain characteristic increases, the consumer preferences for the performance on these characteristics increase as well, representing a technology-push mechanism. Market-pull mechanisms are present in the model as all else being equal; those technologies that show performance that fits better with consumer preferences are adopted more often in the model.

A consumer's budget constraint m and infrastructure availability requirements a are drawn randomly from a normal distribution. In combination with the performance of the technologies and infrastructure development, these consumer preferences and requirements determine consumer choice, which is described in more detail as follows:

1. *Reconsider adoption decision:* The probability that a consumer reconsiders his previous adoption decision and seeks to purchase a new vehicle is ω in each time step, where ω is the average replacement rate. When the consumer adopts a new vehicle, his current vehicle is replaced by either a new vehicle technology or the same vehicle technology as before, which might have improved on some characteristics.
2. *Determine preferences for characteristics:* The consumer updates his preferences for the technology characteristics given the current state of the technological frontier as described previously.
3. *Identify affordable technologies:* A consumer only considers adopting a technology when the current price of that technology is below his budget constraint.
4. *Assess infrastructure availability:* A consumers only considers adopting a technology when the current availability of infrastructure for that technology satisfies his infrastructure requirements.
5. *Determine utility:* For those technologies that fulfil all requirements, the utility the consumer derives from the performance characteristics of that technology is calculated. Utility U_i is the utility of consuming the set of service characteristics X_i of a technology i (Windrum and Birchenhall, 2005; Lancaster, 1971). The preferences for the performance on each characteristic function as thresholds. In case vehicle technologies meet or exceed the preferences Φ of a consumer on all characteristics x, the utility a consumer derives from adopting that technology is equal to 1 (upper part of equa-

tion 3.2). When technology performance does not meet consumer preferences on one or all characteristics, consumer utility is a function of the distance between preferences and actual technology performance. In this case the consumer gains the highest utility from the technology that is closest to his preferences (lower part of equation 3.2).

$$U_i = \begin{cases} 1 & \text{if } x \geq \varphi_x \; \forall_{x_i \varphi_x} : x \in X_i, \varphi_x \in \Phi \\ & \text{else } 1 - \sqrt{\sum_{X_i} (x - \varphi_x)^2} \end{cases} \tag{3.2}$$

6. *Select and adopt technology:* Finally, the consumer weighs the utility and price of the technologies taken into consideration. When multiple options are considered the consumer adopts the technology with the highest utility/price ratio: U_i / P_i^{β}, where β determines the importance of price in the adoption decision of the consumer. The adoption decision of a consumer thus consists of both hard (rules 1, 3 and 4) and soft constraints (rules 2, 5 and 6).

3.3.4 Policy measures

Different policy instruments can affect the decision-making process of consumers by influencing consumer preferences or technology prices (see also Figure 3.1). These instruments can be generic, aimed at all vehicle technologies, or technology specific. Whether generic or specific, policy instruments vary in timing and duration. Duration in the model is either temporary (10 time steps) or permanent (entire model run). Most policy measures are temporary although some countries have implemented long term energy and climate policies. In this chapter policies that lead to the construction of new infrastructure are also considered permanent, as the decay of infrastructure is generally slow (Grübler, 1990).

Generic instruments. A carbon tax on the vehicle purchase price makes vehicle technologies with a low performance on the emissions characteristic (S2) more expensive. This tax is permanent from the time of implementation onwards ($t = 0$, $t = 25$, $t = 50$ or $t = 75$) and is calculated by a linear function for vehicle technologies that perform below *excellent* (0.5) on the emissions characteristic (S2) at time t: $\text{Tax}_{i(t)} = 0.05 - 0.125 \cdot (\text{S2}_{i(t)} - 0.1)$. Hence, the carbon tax is highest when the technology performs *very poorly* (0.1) on the emissions characteristic and declines linearly to zero for technologies that perform excellent (0.5) on this characteristic. Initially all vehicle technologies, except for the BEV technology, are taxed (see Table 3.1).

Specific instruments. Technology-specific support starts at the time of emergence of a specific vehicle technology. The model considers two forms of technology-specific support: 1) the construction of additional initial infrastructure *Infra*, which is a permanent measure; and 2) a temporary technology-specific subsidy *Sub* on the purchase price.

3.3.5 Model dynamics

The interactions of the different model components determine the dynamics of the model. Moreover, technology service characteristics, consumer preferences, technology prices and infrastructure availability change over time. In Figure 3.3 the interactions between the main components are labelled. These interactions will be explained below. The model starts from a situation of lock-in into the ICEV technology, the incumbent technology. 'Lock-in' is defined as the situation where the incumbent technology is adopted by 90% of consumers and where the availability of the technology specific infrastructure is (close to) 100%. The BEV and PHEV technologies arrive in the market at time step zero of the simulation. At that moment 90% of the consumers drive the ICEV technology. When new vehicle technologies emerge, it is assumed that some initial infrastructure will be available to attract the first users. The HFCV technology arrives somewhat later in the market at time step 5, as this vehicle technology is currently not yet market ready. The different vehicle technologies evolve over time starting at time step zero.

Technology dynamics. Radical innovation occurs when low emission vehicle technologies such as PBEV or HFCV enter the market. After market introduction technologies continue to evolve due to incremental innovation and learning effects. Technological progress (arrow *A* in Figure 3.3) in a specific vehicle technology improves the competitive position of that vehicle technology and results in an increase in the number of adopters when the direction of change aligns with consumer preferences (arrow *B*). A technology improves when

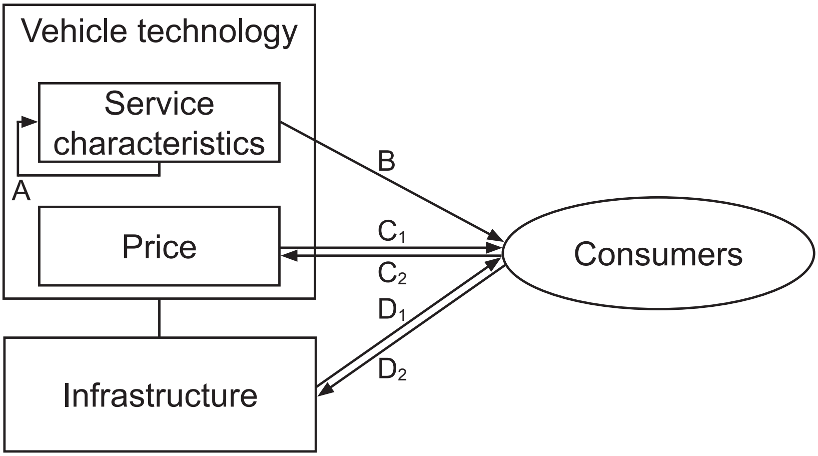


Figure 3.3: Dynamics of a demand-side model of consumer adoption: (A) technological progress; (B) technological performance, (C_1) price and (D_1) infrastructure availability all determine the competitive position of vehicle technologies and therefore the number of adopters; (C_2) adoption affects price represented by a standard learning curve; (D_2) adoption attracts investments in infrastructure.

its performance on the different technological characteristics improves. As the outcomes of R&D are highly uncertain, technological progress due to incremental innovation is modelled as a stochastic process (Aghion and Howitt, 1992; Malerba and Orsenigo, 2002). In each time step of the model innovation can only occur in one characteristic of a vehicle technology, representing a focus of the firm's innovation efforts (Moore, 1965; Nagy et al., 2011). Furthermore, innovation is path dependent (David, 1985); once a firm has built up substantial technological capabilities in engine efficiency, additional R&D efforts in this area are more likely to lead to successful innovation than R&D efforts in areas where the firm has no capabilities. Performance increases are thus more likely if previous incremental innovation has focused on this characteristic.

The probability that characteristic $x \in X_i$ of technology i is selected for innovation is equal to the cumulative number of innovations in characteristic x of technology i (Cum_{xi}), divided by the cumulative number of innovations in all characteristics of vehicle technology i (Cum_i). The state of a characteristic after an incremental innovation is given by Equation 3.3, where γ is the incremental innovation rate. The effects of incremental innovation are large at first, but the effects of subsequent incremental innovations in a characteristic diminish over time.

$$x_{i(t+1)} = x_{i(t)}^{\gamma} \tag{3.3}$$

Besides these changes in quality, the prices of vehicle technologies also change over time. Arrow C_1 in Figure 3.3 represents the effects of a price decrease on consumer adoption, which are twofold: first, a price decrease makes the technology affordable to a larger group of consumers, which might result in an increase in adoption. Second, a price decrease increases the utility/price ratio of that technology, which might also lead to an increase in adoption. The price of a technology decreases over time due to scale economies and learning by doing. An increase in the diffusion of a vehicle technology causes a decline in a vehicle's purchase price (Mansfield, 1988; Arrow, 1962) (arrow C_2). This relationship between price and the number of adopters is given by a standard learning curve (Wright, 1936; Ferioli et al., 2009):

$$P_{i(t)} = P_{i(0)} \cdot \left(\frac{c_{i(0)}}{c_{i(t)}} \right)^{\alpha}, \tag{3.4}$$

where $P_{i(t)}$ is the price of technology i at time t, $P_{i(0)}$ the initial price of the technology (see Table 3.1), $c_{i(0)}$ the initial number of consumers, $c_{i(t)}$ the cumulative number of consumers of a technology and α the learning ability of a technology.

Infrastructure dynamics. Infrastructure co-develops with the size of the adopter group, representing indirect network externalities. An increase in infrastructure availability can enlarge the group of potential adopters, because more consumers will take the vehicle technology into consideration (arrow D_1). Moreover, an increase in the number of adopters of a vehicle technology leads to a higher availability of the infrastructure(s) for that vehicle technology because this attracts investors (arrow D_2) (Grübler, 1990). Infrastructure availability A_g is described by the following:

$$A_{g(t)} = \max \left(A_{g(t-1)}, A_{g(0)} + \sum_{i=1}^{I} S_{i(t)} \cdot \kappa_{i-g} \right), \tag{3.5}$$

where $A_{g(0)}$ is the infrastructure availability at the time of emergence, $S_{i(t)}$ is the market share of a vehicle technology which is equal to the number of consumers who possess technology i at time t divided by the total number of consumers N.

The constant κ_{i-g} is the compatibility factor of infrastructure g with technology i. Therefore the adoption of different vehicle technologies might contribute to the development of a particular infrastructure g.

Consumer dynamics. In the model, a consumer's individual preferences change over time following the maximum observed performance on a characteristic, as described in subsection 3.3.3, whereas budget constraints and infrastructure requirements are fixed. An individual's preferences for the performance of a vehicle technology on the service characteristics are endogenously related to the development of these characteristics, which reflects the idea that both technology-push and market-pull mechanisms are important in innovation processes (Dosi, 1982). Hence, an incremental innovation in a certain characteristic not only directly improves the competitive position of that technology (arrow *B* in Figure 3.3), but also causes a shift in consumer preferences.

3.4 Simulation results and discussion

This section describes the effects of different policy measures on the outcomes of the process of technological change. In the model described previously, *substitution* occurs when the market share of the ICEV technology drops below the market share of one of the emerging low emission vehicle technologies. However substitution is neither a sufficient nor a necessary condition for a *sustainability transition* to occur. For example, it could be the case that the newly emerged technology has a lower performance regarding sustainability compared to the incumbent technology. Additionally, it is possible that no substitution occurs and the incumbent remains dominant while becoming more sustainable. A sustainability transition can thus be realised in different ways (Geels and Schot, 2007) and it is critical to not only take into consideration whether technological substitution takes place, but to also consider the evolution of the service characteristics of the vehicle technologies, when studying the effects of different policy measures.

Each policy measure is simulated for 20 runs. For each simulation run, it is determined: 1) whether technological substitution occurred; and 2) whether a transition toward more sustainable vehicle technologies took place. For each run, the average performance on the different service characteristics is recorded (weighted over the market share of the adopted technologies). A simulation run is labelled as a *transition* when the average performance of one or both of the sustainability-related characteristics, i.e., fuel consumption (S1) and emissions (S2), has substantially improved relative to the other characteristics.[2] Figure 3.4 illustrates the possible combinations of the occurrence of substitution and transition. The two graphs in one cell of the matrix belong to the same simulation run. The top graph in each cell shows the market share of the different vehicle technologies over time, and the bottom graph shows the average performance on each of the service characteristics over time.

Since the market share of the ICEV technology is almost 100% at time step zero, average performance at that time is determined by the initial performance of the ICEV technology, which scores *excellent* at the two traditional performance characteristics T1 and T2, but less on the sustainability-related characteristics S2 (*very poor*) and S1 (*below average*) (see Table 3.1). Although all four possible combinations of the occurrence of transition and substitution were observed in the simulation runs, the *transition, no substitution* case (top right of the matrix in Figure 3.4) occurred most frequently over all simulation runs presented in this chapter (in 91 out of 220 runs), while the case *no transition, substitution* (left bottom of the matrix in Figure 3.4) had the lowest occurrence (in 2 out of 220 runs). The *transition, substitution* case occurred in 64 out of 220 runs and the *no transition, no substitution* case in 63 out of 220 runs.

As a benchmark, Figure 3.5 shows the model outcomes for the case without policy support in two different scenarios. The left side of Figure 3.5 corresponds to a situation in which the environmental concerns of consumers are low and the sustainability-related vehicle characteristics have only a small influence on the direct utility of consumers. Figure 3.5 illustrates that in this case the incumbent ICEV technology hardly loses any market share (averages over 20 simulation runs). In this benchmark case no technological substitution took place and the ICEV technology remained the dominant design, although in 50% of the model runs a transition to sustainability occurred, which was caused by the stochastic nature of technological change in the model, as is shown by the histogram. The right side of Figure 3.5 illustrates a scenario where the sustainability-related and

[2] More specifically, the model outcome is considered as a *transition* when the average performance on one or both sustainability characteristics substantially improves and is at least *average* (0.3) for emissions and *above average* (0.4) for fuel consumption.

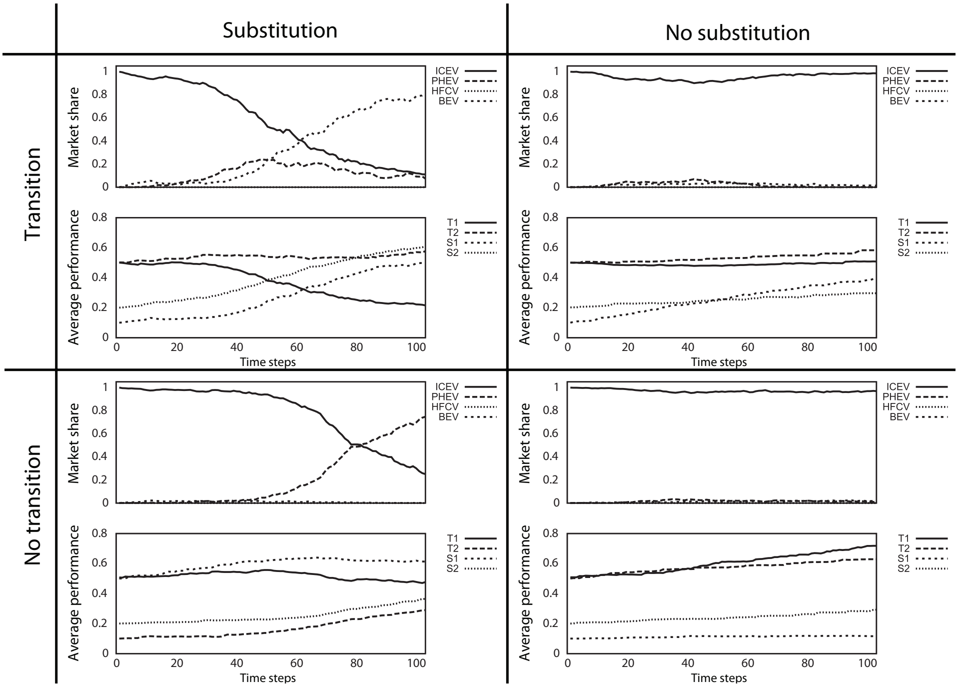


Figure 3.4: Substitution-transition matrix: single runs representing the different combinations of the occurrence of transition and substitution. The cells in the left (right) column represent runs in which (no) substitution occurs. The cells at the top (bottom) row represent simulation runs in which (no) transition is observed. The two graphs in each cell belong to the same simulation run. The bottom graph in each cell shows the average performance on a specific characteristic over all adopted vehicles, which determines whether or not a transition occurred. The top graph in each cell presents the market share of the different technologies, which determines whether or not substitution occurred.

the traditional performance characteristics contribute equally to consumer utility (the default model setting). In this scenario, 6 out of 20 runs showed substitution and in 13 out of 20 runs a transition occurred. The PHEV technology is most prominent as an alternative for the ICEV technology, followed by the BEV technology, and the HFCV technology hardly gained any market share. The figure illustrates that the effects of consumer selection pressure are substantial in the model.

Carbon tax. Figure 3.6 shows the effects of the introduction of a carbon tax at different times ($t = 0, 25, 50$ or 75). In comparison with the benchmark, the carbon

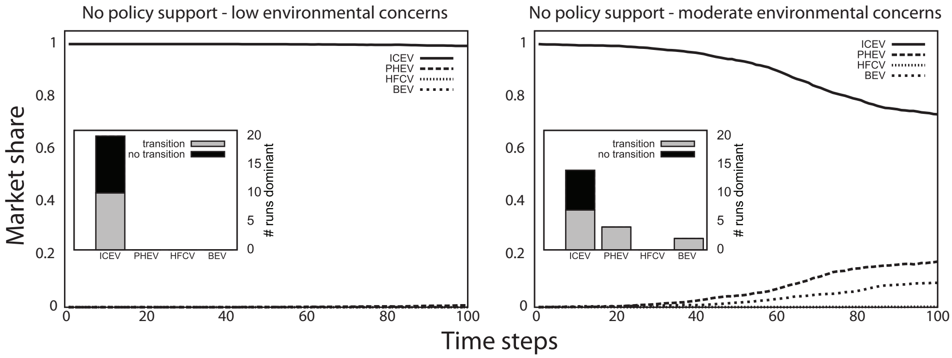


Figure 3.5: Market share of the different vehicle technologies, averaged over 20 runs for two scenarios: no policy support: low environmental concerns (left) and moderate environmental concerns (right). The histograms show how often a vehicle technology was dominant after 100 steps and the associated number of sustainability transitions (grey).

tax leads to increased market share for the low emission vehicle technologies, and a higher number of transitions and substitutions. The individual plots in Figure 3.6 illustrate the importance of the timing of the tax.

First, the market share of the low emission vehicles increases with a later introduction of the tax up until $t = 50$ but then decreases again for $t = 75$. In the latter case, the positive effects of the tax are not realised within the 100 step timeframe of the simulations. When the tax is introduced early, at $t = 0$ and $t = 25$, PHEV realises the highest market share of the low emission vehicle technologies as in the benchmark scenario. Although PHEV is not the most sustainable technology it outperforms the other low emission vehicle technologies on the traditional characteristics. When the tax is introduced later at $t = 50$, the BEV technology overtakes the PHEV technology in terms of average market share. Initially the BEV technology performs excellent on the sustainability characteristics but performs relative weak on the traditional characteristics. At $t = 50$ the BEV technology has had the time to develop solutions for these bottlenecks, which creates a window of opportunity for successful diffusion at the moment of tax introduction. Also, in terms of the number of runs that a technology becomes the dominant design within 100 time steps, the BEV technology benefits most from a tax introduction at $t = 50$. Overall PHEV technology benefits only slightly from the tax introduction compared to the benchmark scenario. The HFCV technology does not benefit from a carbon tax.

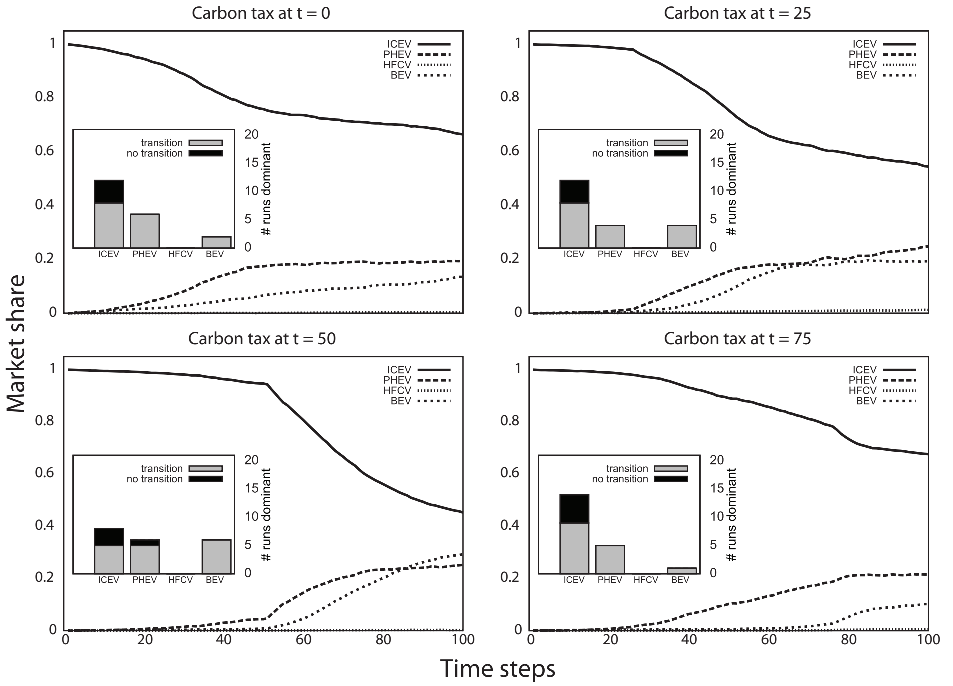


Figure 3.6: Carbon tax: implementation at time 0 (top left), time 25 (top right), time 50 (bottom left) and time 75 (bottom right). The histograms present how often a vehicle technology appeared as the dominant design after 100 time steps and how often this resulted in a transition to sustainability (grey). The lines present the average market share of a vehicle technology over the time steps averaged over 20 runs.

Second, the observed number of transitions and substitutions is compared to the benchmark scenario. The number of transitions increases compared to the benchmark scenario in Figure 3.5: it is around 16 (out of 20 runs) for each time of introduction. Thus the carbon tax provides incentives for a transition towards sustainability. However, according to the observed number of substitutions the carbon tax does not provide a selection pressure sufficient to support fast technological change, as for a tax introduction at $t = 0$ and $t = 25$ half of the transitions are realised by increased sustainability of the incumbent technology. Only for a tax introduction at $t = 50$, most transitions are associated with substitutions by low emission vehicles.

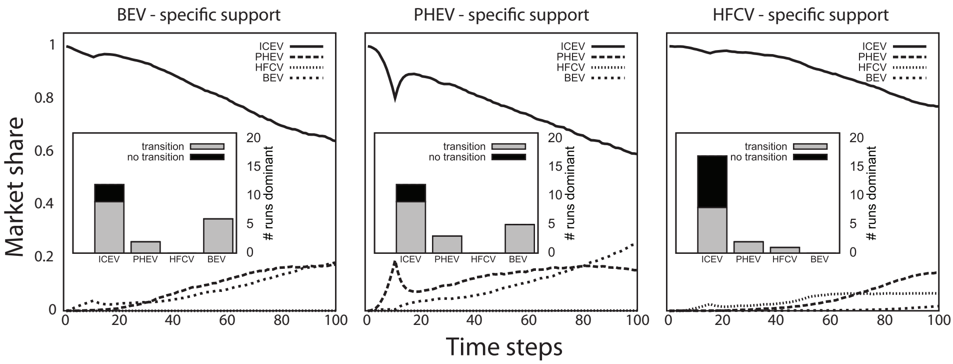


Figure 3.7: Technology-specific support: BEV-specific support (left), PHEV-specific support (middle) and HFCV-specific support (right). The histograms present how often a vehicle technology appeared as the dominant design after 100 time steps and how often this resulted in a transition to sustainability (grey). The lines present the average market share of a vehicle technology over the time steps averaged over 20 runs.

Technology-specific support. In the model technology-specific support consists of infrastructure investments and a temporary purchase price subsidy at the time of market introduction. Figure 3.7 presents the results when specific support is given to the BEV technology (left), the PHEV technology (centre) and the HFCV technology (right). Both the support for the BEV technology and the support for the PHEV technology lead to competitive advantages for the BEV technology due to the dependence on a common infrastructure. Note that the average market share of the BEV technology is highest when the PHEV technology receives specific support. Specific support for the HFCV technology, which has a larger distance to market, leads to lower overall sustainability results. Both the number of substitutions (3 out of 20 runs) and the number of transitions (11 out of 20 runs) are significantly lower in case of specific support for the HFCV technology than in case of specific support for the PHEV (14 transitions and 8 substitutions) or the BEV technology (17 transitions and 8 substitutions).

The model outcomes illustrate that the PHEV technology can serve as a stepping-stone technology for the BEV technology. Supporting or investing in the PHEV technology may thus also be an effective strategy for those that seek large-scale deployment of the BEV technology. In the model presented here, there is no risk of becoming locked-in into the PHEV technology due to the compatibility between infrastructures. Collaboration between suppliers and the standardisation

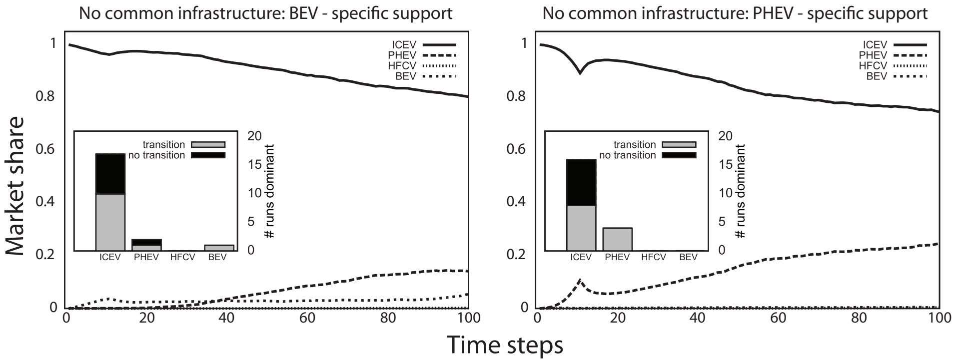


Figure 3.8: Technology-specific support without a common infrastructure: BEV support (left) and PHEV support (right). The histograms present how often a vehicle technology appeared as the dominant design after 100 time steps and how often this resulted in a transition to sustainability (grey). The lines present the average market share of a vehicle technology over the time steps averaged over 20 runs.

of the required infrastructure for PHEV and BEV technologies may thus lead to synergies of which mainly the BEV technology benefits.

The importance of infrastructure compatibility and standardisation is further illustrated in a rerun of the model with technology-specific support but without infrastructure-related compatibility between PHEV and BEV. In this experiment, both technologies solely depend on their own technology-specific electric infrastructure such that the adoption of either PHEV or BEV has no positive feedbacks on the other technology. Figure 3.8 presents the outcomes of these simulation runs for BEV (left) and for PHEV (right). The figure illustrates that the dependence on a common infrastructure is crucial for this stepping-stone effect to occur, since the BEV technology hardly gains any market share when supported. In the Dutch energy and mobility transition, the BEV technology was proposed as a stepping-stone technology towards a sustainable mobility system dominated by HFCVs (Farla et al., 2009). As the BEV and HFCV technologies do not have a shared infrastructure this transition pathway is not supported by the model outcomes.

3.5 Conclusions and management implications

The simulation of co-evolving consumer preferences, low emission vehicle technology characteristics and environmental policies enable us to derive strategic implications for firm actors involved in green technology management. The simulations suggest three important implications for strategy.

First, the results illustrate that the impact of consumer selection pressure on the future success of different low emission vehicle technologies can be substantial. In the model, consumer adoption decisions co-determine the direction of technological change. Combined with the presence of increasing returns to adoption, the model illustrates that it is not necessarily the most sustainable technology that becomes dominant. This is in line with earlier results by Arthur (1989, 1988) and Zeppini and van den Bergh (2011) for technologies that do not depend on a specific physical infrastructure. Current scenario studies on future sustainable mobility systems mostly focus on supply-side developments related to technology improvement and cost reductions. This model illustrates the need for both firm actors and policymakers to include heterogeneous and evolving demand in their forecasts.

Second, the results illustrate the effects of the timing of policy measures in relation to the stage of development of the technology. Early introduction of a carbon tax favours technologies that are relatively similar to the incumbent technology over more sustainable alternatives. Technologies thus benefit most from the introduction of a carbon tax when their characteristics are well aligned with consumer preferences. This is in line with findings by Geels and Schot (2007) and Alkemade and Suurs (2011), who state that the timing of pressure on the regime, which creates windows of opportunity for technological change, is particularly important. The strategic implication of these timing effects include the need to take into account the stage of development of a new technology when considering investments, or lobbying for market support measures such as a carbon tax, as it is not necessarily the most sustainable alternative that benefits most in terms of market share.

Third, the results illustrate how common infrastructures can facilitate stepping-stone effects. Collaboration and standardisation strategies can lead to synergies that contribute to technological change without risking the early lock-in into one of the supported alternatives. This implies that "running in packs" and making a technology compatible to other new or old technologies creates opportunities for technological change. Such standardisation efforts are important from the perspective of both technology managers and policymakers, as standardisation allows the coexistence of different low emission vehicle technologies and decreases the risk of technological lock-in. It is thereby important to focus standardisation efforts not only on a single technology group such as PHEV but also to extend the effort to include possible future technology generations such as BEV.

Overall the results illustrate the value of using a bottom-up simulation approach for evaluating different policy measures. Agent-based simulation models can help firm actors to adapt their strategy in response to such policies.

4 Product portfolios with radically different technologies*

4.1 Introduction

Road transport is the second largest source of greenhouse gas emissions in the EU. It is responsible for about 20% of the EU's total CO_2 emissions (Hill et al., 2012). Passenger cars alone are responsible for about 12% of EU CO_2 emissions. The transition to a system in which the use of passenger cars generates less CO_2 emissions is a challenge with multiple possible outcomes. Such a technological transition requires diverse policy instruments that put pressure on the existing system and creates opportunities for niche innovations.

Stimulating the development and the diffusion of cleaner vehicles is an important aspect of policies aiming at CO_2 reduction. However, we only have fragmented knowledge about the effect of such a policy on the supply and demand for cleaner vehicles, such as plug-in hybrid vehicles (PHEVs), battery electric vehicles (BEVs) or hydrogen fuel cell vehicles (HFCVs). Based on U.S. data trends, Diamond (2009), Skerlos and Winebrake (2010) and Morrow et al. (2010) provide relevant insights on the effects of different individual incentive policy instruments (fuel taxes, tax credit, increasing fuel efficiency standards, etc.). Several studies support the use of a policy mix to stimulate the development and diffusion of clean technologies (Acemoglu et al., 2012; van den Bergh, 2013), but it remains a challenge to predict the interactions between the different instruments of a policy mix (CE Delft, 2012; Veugelers, 2012). According to Borras and Edquist (2013) it is important to look at complementary, synergetic, and contrasting effects of the instruments combined in a policy mix. The main contribution of the chapter is to explore the ways in which mixes of heterogeneous policy instruments impact on economic and technological decisions of firms, consumer choice, global CO_2 emissions and public finance.

The assessment of policies that influence individual purchase decisions of new vehicles requires coping with a large number of decision makers facing a

* This chapter is forthcoming as: van der Vooren, A. and Brouillat, E.: Forthcoming, Evaluating CO_2 reduction policy mixes in the automotive sector, *Environmental Innovation and Societal Transitions*. doi: 10.1016/j.eist.2013.10.001.

multitude of alternative products. This implies complex evolving interactions and feedbacks between heterogeneous firms and consumers. As pointed by Peters et al. (2008) and Eppstein et al. (2011), agent-based modelling (ABM) is a powerful method to address complex evolving interactions. It enables us to model technological diversity, the behaviour of heterogeneous agents, policy instruments, and the dynamic interactions between different policy instruments in a policy mix. ABM has become increasingly popular in studies of car market dynamics (De Haan et al., 2009; Mueller and de Haan, 2009; Sullivan et al., 2009; Eppstein et al., 2011). By focusing on purchase decision, most existing ABM applications to cleaner vehicles do not explicitly account for technological change at the supply side and resulting feedbacks between vehicles sales, R&D and manufacturing. They are mainly adoption/diffusion models in which the innovation process on cleaner technologies is not endogenous. The aim of this chapter is to fill this gap by presenting an ABM for the market of passenger cars in which firm technological strategies, market structure and consumer choices co-evolve. Depending on market feedbacks, characteristics of cars change through innovation, leading firms to develop and market new cleaner vehicles. Model calibration and main mechanisms are based on empirical data and stylised facts.

Our ABM exhibits two particular features: a) car manufacturers can develop both internal combustion engine vehicles and new low-emission vehicles in a technology portfolio; b) the impact of policy on technological and market dynamics is investigated through both stand-alone policy instruments and policy mixes. Impact is measured along four output dimensions: impact on CO_2 emissions, on technological change, industrial organisation and public finance. In particular, we show how the dynamics of the system can lead to a technological lock-in into internal combustion technologies and how combinations of policy instruments can contribute to breaking this lock-in. Hereby we address the complementary, synergetic or contrasting effects between policy instruments. For policymakers this chapter provides insights into more effective policy mixes.

The chapter is organised as follows: Section 4.2 provides the theoretical background and stylised facts of technological transitions. Section 4.3 presents the model. Section 4.4 presents the simulation results of the model and Section 4.5 provides our conclusions.

4.2 CO_2 emissions, technological transition and policy

There are two ways to reduce the total amount of CO_2 emission produced by cars:

- Behavioural change (demand): less driving through carpooling, working from home, or using public transport (modality changes).
- Technological change (supply): using cleaner vehicles either by reducing the CO_2 emissions of existing vehicle technologies or through new low or zero emission vehicle technologies, such as PHEV, BEV or HFCV.[1]

Our analytical focus is on the second solution. We investigate the ways in which different policy mixes can foster technological transition by putting pressure on the different aspects of the existing system. In the remainder of this section we discuss the technologies and the actors involved, the policy instruments studied and their impact on actors, technologies and public finance.

4.2.1 Technologies and actors

Technologies. Different combinations of powertrains and fuels are suggested as a 'Green' technology for the future (European Expert Group on Future Transport Fuels, 2011; Offer et al., 2010; Ogden and Anderson, 2011; European Expert Group on Future Transport Fuels, 2011). The most visible alternatives for the currently dominant internal combustion engine vehicle (ICEV) are the PHEV, BEV and HFCV (Oltra and Saint Jean, 2009; Thiel et al., 2010; Ogden and Anderson, 2011).

In our study of the competition dynamics between the incumbent ICEV and the 'Green' alternative technologies, we focus on the BEV as a leading example as it is the most advanced Green alternative to ICEV.[2] The ICEV has dominated the market for years and currently outperforms BEV on most of the characteristics that consumers value, such as energy capacity (i.e.,the amount of energy units that can be stored in the vehicle), purchase price and the availability of infrastruc-

[1] There are more ways to influence the demand and supply than those listed here e.g. planning measures, promotion of intermodal information systems, promotion of new business models.

[2] Even if it is an advanced Green technology, we do not choose (P)HEV as a leading example because it is difficult to calibrate; its dependency on the existing infrastructure varies significantly for each car model. The HFCV is also difficult to calibrate because it is not market ready yet. In order to reduce complexity we only consider two competing technologies in this version of the model. It requires further research to develop a multiple technology model.

ture. However, the ICEV performs worse than the BEV on characteristics related to energy consumption and direct CO_2 emissions. While the energy efficiency of the ICEVs has steadily improved over the past years, there is no potential to render the chain from 'well to wheel' a zero emission chain (Taylor, 2008; Thiel et al., 2010), this is possible for the BEV by using renewable energy. Disadvantages of BEV technology are the expensive battery, limited battery capacity and consequently small driving range, and long recharging time. Another problem pertains to the limited availability of recharging stations (Van Mierlo et al., 2006; Oltra and Saint Jean, 2009; Thomas, 2009; Thiel et al., 2010; Ogden and Anderson, 2011).

Actors. The passenger car market is a typical example of monopolistic competition, with many competing firms, differentiated products and natural entry barriers. The profitability of car manufacturers depends on strategic actions regarding their product portfolio and their R&D expenditures. Currently, several incumbent firms are diversifying their product portfolio by entering the BEV market (Sierzchula et al., 2012) while still producing ICEVs.

Consumers have to select one of the available technologies. And they have preferences with respect to the characteristics of vehicles, such as purchase price, energy consumption, CO_2 emissions and the availability of infrastructure. Their purchase decision, in particular their choice between an ICEV and a BEV depends mainly on these preferences.

4.2.2 Policy design and pressure on the existing system

Policy mix. We investigate in this article the effects of several stand-alone policy instruments but also policy interventions that combine these instruments in a policy mix.

Pollution control policies used to be based mainly on command and control instruments (Lehmann, 2012). However, recent trends in climate change policies tend to supplement these instruments with market-oriented schemes due to their supposed higher efficiency and market acceptance (Oikonomou and Jepma, 2008). As a result, in many countries CO_2 reducing policy is designed as a policy mix.

Under the assumption of perfect markets and zero cost policy implementation, pioneers of environmental economics supported the use of one single policy instrument and the removal of all others (Pigou, 1920; Dales, 1968; Cropper and Oates, 1992; Lehmann, 2012). The use of multiple policy instruments was considered a redundancy at best and inefficient at worst (Johnstone, 2003; Lehmann, 2012).

More recent environmental economics studies investigate a second-best world; i.e., imperfect markets with numerous constraints in policy implementation. They highlight that in such a context it may be more efficient to use multiple rather than single policy instruments. Instruments applied simultaneously may generate complementary or synergetic effects that reinforce each other and compensate for disadvantages of stand-alone instrument strategies (Gunningham and Grabosky, 1998; Howlett and Rayner, 2007). As pointed out by Lehmann (2012), the main rationales for using policy mix are (i) pollution externality reinforced by multiple failures of private governance structures, such as technological spillovers (Katsoulacos and Xepapadeas, 1996; Johnstone, 2003; Sorrell et al., 2003; Jaffe et al., 2005; Fischer, 2008) and asymmetric information (Gabel and Sinclair-Desgagné, 1998; Jaffe et al., 2002, 2005; Sjim, 2005; Bennear and Stavins, 2007; Sartzetakis et al., 2012); (ii) excessive transaction costs associated to a single first-best policy because of non-compliance by polluters (Porter, 1974; Yohe and MacAvoy, 1987; Swierzbinski, 1994; Fullerton and West, 2000; Fullerton and Wolverton, 2005) or heterogeneity of marginal pollution damages (Atkinson and Tietenberg, 1982; Krupnick et al., 1983; Baumol and Oates, 1988) and abatement costs (Roberts and Spence, 1976; Weitzman, 1978; Pizer, 2002; Jacoby and Ellerman, 2004); (iii) pollution externality coexisting with market power in the output market (Baumol and Oates, 1988; Gersbach and Requate, 2004; Cato, 2010). Several studies of environmental policy focus on innovation and technological change (Jaffe et al., 2005; Requate, 2005; Acemoglu et al., 2012; Chappin et al., 2009; Kemp and Pontoglio, 2011; Veugelers, 2012; van den Bergh, 2013). They stress the need to combine environmental and technological policies to foster emissions reduction as well as the development and adoption of cleaner technologies. Nevertheless, as pointed by Veugelers (2012, p. 1773) *"we still have a very incomplete view on which combination of policy instruments is most effective in stimulating clean innovation creation and diffusion"*. In addition, it cannot be assumed that all instrument combinations will automatically be complementary or synergetic (Gunningham and Grabosky, 1998; Oikonomou and Jepma, 2008; Borras and Edquist, 2013). Some policy mixes may be counterproductive by generating contrasting effects (Grabosky, 1995; Howlett and Rayner, 2007; Chappin et al., 2009). Identifying which particular combinations are complementary, synergetic or counterproductive is then a critical task. However, *"the answers to the question 'which ones are complementary or otherwise, and why?' are themselves both complex and qualified"* (Gunningham and Sinclair, 1999, p. 52). The purpose of this article is to investigate these questions by exploring CO_2 reducing policy in the market for passenger cars.

Policy instruments for CO_2 reduction. We will limit our analysis to four frequently discussed and used policy instruments: implementing a feebate system, awarding a rebate for purchasing radically new technologies, imposing CO_2 (sales) taxation, and setting CO_2 emission standards. We will investigate the effects of both stand-alone policy instruments and policy interventions that combine these policy instruments in a policy mix.

A *feebate system* is - among others - applied in France, the Netherlands (2002 - 2009), Norway and Denmark (Bunch and Greene, 2010). In this system vehicles are divided into CO_2 emission classes. Consumers buying cars with low CO_2 emissions receive a rebate, while those buying cars with high CO_2 emissions pay a fee. Some authorities have introduced an evolving system that becomes tighter when cleaner cars become available. This system puts pressure on the existing firms to reduce the CO_2 emissions of their portfolio. According to Callonnec and Sannié (2009), the French "bonus-malus" system has contributed to a reduction of CO_2 emissions although empirical assessment of this policy remains difficult (Givord and d'Haultfoeuille, 2012).[3]

A rebate on purchase price for radically new technologies aims to make them more competitive and foster their diffusion. Initially, radically new technologies are usually more expensive than competing technologies. A rebate to lower the purchase price might increase consumer demand and puts pressure on firms to broaden their product portfolio and develop new technology products. Several empirical studies and simulation models (van der Vooren and Alkemade, 2012) indicate that price subsidies for cleaner vehicles are effective.

A CO_2 (sales) tax on the purchase price of the vehicle is implemented in many countries. A sales tax that increases with the amount of CO_2 emissions per kilometre produced by the vehicle puts pressure on firms to reduce the CO_2 emissions of their vehicles as it punishes consumers who buy the more polluting

[3] The period following the introduction of the feebate system in France was disrupted by the economic crisis and the introduction of another major policy; a premium to scrap older vehicles (Givord and d'Haultfoeuille, 2012).

cars. However, the design of the sales tax varies among countries. We analyse a tax that is directly linked to CO_2 emissions and varies continuously across the spectrum of CO_2 emissions, as this is said to be most effective for reducing pollution (He and Bandivadekar, 2011).

Authorities might also directly regulate CO_2 emissions by implementing CO_2 emissions standards. CO_2 emissions standards can be implemented in various ways.[4] In this chapter we analyse an extreme standards system, where car companies are not allowed to sell vehicles that do not comply with the minimum requirements.[5] Standards are considered one of the most effective ways to control greenhouse gas emissions (Ann and Sauer, 2004).

Policy and the pressure on public finance. The consequences of policy for public finance are important to take into account as well, especially in times of economic crisis. Although the French feebate system was expected to be neutral with respect to the state budget, its cumulative costs over the four first years (2008 - 2011) were 1.451 billion euros.[6] Benefits from the penalty covered 53% of the bonus expenses in 2011 and only 36% over the period 2008 - 2011. CO_2 standards are not intended to affect public finance, since it is not a financial policy instrument.

4.3 The model

4.3.1 Modelling transition to cleaner vehicles

Assessing policies that influence individual purchase decisions of new cleaner vehicles requires coping with a large number of decision makers facing a multitude of alternative products. This implies complex evolving interactions and feedbacks between heterogeneous firms and consumers. Traditional discrete-choice models of cleaner car adoption focus on the demand side and assume a

[4] See Ann and Sauer (2004) for an overview of the various greenhouse gas emissions and fuel economy standards around the world.

[5] Similar to a feebate system, the standards are evolving over time to keep close to the state of the art with respect to CO_2 emissions.

[6] Source: Cours des Comptes.

static distribution of decision strategies (Bunch et al., 1993; Ewing and Sarigollu, 2000; Hayashi et al., 2001; Ziegler, 2012; Lee et al., 2013a). Recent discrete-choice models support consumer behaviour change in response to external pressures (Ahn et al., 2008; Mau et al., 2008; Axsen et al., 2009) but there is a rather low level of detail regarding the feedbacks towards firms' technological choice (Lee et al., 2013b). Lee et al. (2013b) consider the feedback effect of market share on technical attributes, but their framework does not include any extensive endogenous innovation process on technological features of cars and the assessment of the impact of policy instruments on the system is not performed.

Agent-based modelling (ABM) is a powerful method to address complex evolving systems (Peters et al., 2008; Eppstein et al., 2011). ABM simulates explicit behaviours and complex interactions of autonomous and heterogeneous agents in order to generate and study the emergence of coherent system behaviours. ABM enables us to model technological diversity, the behaviour of heterogeneous agents and the dynamic interactions between different policy instruments in a policy mix. Several ABM studies focus on transition challenges for cleaner vehicles. Most of them investigate the contribution of individual policy instruments to the diffusion of low emission vehicles. Mueller and de Haan (2009) develop an ABM for the assessment of policies that influence individual purchase decisions of new passenger cars. De Haan et al. (2009) apply this framework to forecast the effects of feebate systems based on an energy-labelling scheme. Several ABM studies explore the effect of stand-alone policy measures on the diffusion of HFCV (Schwoon, 2006; Huétink et al., 2010; Köhler et al., 2010; van der Vooren and Alkemade, 2012). The scholarly analysis of dynamic interactions between different policy instruments in a policy mix is less developed. The ABMs developed by Sullivan et al. (2009) and Eppstein et al. (2011) study the impact of policy mixes on PHEV market penetration. Sullivan et al. (2009) show that PHEV penetration strongly depends on permanent PHEV tax rebates, subsidies, and sales tax exemptions. In the same way, Eppstein et al. (2011) show that combinations of policies and procedures (such as gasoline tax, purchase rebates or media instruments) can produce synergetic effects that foster PHEV penetration. These ABM applications to cleaner vehicles mainly focus on purchase decision. They do not explicitly account for technological change on the supply side and resulting feedbacks between vehicles sales, R&D and manufacturing. They are mainly adoption/diffusion models in which the innovation process on cleaner vehicles is not endogenous. Our modelling exercise intends to supplement this weakness by deploying an ABM that simulates the impact of CO_2 reducing policy mixes on the market for passenger cars in which firm strategies, market structure and consumer choices co-evolve.

The model. The objective of this modelling exercise is to simulate the impact of CO_2 reducing policy mixes on the market for passenger cars in which firm strategies, market structure and consumer choices co-evolve. Although, the main mechanisms of the model and its calibration are based on stylised facts and empirical data, our purpose is not to predict the diffusion paths for BEV. The model aims to provide insights into the pressures generated by the implementation of CO_2 reducing policy instruments in the domain of private transportation.

In the model, we account for two categories of agents: firms (i) that produce and market vehicles (j) and consumers (k) who buy and use them. We assume that two classes of vehicles can co-exist on the market, defined by the type of engine technology they employ:

- Gas-tech: vehicles with a fossil-fuel-based internal combustion engine (the old/incumbent technology);
- Green-tech: vehicles with an electric engine (new technology).[7]

For a given firm i, j then represents the type of vehicle: Gas-tech or Green-tech. Consumers driving a car will emit a particular amount of CO_2 depending on the selected vehicle and their driving habits. Authorities will define policy instruments in order to limit and decrease CO_2 emissions. The objective is to encourage or compel firms to produce low emission vehicles, and to encourage consumers to buy them. Figure 4.1 depicts the main structure of the model. The building blocks of the model will be explained from paragraph 4.3.3 onwards, but first we will define the product around which this model is build.

[7] For the calibration of the parameter values of the Gas-tech and the Green-tech we use two vehicles that have a rather similar performance: the Renault Megane TCe 130 (2011) and the Nissan Leaf (2011).

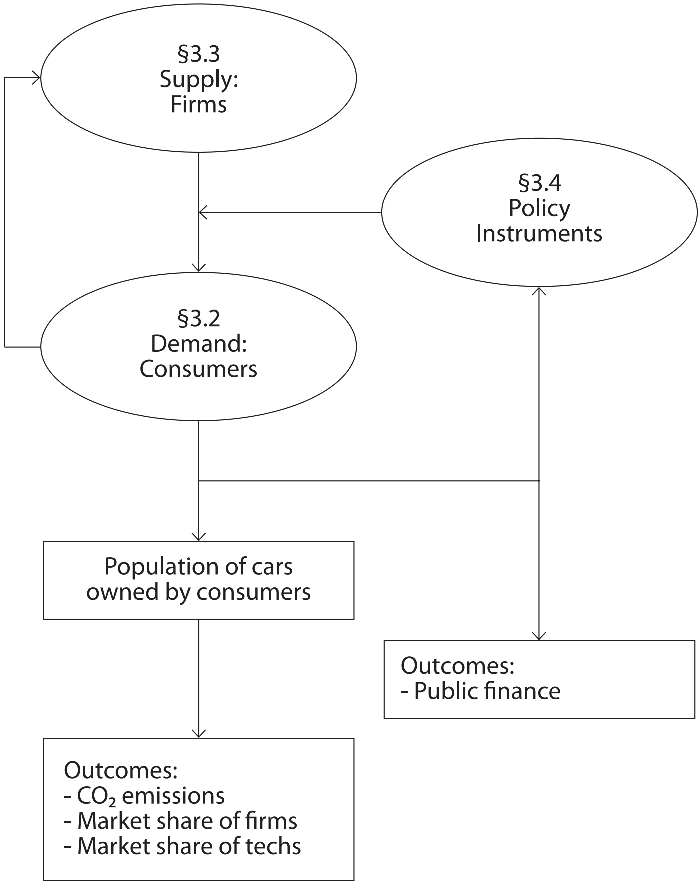


Figure 4.1: Model structure.

4.3.2 Product features

In the model presented in this chapter, vehicle j of firm i is described in a Lancasterian way (Lancaster, 1966), as a vector $j = \{PC_{ij}, EE_{ij}, EC_{ij}, QL_{ij}\}$ that determines its performance within a specific power class, where:

- PC_{ij} is the vehicle's production cost;
- EE_{ij} is the vehicle's energy economy, defined as the distance (km) it can travel per unit of energy consumed;
- EC_{ij} is the vehicle's energy capacity, defined as the amount of energy units that can be stored in the vehicle, in a battery or fuel tank, for example;

- QL_{ij} is the vehicle's quality level (QL_{ij}), i.e., a performance measure for miscellaneous quality characteristics.

Each characteristic has an outer limit (PC_{min}, EE_{max}, EC_{max} and QL_{max}) that is identical for the two technologies. Outer limits of technological performance are difficult to calibrate. Choosing identical outer limits prevents that one technology per definition outperforms the other technology in the long run.[8] Table C.2 in the Appendix provides the initial parameter values of the different vehicle technologies. Depending on the technology, the initial value for the four characteristics can be different. Since the Green technology is an emerging technology, we assume that producing electric vehicles is initially more expensive; i.e., at $t = 0$, $PC_{min} < PC_{ij=Gas} < PC_{ij=Green}$. Regarding EE, one of the main reasons that the Green technology is labelled as 'Green' is that the current energy economy of electric vehicles is higher than the Gas technology. We assume that initially the Green technology is already at its maximum whereas the Gas technology can still be improved; i.e., at $t = 0$, $EE_{ij=Green} = EE_{max}$ and $EE_{ij=Gas} < EE_{max}$.

On the contrary we assume that the energy capacity of the Gas technology does not need improvements anymore, while the Green technology is quite far away from the outer limit; i.e., at $t = 0$, $EC_{ij=Gas} = EC_{max}$ and $EC_{ij=Green} < EC_{max}$.

For simplicity reasons and because the BEVs that are currently available are relatively similar to their ICEV equivalents, we assume that the quality of both technologies and all firms is initially the same,[9] i.e., at $t = 0$, $QL_{ij=Gas} = QL_{ij=Green} < QL_{max}$. Production costs ($PC_{ij}$), energy economy ($EE_{ij}$) and energy capacity ($EC_{ij}$) define:

- The driving range of the vehicle (DR_{ij}), that is the total distance in km that the vehicle can travel with full capacity (full gas tank for Gas-tech vehicles and fully charged battery for Green-tech vehicles):

$$DR_{ij,t} = EE_{ij,t} \times EC_{ij,t} \tag{4.1}$$

- The use costs per km travelled by the vehicle (UC_{ij}):

$$UC_{ij,t} = \frac{pe_t}{EE_{ij,t}} \tag{4.2}$$

[8] A technological frontier is important for modelling the decreasing rate of technological progress when technologies come close to the frontier (Malerba et al., 1999; Brouillat and Oltra, 2012).

[9] It is difficult to validate empirically differences in a miscellaneous characteristic such as quality.

where *pe* are the costs per energy unit. We assume that use costs depend solely on energy issues; we do not take into account maintenance, insurance, et cetera. We follow the baseline scenario (European Union, 2012) for oil prices and power generation costs to model the development of gas prices and electricity prices respectively.[10] Both scenarios have an upward trend where $pe^{Green} < pe^{Gas}$.

- The direct CO_2 emissions per kilometre travelled by the vehicle (E_{ij}):

$$E_{ij,t} = \frac{em}{EE_{ij,t}} \tag{4.3}$$

where *em* is a fixed parameter reflecting the level of direct individual CO_2 emissions per energy unit.[11] We assume that $em^{Green} \simeq 0$ and $em^{Gas} > 0$.

- The price of the vehicle (p_{ij}):

$$p_{ij,t} = (1 + VAT) \times (1 + \lambda) \times PC_{ij,t-1} \tag{4.4}$$

where λ is a cost mark-up factor and VAT is the value added tax. To simplify we assume that λ and VAT are fixed and identical for all the firms.

We define the variable W to reflect the availability of fuel or charging stations: $W \in [1, 2]$ and W is increasing with the development of a charging station network. We assume that initially $W^{Green} = 1$ and $W^{Gas} = 2$. We assume that the dynamics of W^{Green} depend on the market share of Green-tech vehicles: the faster this type of product diffuses, the faster the station network will develop:

$$W_t^{Green} = 1 + maxMS_t^{Green} \tag{4.5}$$

where maxMSGreen is the maximal market share of Green-tech vehicles ever reached in a single simulation run[12].

[10] Annual growth rates are calculated based on five-year averages.

[11] See Table C.2 in the Appendix for the conversion rate: CO_2 emissions per unit of energy.

[12] Following this equation, the minimum level for W^{Green} is 1, and the network will develop as soon as the minimal threshold is reached, but if the market share of Green-tech vehicles stops increasing, the network will stop developing.

4.3.3 Demand

In each period consumers take the steps described in Figure 4.2.[13] (A) Every consumer has a fixed probability of adopting a new car.[14] (B) When they decide on the adoption of a new vehicle, consumers scan all the cars on the market. (C) Consumer behaviour is characterised by a reservation price ($pmax_k$). Any car with a price higher than $pmax_k$ is automatically discarded from their pre selection. Consumers who cannot afford any vehicle will keep using their old car. (D) There is a threshold on the driving range as well. All consumer behaviour is characterised by a minimum required value for vehicles' driving range (d_k). Any car that cannot cover the distance d_k is automatically discarded from their pre selection. (E) The purchase process of consumers is boundedly rational (Simon, 1955), so that consumers only evaluate some of the eight product, technology and firm features presented in Table 4.1. As pointed out by Valente (2012, p. 5), *"with respect to producers, consumers are likely to be less committed to, and less expert of, the products and services they purchase. [...] Of course, people do not like to waste money or buy lemons, as long as they can prevent it. Their capacity to do so will vary, resulting in a larger or smaller probability to identify the best products available"*.[15] Thus, we assume that consumers cannot perfectly evaluate all the different features of the product they purchase. They randomly select two features from Table 4.1 that are

Demand: in each period consumers take the following steps

A. Consumers decide on willingness to buy a new car
 (yes → B, no → stop)
B. Consumers scan all cars offered by firms
C. Consumers make a pre selection of the cars affordable to them
 (no affordable cars → stop)
D. Consumers narrow down their pre selection by abandoning the cars that have an insufficient range for them
 (no cars in pre selection → stop)
E. Consumers select two features that are most important to them
F. Consumers buy the car from the pre selection that has the highest performance on the chosen characteristics

Figure 4.2: Demand.

[13] See Table C.2 in the Appendix for the parameter values of consumer characteristics and the sources we have used for calibration.

[14] This probability is chosen arbitrarily for simplification.

[15] In addition, when consumers buy the 'wrong' product (i.e., a dominated alternative compared to the optimal choice), there is no economic penalty that could push them to either correct their choice or to leave the market.

Table 4.1: The product, technology and firm features that may affect consumer decisions.

Product, technology and firm features	
Affordability of the car	$(1/p_{ij,t})$
Affordability of use	$(1/pe_t)$
Availability of fuel or charging stations	$(W_{i,t})$
Market share of a firm[16]	$(MS_{i,t} + \varepsilon_{MS})$
Energy capacity	$(EC_{ij,t})$
Cleanness of the car	$(1/E_{ij,t})$
Quality level	$(QL_{ij,t})$
Brand effect[17]	$(Br_{i,t})$

most important to them and focus their attention on these attributes. (F) From all affordable cars that have a sufficient driving range the consumer buys the car that generates the highest utility; $U = X_1 \times X_2$ with X_1 and X_2 the two chosen characteristics. After acquiring their preferred vehicle, consumers become a customer of the selected firm until another vehicle is bought.

Consumer k will drive a specific number of kilometres over the period (D_k). This will determine her CO_2 emissions (Em_k):

$$Em_{k,t} = D_{k,t} \times E_{k,t} \tag{4.6}$$

where E_k are the direct CO_2 emissions per kilometre travelled by the vehicle used by consumer k. We accumulate these emissions over consumers to obtain the global CO_2 emissions of vehicles under use over the period. This is the main environmental indicator of our model.

4.3.4 Supply

In each period, firms take the steps described in Figure 4.3 below.[18]

A. Setup. (A.1) Initially there are only Gas-tech vehicles offered by firms. (A.2) The performance characteristics of these Gas-tech vehicles are similar for all firms at this starting point. (A.3) Firms differ only with regard to their initial budget B_0, which is set at random.

[18] See Table C.2 in the Appendix for the parameter values of firm characteristics. The parameter values are set such that the firm behaviour shows no abnormal dynamics.

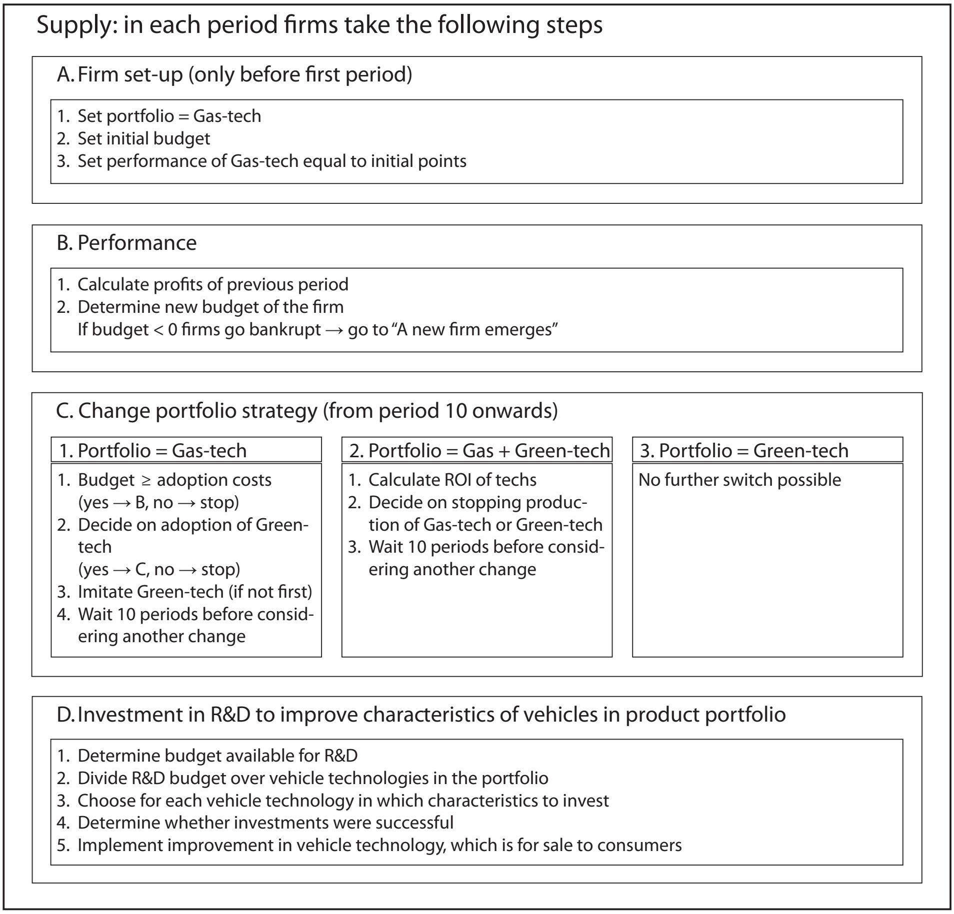


Figure 4.3: Supply.

B. Performance. The budget B_i is used (1) to cover any losses of the firm in the previous period, (2) to finance the adoption costs caused by changes in their portfolio strategy in the previous period and (3) to finance investments made in R&D with the aim of improving the characteristics of the vehicles in their portfolio:

$$B_{i,t} = B_{i,t-1} + \pi_{i,t-1} - C^{Ad}_{t-1} - RD_{i,t-1} \tag{4.7}$$

where π_i is the firm's profit, C^{Ad} are the adoption costs[19] and RD_i are the R&D investments. (B.1) So, firms will feed their budget depending on their profits. The firm's profit is given as:

$$\pi_{i,t} = \sum_j (p_{ij,t} - PC_{ij,t}) \times Q_{ij,t} - F \tag{4.8}$$

where Q_{ij} are the total number of vehicles j from firm i sold over the period and F are fixed costs identical for all the firms. B.2) Firms with a negative budget B_i will go bankrupt and disappear from the market. The number of firms in the industry is kept constant, so when a firm goes bankrupt, a new firm emerges. This procedure will be explained at the end of this paragraph.

C. Change portfolio strategy. Firms are not locked forever into a portfolio with only the Gas technology. From period 10 onwards, firms examine every period the possibility to change their portfolio strategy. (C.1.1) If firms have sufficient budget to bear the adoption costs (C^{Ad}), they may consider the possibility to develop the Green technology as well. (C.1.2) The probability that a firm will try to adopt the Green technology is given by the following equation inspired by Malerba et al. (2001):

$$PR^{Ad}_{i,t} = \left(\frac{(EE_{ij,t}/EE_{max}) + (PC_{min}/PC_{ij,t})}{2} \right)^{\omega} \times (MS^{Green}_t + \varepsilon)^{(1-\omega)} \tag{4.9}$$

MS^{Green} is the total market share of Green-tech vehicles,[20] ε is a parameter that triggers a firm to be the first to adopt the Green-tech.[21] The first term in brackets represent the fraction of the Gas technology frontier covered by firm i. The parameter ω measures the general difficulty of producing the new technology. The probability that a firm will try to adopt the Green technology depends positively on the closeness of the firm to the technological frontier, but also on how the new Green technology diffuses on the market.

(C.1.3) Firms that decide to adopt the Green technology will select a firm developing a Green-tech vehicle to imitate. This firm is randomly chosen with

[19] We assume that these costs are fixed and identical for all the firms. Adoption costs encompass expenditures in infrastructure and equipment, training of engineers, etc.

[20] It therefore represents the size of the Green-tech market.

[21] ε takes a positive value if a firm is the first that adopts the Green-tech ($MS^{Green} = 0$) and it takes the value of zero if there already is at least one firm successfully producing the Green technology ($MS^{Green} \neq 0$).

probabilities proportional to its market share of Green-tech vehicles.[22] The values for PC, EC and QL are then randomly selected between their initial value (at t_0) and the current value of the imitated firm.[23] This limits the probability that a firm new to the market is as good as an incumbent firm, which has some years of experience.

Firms that decide to adopt the Green technology do not immediately abandon the Gas technology. They continue designing, producing and selling Gas-tech vehicles. In other words, they have a portfolio containing the Gas-tech vehicles and the Green-tech vehicles, both with their own individual characteristics.

(C.2.1) Based on the return on investments of technologies in their portfolio (ROI_{ij}), firms can decide to abandon one of their technologies and focus on the development of a single technology. Return on investments for vehicle j in the portfolio of firm i is calculated as the gross profit that firm i makes on vehicle j over the period, divided by the R&D investment made in vehicle j at the previous period (discussed in Figure 4.3, block D):

$$ROI_{ij,t} = \frac{\lambda \times PC_{ij,t} \times Q_{ij,t}}{RD_{ij,t-1}} \tag{4.10}$$

(C.2.2) Firm i will decide to abandon technology j according to probabilities that depend on ROI_{ij} and the total number of periods in which the firm has developed technology j: the lower the return on investment of technology j, the higher its probability of being abandoned, and the longer the experience has lasted, the harder it is to abandon.[24] (C.3) Another type of firm can then appear: firms producing and selling only Green-tech vehicles (called *Green firms*).[25]

D. Investment in R&D to improve characteristics of vehicles in portfolio. In our model firms can only improve the performance of the vehicles in their portfolio by incremental innovation through investments in R&D.[26] (D.1) Every firm will

[22] The higher the market share of the Green-tech vehicle of a firm, the higher its probability to be selected.

[23] In case a firm is the first mover, then its Green technology has initial values of PC, EC and QL.

[24] C.1.4/C.2.3) When firms adapt their portfolio (by adding a new technology or by abandoning one), we assume that they cannot implement another transition for the next 10 periods.

[25] We also assume that Green firms abandon the Gas technology once and for all. They cannot go back and develop it again.

[26] This modelling is inspired by Malerba et al. (1999) and Desmarchelier et al. (2013).

use its budget to finance R&D projects to improve the characteristics PC, EE, EC and QL. The global R&D expenditure of the current period (RD_i) is given by the following equation:

$$RD_{i,t} = \mu \times B_{i,t} \tag{4.11}$$

where μ is a random parameter.[27]

(D.2) Firms will divide their global R&D investments over improving the Gas technology and the Green technology. The R&D investment allocated to vehicle j is given by the following equation:

$$RD_{ij,t} = \eta \times RD_{i,t} \tag{4.12}$$

where η is a parameter; $\eta = 1$ if firm i develops one technology and $\eta = 0.5$ if firm i develops both Gas technology and Green technology.

Technological change means improved performance of the vehicle. D.3) We assume that firms can only invest in one characteristic of each vehicle technology at a time. This means improving PC, EC or QL for Green-tech vehicles and PC, EE or QL for Gas-tech vehicles.[28] This characteristic is chosen at random. For each characteristic, the innovation process is divided into two steps: D.4) first the firms determine whether or not their investments have led to an innovation for the considered characteristic. D.5) Secondly, the firms determine the new value of the characteristic: either there is an improvement in innovation, or it remains the same.

An innovation occurs for vehicle j if the following condition is satisfied:

$$rdm \in [0,1] < 1 - exp(-\alpha_1 \times RD_{ij,t}) \tag{4.13}$$

α_1 is a scale parameter and rdm is a uniform random draw within the admissible range $[0,1]$. The higher the value for rdm, the more difficult it is to satisfy the condition with a given R&D investment. If the innovation draw for PC is a success, the improvement of the value of this characteristic is given by:

$$\delta^{PC}_{ij,t} = \alpha_2 \times rdm \in [0,1] \times (PC_{ij,t} - PC_{min}) \tag{4.14a}$$

[27] However, there is a minimum investment (RD_{min}) to ensure some technological progress for firms with low budgets or without R&D budget.

[28] We assume that no changes will occur in EE for the Green technology and in EC for the Gas technology.

where α_2 is a scale parameter. The same applies to EE, EC and QL:

$$\delta_{ij,t}^{EE} = \alpha_2 \times rdm \in [0,1] \times (EE_{max} - EE_{ij,t}) \tag{4.14b}$$
$$\delta_{ij,t}^{EC} = \alpha_2 \times rdm \in [0,1] \times (EC_{max} - EC_{ij,t}) \tag{4.14c}$$
$$\delta_{ij,t}^{QL} = \alpha_2 \times rdm \in [0,1] \times (QL_{max} - QL_{ij,t}) \tag{4.14d}$$

where rdm reflects the efficiency of the R&D process. It has a positive impact on vehicle improvement. The last term of each equation represents the distance of the achieved design to the technological frontier. It reflects the traditional effect of depletion of technological opportunities; progress becomes progressively slower as the level of the characteristic nears the frontier. If innovation draws are failures, there is no improvement in vehicle characteristics:

$$\delta_{ij,t}^{PC} = \delta_{ij,t}^{EE} = \delta_{ij,t}^{EC} = \delta_{ij,t}^{QL} = 0 \text{ [29]} \tag{4.15}$$

4.3.5 A new firm emerges

The number of firms in the industry is kept constant. If a firm goes bankrupt, a new firm emerges (see steps in Figure 4.4). To fix its initial strategy and performance, we assume that the new firm imitates an existing one. This choice is random with probabilities proportional to market shares. (A) The new firm copies the portfolio of the imitated firm (Gas-tech, Green-tech, or Gas-tech and Green-tech). We assume that if a firm with a Gas-tech and a Green-tech portfolio is imitated, there is only a one-third chance that the new firm will imitate both, because it is unlikely that a new firm starts off with the Gas technology and the Green technology in its portfolio. (B) The values for PC, EC and EE are randomly selected between their initial (t_0) value and the current value of the imitated firm. (C) The initial budget of new firms is set with a similar procedure as the initial budget for the firms present at the start of the model (A.2 in Figure 4.3).[30]

[29] δ is added to the current value of the characteristic.

[30] We assume that the initial costs of developing the technologies new firms start-off with are made before new firms enter the market. So, the initial budget is the initial budget after development costs.

A new firm emerges

A. Set portfolio
B. Imitate performance of vehicle characteristics
C. Set initial budget → go to "Supply: in each period firms take the following steps"

Figure 4.4: A new firm emerges.

4.3.6 Policy instruments

The objective of any policy is to speed up the decrease of global CO_2 emissions per period. Below we explain the ways in which the four types of policy instruments discussed in Section 4.2 will be implemented in the model.

Authorities can fix emission standards for Gas-tech vehicles[31] (*Emax*), which will be revised every period. The average CO_2 emissions of the vehicles sold in the previous time step sets the benchmark (*Ebench*) for the next time step. The new *Emax* will be $e \in [0, 100\%]$ higher than *Ebench*,[32] where e determines the tightness of the standards. Vehicles that do not satisfy the standard cannot be sold.

Another possibility is imposing a sales tax on CO_2 emissions. The tax is specific to vehicles and is proportional to the emissions of the considered vehicle, and it is added to its purchase price.[33]

A feebate system will be investigated. Starting from the benchmark (*Ebench*), authorities will add an amount (fee) to the selling price if the emissions of the vehicle exceed the benchmark ($E > Ebench$), or they will lower the price (rebate) if these emissions are below the benchmark ($E < Ebench$).[34] The more the emissions exceed or fall short of the target, the greater the fee or the rebate will be. Starting form *Ebench*, we distinguish different categories (see Table C.1 in the Appendix), comparable to the French and Dutch feebate systems. The category to which a firm's vehicle belongs depends on the vehicle, but also on the average CO_2 emission of all vehicles sold in the previous time step; i.e., the performance of other firms and consumer preferences.

[31] There is no emission standard for Green-tech vehicles because their emissions are null.
[32] See Table C.2 in the Appendix for the lowest and highest standards we have analysed, which are the extreme values.
[33] The tax is set such that the tax is comparable with the size of the feebate and rebate system (see Table C.2 in Appendix).
[34] If $E = Ebench$, the price is not modified.

The fourth and last policy instrument is a rebate to support the sales of the Green-tech vehicles. Authorities can award purchase price subsidies in order to lower the relatively high prices of Green-tech vehicles.[35]

4.4 Simulation results

In this section we present the ways in which policy mixes contribute to a transition towards a system in which passenger cars generate less CO_2 emissions. In addition we evaluate how these policy instruments affect changes in *technology*, *industrial organisation*, and *public finance* (see Table 4.2).

We use NetLogo to simulate the model (Wilensky, 1999). The simulated market consists of 8 firms and 2000 consumers that interact for 40 periods. All results in this section present averages over 100 simulation runs with unique seeds.[36] Most parameters and initial values for variables are calibrated with empirical data. For more details, see Appendix (Table C.2).

First, we will present a benchmark scenario without any policy. Second, the impact of stand-alone policy instruments is analysed. Finally, we will study the impact of policy mixes.

4.4.1 Benchmark

The benchmark scenario in Figure 4.5 illustrates the index of total CO_2 emissions (*pollution*) and the adoption of the Green technology (*technology*) and the develop-

Table 4.2: Regulation criteria and indicators.

Criteria	**Pollution**	**Technology**	**Industrial organisation**	**Public finance**
Indicator	Total CO_2 emissions per period	Market share of the Green technology	Market share of new firms	Public income (net benefits)

[35] See Table C.2 in the Appendix for parameter values and the source used for calibration.
[36] Increasing the number of simulation runs would lower the standard deviation of average values.

ment of the market share held by new firms (industrial organisation).[37] Since no policy instruments are in place besides the value added tax (VAT), there is no effect on *public finance*. The VAT benefits are used as a benchmark for the other scenarios with government regulation.[38]

4.4.2 Stand-alone policy instruments

In this paragraph we discuss the pressure on the system generated by different policy instruments. Experiments are run for four policy instruments: imposing a sales tax on CO_2 (tax), setting CO_2 emissions standards (standards), implementing a feebate system for Gas-tech vehicles (feebate) and awarding a rebate for Green-tech vehicles (rebate). Each policy instrument is tested for a range of nine different stringency/flexibility levels between a flexible (low) and a stringent (high) regime scenario. The outcomes that are presented below are comparisons of the diverse indicators to the benchmark scenario (additional effects), after 40 periods.[39] Wilcoxon-Mann-Whitney *U*-tests are performed, over the batch of simulation runs for low and high stringency levels, to test whether there is a significant difference between the benchmark scenario and the stand-alone policy instrument. The outcomes of the significance tests are presented in Table C.4 in the Appendix. They show that the low regime scenarios hardly generate significant changes with reference to the benchmark.

Figure 4.6 (top left) illustrates that all policy instruments contribute to an additional reduction in CO_2 emissions. Most instruments show a gradual reduction in CO_2 emissions as the stringency level increases, except for *standards*. *Standards* that are not stringent have a minor effect on CO_2 emissions reduction, while *high standards* have a large effect on CO_2 emissions reduction. We do not compare the

[37] Table C.3 in the Appendix shows the average results after 40 periods on each indicator. The benchmark results are compared with policy results in Sections 4.4.2 and 4.4.3. The figure shows that CO_2 emissions are decreasing. In period 40 the CO_2 emissions are slightly below 54% of the CO_2 emission in period one. This CO_2 reduction is explained by technological progress due to R&D investments of firms, rising energy prices creating pressure on the less efficient vehicles, and the purchase decisions of consumers with 'Green' preferences. New firms benefit from this rising pressure, as almost 20% of the market is in the hands of new firms in period 40.

[38] Table C.3 in the Appendix shows the cumulative benefits as a result of collecting VAT.

[39] Section 4.2 provides an overview of expected outcomes of the different policy instruments.

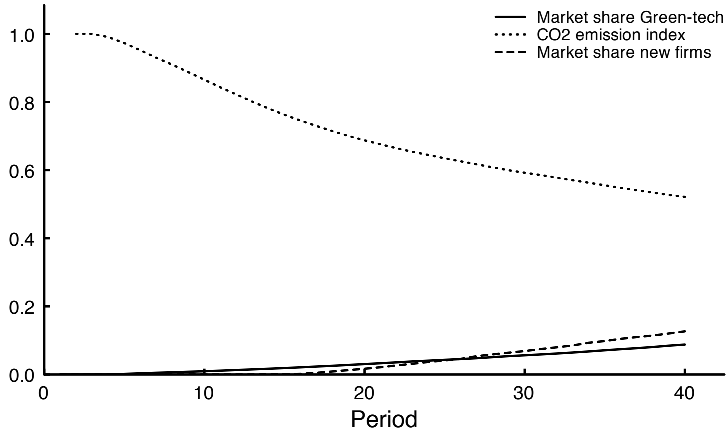


Figure 4.5: Benchmark: change on indicators over 40 periods.

effect size of different policy instruments, since a *high* stringency level for one policy instrument is not equivalent to a *high* stringency level of another policy instrument. We do compare the different foundations of the additional pressure to reduce pollution.

Rebate. Figure 4.6 (top left) illustrates that with a *rebate* the reduction in CO_2 emissions is explained by the rapid diffusion of the Green-tech vehicles at the expense of the Gas-tech vehicles. While we would expect this to create a pressure on incumbent firms, the opposite seems to be the case, as the market share of new firms decreases compared to the benchmark (no policy). Apparently the pressure to adopt the Green technology is so strong that incumbent firms adopt it early on in the model, which leaves no opportunities for new firms. A disadvantage is that public income reduces substantially, as a *rebate* is an expensive policy instrument.

Tax. Besides some additional diffusion of the Green technology, for *tax* the CO_2 reduction is explained mainly by an increased pressure to improve the sustainability of the Gas technology (Figure 4.6). Also we found that if a sales tax is introduced a small group of consumers in our model cannot afford to buy a car, which also

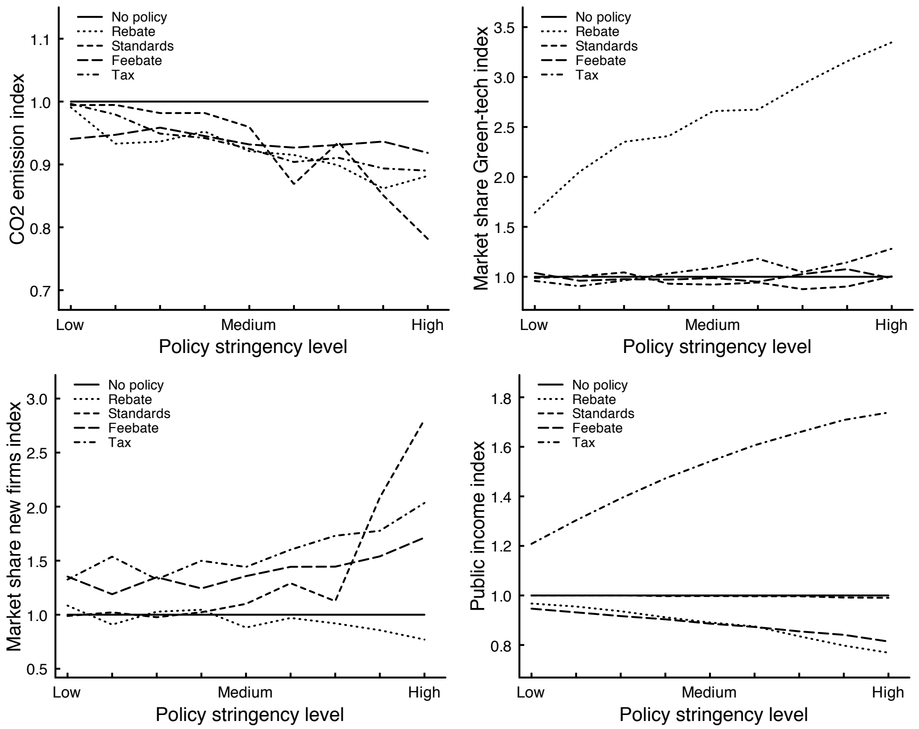


Figure 4.6: Additional changes on indicators generated by the stand-alone policy instruments: *pollution* (top left), *technology*(top right), *industrial organisation* (bottom left), and *public finance* (bottom right).

reduces CO_2 emissions.[40] With a *tax*, new firms successfully gain some market share. An advantage of a tax regime is the extra income generated for the benefit of public finance.

Standards. In Figure 4.6 (top left) we observe that mainly *high standards* generate an additional CO_2 reduction. Figure 4.6 (top right) illustrates that no additional diffusion of the Green technology is generated with standards. This means that the reduction in CO_2 emissions is only explained by increased pressure to improve the sustainability of the Gas technology. *Standards* have impact on indus-

[40] The sum of market shares for the Gas and the Green technologies with *tax high* is about 4% lower with reference to the benchmark.

trial organisation. Because *high standards* act as a strong market selection force, firms have difficulties meeting these *high standards* and new firms successfully gain a market share. As was expected, *standards* do not have a substantial impact on public finance.

Feebate. Figure 4.6 (top right) shows that the additional CO_2 reduction is only explained by increased pressure to improve the environmental performance of the Gas technology. With a *feebate* new firms gain some additional market share. A *feebate* system is rather expensive. The fee does not fully cover the rebates that are paid by the authorities.

To summarise, we have observed that a *rebate* is an expensive instrument, which even reduces the pressure on the incumbent firms. However, a *rebate* generates significant pressure on the Gas technology. The market for the Green technology is booming, which leads to a substantial additional decrease of CO_2 emissions. A *tax* is beneficial in terms of finance, generating moderate pressure on (incumbent) firms when stringent, and leading to substantial reduction in CO_2 emissions which is mainly explained by a reduced possession of cars by consumers and incremental improvement of Gas technology. The implementation of *standards* is not a financial instrument but it gives rise to enormous pressure on (incumbent) firms and creates opportunities for new firms, which is caused by the high pressure to reduce CO_2 emissions. With standards competition is mainly focused on the Gas technology, leaving the Green technology unable to benefit. A *feebate system* is rather expensive. Its additional pressure on (incumbent) firms is mild, and it hardly creates any additional pressure on the Gas technology. The analysis of stand-alone policy instruments illustrates that there are trade-offs. It therefore depends on the authorities' objectives which instrument they consider most desirable.

4.4.3 Policy mixes

For the analysis of the policy mixes we study each policy mix of two policy instruments. Each mix is tested for the four combinations of the 'extreme' stringency levels: low-low, low-high, high-low and high-high. These four extreme cases provide insights into the range of possible outcomes for each policy mix.

Table 4.3 presents the additional effects generated by the different policy mixes with reference to the benchmark (no policy) on the criteria pollution, technology and public finance. First, it is analysed whether the effects are significantly different from the benchmark with a Wilcoxon-Mann-Whitney *U*-test. Second, the effects are labelled as complementary ($+$ or $-$), synergetic ($++$ or $--$), or contrasting ($-+$).[41] For example, the CO_2 reduction as a result of the policy mix *tax high* + *standards high* is labelled as complementary because the additional effect of this mix is greater than the additional CO_2 reduction as a result of *tax high* and greater than additional CO_2 reduction as a result of *standards high*.[42]

The table shows that policy mixes mainly generate significant effects for CO_2 reduction, except for *low-low* combinations. In all cases *high-high* policy mixes show positive complementary or synergetic effects for CO_2 reduction. Changes in the diffusion of the Green technology are only significant if *rebate* is one of the instruments in the policy mix. Although a *rebate* is a necessary condition for additional diffusion with respect to the benchmark, it is not a sufficient condition for complementary or synergetic effects.[43] For public finance mixing policy instruments has mostly contrasting or negatively complementary or synergetic effects, meaning that it is possible that an income generating policy instrument can offset the costs of an expensive policy instruments, but that some policy mixes generate even higher expenses. There are only a few policy mixes that have a combination of stringency levels generating positively complementary or synergetic effect on both pollution and technology. Such combinations are possible only with a *tax* + *rebate* or a *standards* + *rebate* policy mix. Below, we will discuss the policy mixes in more detail, illustrating that more often than not a trade-off is present between the different criteria.

[41] *Complementary* refers to an additional effect of the policy mix that is greater (lower) than the additional effects of both stand-alone policy instruments (present in the policy mix). *Synergetic* refers to an additional effect of the policy mix that is complementary and even greater (lower) than the sum of the additional effects of both stand-alone policy instruments. *Contrasting* refers to an additional effect of the policy mix that is smaller than at least one of additional effects of both stand-alone policy instruments.

[42] The industrial organisation criterion is not presented here since it is arbitrary to label changes in industrial organisation caused by a policy mix as synergetic or complementary.

[43] The market share of the Green-tech as result of a policy mix, which includes a rebate, is not necessarily higher than the market share of the Green-tech as result of a rebate as a stand-alone policy instrument.

Table 4.3: Simulation results of policy mix w.r.t. the benchmark. Average values over 100 simulations runs. Stars indicate whether results are significantly different from the benchmark. Signs indicate effect type: $-+$ (contrasting), $+$ or $-$ (complementary), $++$ or $--$ (synergetic).

Policy mix			CO_2 emissions reduction in %		Market share Green-tech increase in %		Public income increase in %	
Tax	+	Standards						
Low	+	Low	- 0.1	−−	- 10.8	−−	18.0***	−+
Low	+	High	22.7***	+	- 13.6	−−	13.5***	−+
High	+	Low	10.0***	−+	18.7	−+	69.6***	−+
High	+	High	23.4***	+	- 5.7	−−	60.1***	−+
Rebate	+	Feebate						
Low	+	Low	5.5**	−+	64.6***	+	- 9.5***	−−
Low	+	High	10.5***	++	71.7***	+	-21.6***	−
High	+	Low	17.4***	+	226.0***	−+	-27.7***	−
High	+	High	21.7***	++	233.8***	−+	-37.3***	−
Tax	+	Feebate						
Low	+	Low	5.6***	−+	- 12.3	−−	12.0***	−+
Low	+	High	7.9***	−+	- 1.6	−+	- 1.4***	−+
High	+	Low	11.5***	+	21.9	−+	64.7***	−+
High	+	High	12.9***	+	13.3	−+	52.0***	−+
Standards	+	Rebate						
Low	+	Low	- 0.4	−−	58.3***	−+	- 5.4***	−−
Low	+	High	10.5***	−+	227.2***	−+	-24.3***	−−
High	+	Low	25.2***	++	80.4***	++	- 6.7***	−−
High	+	High	33.9***	++	246.9***	++	-28.2***	−−
Tax	+	Rebate						
Low	+	Low	5.5***	++	77.6***	++	14.8***	+
Low	+	High	15.5***	++	238.8***	++	- 6.7***	−+
High	+	Low	19.6***	++	134.5***	++	61.5***	−+
High	+	High	38.5***	++	366.5***	++	24.2***	−+
Standards	+	Feebate						
Low	+	Low	5.4**	−+	- 6.3	−−	- 7.3***	−−
Low	+	High	8.9***	++	- 7.3	−−	-20.0***	−−
High	+	Low	20.2***	−+	- 2.8	−−	- 6.3***	−−
High	+	High	22.3***	+	- 2.9	−−	-15.2***	−+

* Significance at $p < .05$, ** Significance at $p < .025$, *** Significance at $p < .01$

Tax + standards. This policy mix generates a complementary reduction in CO_2 emissions with *standards high*. The mix generates mainly negatively synergetic effects and no significant pressure to adopt the Green technology. So, the additional CO_2 reduction is explained by the selection of less polluting Gas-tech vehicles, which both instruments aim at, as we have seen above. The *tax* regime in this portfolio keeps the effect on public finance positive. Only with *tax high* + *standards low* do we observe positive changes (not significant for technology) on all three indicators compared to the benchmark. However, these positive changes are all lower than with a *tax high* stand-alone.

Rebate + feebate. The mix mainly generates positively complementary and synergetic effects for CO_2 reduction when a *high* stringency level is implemented. Contrasting effects are present for the diffusion of the Green technology when rebates are *high*. So, the *feebate* system slightly dampens the high pressure generated by *rebate* to adopt the Green technology. In terms of public finance there are significant negatively complementary and synergetic effects as mixing these two expensive policy instruments become even more expensive. The combination of *rebate low* + *feebate high* generates positively synergetic and complementary effects for pollution and technology, but the costs are high.

Tax + feebate. This mix has only positively complementary effects for CO_2 reduction when tax is *high*, but it provides no significant additional pressure to adopt the Green technology. The effects for public finance are contrasting, but remain positive. So, this mix generates positive change with reference to the benchmark with *tax high* only, but these effects are hardly complementary or synergetic.

Standards + rebate. The implementation of *standards high* on top of a *rebate* generates positively synergetic effects for CO_2 reduction as well as positively synergetic effects to adopt the Green technology. The high standards provide the system with pressure to discard polluting Gas-tech vehicles, while the *rebate* simultaneously creates incentives to adopt the Green-tech. The only negative issue of *rebate* + *standards high* is that there are negatively synergetic effects for public income, which is caused by the positive effects of this mix for pollution and technology.

Tax + rebate. Only positively synergetic effects on CO_2 reduction and market share Green are present with *tax* + *rebate*. All stringency combinations show positive and significant changes on all criteria with reference to the benchmark, except for public income in case of *tax low + rebate high*. The explanation for this win-win situation is that this policy mix decreases the price gap between the Gas-tech and the Green-tech vehicles from both sides, making the price of the Green-tech vehicles more competitive with the Gas-tech ones. Moreover the tax fully covers the expensive rebates (except for *tax low + rebate high*).

Standards + feebate. The results demonstrate that both instruments in this mix aim at the selection of less polluting Gas-tech vehicles. All combinations of this policy mix create barriers for the diffusion of the Green-tech. With *feebate high* positively complementary and synergetic effects are present for CO_2 reduction. However, the policy mix is expensive. Moreover, with *feebate low* the policy costs increase significantly without any beneficial effect on pollution or technology.

To summarise, successful policy mixes can be designed in order to generate additional pressure to reduce CO_2 emission or to increase the market share of a Green technology. However, the results illustrate that it is difficult to achieve complementary or synergetic effects on both criteria simultaneously with a policy mix, particularly if positive effects for public finance are desirable. The most effective results are mainly found when policy instruments with different foci are combined, such as a rebate for the Green technology and a sales tax on CO_2 emissions. Moreover, the results illustrate that policy mixes can increase costs significantly without any beneficial effect at all, as in some combinations of standards and a feebate. Policy mixes can also help authorities to select the different stand-alone policy instruments or to limit undesirable effects such as high costs.

4.5 Conclusions

This article presents an original ABM that explores how policy mixes may contribute to the transition towards a system in which the use of passenger cars contributes less to the total CO_2 emissions. We considered four types of instruments, which are the setting of emission standards, imposing a sales tax on CO_2 emissions, implementing a feebate system for internal combustion engine vehicles (Gas-tech vehicle) and awarding a rebate for electric vehicles (Green-tech vehicles).

First of all, the dynamics of our model highlight that even if there is no regulation, there is some pressure on the incumbent firms to reduce CO_2 emissions of the Gas technology and/or to switch to Green-tech vehicles. This 'natural' pressure is the result of a natural rate of technological progress, due to R&D investments of firms, the rising energy prices and the preference of consumers for new technologies or new characteristics of technologies. We subsequently investigated to what extent policy instruments increase this pressure and foster radical change in technologies and associated CO_2 emissions.

We show that stand-alone policy instruments significantly increase the pressure to produce and use more sustainable vehicles, but policymakers will have to face trade-offs. Taxes and the setting of standards are beneficial and neutral, respectively, in terms of public finance, and they both lead to substantial reduction in CO_2 emissions. However, they do not additionally boost the Green technology, and the setting of standards dramatically increases market concentration. A feebate system also leads to significant reduction in CO_2 emissions, but it is a rather expensive measure and it also fails to boost the Green technology. Awarding a rebate for Green-tech vehicles is the only instrument that provides this boost. It fosters the transition towards Green-tech vehicles, leading to a consistent reduction in CO_2 emissions, but it is an expensive instrument.

Is it rewarding, then, to combine instruments to achieve the best of different stand-alone policy instruments? Our results emphasise that policy mixes can be effective to generate additional pressure to reduce CO_2 emissions or to increase the market share of the Green technology, but this effect does not apply to all combinations. Positively complementary and synergetic effects are mainly found when policy instruments are combined that focus on different technologies, such as awarding a rebate for radical new technologies and imposing a CO_2 (sales) tax on the incumbent technology. In some cases policy mixes can help to cancel out the high burden on public finance. But mixing policies might also increase the burden on public finance, even without any positive effect on CO_2 emissions or the Green-tech. So, only in some cases do policy mixes lead to synergies that are desirable, and careful design is therefore important. Moreover, the chapter illustrates that model simulations may be a useful tool for *ex ante* evaluation of policy mixes.

5 Incremental improvements towards a more sustainable car market*

5.1 Introduction

Both in the EU and in the US energy-labelling or eco-labelling schemes are an increasingly popular instrument to stimulate the demand for and supply of more environmentally friendly goods (EPA, 2011; EU Directive, 75EC, 94EC). The main idea of energy-labelling schemes is that these labels will increase consumer demand for eco-friendly goods and, as a consequence, stimulate firms to produce and supply more of those goods. Firms can achieve a cleaner product portfolio by reducing the environmental impact of existing products, through adding products with low environmental impact to their portfolio, and/or by discontinuing the supply of their most polluting products. It has, however, been difficult to assess whether energy-labelling schemes realise their intended outcomes and in several studies no clear environmental effect of energy-labelling was found (AEA, 2011; OECD, 1997; Teisl et al., 2002).

Most studies focus on the demand-side rather than on the supply-side effects of emission reduction incentives such as energy labels and carbon taxes, as ultimately the behaviour of consumers determines the effectiveness of such incentives (Noblet et al., 2006; Rogan et al., 2011; Small, 2012; Beck et al., 2013; van der Vooren and Alkemade, 2012). An exception is Jamalpuria (2012), who demonstrates that from a social welfare perspective it is desirable that governments provide tax incentives to firms to encourage the use of energy labels. Thus by attaching financial incentives to the labels, policymakers have an additional influence on firm and consumer behaviour. For policymakers it is also important to understand the effects of these incentives as it is an intermediate step in realising the intended benefits of energy-labelling schemes. The extent to which firms adapt their product portfolios should be taken into account when assessing the effects of energy labels and other emission reduction incentives. Firms decide on product portfolio decisions not only in relation to consumers, but also with

* This chapter is published as: van der Vooren, A., Alkemade, F. and Hekkert, M.P.: 2013, Environmental performance and firm strategies in the Dutch automotive sector, *Transportation Research part A: Policy and Practice* 54, 111 - 126.

respect to the (expected) strategies of other firms, and other incentives provided by EU and national regulations. These product portfolio decisions of firms are the topic of the current chapter.

Energy labels provide consumers with information about the environmental performance of a product (Gallastegui, 2002). Energy labels thereby introduce an additional product characteristic that consumers can take into account in their purchase decision (Truffer et al., 2001). Consumers differ in their preferences for environmentally friendly products, but environmental characteristics have generally gained importance in recent years (Banerjee and Solomon, 2003). For firms, environmental performance thus provides an additional source of consumer heterogeneity. Firms can exploit this heterogeneity through strategic product positioning (Anderson et al., 1992). For firms, the introduction of energy labels thus creates opportunities for repositioning. The results of a firm's positioning strategy therefor strongly depend on whether competitors choose similar or different strategies. The aim of this chapter is to investigate firms' behaviour since the introduction of energy-labelling schemes. Our application domain is the automotive sector. The car market is one of the largest for durable goods and is a large contributor to the emissions of greenhouse gasses (IPCC, 2011). In 2001 the EU implemented a labelling scheme for cars (EU Directive, 94EC), and more recently the US adopted this policy instrument (EPA, 2011). The main research question of the chapter is therefore:

How have the portfolios of car manufacturers changed with the introduction of energy labels?

To study how the introduction of a new characteristic affects changes in product portfolios we make use of evolutionary theories of economic change (Nelson and Winter, 1982). Evolutionary theories describe that firms need to adapt to changes in the selection environment in order to survive (Metcalfe, 1994; Nelson and Winter, 1982; Silverberg et al., 1988). The introduction of a new characteristic such as energy labels is a typical situation of a change in the selection environment. In particular theoretical extensions of Lancaster's characteristics approach (Lancaster, 1966) by Saviotti and Pyka (2004, 2008a,b) and Saviotti and Metcalfe (1984) on products clouds and characteristics contribute to insights into portfolio change. Portfolio dynamics can be observed empirically when the cloud of products changes position and shape, showing differentiation or specialisation strategies of firms and changes in the intensity of competition.

The empirical base for the analysis is a unique database consisting of all 41,000 car models (versions) that were offered on the Dutch car market between 2001 and 2010. The database contains information on performance characteristics of the car models, including energy labels and CO_2 emissions but also characteristics describing fuel type, weight and type of car (for example, hatchback or sedan). Using this database we determine the product portfolio strategies regarding three strongly related characteristics: the CO_2 emissions, the weight and the list price of the cars. Changes in car manufacturers' portfolios regarding these characteristics provide us with insight into firm strategies and competition in the automotive sector. The results of the analysis show that manufacturers move in a similar direction towards cleaner vehicles, however the different manufacturers have chosen very different portfolio management strategies. Manufacturers with relatively large reductions in CO_2 emissions tend to perform better than manufacturers with relatively small reductions.

The remainder of this chapter is structured as follows: Section 5.2 provides a background on evolutionary theories of economic change and product portfolios, Section 5.3 describes the Dutch car market and the introduction of energy labels. Section 5.4 provides the data and methods. Section 5.5 presents the empirical analysis and Section 5.6 concludes.

5.2 Theory

In evolutionary theories of economic change, the firm is usually the unit of selection. A firm with a high fitness, i.e. a high degree of adaptation to its selection environment, will increase its sales numbers, profits or other performance measures compared to other firms with lower fitness (Metcalfe, 1994; Nelson and Winter, 1982; Silverberg et al., 1988). Cantner et al. (2012) argue that in reality it is not the firm but its multiple products that are subject to direct market selection. The fitness of the firm is determined by the aggregated fitness of its individual products. However, for multi-product firms this aggregation might be complex as they are influenced by different, possibly interrelated, selection processes in parallel (Cantner et al., 2012). This chapter is therefore focused on the product portfolio of a firm.

This chapter describes the products in a firm's portfolio by using the characteristics approach, in which consumers select one of the products based on their preferences for a number of characteristics that the product possesses (Hotelling, 1929; Lancaster, 1966; Saviotti and Metcalfe, 1984). According to Frenken (2006b) the characteristics approach provides an adequate representation of product competition. Consumers thus have preferences for the characteristics of the product and not for the product as such. As long as a homogenous product population is analysed a rather similar set of characteristics can be expected. The products of various firms and the different products within a single firm's portfolio differ in their values or performance levels of the same characteristics (Saviotti and Pyka, 2004).

Saviotti and Metcalfe (1984) extended the characteristics approach by representing a technological model by its performance on two sets of characteristics: the internal structure of the product's technology and the services provided by the product technology to consumers, which are labelled the technological characteristics and the service characteristics, respectively. The services performed for its consumers follow from the technological characteristics of the product technology. So, innovation in technological characteristics determines changes in the environmental impact of the product, i.e. the service characteristic. Because consumers select on service characteristics and not so much on changes in technological characteristics, in this chapter we focus mainly on changes in service characteristics. Graphically, each product can be represented by one point in an n-dimensional space of characteristics. Since firms produce multiple products with different performance on the service characteristics, the technological population is represented by a cloud of points. Figure 5.1 illustrates different situations of the product portfolio of two competing firms in an industry. A firm's competitive position is determined by the part of the total product cloud produced by all firms in the industry that is covered by a firm's product portfolio. The more overlap between the firms' portfolio, the more intensive their competition is. A more elaborate discussion of the different portfolio changes, illustrated in Figure 5.1, will be presented towards the end of this section.

Evolutionary technological change means that product portfolios and competition are dynamic. Product portfolios can change position and shape, or completely new product populations can emerge (Saviotti and Mani, 1995). In this chapter product portfolio dynamics are analysed as a response to the introduction of a new service characteristic. Such technological change can be induced by changes in the selection environment of the firm or through product positioning strategies enabled by innovation. In practice it may be difficult to distinguish these two motives as they may occur simultaneously.

The notion of selection environment comprises factors that affect the competition process such as consumer demand, governmental policy and availability of resources (Lambooy, 2002; Nelson and Winter, 1982). If changes occur in the selection environment, due to changing consumer preferences, government intervention or depletion of resources, the firm has to adapt its strategies in order to survive. For example, the EU introduced energy labels for cars to stimulate the supply of and demand for more environmentally friendly cars, which is desirable from a societal point of view. While the underlying technical characteristic already existed, energy labels provide a new service characteristic to consumers, i.e. environmental performance. The introduction of environmental performance as new service characteristic changes the selection environment since it is expected that consumers take environmental performance of a car into account more when energy labels are provided. This effect is the main policy rationale for the introduction of energy-labelling schemes. In addition, labels enable the use of financial policy instruments to influence the purchase behaviour of consumers. However, consumers will evaluate this additional service characteristic differently. Firms can exploit this additional source of consumer heterogeneity through differentiation within their own product portfolio and by setting their own portfolio apart from the portfolio of competitors.

The introduction of a new characteristic might be supply driven as well, when firms innovate and change their portfolio strategy in order to escape competition (Swann, 2009). When firms position themselves in unoccupied regions of the characteristics space they might temporarily escape the competition and benefit from monopoly power (Saviotti and Pyka, 2004). Such a first-mover advantage holds until other firms take that position as well. The motivation to innovate, i.e. to escape from the competition, is higher when the competition is more intense (Saviotti and Pyka, 2008a). Whether or not a firm is actively involved in a neck-and-neck race to have the best product with regard to the new characteristic, the strategy and search process to reposition its portfolio of products might vary significantly from other firms. Search activities have an incremental nature when changes occur within the existing product population and a more radical nature when a new product population emerges (Saviotti and Pyka, 2008a). Search activities are constrained by a firm's current position and routines (Nelson and Winter, 1982; Teece et al., 1997).

In reality, the co-evolution of the selection environment on the one hand and changing portfolio strategies on the other hand, will cause the dynamics in product portfolios. These dynamics can be observed when the clouds of products change position and shape or when completely new clouds emerge (Saviotti and Mani, 1995). Figure 5.1 illustrates four typical changes in product clouds with two competing firms, A and B. The position of the industry product cloud, A + B, will change position when the product portfolios of both firms move in a similar direction. Figure 5.1 (top left) shows the shift from firm A to A′ and firm B to B′. Figure 5.1 (top right) illustrates that if firm A and B move in opposite directions the range increases and the density of the cloud decreases. Figure 5.1 (bottom left) shows that the more similar the product portfolio of firm A and firm B become, the higher the density of the industry product cloud, and the more intense is the competition amongst the firms (Saviotti and Pyka, 2008a). A higher degree of differentiation therefore decreases the intensity of the competition. Figure 5.1 (bottom right) illustrates that when a firm (firm A) exploits the additional consumer heterogeneity through differentiation, this decreases the density of its product portfolio, at least when the number of products remains the same. In this case firm A becomes a generalist while firm B in this figure tends towards specialisation.

With the introduction of a new service characteristic it is not necessarily the case that firms exploit consumer heterogeneity by differentiation, as illustrated by the seminal paper by Hotelling (1929). Hotelling shows that two competing firms tend to agglomerate on a particular product dimension in an effort to catch as many consumers as possible that are served by the other firm. Anderson et al. (1992) refine these results and argue that firms agglomerate on pre-existing dimensions while they become more dispersed on a new and additional dimension when consumers attach more importance to this new dimension. The introduction of a new dimension thus creates different opportunities for repositioning (Anderson et al., 1992). The results of a firm's positioning strategy thereby strongly depend on whether competitors choose similar or different strategies.

In this chapter we also study empirically how the introduction of a new service characteristic changes the product cloud in general and how firms have different strategies to reposition their portfolio of products in particular. In order to answer this question we study changes in the portfolio position of car manufacturers since the introduction of graded energy labels. We thereby focus on the

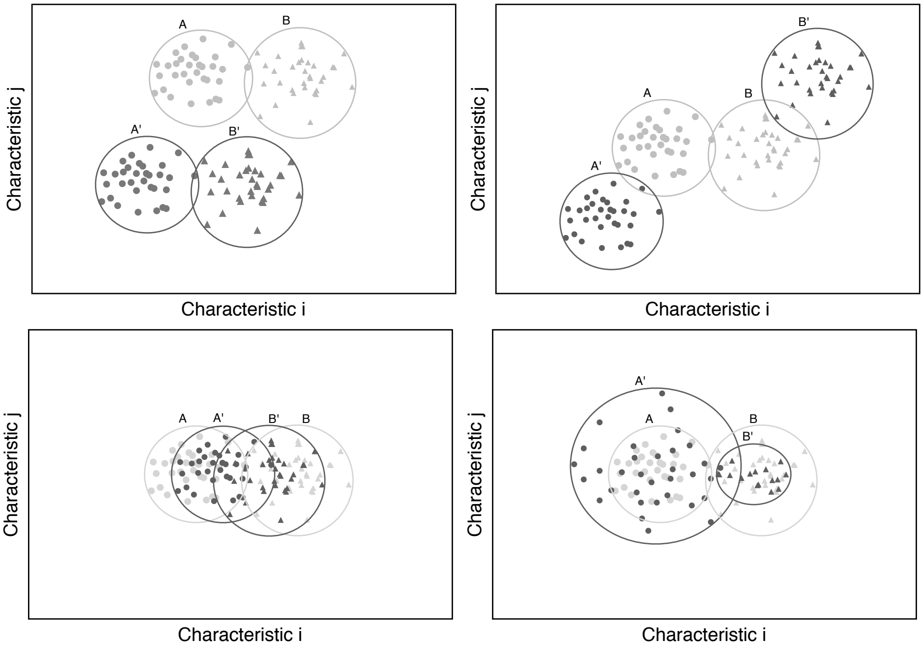


Figure 5.1: Firm A and firm B are competing and change their portfolio of multiple products towards A′ and B′. Four typical changes in product clouds may occur: a change in industry product cloud (top left); increase in range and decrease in density (top right); an increase in density and competition intensity (bottom left); a generalisation strategy by firm A and a specialisation strategy by firm B (bottom right).

search and strategy process of car manufacturers that have an incremental nature, leaving out entirely new types of vehicles such as hydrogen or battery electric vehicles. The technological population exists of cars that have a fossil-fuel-powered internal-combustion engine as their principal propulsion. Hence, changes in the position and shape of the cloud of products will be studied, while the emergence of new clouds is not taken into account.

5.3 The 'Dutch' car market

The 'Dutch' passenger car market provides an interesting case to study how the introduction of a new service characteristic changes the product cloud and the portfolio position of firms. With the introduction of energy labels in 2001 environmental performance emerged as a new service characteristic which consumers and firms may take into account. The 'Dutch' car market is put in between quotes as no significant automobile production takes place in the Netherlands (48,025 passenger cars in 2010 (OICA, 2012)). In addition, none of the major passenger car manufacturers have the Netherlands as their home country. Despite the fact that most cars are imported, with more than 7 million passenger cars on its roads (2010) (European Union - Eurostat, 2012), the Netherlands is the sixth largest automotive market in Europe. The car density, i.e. the number of passenger cars per one thousand inhabitants was 467 in 2010 (European Union - Eurostat, 2012). About half a million cars were sold in the Netherlands in 2010 (BOVAG-RAI, 2011).

In this chapter we will analyse the portfolio changes from 2001 to 2010 by the fifteen car manufacturers with the highest market shares on the Dutch market in 2010. Figure 5.2 below shows the sales figures of the fifteen manufacturers on the Dutch market for the years 2001 and 2010. The fifteen selected companies represent 82.5% (77.7%) of the total Dutch car market in 2010 (2001).

5.3.1 The Dutch energy-labelling scheme

In order to create a more sustainable and environmentally friendly car market the EU agreed upon a graded energy-labelling scheme for cars (EU Directive, 94EC). The energy label is a new service characteristic. It enables consumers to weigh their preferences for the environmental impact of a product against the price and other important service characteristics of the product (Sammer and Wüstenhagen, 2006).

The graded labelling scheme was implemented in the Netherlands in 2001. The mandatory energy labels show the relative performance of a car regarding CO_2 emissions in its own class (determined by length and width of the car). On a scale of A to G an A-label indicates that a car belongs to the cleanest vehicles in its class, while a G-label indicates the most polluting cars in terms of carbon emissions. The labels are dynamic in the sense that the standards may become stricter from year to year when cleaner vehicles become available. For example, a car that is labelled A one year, can be labelled B in following year (AMvB BWBR0011761, 2012).

The Netherlands had a slow reduction of CO_2 emissions of new passenger

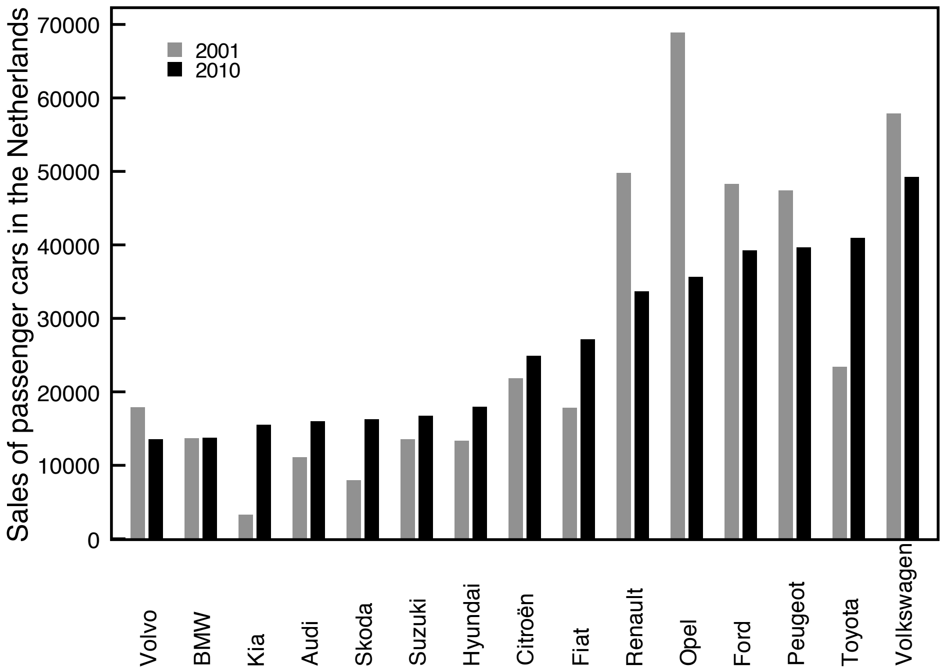


Figure 5.2: Sales of passenger cars in the Netherlands in 2001 and 2010. Source: (BOVAG-RAI, 2006, 2011).

cars for years, compared to other EU countries. However, thanks to progressive tax policies regarding greening of the Dutch car market, the CO_2 emissions of new passengers in the Netherlands were below the European average again in 2009 (Geilenkirchen et al., 2012). Figure 5.3 shows the share of each label in the total sales of the Netherlands. Both the demand for (Fig. 5.3 left) and supply of (Fig. 5.3 right) A and B labelled cars tripled from 2001 to 2010. The increase in the presence of A and B labelled cars took off by 2006 and increased rapidly by 2008. This increase is explained by tax policies and the fact that standards were not adjusted between 2007 and 2009, even though technological progress took place (CBS, PBL and Wageningen UR, 2012).

With the introduction of tax policies in 2006 the Dutch government attempted to add momentum to the energy labels. A feebate system[1] based on these labels

[1] A feebate system is intended as a self-financing system of fees and rebates to change the behaviour of consumers. For more information on the effectiveness of feebate systems see Brand et al. (2013).

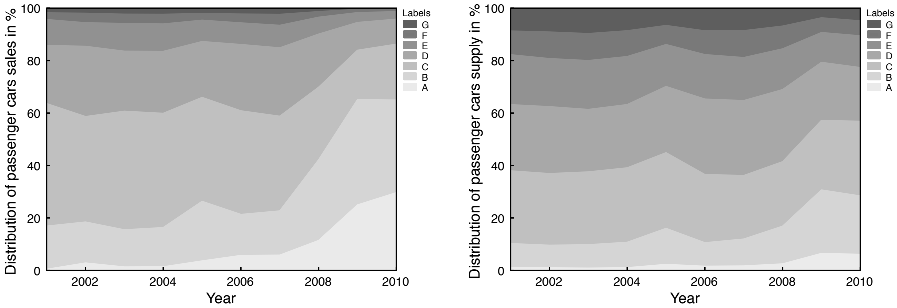


Figure 5.3: Distribution of passenger car sales (left) and supply (right) over energy labels. Source: (CBS, PBL and Wageningen UR, 2012) based on data from RDW.

was introduced in 2006.[2] The amounts shown in Table 5.1 are in addition to other private vehicle taxes consumers had to pay. Consumers buying cars with a relatively green label receive a rebate, while those buying cars with a dirty label pay a fee. In 2008 the Dutch government started with a CO_2 tax as well. In 2010 this tax, based on the absolute CO_2 emission of cars, completely replaced the feebate system as well as other private vehicle taxes. After 2010, also the monthly taxes that consumers pay for the private use of company cars (leasing) have been directly related to absolute CO_2 emissions. Kieboom and Geurs (2009) found that the rebates for A and B labelled cars were effective, but the limited number of cars with an A or a B label hampered the success. However, the low fees compared to the purchase price of the vehicle were not at all effective.

The second explanation for the rapid increase of A and B labelled cars is the labelling procedure applied by the Dutch government. In 2008 and 2009 the government kept the standards for adjudging the labels fixed to the 2007 level. As cars became cleaner in these years a significant share of them received an A or B label. The standards for the labels were revised again in 2010 (CBS, PBL and Wageningen UR, 2012).

Since car prices are directly linked to energy labels and CO_2 emissions these service characteristics of environmental impact guide consumers in their purchase decision. In this chapter CO_2 emission as the key determinant of energy labels will be used as the new service characteristic. The reason for using absolute CO_2 emis-

[2] A different scheme was put in place for hybrid cars.

Table 5.1: The Dutch feebate system for petrol-based passenger cars: 1-7-2006 to 31-1-2008 (Top), 1-2-2008 to 31-12-2009 (Bottom).

Label A >20% lower consumption	Label B 10%-20% lower consumption	Label C 0%-10% lower consumption	Label D 0%-10% higher consumption	Label E 10%-20% higher consumption	Label F 20%-30% higher consumption	Label G >30% higher consumption
- €1000	- €500	0	+ €135	+ €270	+ € 405	+ € 540
- €1400	- €700	0	+ €400	+ €800	+ €1200	+ €1600

sions instead of labels is threefold. First, more and more financial policy incentives are based on absolute CO_2 emissions. Secondly, energy labels are established based on parameters provided by the government. As we explained above the Dutch government does not consistently measure and update these parameters, and therefore using the labels might give a disturbed picture of technological progress and positioning of manufacturers. Thirdly, absolute CO_2 emissions are used because they are measured for all vehicles sizes in a similar manner.

5.4 Data and methods

5.4.1 Data description and sample selection

We use a unique supply-side panel database of cars offered on the Dutch market to study how the portfolio of car manufacturers has changed with the introduction of energy labels. The 'carbase' database available at www.autoweek.nl encompasses more than 3,400 different car models and 60,000 different car versions offered on the Dutch market from 1980 onwards.[3] The dataset presents the performance on more than 150 characteristics of each of these car versions. Among others the characteristics provide insights into the engine technology, car size, list price and standard accessories.

The characteristic we are most interested in this chapter, the CO_2 emissions of cars, has been structurally recorded in the dataset since the introduction of energy labels for cars in 2001. Besides CO_2 emissions we also take into account

[3] The data in the database is submitted by the car manufacturers to Autoweek.

Table 5.2: Descriptive statistics of characteristics incorporated in the analysis (1,716 car versions in 2001 and 3,077 car versions in 2010).

	Characteristics	Mean	(SD)	Median	Min	Max
2001	CO_2 emissions in g/km	208	(40)	202	118	396
	Weight in kg	1297	(228)	1280	730	2235
	Price in 2001 Euros	29,092	(16,393)	24,797	7,576	173,072
2010	CO_2 emissions in g/km	177	(41)	169	89	375
	Weight in kg	1399	(269)	1402	775	2485
	Price in 2001 Euros	33,306	(22,599)	27,136	5,856	179,797

the list price and the weight of the car versions. List prices include private vehicle taxes, but might differ from the actual transaction prices. However, corrected for inflation, the list price is often used as indicator to study firm strategies and price changes (Uri, 1988; Wells et al., 2013). Price and CO_2 emissions are linked due to policy instruments, as noted in the final paragraph of the previous section. The CO_2 emissions and the purchase price are therefore important factors that guide the purchase decisions of consumers. The weight of cars is taken into account to distinguish between the different search strategies that manufacturers may have adopted to change their portfolio position. For example, reducing CO_2 emissions of a portfolio, while keeping weight fixed, reflect propulsion efficiency improvements. And reducing CO_2 emissions of the portfolio by reducing the weight of the portfolio reflects either of two strategies. Manufacturers may innovate regarding the technological design of a vehicle or they may put an end to their heavy vehicles and embrace lighter vehicles.

Moreover, the three characteristics, CO_2 emissions, price and weight of car versions are highly correlated.[4] Together they provide a picture of how manufacturers have adapted their portfolio of car versions. Table 5.2 provides the descriptive statistics of the three characteristics. It shows that the average CO_2 emissions decreased from 2001 to 2010, while the average weight and price increased.

Car models and versions. Consumers can choose between many different versions of a single car model. These versions may differ on the product characteristics that are the focus of the analysis such as CO_2 emissions, price and weight

[4] Correlation between key variables in 2010: weight CO_2 emissions (.860); weight price (.859); CO_2 emissions price (.832).

and different versions of the same car model may even be assigned different energy labels. The version is therefore the appropriate level of analysis. For example, the Ford Focus is available in the Netherlands as a four-door sedan, a five-door hatchback and a five-door station wagon. Each of these model variants has a range of versions, from a low-priced simple car to a more expensive luxury car, with a petrol or diesel engine. Cantner et al. (2012) aggregate over different versions using the model variant as data point. Since we focus on CO_2 emissions, which can vary substantially among versions of a single model variant, this would be problematic in our case. So, we include each unique car version in our analysis. Note, however, that a 'new' car version introduced by a manufacturer might actually be a version that is not substantially different from existing car versions. Car manufacturers that use this strategy change the position of their portfolio without technologically introducing something new to the market.

Sample selection. A comparison between the portfolio changes of the 15 selected manufacturers is possible only for rather homogeneous portfolios of car versions. Therefore we choose to take into account only those versions that qualify as a family car, which we define as four or five-door cars with a petrol engine as their principal drivetrain.[5] So, versions with diesel engines that are mainly used in the professional market, sports cars, pick-ups and jeeps for example, are excluded from the analysis. While diesels capture increasingly large shares of the new vehicle market in Europe (Schipper and Fulton, 2013), this trend is not observed in the Netherlands. In 2010, petrol cars represented 75.4% of the new vehicle market in the Netherlands, while diesel cars accounted for 20.4% (BOVAG-RAI, 2011).[6] In the period between 2001 and 2010 12,961 different family car versions have been offered by the fifteen selected companies, of those car versions 4,793 are in our sample, as we focus on the years 2001 (1,716 versions) and 2010 (3,077 versions).

[5] This is in line with the criteria for the family car of the year contest of the ANWB, the Dutch Automobile Association.

[6] The share of the new vehicle market in the Netherlands captured by diesels fluctuates between 20% and 28% in the period between 2001 and 2010.

5.4.2 Steps for analysing portfolio strategies

The portfolio strategies of manufacturers are analysed in three steps that are introduced here. A more detailed and formal description of each step will be integrated in the empirical analysis. First, changes in the product portfolio of manufacturers are analysed regarding CO_2 emissions and the purchase price, because these are important factors that guide the purchase decisions of consumers. We measure changes in the position, the range and the density of car manufacturers portfolios. Secondly, an analysis is performed towards the search strategies that manufacturer performed in order to realise the reduction in CO_2 emissions. Hereby the relative portfolio changes regarding weight and CO_2 emissions compared to industry changes are used to determine the search strategy of manufacturers. A cluster analysis is performed to group manufacturers with similar portfolio strategies. Thirdly, an evaluation of the portfolio change and search strategies is performed. Strategies are evaluated based on the relative increases in car manufacturers' sales.

5.5 Empirical analysis

5.5.1 Measuring portfolio change

A plot of the family car versions offered by a manufacturer on two product characteristics is sufficient to create a static picture of the product cloud as in Saviotti (1985). Changes in such a product cloud become visible when the car versions offered in two different years are presented in one graph. For example, Figure 5.4 (left) plots the CO_2 emission (grams per kilometre) and the price of all BMW versions in our sample for 2001 and 2010. To analyse how the portfolio changed shape and position we measure where the core of the portfolio moved, how the range of the portfolio changed and whether the density of the portfolio increased or decreased from 2001 to 2010. Three indicators are used to determine portfolio change: the median[7] representing the core of the portfolio at time t, boxplots to provide insight into the range in which products are offered, and the average distance of the versions in the portfolio to measure the density.

[7] The median is preferred over the average as it is less sensitive for outliers.

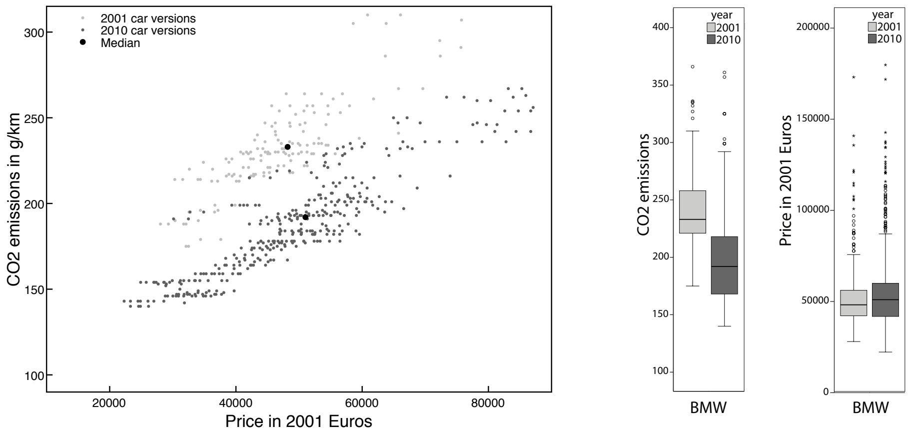


Figure 5.4: Left: overview of the BMW's portfolio of "family" car versions up to 90,000 euro in 2001 and 2010. Right: boxplots provide an overview of range of BMW's portfolio of "family" car versions in terms of CO_2 emissions and price in 2001 and 2010.

The large black dots in Figure 5.4 indicate the median values, i.e. the core of the portfolio. Changes in the core (median) of the portfolio provide a quantified measure of shifts in the product cloud of a manufacturer. A non-parametric Mann-Whitney test (Mann and Whitney, 1947) is used to analyse whether the portfolio of versions in 2001 is similar to the portfolio of versions in 2010, regarding a characteristic. For example, a significant Mann-Whitney test indicates that the CO_2 emissions of the 2001 portfolio are larger than the CO_2 emissions of the 2010 portfolio. The figure illustrates that the core position (median of car versions) of BMW in 2010 is cleaner but slightly more expensive than in 2001.

The boxplot for CO_2 emissions on the right of Figure 5.4 shows that BMW offered versions in a range from 140 to 361 g CO_2/km in 2010. BMW expanded its range of versions in terms of CO_2 emissions; on the one hand it shifted its focus towards cleaner vehicles, but on the other hand also increased the emissions of its most polluting models. In terms of prices, changes are small: BMW only slightly increased its price range.

The average distance between car versions in BMW's portfolio increased from

.16 in 2001 to .19 in 2010.[8] Despite an increase in the number of car versions, from 164 in 2001 to 393 in 2010, the portfolio of BMW is less dense and therefore more diversified.

5.5.2 Portfolio change

Table 5.3 provides an overview of the portfolio positions of the manufacturers in 2001 and 2010. For each manufacturer a comparison between the 2001 and 2010 portfolio is conducted with a Mann-Whitney test. Besides the median values, the table indicates the Mann-Whitney's U statistic, the effect size r and its significance.[9] The table shows that the CO_2 emissions of each manufacturer decreased significantly from 2001 to 2010. Effect sizes range from $-.15$ (Volvo) to $-.63$ (Fiat). The cloud of car versions of 'All' car manufacturers together moved from 202 g/km in 2001 to 169 g/km in 2010. With respect to price changes are small (Wells et al., 2013), only the portfolio position of Fiat, Skoda, Toyota, Volkswagen and Volvo changed significantly. Of these five manufacturers Fiat ($r = -.30$) and Toyota ($r = -.15$) reduced their prices, while Skoda ($r = .14$), Volkswagen ($r = .15$) and Volvo ($r = .39$) became more expensive. The cloud of 'All' car versions moved from $24,797$ Euro in 2001 to a price of $27,136$ Euros in 2010.

Figure 5.5 shows the portfolio position of the manufacturers with respect to price and CO_2 emissions. The arrows illustrate the direction and size of the change from 2001 to 2010. The figure shows that all manufacturers lowered the CO_2 emissions of their portfolio and that there is a correlation between price and CO_2 emissions. This correlation is mainly caused by engine size and weight, although registration taxes are increasingly dependent on CO_2 emissions. Car versions with low CO_2 emissions become relatively less expensive, while polluting cars become

[8] The average distance is based on the Euclidean distance. Both CO_2 emissions and price are normalised with respect to all versions in the selected sample of the 15 manufacturers.

[9] The test statistic U is based on the sum of ranks for the portfolio in a year. The smaller the U (taking into account the number of car versions in each year), the less likely it is that the difference has occurred by chance. The significance illustrates the two-tailed probability that the test statistic is a chance result. If significant this indicates that the 2001 portfolio had significantly higher CO_2 emissions than the 2010 portfolio. And, a larger effect size indicates a larger difference between the 2001 and 2010 portfolio (Field, 2009).

Table 5.3: Comparison of the portfolio of car versions in 2001 and 2010. Median values represent the portfolio position in 2001 and 2010. Mann-Whitney test with U is Mann-Whitney's U statistic, r is the effect size estimate.

	CO_2 emissions in g/km				Price in 2001 Euros ($\times 1,000$)				Number of car versions	
	2001	2010	U	r	2001	2010	U	r	2001	2010
Audi	230	175	11,106	-.51***	42	42	29,596	.02	171	340
BMW	233	192	12,426	-.49***	48	51	34,379	.05	164	393
Citroën	191	167	1,177	-.45***	23	24	3,056	.04	44	132
Fiat	201	146	318	-.63***	18	15	931	-.30***	37	80
Ford	190	179	6,980	-.37***	22	25	15,389	.21	127	195
Hyundai	190	152	1,390	-.32***	17	18	2,941	.12	38	133
Kia	220	165	359	-.55***	18	18	1,522	-.04	30	108
Opel	200	167	15,988	-.43***	23	23	30,341	-.05	296	217
Peugeot	188	155	3,649	-.57***	19	21	11,249	.03	132	165
Renault	177	174	11,739	-.20***	20	22	15,806	.03	164	186
Skoda	185	155	3,599	-.42***	17	18	11,296	.14*	67	281
Suzuki	173	143	685	-.48***	15	13	1,254	-.14	40	75
Toyota	196	155	1,541	-.60***	25	23	4,492	-.15*	80	136
Volkswagen	204	159	21,495	-.39***	26	28	46,136	.15***	245	322
Volvo	215	198	9,971	-.15***	27	39	19,883	.39***	81	314
All	202	169			25	27			1,716	3,077

* significance at $p < .05$
** significance at $p < .025$
*** significance at $p < .01$

more expensive. The figure shows that the portfolios of Fiat and Suzuki are the most affordable and least polluting. However, Toyota is a close third with respect to CO_2 emissions. The high-end of the market is covered by Volvo, BMW, and Audi, of which Audi and BMW made substantial improvements in reducing the CO_2 emissions. Volvo became much more expensive.

The last two columns of Table 5.3 show the number of cars versions in the portfolio. Except for Opel, all manufacturers increased the variety of car versions on offer. This number almost doubled in ten years' time. This does not necessarily mean that all manufacturers increased the range in which versions are offered. The boxplots in the Figures 5.6 and 5.7 below show the product range per manufacturer on the price characteristic (Figure 5.6) and on the CO_2 emissions characteristic (Figure 5.7).[10]

[10] The circles represent outliers between 1.5 and 3 interquartile ranges from the edge of the box. Stars represent outliers farther than 3 interquartile ranges from the edge of the box.

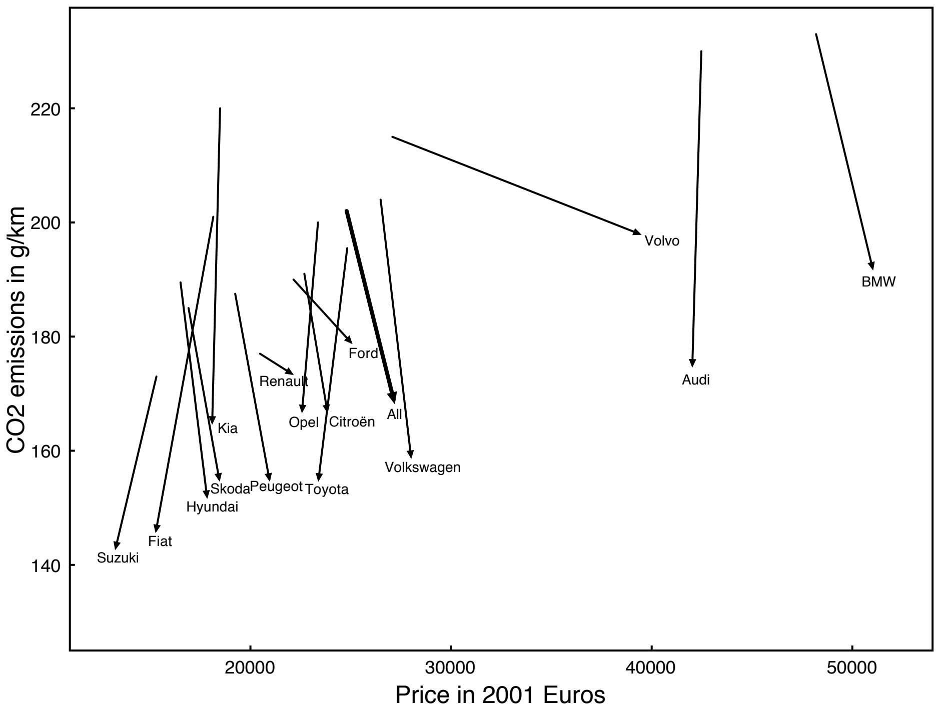


Figure 5.5: Portfolio change of car manufacturers in median price and CO_2 emissions between 2001 and 2010.

In Figure 5.6 the price range of the car manufacturers up to 100,000 Euro is presented in ascending order with respect to the median price in 2010. The figure shows that the price range in which manufacturers offer versions is larger for manufacturers that focus on the high-end of the market. Most firms increased their range from 2001 to 2010, except for Toyota, which discontinued most of its more expensive car versions. Quite some manufacturers started to sell more exclusive versions (or premiums cars) such as Volkswagen and Volvo, and to a lesser extent Hyundai and Skoda.

In Figure 5.7 the CO_2 emission range of the car manufacturers is presented in ascending order with respect to the median CO_2 emission in 2010. The figure shows that most manufacturers added versions with lower CO_2 emissions to their portfolio. In the case of Citroën en Peugeot this has even resulted in outliers at the bottom of the boxplot, because these versions are much cleaner than the rest of

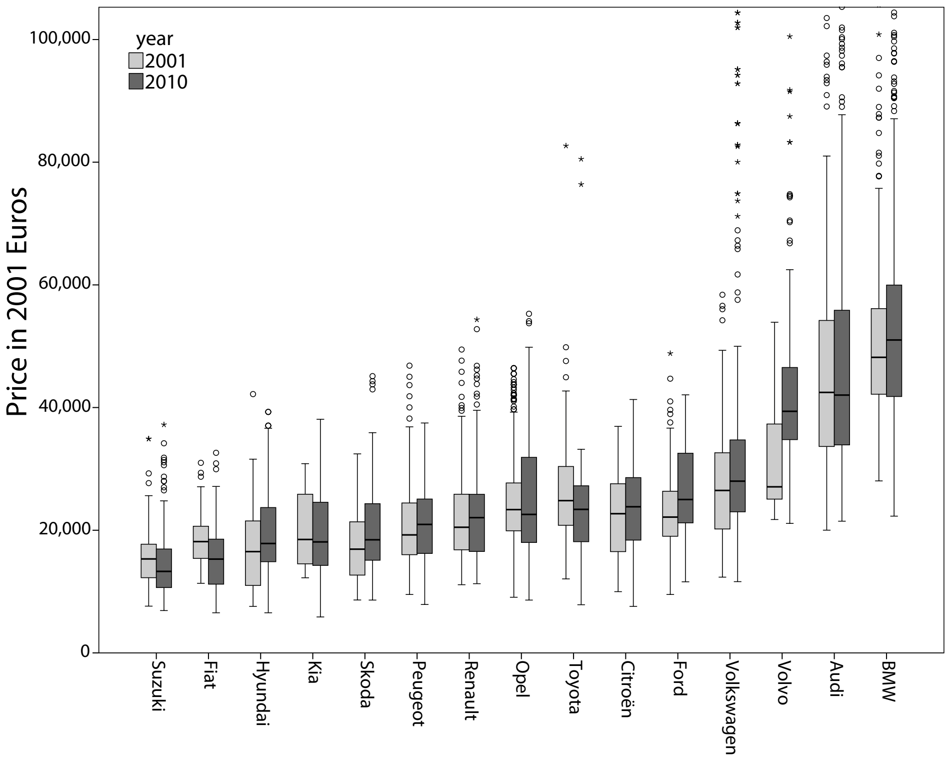


Figure 5.6: Boxplots of manufacturers' portfolio of car versions in terms of price in 2001 and 2010.

their portfolio.[11] From a theoretical perspective these firms may be said to attempt to temporarily escape the competition by positioning themselves in unoccupied regions of the characteristics space. Besides adding cleaner car versions, most manufacturers discontinued their most polluting versions. As described above, some manufacturers started to sell more exclusive versions. In particular for Volkswagen it is visible that these more exclusive versions come with high CO_2 emissions.

Since most manufacturers increased the number of versions as well as the

[11] It is not a coincidence that these car versions have similar CO_2 emissions, because they are practically the same cars sold by "different" manufacturers under the same holding company (PSA): Citroën's C1 and Peugeot's 107. This car is also sold by Toyota as the Aygo.

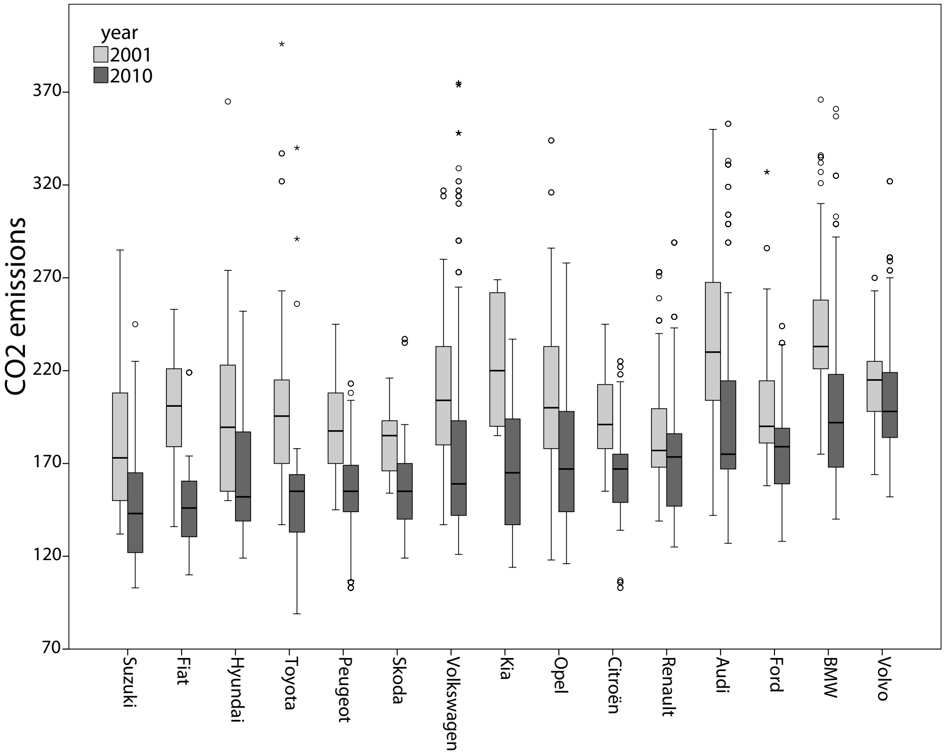


Figure 5.7: Boxplots of manufacturers' portfolio of car versions in terms of CO_2 emissions in 2001 and 2010.

range in which they offer cars, it is not obvious how the density of the product portfolios changed. The change in density of the individual manufacturers is presented in Figure 5.8. In addition, the figure presents the change in density for the population of 'All' car versions in the sample. The *x*-axis presents the number of versions offered by the manufacturers (mean number of versions for 'All') and the *y*-axis presents the normalised average distance.[12] Both the average distance and the average number of versions of 'All' car versions increased from 2001 to 2010. It should be noted here that the manufacturers with a larger portfolio have a higher weight in the calculation of the average, as they offer more versions. The

[12] The average distance is based on the Euclidean distance. Both CO_2 emissions and price are normalised with all car versions in the selected sample of the 15 manufacturers.

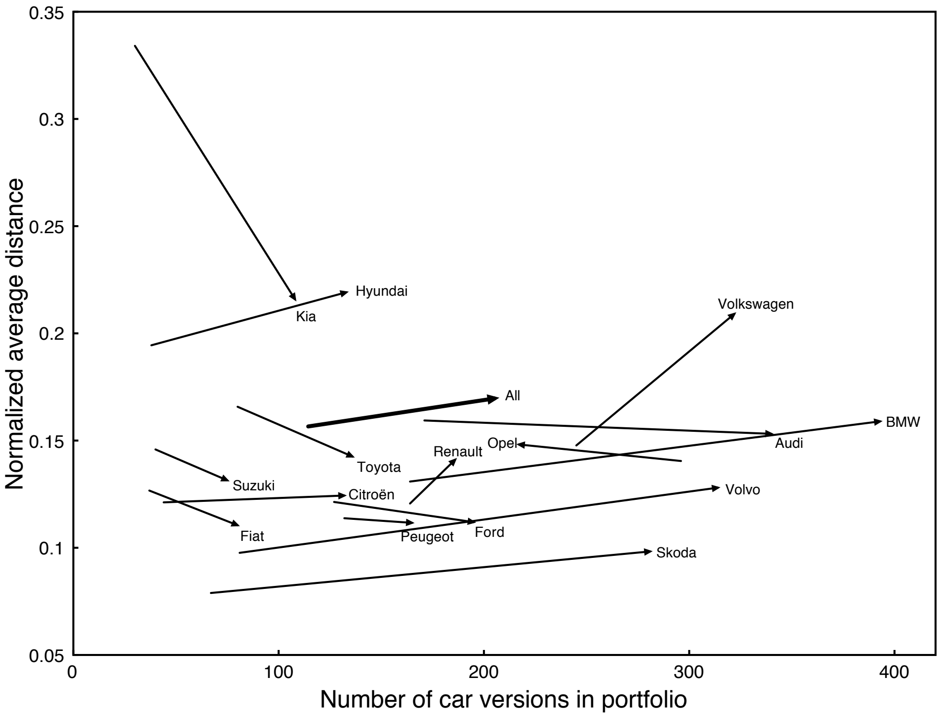


Figure 5.8: Manufacturers' portfolio change in average distance and number of car versions and between 2001 and 2010. The average distance is based on the Euclidean distance. Both CO_2 emissions and price are normalised with all car versions in the selected sample of the 15 manufacturers.

figure illustrates that larger firms tend to increase the average distance between the versions they offer. This is in line with Figure 5.6, which shows that the manufacturers active in the high-end of the market increased their range. These firms are also the manufacturers with the larger portfolios. The manufacturers that increased the density of their portfolio, i.e. lower average distance, are those firms with a smaller portfolio of car versions. Toyota and Volkswagen are the extremes with respect to changing their density. Toyota increased the density of its portfolio substantially, which corresponds to the fact that Toyota pulled its most polluting versions from the Dutch market (Figures 5.6 and 5.7). Volkswagen decreased the density of its portfolio by offering more exclusive versions as well in 2010 (see Figure 5.6). So, Volkswagen adopted a twin-track strategy by offering cars to consumers that prefer cars with low energy consumption as well as consumers that do not prefer these. However, Toyota adopted a strategy, where reduction of energy consumption is its guiding principle.

To summarise, since the introduction of energy labels each car manufacturer reduced the CO_2 emissions of its portfolio. However, the extent to which they reduced their CO_2 emissions differs substantially: it ranges between 3 g/km (Renault) and 55 g/km (Audi and Kia). Portfolio changes in terms of price are limited and go in both directions. The manufacturers with large reductions in CO_2 emissions added versions with lower CO_2 emissions to their portfolio, while discontinuing their most polluting versions. The manufacturers with lower reductions in CO_2 emissions also added versions with lower CO_2 emissions, but these firms tend to keep the more polluting versions in their portfolio as well. Many manufacturers increased the range in which they offer versions by adding more expensive versions to their portfolio. A more expensive version tends to have higher CO_2 emissions and therefore increases the range of their portfolio. However, the range of the product portfolio can increase in one direction while the core of the portfolio shifts into another direction. An increase in range tends to increase the average distance between versions as long as the number of car versions is constant, which is not the case. The number of versions increased substantially. The manufacturers with large portfolios mostly decreased the density of their portfolio, while those with smaller portfolios mostly increased the density of the portfolios. So, manufacturers with a large portfolio became more generalised, while manufacturers with a small portfolio became more specialised.

5.5.3 Search strategies of car manufacturers

The introduction of energy labels as a new service characteristic in combination with tax policies requires that car manufacturers reposition their portfolio and reduce their CO_2 emissions. The previous section showed that most manufacturers substantially shifted their portfolio towards lower CO_2 emissions, but only minor attention was paid to how manufacturers reduced the CO_2 emissions of their portfolio. This section therefore discusses the search strategies of car manufacturers towards lower CO_2 emissions.

There are basically two search strategies for car manufacturers to reduce the CO_2 emissions of their product portfolio. When firms use the first, incremental search strategy, firms innovate to reduce vehicle emissions while maintaining their performance levels on the other product characteristics. This innovation strategy is labelled an *efficiency improvement*: the per kilogram CO_2 emissions of the car decrease. A second search strategy for firms is a portfolio shift, where firms introduce lighter car models in their portfolio to meet the demand for vehicles with lower emissions. This *weight positioning* strategy can be effective as about one-third of a passenger car's fuel consumption is directly dependent on its weight (European Commission, 2009). The data show that weight reduction of existing car models appears not to be a manufacturer strategy.[13]

Another strategy for car manufacturers to reduce the CO_2 emissions of their product portfolio, which is not considered in this chapter, is to increase the share of diesels in the portfolio. Diesel models may have up to 25% lower CO_2 emissions than their petrol equivalents, although in practice new diesels bought in 2009 had only 2% lower average CO_2 emissions than new petrol cars, because diesel buyers choose large and more powerful cars (Schipper and Fulton, 2013; Zachariadis, 2013).

Table 5.4 provides an overview of the portfolio positions of the manufacturers with respect to *weight* in kg and *propulsion efficiency* in CO_2/kg. Similar to Table 5.3 a comparison between the 2001 and 2010 portfolio is conducted for each manufacturer with a Mann-Whitney test. The table shows that reducing the weight of the portfolio was clearly not the key strategy to reduce CO_2 emissions. The portfolio position of 12 out of the 15 manufacturers increased significantly in terms of weight. Fiat and Kia are the only manufacturers that reduced the weight of their median car version, however, no significant reduction in the weight of the portfolios is observed. All car manufactures did significantly improve their portfolio with respect to propulsion efficiency.

In addition to insights into how these positions of car manufacturers changed over time, the relative changes in portfolio position are measured relative to the

[13] We followed the evolution of popular car models (in the Netherlands) of each car manufacturer that was available from 2001 to 2010. We explicitly focused on the weight development of the car version with the lowest CO_2 emissions. The weight of these car models remained stable or increased over time (Zachariadis, 2008). Exceptions are the Skoda Fabia and Volvo V70, which that became 24 and 30 kg lighter, respectively. Other car models we followed are: Audi A4 4-doors sedan, BMW 3 4-doors sedan, Citroën C5 5-doors hatchback, Fiat Punto 5-doors hatchback, Ford Fiesta 5-doors hatchback, Opel Corsa 5-doors hatchback, Peugeot 206 5-doors hatchback, Renault Clio 5-doors hatchback, Suzuki Alto 5-doors hatchback, Toyota Yaris 5-doors hatchback, Volkswagen Golf 5-doors hatchback.

Table 5.4: Comparison of the portfolio of car versions in 2001 and 2010. Median values represent the portfolio position in 2001 and 2010. Mann-Whitney test with U is Mann-Whitney's U statistic, r is the effect size estimate.

	Weight in kg				Propulsion efficiency in CO_2 / kg			
	2001	2010	U	r	2001	2010	U	r
Audi	1,450	1,550	1,205	.25***	.17	.12	1,205	-.78***
BMW	1,515	1,600	37,479	.13**	.16	.12	1,657	-.75***
Citroën	1,290	1,461	3,842	.24***	.15	.12	44	-.74***
Fiat	1,175	1,155	1,225	-.14	.16	.13	50	-.78***
Ford	1,274	1,337	15,390	.21***	.16	.14	3,002	-.64***
Hyundai	1,199	1,211	2,936	.12	.17	.13	232	-.65***
Kia	1,261	1,217	1,660	.02	.18	.13	43	-.69***
Opel	1,260	1,390	41,626	.25***	.16	.13	843	-.83***
Peugeot	1,194	1,371	14,391	.28***	.16	.12	259	-.84***
Renault	1,225	1,295	19,191	.22***	.15	.13	2,488	-.72***
Skoda	1,105	1,190	11,728	.17**	.16	.13	1,419	-.58***
Suzuki	965	995	1,846	.19*	.18	.14	32	-.80***
Toyota	1,225	1,375	6,394	.15*	.16	.12	165	-.81***
Volkswagen	1,268	1,403	53,301	.30***	.16	.12	2,603	-.80***
Volvo	1,295	1,468	18,007	.29***	.16	.14	4,042	-.48***
All	1,280	1,402			.16	.13		

* significance at $p < .05$
** significance at $p < .025$
*** significance at $p < .01$

other manufacturers. The relative change in the portfolio position ΔRp_i^X on characteristic X of manufacturer i compares the absolute median (Mdn) portfolio position change $Mdn_{i,t-1}^X - Mdn_{i,t}^X$ of manufacturer i to the absolute median portfolio change of the car versions of all 15 manufacturers together $Mdn_{t-1}^X - Mdn_t^X$:

$$\Delta Rp_{i,t}^X = \frac{Mdn_{i,t-1}^X - Mdn_{i,t}^X}{Mdn_{t-1}^X - Mdn_t^X} \tag{5.1}$$

The relative portfolio changes of the car manufacturers are discussed by using a cluster analysis. A cluster analysis illustrates which firms had similar strategies. The relative change in weight and the relative change in propulsion efficiency are used as input variables for this cluster analysis. The relative portfolio change on *weight* and *propulsion efficiency* are presented for each manufacturer in Figure 5.9. Both for the relative change in weight and the relative change in propulsion efficiency, a positive position refers to a favourable change from the perspective of a reduction in CO_2 emissions compared to the median of all manufacturers. On both variables manufacturers can perform above or below the median of all 15 manufacturers together, which means that there are four combinations of the two variables possible. Therefore we first ran a two-step cluster analysis in SPSS with four clusters to group the manufacturers into the different strategies. Figure 5.9 shows the four clusters generated by SPSS. Although the *cluster quality* is good (.6), we also analysed this test with other numbers of clusters. We found that a cluster analysis with five groups not only has a higher *cluster quality* (.7), also it separates Volvo from Ford and Renault, which have a more favourable relative change in weight. The dashed eclipses in Figure 5.9 show the two smaller clusters. Below we discuss the five clusters represented in Figure 5.9:

Cluster 1. The first cluster represents Volvo in the bottom left corner of Figure 5.9. Volvo changed its portfolio position from 2001 to 2010 such that they became relatively less efficient and heavier than the other manufacturers. Volvo is alone in the cluster because it acted differently from all other manufacturers. In terms of innovation to reduce CO_2 emission, this is the least effective strategy.

Cluster 2. The second cluster in the bottom right corner of Figure 5.9 consists of Ford and Renault. Similar to Volvo the improvement of the *propulsion efficiency* (CO_2/kg) by Ford and Renault lags far behind that of the other manufacturers. With respect to the relative *weight* change, through the introduction of lighter models, they do relatively well, which means in this case that they increased less in weight than most other manufacturers. Although Ford and Renault perform relatively well on weight change, this is not enough to offset their weak improvement in propulsion efficiency, such that the relative CO_2 emission reduction is above the median.

Cluster 3. The third cluster, with Citroën, Peugeot, Opel, BMW and Skoda, is in the centre of Figure 5.9. Particularly in terms of propulsion efficiency, these manufacturers have about a median rate of change: they have no clear performance above or below the median. Their performance on relative weight change is more diverse, but close to the median as well. This cluster is labelled the 'median cluster'.

Cluster 4. The fourth cluster representing Toyota, Volkswagen and Audi is at the top of Figure 5.9. These manufacturers are ahead of the others mainly in terms of

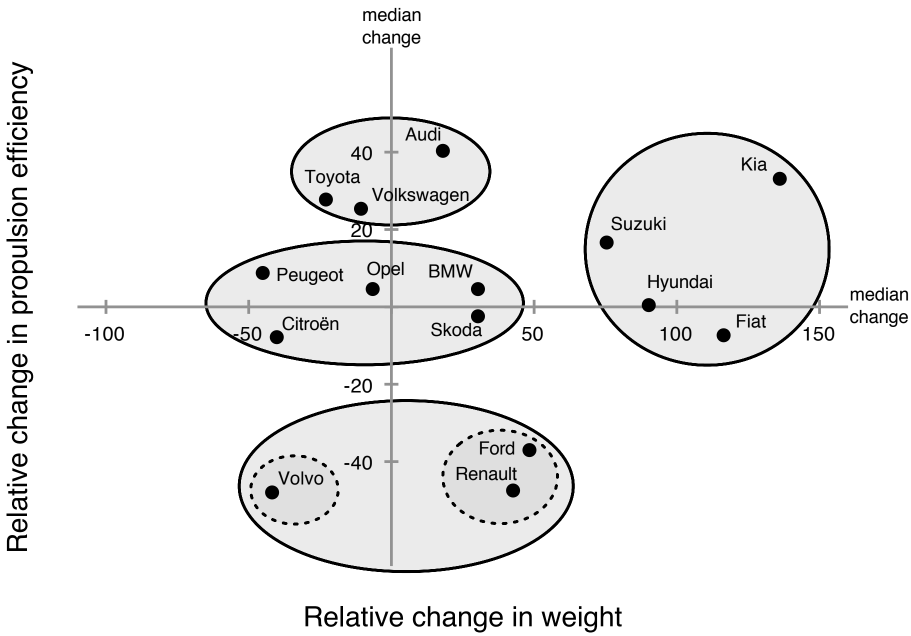


Figure 5.9: Relative change in propulsion efficiency and weight of the 15 selected manufacturers. A positive position refers to a favourable change from the perspective of a reduction in CO_2 emissions. The eclipses show the clusters as a result of a two-step cluster analysis in SPSS (dashed lines with 5 clusters).

propulsion efficiency improvement. Kia alone could have been placed in the same cluster if propulsion efficiency had been the only variable. The weight change of Toyota, Volkswagen and Audi is just below or above the median.

Cluster 5. The fifth cluster at the right side of Figure 5.9 represents Fiat, Hyundai, Suzuki and Kia. This cluster performs relatively well on weight change as well as propulsion efficiency. However, it is mainly Kia that has an outstanding position. Suzuki, Hyundai and Fiat mainly perform well on weight change, through their focus on introduction of lighter models. But in terms of propulsion efficiency these manufacturers have a mixed performance.

In summary, the search strategies of manufacturers to reduce their CO_2 emissions seems rather similar in absolute terms. However, a cluster analysis of the relative portfolio changes illustrates that there are differences in their strategies. Although 12 out of the 15 car manufacturers increased rather than reduced the weight of their portfolio, it still appears to be a valuable indicator to cluster the manufacturers by relative change in weight. In the next section we will present a rough evaluation of whether the search strategies and relative CO_2 reduction contributed to the car sales.

5.5.4 Evaluation of search strategies

Figure 5.9 shows the relative change in weight and the relative change in propulsion efficiency of the 15 car manufacturers. The next step is to evaluate how the relative performance of the manufacturers on change in CO_2 emissions affects their relative change in sales. We use the aggregate passenger car sales of each manufacturer as an indicator for the performance of its positioning strategy. Because both petrol cars and family cars are the majority of the car sales in the Netherlands this is a relevant performance indicator (exact numbers of the combination of petrol cars and family cars are not publicly available). Only Volvo and Skoda have a minority of petrol car sales in 2010, 39% and 48% respectively.

The sales figures are used as a performance indicator in the following way: the relative change in sales $\Delta S_{i,t}$ of manufacturer i at time t is calculated as the absolute change in sales $Q_{i,t-1} - Q_{i,t}$ relative to the mean change in sales of the 15 manufacturers $\mu^Q_{t-1} - \mu^Q_t$:

$$\Delta S_{i,t} = \frac{Q_{i,t-1} - Q_{i,t}}{\mu^Q_{t-1} - \mu^Q_t} \tag{5.2}$$

Figure 5.10 shows the relative performance change of the car manufacturers on CO_2 emissions and sales between 2001 and 2010. A positive position refers to a favourable change in terms of CO_2 emissions and sales compared to the median of all manufacturers. The figure shows that the manufacturers from clusters 1 and 2 (Volvo, Renault and Ford) performed relatively poorly both in terms of sales and in terms of CO_2 reduction. In contrast, most manufacturers in clusters 4 and 5 performed relatively well in terms of sales and in terms of CO_2 reduction. This holds for Audi, Fiat, Kia, Hyundai and Toyota. Volkswagen's (cluster 4) relative sales improvement is below the median, but they perform well on the relative change in CO_2 emissions. Suzuki's (cluster 5) relative change in sales is above the

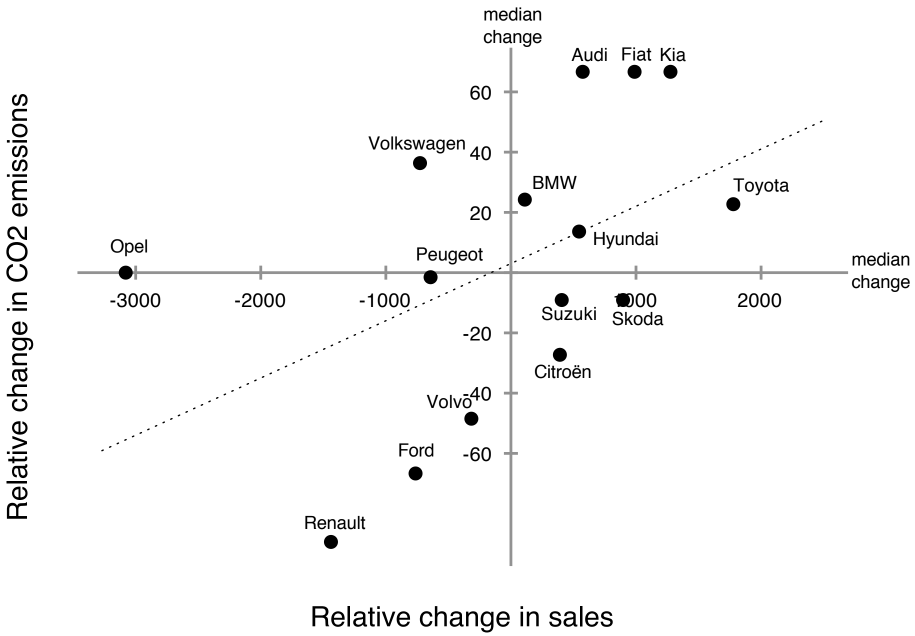


Figure 5.10: Relative change in CO_2 emissions and sales of the 15 selected manufacturers. A positive position refers to a favourable change in terms of CO_2 emissions and sales.

median, but they perform just below the median on change in CO_2 emissions. The manufacturers in the 'median cluster (3) are also close to the median with respect to relative change in sales and relative change in CO_2 emissions. Of this cluster only Opel is an outlier. Opels sales dropped dramatically, while its relative change in CO_2 emissions is at the median. While we present mainly aggregated outcomes of manufacturers, there are specific explanations for each manufacturer's performance. Box 1 in Appendix E.1 provides some insights into those explanations by zooming in on the portfolio performance of some car manufacturers.

The trend line in Figure 5.10 shows a positive correlation between the relative change in CO_2 emissions and relative change in sales.[14] The least innovative car manufacturers experienced a relative decrease in sales in the Netherlands from

[14] Correlation .479 (.071)

2001 to 2010, while the most innovative manufacturers saw an increase in sales from 2001 to 2010. So, CO_2 emission reduction seems to be rewarding for car manufacturers, but in the absence of a joint analysis of other car attributes (e.g. engine power, car size, etc.) this conclusion has to be treated with caution.

The results presented in Figure 5.10 are robust with respect to our choices to use only 2001 and 2010 data and our focus on cars with a petrol engine as principal drivetrain (including non-family cars). When using 3 year average sales numbers for both 2001 (2000 - 2002) and 2010 (2009 - 2011) some manufacturers perform slightly better (Volvo and Skoda) or worse (Suzuki), but overall results are robust and a similar trend is observed. Results are also robust when we include only petrol cars. In this case we observe that BMW, Suzuki, Volvo and Skoda perform worse and Citroën and Peugeot better. For Volvo and Skoda this might be related to their (increased) focus on diesel cars.

5.6 Conclusions

Policymakers and consumers increasingly express the need for a more sustainable transport system. This chapter studies car manufacturers' behaviour in this changing socio-economic environment. More specifically we have investigated how firms' product portfolios changed with the introduction of energy labels for cars by analysing the CO_2 emissions of the top 15 manufacturers in the Netherlands. Increased understanding of car manufacturers' behaviour provides policymakers with insights into the consequences of emission reduction incentives such as energy-labelling schemes.

The Dutch case showed that car manufacturers reduced their CO_2 emissions substantially. The range in which car manufacturers offered versions increased and the cloud representing the product portfolio of versions of all car manufacturers increased in size. In addition to an increase in the number of versions, we also observed an increase in the average distance between versions when considering the price and CO_2 emissions of cars. The manufacturers with large portfolios are mainly responsible for this increase in average distance. These large portfolio firms became more generalised and adopted a twin-track strategy by offering cars to both consumers who prefer cars with low energy consumption and consumers who do not prefer such cars, while most manufacturers with small portfolios became more specialised and adopted a one-track strategy with reduction of energy consumption as their guiding principle.

Although all manufacturers moved in a similar direction by reducing their CO_2 emissions, the Dutch car market did not follow the pattern predicted by Hotelling's (1929) theory that firms tend to agglomerate. We found that the Dutch car market became less dense, i.e. more differentiated. Neither did the Dutch car market follow the pattern predicted by the theory of Anderson et al. (1992) who claim that firms agglomerate on pre-existing dimensions while they become more dispersed on a new and additional dimension when consumers put more weight on this new dimension. The product range increased both in terms of price, the pre-existing dimension, and CO_2 emissions, the new dimension. The Dutch car market did follow a pattern predicted by Saviotti and Pyka (2004), however, who argue that firms position themselves in unoccupied regions of the characteristics space as they attempt to escape the competition, resulting in a more dispersed product cloud. In the car market a more dispersed product cloud is supported by technological innovations that have led to a decrease in costs of offering additional versions (Autocar, 2007).

Finally, we show that innovation to reduce CO_2 emissions seems rewarding in a country with tight environmental regulation such as the Netherlands, but in the absence of a joint analysis of other car attributes (e.g. engine power, car size, etc.) this conclusion has to be treated with caution. The chapter shows that the frontrunners in CO_2 emission reduction experienced the highest relative increase in sales. In particular the manufacturers that followed an innovation strategy of propulsion efficiency improvements and relatively stable weight increased their sales numbers compared to other car manufacturers. Manufacturers lagging behind with CO_2 emission reduction performed weak in terms of sales.

6 Competition intensity and technological change

6.1 Introduction

The transition towards a more sustainable society requires technological change. Its realisation requires an increase in the demand for and supply of more environmentally friendly goods, i.e., (eco-) innovation. An industry's competition intensity is an important determinant of its innovativeness (Aghion et al., 2005; Boone, 2001; Romer, 1990). In the literature different, and sometimes contradictory, effects of competition on innovation are found. Existing models predict that increased product market competition *decreases* innovation (Aghion and Howitt, 1992; Romer, 1990) and that increased product market competition *increases* innovation (Hart, 1983). The widely accepted theory by Aghion et al. (2005) takes both conflicting outcomes into account. They assume that sectors consist of both neck-and-neck competing producers and laggards that innovate to catch-up with their rivals. If competition intensity is low, neck-and-neck competing incumbents dominate a sector, and an increase in competition will increase the incentives to innovate (escape-competition effect). If competition intensity is high, laggard firms dominate the sector, and an increase in competition reduces the benefits of catch-up with rivals, such that incentives to innovate are low (Schumpeterian effect). These two mechanisms lead to an inverted u-shaped relationship between competition intensity and innovativeness.[1] According to Swann (2009) this relationship exists because the incentives to innovate increase, and the opportunities to innovate decrease with an increase in the competition intensity. Following this theory we expect that the degree of technological change is slow and improvements in sustainability are limited in monopolies[2] with few incentives to innovate and in highly competitive markets with few opportunities to innovate. According to these theories, improvements in sustainability through innovation are highest for oligopolies.

In an effort to stimulate innovation and accelerate the transition towards a

[1] The possibility of an inverted u-shaped relationship is first described by Scherer (1967).
[2] Contestable monopolies are not taken into account.

more sustainable society governments can provide the industry with incentives to innovate (Del Rio Gonzalez, 2009; Kemp, 1997). With regard to the relationship between competition intensity and innovativeness most studies focus on policy instruments directed at increasing competition intensity, such as the EU Single Market Program (Bottasso and Sembenelli, 2001) or the privatisation of industries (Aghion et al., 2005; Bouché and Volden, 2011). Based on a panel of 745 Italian firms Bottasso and Sembenelli (2001) do find empirical support for reduced market power and increased competition. However, no evidence is found for an increase in innovative activities due to the EU Single Market Program. Aghion et al. (2005) empirically support their theory of the inverted u-shaped relationship by studying various sectors in which policy instruments affected the degree of competition over time. These studies often use a narrow definition of innovation: R&D spending or patent counts as proxy for innovation. Our research extends these earlier studies in two ways: firstly, this chapter focuses on innovation as the supply of and demand for more environmentally friendly goods. Secondly, this chapter studies the effects of policy instruments that are directly aimed at increasing innovativeness, such as technology-push and market-pull instruments. The effects of those policy instruments are measured under different levels of competition intensity.

Successful innovative activities lead to technological change. It is widely recognised that a combination of technology-push and demand-pull is necessary to innovate, as they closely interact (Dosi, 1982; Di Stefano et al., 2012; Mowery and Rosenberg, 1979; Peters et al., 2012). Demand-pull as well as technology-push instruments have been shown to stimulate innovation in general (Pavitt, 2000; Taylor et al., 2005), and eco-innovation in particular (Horbach et al., 2012). Innovation requires the development of new technological products by firms as well as the adoption of these new products by consumers. With respect to eco-innovations, demand-pull instruments aim at increasing the demand for environmentally friendly products; technology-push instruments focus on an increase in the supply of environmentally friendly products. On the one hand, empirical research shows that demand-pull as well as technology-push efforts can positively affect the transition towards a more sustainable society, and on the other hand it shows that there exists an inverted u-shaped relationship between competition and innovation. However, it is unclear how the effectiveness of both instruments in supporting environmental performance varies under different market structures. This question, which provides important insights for policymakers that want to accelerate the transition towards a more sustainable society, is the topic of the current chapter.

To study this question we have built a computational model of a market, as the transition to a more sustainable society requires the development of new technological products by producers as well as the adoption of these new products by consumers. Producers compete on the market by offering products. Competition intensity is high when the number of producers is high, and the market share is equally distributed over competitors, and the products on offer are close substitutes. Consumers determine whether producers' products are successful and whether products with a better environmental performance are preferred. In our model innovation is measured as progress in the environmental performance of products. The characteristics approach (Hotelling, 1929; Lancaster, 1966; Saviotti and Metcalfe, 1984) is used to focus on environmental performance as one of the characteristics of a product. In this approach consumers select products based on their preferences for a number of product characteristics.

These types of models are referred to as location or address models in economics (Hotelling, 1929), as product positioning models in marketing (Kaul and Rao, 1995), and as party competition models in political science (Laver and Sergenti, 2011). They describe (sub)markets in which firms take a position in a multi-dimensional characteristics space in order to attract consumers that have preferences for these characteristics. Firms optimise profits, revenues or market share, which are affected by product characteristics, marketing strategies, competition, consumer characteristics and the state of the technology. Firms reposition in the characteristics space, based on either their previous performance, or changes in consumer preferences, or changes in the position of competitors (Kaul and Rao, 1995; Schmalensee and Thisse, 1988). Since the seminal paper of Hotelling (1929)[3] these models have advanced significantly, as described in an extensive review by Kaul and Rao (1995).

This chapter presents a dynamic competition model of multiple producers

[3] In his paper Hotelling presents a simple model of two ice-cream sellers on a beach that compete for consumers that are uniformly distributed over a beach. The ice-cream buying consumers take into account only one dimension: the distance to the ice-cream van. Hotelling illustrates that if the ice-cream sellers maximise their market share, then they end up clustered in the middle of the beach. This equilibrium emerges as the sellers have an incentive to move their vans towards the other in case the other has a higher market share.

offering multiple products in an attempt to optimise their market share of heterogeneous consumers. Consumers update their preferences based on the new product offerings by producers and policy incentives. The model illustrates that (i) in accordance with the theory an inverted u-shaped relationship exists between competition intensity and innovative activities that improve the environmental performance; (ii) to accelerate the transition towards a more sustainable product market, policymakers must take into account that the effectiveness of policy instruments to stimulate environmental performance depends on the market structure of a sector.

The remainder of the chapter is structured as follows: Section 6.2 provides a theoretical and empirical background on competition and sustainability improvements in a product market. Section 6.3 describes our competition model. Section 6.4 presents the results, and Section 6.5 provides the conclusion.

6.2 Competition and sustainability improvements

The intensity of competition in a market can be described in various ways. One approach is to count the number of firms active on the market or the concentration of market shares of these firms (H-index). Another approach is to evaluate the similarity of products on a market. Products that are similar are assumed to be close substitutes that compete more heavily than dissimilar products. The density, i.e., closeness of the products offered on a market, is a measure of product similarity. Lancaster's (1966) characteristics approach enables one to determine the density of product markets (Saviotti and Metcalfe, 1984). According to Anderson et al. (1992) it provides an adequate representation of product competition. In the characteristics approach consumers select products based on their preferences for a number of product characteristics (Hotelling, 1929; Lancaster, 1966; Saviotti and Metcalfe, 1984). Consumers thus have preferences for the characteristics of the product and not for the product as such. As long as a homogenous product population, such as the car market, is analysed, a rather similar set of characteristics can be expected. The products of various firms differ in their values or performance levels on the same characteristics (Saviotti and Pyka, 2004). Graphically, each product can thus be represented by a single point in an n-dimensional space of characteristics. Since firms often produce a portfolio of multiple products with different performance levels on each characteristic, the product portfolios can be represented by a cloud of points.

Moreover, the characteristics approach allows us to follow the development of a characteristic's performance over time. For example, the development of the environmental impact of a durable good such as a car can be measured by the CO_2 emissions in g/km. Chapter 5 uses the characteristics approach to study the evolution of environmental performance on the Dutch car market. Based on Chapter 5, Figure 6.1 shows the population of family cars offered by the top 15 car manufacturers on the Dutch market in 2001 (dark) and in 2010 (light). Each point represents the CO_2 emissions and a general performance characteristic (price or weight) of one car version. It shows a shift towards higher environmental performance while the performance on price and weight is rather stable between 2001 and 2010. The competition intensity between the 15 largest car manufacturers in terms of market concentration increased[4], meaning that the market shares of the 15 firms are more equally distributed and competition is more intense. The average distance between a version and all other car versions increased[5], meaning that on average car versions are more diversified in terms of price and CO_2 emissions.

This example of the car market provides no unambiguous proof of a causal relationship between competition intensity and innovation, where innovation is measured as the improvement in environmental performance. Moreover, several different policy instruments, both demand-pull and technology-push, were introduced in the Netherlands in this period, which makes it difficult to assess their effectiveness. In this chapter we are particularly interested in the effectiveness of market-pull and technology-push instruments on changes in the environmental performance of the products on offer. In the next section we present a model of the interaction between producers and consumers. The changes in the environmental performance of the products on offer due to policy interventions are analysed for different market structures.

[4] Measured by the Herfindahl (H) index, which is the sum of the squared market share of the 15 car manufacturers: .101 in 2001 to .073 in 2010.

[5] See Figure 8 of Chapter 5. The normalised average distance is based on Euclidian distance.

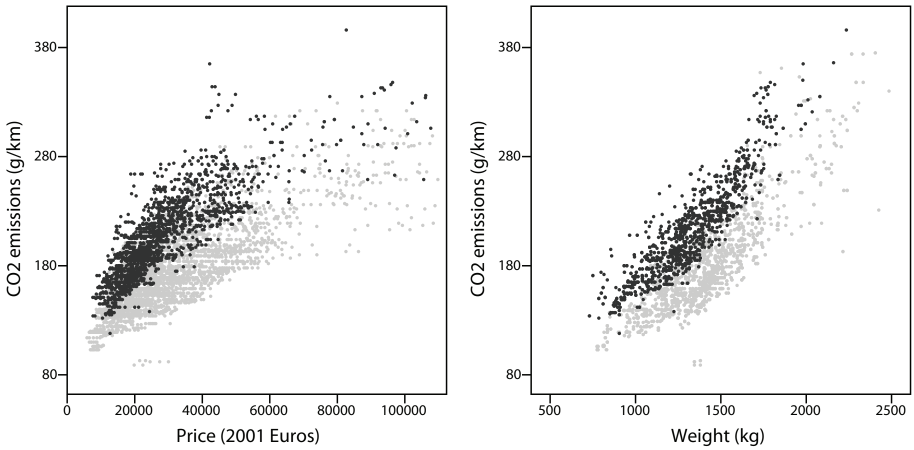


Figure 6.1: The population of family cars offered by the top 15 car manufacturers on the Dutch market in 2001 (dark) and in 2010 (light).

6.3 A competition model

The market consists of two types of agents: producers and consumers. Producers compete in a two-dimensional space for market share. These dimensions are *environmental performance* and a *general performance* characteristic, which refers to another characteristic of the products other than the price. A producer can offer multiple product versions in different locations of the product space in order to optimise his market share. Market share is the share of the consumer population that buys one of a producer's product models. Consumers are assumed to buy one product in each round and have intrinsic preferences for each dimension. The intrinsic preferences form an ideal point in the two-dimensional space, one of the dimensions being the general performance and the other the environmental performance of the product. Consumers buy the model closest to their ideal point. The consumer's taste therefore determines the preferred product model. According to Kaul and Rao (1995) this is an assumption that simplifies without losing important insights.

The model starts with consumers drawing randomly assigned intrinsic preferences from a normal distribution for both dimensions as illustrated in Figure 6.2 (grey dots). The large black dot indicates the initial position of producers at which they offer their first products. Their initial position is located at the average of

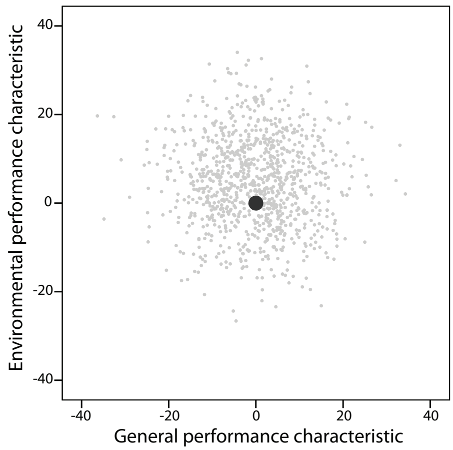


Figure 6.2: Initial set-up of consumers (grey) and producers (black).

consumers' preferences. However, with respect to the environmental performance characteristic producers initially perform slightly below the average of consumer preferences in order to let consumers on average be in favour of more environmentally friendly goods.[6] Table E.1 in the Appendix describes the parameter settings of the model. Figure 6.3 describes the model dynamics. Consumers buy the product closest to their intrinsic preferences. In this simplification of a consumer's decision-making process, we assume that products have similar prices and consumers have identical budgets, i.e., we model a single market segment. As soon as all consumers have bought a product, producers adapt their portfolio of products in order to gain more market share in the next round. Once the producers have adapted their portfolio, the consumers update their intrinsic preferences to take into account the new offerings on the market. This dynamic process iterates for T time steps. Each stage will be described in more detail below.

Purchase decision of consumers. Consumers buy the product closest to their intrinsic preferences (Euclidian distance). If multiple products have a similar distance to the consumer's preferences, the consumer will randomly select one of those products.

[6] This is to ensure that producers have some incentives to improve instead of decline the environmental performance of their products.

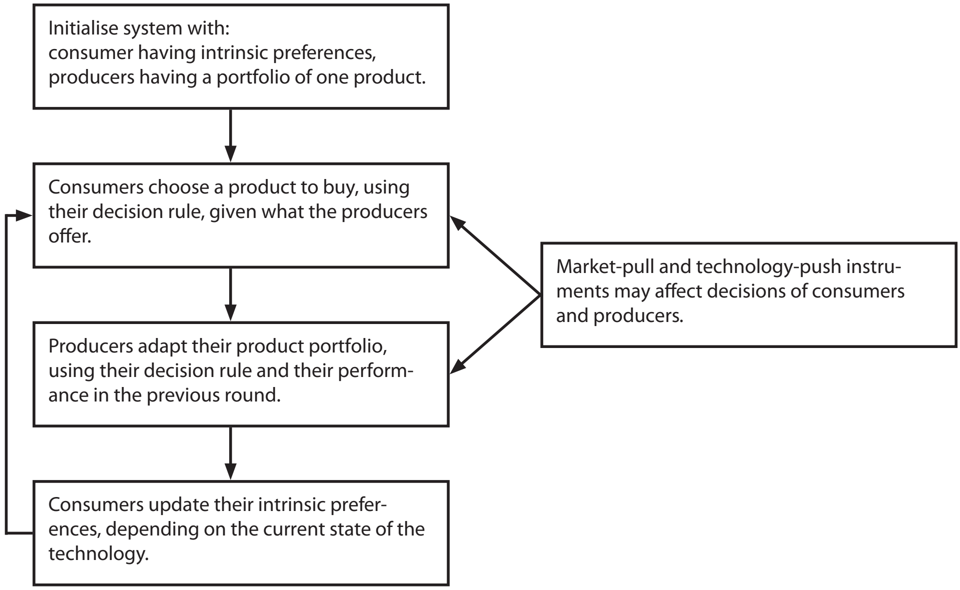


Figure 6.3: Model dynamics.

Adaptation decision of producers. Although producers enter the market with a single product, in each round they can expand their portfolio by a random number of products versions between one and n. The producers then offer multiple products versions. All producers simultaneously adapt their product portfolio in order to gain more market share, but they are not aware of adaptations made by competitors in the same round. They do have information about their own performance in the previous round. All producers apply a similar algorithm to introduce a new product. The basic rule of the algorithm is to expand a producer's portfolio where it is most successful. To be more specific, in each period producers innovate around the product in their current portfolio that attracts most consumers. With radius r, $\in [1 - n]$ new products are offered, each in a random angle from the most popular product. Figure 6.4 illustrates this algorithm by showing the product portfolio of one producer. The largest dot indicates the most popular product. This producer will expand his portfolio in the top left corner of the characteristics space, as his most popular product is located there. This producer will introduce $\in [1 - n]$ new products somewhere on the circle with radius r.

Besides expansion of the portfolio, producers also reduce the number of prod-

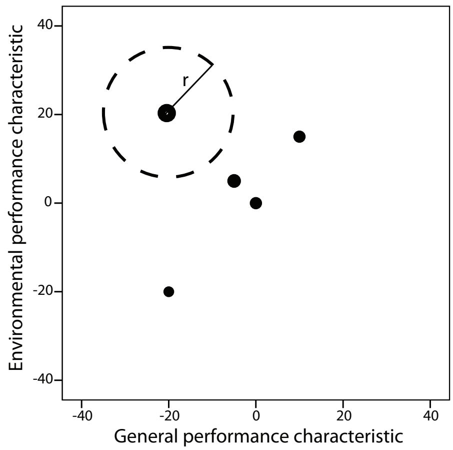


Figure 6.4: An example of a producer's innovation algorithm. This producer will introduce new products around his most popular product, somewhere on the circle with radius *r*.

ucts in their portfolio when their products attract too little consumers. Each period, the products attracting less than *c* consumers will be removed from the portfolio.[7]

Updating consumer preferences. Consumers have fixed intrinsic preferences for the general performance characteristic, but their intrinsic preferences for the environmental performance characteristic are updated over time. The state of the technology, which depends on the products offered to consumers, determines consumers' intrinsic preferences for the environmental performance characteristic. When the environmental performance of the average product offered by producers increases with distance *d*, consumers' intrinsic preferences for the environmental performance of products equally increases with distance *d*. In this way we ensure that the relative preferences of consumers towards the 'new' characteristic does not change over time.

Demand-pull mechanism. Consumer preferences might change due to incentives provided by governments. Governments may implement subsidy programs or tax

[7] Parameter *c* is identical for all producers.

exemptions to make products with higher environmental performance more attractive. Although consumer budget and product prices are ignored in the model, such incentives provided by the government might cause (temporary) shifts in consumer preferences. In the model consumers make an additional and temporary shift in their preferences for the environmental performance characteristic in each round depending on the size of the incentives dp provided by the government. For example, if dp is .5, a consumer's preference for the environmental performance characteristic is his intrinsic preference $+dp$. So, consumers are affected identically by the implementation of subsidies, regardless of their view on environmental performance.

Technology-push mechanism. Besides demand-pull mechanisms a government may choose to implement policy measures that have a technology-push effect. Because it can be difficult to attract sufficient consumers to keep an innovative green product alive, a government may implement a subsidy to stimulate the production of cleaner products. In the model a producer will discontinue products that attracted less than c consumers in the previous round. The technology-push mechanism that is implemented reduces this threshold c for products with a better environmental performance. The costs c_i of product i is determined by the relative environmental performance REP of product i compared to the cleanest product EP_{min} and the dirtiest products EP_{max} available on the market:

$$REP_i = \frac{EP_{max} - EP_i}{EP_{max} - EP_{min}} \tag{6.1}$$

The number of consumers necessary c_i to continue the production of the product i is then given by the following equation:

$$c_i = c - (c \times tp \times REP_i) \tag{6.2}$$

where c is the number of consumers necessary to continue the production without any subsidy in place, and tp a parameter that determines the value of the subsidy. So, the better a product's relative environmental performance is, the lower c_i becomes.

6.4 Model analysis and results

We have implemented the model in NetLogo (Wilensky, 1999), an environment that is suitable for simulating such competition dynamics. In this section we will first discuss the simulation settings and the analysed output measures. Secondly, the observations from single simulation runs will be presented to illustrate the micro level mechanisms of the product market due to the introduction of policy instruments. Thirdly, as our model contains a number of random variables it is necessary to systematically analyse the effect of policy measures with batch simulations. We will show simulation runs for different values of the demand-pull and the technology-push policy instruments and illustrate how such policy instruments affect the improvements in environmental performance on a population level in different market structures: monopoly, oligopoly and a competitive market.

In the model we are simulating different market structures by setting the initial number of producers present on the market. However, market concentration, which is an important determinant of the market structure, can change over the periods of the model, as producers can outperform each other.[8] We measure market concentration by the Herfindahl index (see Section 6.2). In addition we measure the competition intensity at the end of a simulation run by the density of the product cloud.[9] So, the number of producers at the start of a model run and the market concentration and the density of the product cloud at the end of a single run are therefore used as indicators of competition intensity. The initial number of producers is set to 1, 5 and 25 to represent a monopoly, an oligopoly and a competitive market structure, respectively.

The key indicator that we are analysing is the environmental performance of the product population. The environmental performance of the median product is used as an indicator of the population performance, as it is less sensitive for out-

[8] Only if a single initial producer is present in the model, no change in market concentration will occur. After all, in a monopolistic market structure 100% of the consumer market is in the hands of a single producer. The emergence of new entrants is out of the scope of this chapter.

[9] The density is measured by the number of products divided by the surface area of the product cloud. The approximate surface area is calculated by using the range (maximum - minimum) in which products are on offer. Since the product clouds are quite symmetric we use the average of the range of the general and the environmental performance characteristic as the diameter to calculate the area of a circle.

liers than the average or the maximum environmental performance. The opportunity and incentive to innovate depend on the number of products and density of the product cloud. If many products have been introduced and the density is high, there is a high incentive to innovate in order to escape the competition. A low density and a limited number of products that have been introduced means that the opportunity to innovate is high, as there is sufficient space for new products. The opportunity and incentive to innovate is a producer specific issue as well, as producers with a large market share may have higher opportunities but lower incentives to innovate. Those producer specific incentives and opportunities are only addressed to a minor extent, as we are focusing on macro level outcomes of the policy instruments.

6.4.1 Results of single simulation runs benchmark

Figure 6.5 shows the product population offered by all producers together in round 75 of the simulation without any policy present for the three different market structures.[10] Each dot represents a single product version with its y-coordinate reflecting the environmental performance and the x-coordinate representing the general performance of the product version. Each producer's products have a unique symbol-colour combination.

The population's environmental performance in the initial set-up of the model is 0. After 75 rounds the median environmental performance improved slightly for the three different market structures. The lowest progress in environmental performance was observed for a competitive market structure. Although these are results from a single simulation run, it is visible that for all three market structures there is little pressure to improve the environmental performance. This is not a surprise, as it is the direct result from our choice to set the initial average consumer demand for a product's environmental performance slightly above what is offered on the market. The environmental performance in Figure 6.5 suggests that with fewer producers present, the improvements in environmental performance are higher.

[10] The number of periods can be set lower or higher. The higher the number of periods, the more the effects of policy instruments are blown up. The number of products in the market stabilises over time.

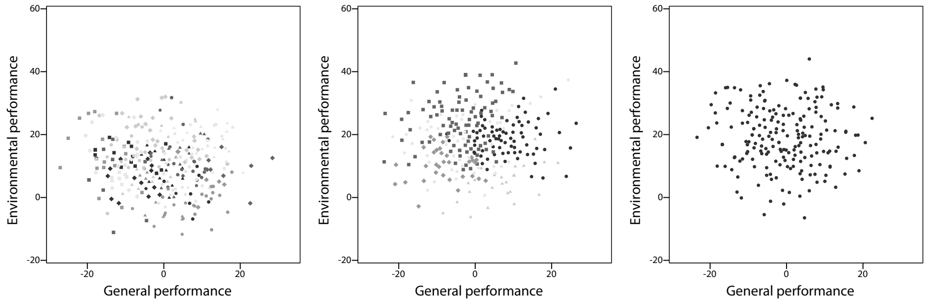


Figure 6.5: The product cloud without any policy instruments implemented (benchmark). The market structure at the start of each model differs for the figures: competition (left), oligopoly (centre), monopoly (right). Each producer's products have a unique symbol-colour combination.

The density of the product cloud depends on the number of products on offer, which in each market structure is a direct result from modelling choices. The number of new products that producers can launch on the market in each round remains constant, and it is therefore obvious that the number of products present in the population is decreasing with a decrease in the number of producers (competition = 314, oligopoly = 286, monopoly = 196).

In Figure 6.5 we observe that on a population level with competition the product cloud is relatively dense (.162) and the number of empty spots relatively limited compared to the oligopoly and monopoly. So the opportunities for introducing successful new products are low and incentives to innovate are high. Figure 6.6 shows that successful producers are those that tend to have a high environmental performance. However, the figure shows that it is not necessarily the producer with the highest environmental performance that is rewarded with the highest market share.

With an oligopoly we observe competitive positioning of producers. The producers tend to have their own market niche. As producers expand their portfolio around their most popular product they specialise in a specific performance segment. If the number of competitors is limited the producers have their own niche. In a very competitive market producers specialise as well, but the niches are less clearly defined and producers share their niche with competitors. The product cloud is less dense (.149) than in the competitive market structure, which makes the opportunities for launching successful new products larger. The incentives to

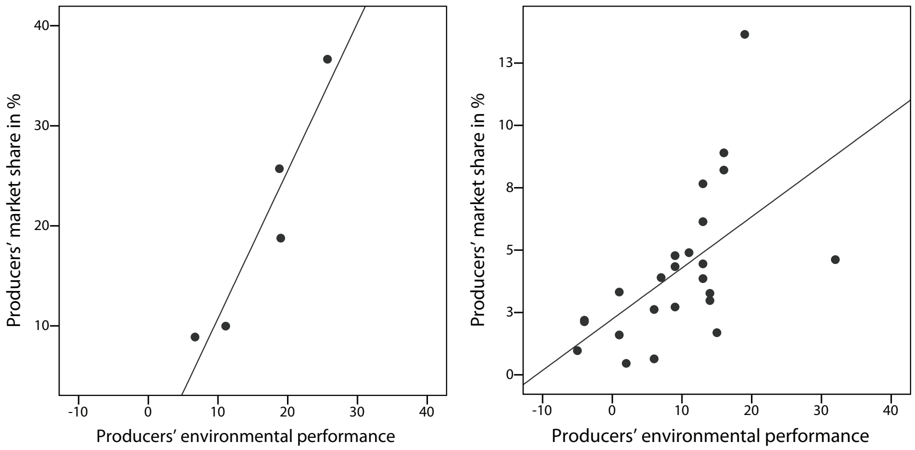


Figure 6.6: Producer performance in a competitive market structure (left) and an oligopolistic market structure (right).

improve environmental performance in an oligopoly are high as well. This in contrary to a monopoly, where density is lowest (.108), because incentives are low due to a lack of competition. On the other hand opportunities are high, as there is sufficient space for the introduction of new products. Moreover, it is quite easy for the monopolist to respond to changes in consumer demand.

6.4.2 Results of single simulation runs with policy incentives

Demand-pull and technology-push instruments can increase producers' incentives and opportunities to improve their environmental performance. The population's environmental performance provides insights into the contribution of the instruments. Figure 6.7 shows the product population of a single model run after 75 rounds with (light) and without (dark) policy instruments in place. The top row of the figure shows the effect of implementing a demand-pull mechanism ($dp = 1$) in a situation of competition, oligopoly and monopoly respectively. The bottom row shows the effect of a technology-push mechanism ($tp = 1$).

For these specific model runs we observe that the demand-pull instrument shifts the product population towards a higher environmental performance for each market structure. While for an oligopoly the number of products (266) and

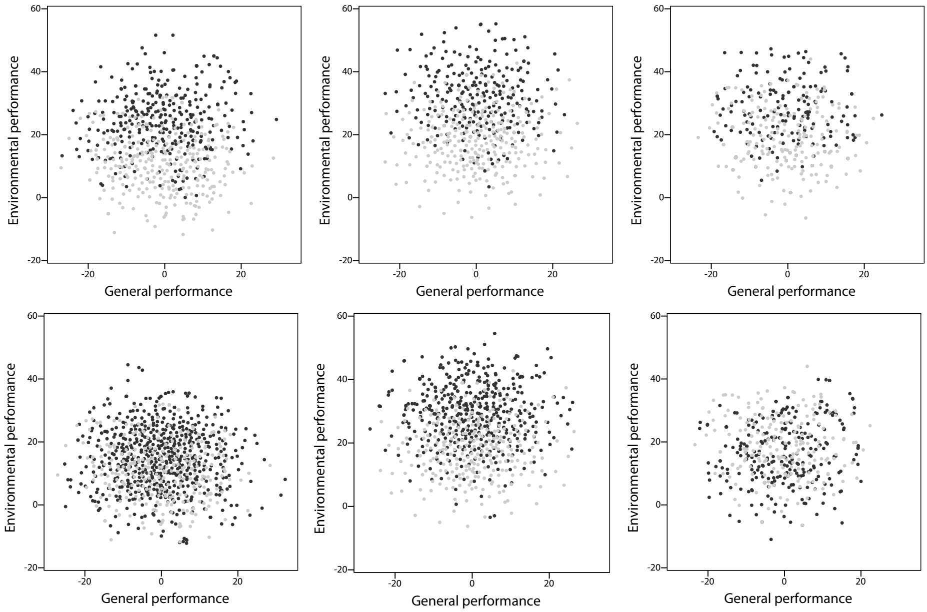


Figure 6.7: The top (bottom) row shows a single simulation run when a demand-pull (technology-push) mechanism is implemented. In dark colour dots it shows the product cloud of a simulation run with a policy mechanism implemented. The benchmark (without policy) is presented in light colour dots. The initial market structure differs from left to right: competition (left), oligopoly (centre), monopoly (right).

density (.139) is rather stable compared with the benchmark, this is not the case for a monopoly and competitive market. In a competitive market the number of products (176) and in density (.112) decrease compared to the benchmark. So, the demand-pull instrument increases the opportunities, but decreases the incentives to innovate for a competitive market. For a monopoly it is the other way around, as the number of products increases (333) and the density decreases (.146) with the introduction of a demand-pull instrument. Demand-pull instruments, then, provide more opportunities to innovate for competitive markets and more incentives to innovate for a monopoly. According to the theory this is exactly what is necessary to stimulate innovation in those market structures.

With the implementation of a technology-push mechanism it is easier to keep products with a higher relative environmental performance alive, as the threshold c for those products is lower. So this mechanism creates incentives and opportunities to launch products with a relatively high environmental performance. In the competitive market structure we observe a rapid increase in the number of products (617) and density (.240). This further increase in the incentives and further decrease in the opportunities to innovate does not stimulate the environmental performance very well, as only a minor increase in environmental performance is observed. In an oligopolistic market structure the technology-push instrument increases the number of products (431) and density (.180) as well. But in this case a substantial increase in environmental performance is observed. In a monopoly the number of products (266) and density (.155) increase as well, which means that the incentive to innovate increases and opportunity to innovate decreases. However, in a monopoly this does not contribute to improvements in environmental performance.

6.4.3 Results of batch simulations

To study how demand-pull and technology-push policy instruments affect the relationship between competition intensity and an industry's improvements in environmental performance we analyse a systemic simulation experiment (batch simulations). In this simulation experiment we test the whole range of the initial number of producers between monopoly (1 producer) and competition (25 producers). We analyse the improvement in environmental performance (with reference to the environmental performance in period 0) after 75 rounds, and averaged results over 100 repetitions.[11]

Figure 6.8 presents the results of the experiment, where we consider three different values of both policy parameters dp (demand-pull) and tp (technology-push), i.e., low (.5), medium (.75) and high (1) values. The results are compared with the benchmark situation with no policy in place. We present the relationship between the market concentration observed in round 75 and the improvement in environmental performance in this period. It shows an inverted u-shaped relationship between competition intensity and improvement in environmental performance. At first the improvements in environmental performance increase

[11] Increasing the repetitions lowers the standard deviation of the average environmental performance. The results for more than 25 producers are not qualitatively different from the results with 25 producers.

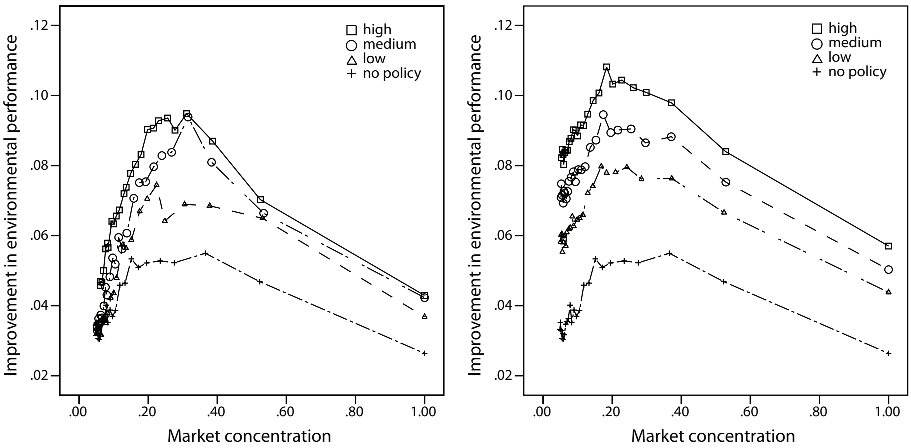


Figure 6.8: Effects of policy instruments on environmental performance: technology-push (left) and demand-pull (right) instruments.

when concentration increases. Optima are obtained for market concentrations between .2 and .3, followed by a decrease in environmental improvement when the market concentration rises towards a monopoly.

In general demand-pull and technology-push mechanisms have a positive impact on the environmental performance of the products. The simulations show that additional incentives created by the technology-push mechanism are not contributing to an improvement in the environmental performance of a product population in a highly competitive market structure. However, when market concentration increases, additional incentives created by the technology-push instruments are effective. Although there is an increase in incentives, the improvements in environmental performance are only moderate in a monopoly. So the technology-push instrument only provides additional incentives, while these are not always necessary to stimulate innovation.

The demand-pull mechanism that provides additional incentives to innovate shifts the curve in Figure 6.8 (right) upwards such that for each market structure a substantial improvement in environmental performance is observed. This positive effect of the demand-pull mechanism on the whole range of market structures occurs because this instrument provides more opportunities to innovate in competitive markets and more incentives to innovate for a monopoly. The demand-pull instrument thus stimulates both the incentive to innovate and the opportunity to innovate when they are most necessary. So, when producers need to respond to changing consumer preferences the improvements in environmental performance are high.

6.5 Conclusions

In this chapter we presented a dynamic competition model to study the effectiveness of both demand-pull and technology-push instruments for the transition towards a more environmentally friendly product market. We questioned how this effectiveness changes under different market structures, as this provides important insights for policymakers who attempt to stimulate this sustainability transition in different product markets with varying competition intensity. In the model multiple producers compete by offering multiple product versions in an attempt to optimise their market share of heterogeneous consumers. Consumer behaviour as well as producer behaviour are affected by the demand-pull and the technology-push mechanisms.

The model results show that in accordance with the theory an inverted u-shaped relationship exists between competition intensity and improvements in environmental performance, i.e., innovation. This inverted u-shaped relationship is still observed when policy incentives are introduced to the market. The shape of the curve, however, is affected by the policy instruments. In other words, the effectiveness of policy schemes to stimulate environmental development depends on the market structure.

The simulations show that in general demand-pull and technology-push instruments have a positive impact on improvements in environmental performance. Technology-push instruments appear to be successful when competition intensity is low, as they mainly provide additional incentives to innovate. Demand-pull mechanisms are able to guide any market structure to improve environmental performance. Demand-pull mechanisms generate more incentives to innovate in a monopoly, the situation where, according to the theory, incentives are low. Moreover, these instruments generate more opportunities to innovate in competitive markets, where according to the theory, the opportunities to innovate are generally low.

7 Conclusions and policy implications

The transition towards a more sustainable transport system requires technological change. Its realisation requires the production of new vehicle technologies by technology providers, the adoption of those technologies by consumers, and facilitating policy instruments. Technological change in the transport sector is not easy, as it is locked in into fossil-fuel-based internal combustion engine vehicles. Escaping this lock-in is difficult, because vehicle technologies are dependent on infrastructures, which are characterised by high switching costs and network externalities. Moreover, negative externalities inherent in environmental problems are insufficiently internalised in the costs of technologies, which is a disadvantage for the competitive position of more environmentally friendly technologies.

This thesis provides insights into the mechanisms of technological change by capturing the complexity that characterises the current technological transition of the transport system into evolutionary models of technological change. In contrast with earlier studies this thesis explicitly addresses the infrastructure dependence of vehicle technologies. In addition the models cover the emergence of multiple new technologies; the compatibility between different old and/or new technological systems; and technologies that emerge at different moments in time; the effects of significant incremental improvements in the existing technologies. This chapter presents the two main overall conclusions of this thesis, both of which have major implications for policymakers who intend to accelerate technological change. First, it is concluded that the emergence of a large variety of radically new vehicle technologies that depend on a physical infrastructure may hamper the diffusion of any one of those radically new vehicle technologies. Second, incremental improvements in the environmental performance of the existing vehicle technology may hamper the diffusion of radically new technologies with a higher environmental performance potential. Both conclusions are explained below, as well as their policy implications.

7.1 Conditions for technological change

1. *The emergence of a large variety of radically new vehicle technologies that depend on a physical infrastructure may hamper the diffusion of any one of those radically new vehicle technologies.*

A variety of radical new vehicle technologies has emerged that may replace (parts of) the existing system, such as the plug-in hybrid vehicle (PHEV), the battery electric vehicle (BEV) and the hydrogen fuel cell vehicle (HFCV). Variety creation is an important condition for technological change, as it increases the probability of a successful alternative technology and recombinant innovation. However, Chapter 2 of this thesis indicates that when vehicle technologies depend on a physical infrastructure, a trade-off exists between variety creation and gaining 'critical mass'. Radically new vehicle technologies need to gain 'critical mass' in order to survive and replace the existing technology. When the variety of radically new vehicle technologies is too large, none of the alternative technologies can gain sufficient critical mass to compete with the existing system. First, initial infrastructure is crucial for the diffusion of new vehicle technologies. When investments for the roll out of infrastructures are distributed among different vehicle technologies, this might be too little for each technology to generate critical mass. Secondly, the heterogeneity of consumer preferences, which has been recognised as an important source for escaping lock-in, paradoxically also frustrates the escape of lock-in in the case of multiple competing alternative technologies. It is more beneficial for technological change when all consumers adopt the same alternative vehicle technology, as this will generate the necessary critical mass.

Technological change is thus most likely when the portfolio of alternative vehicle technologies is limited. The size of the desired technological variety depends on the composition of the portfolio. In Chapters 2 and 3 of this thesis I identified three conditions for which a somewhat larger technological variety may accelerate technological change. First, the model results in Chapter 2 illustrate that the probability of technological substitution increases when sufficient investments are made in the roll out of the necessary infrastructures for each vehicle technology, such that emerging vehicle technologies do have a chance of gaining critical mass. Second, technological change is more likely when the new vehicle technologies are sufficiently different with respect to their technological performance, as the probability of a successful technology increases. Moreover, winners and losers will manifest faster when disparity between vehicle technologies is larger in early stages of technological change. As consumers are less dispersed over technological options it is easier to generate critical mass. Third, model results of Chapter 3 illustrate that technological change benefits from vehicle technologies that make use of the same infrastructure. Critical mass can be achieved faster with compatibility in infrastructure, because it creates shared increasing returns to adoption. The model results show for example that plug-in hybrids can serve as a stepping stone technology for battery electric vehicles, as both make use of a recharging infrastructure.

2. *Incremental improvements in the environmental performance of the existing vehicle technology may hamper the diffusion of radically new technologies with a higher environmental performance potential.*

In addition to radically new vehicle technologies, incremental improvements in the environmental performance of the existing vehicles contribute to the reduction of CO_2 emissions and other greenhouse gasses.[1] Such incremental innovations can be realised relatively quickly and easily as the costs are low and no change in infrastructure is necessary. Chapter 5 empirically shows that most car manufacturers successfully improved the environmental performance of their portfolio of car versions offered on the Dutch market since the introduction of energy labels for cars in 2001. The model in Chapter 6, which is based on this empirical study, indicates that both demand-pull and supply-push instruments aiming at improving the environmental performance of the existing system are effective for realising such incremental innovations. While this is beneficial for sustainable development in the short term, it is not necessarily best in the long run. More specifically, model results in Chapter 4 show that the main disadvantage of such incremental improvements is that they frustrate the diffusion of radically new vehicle technologies. More sustainable versions of the existing vehicle technology reduce the competitive position of radically new vehicle technologies that have low environmental impact as one of their unique selling points. Incremental improvements in environmental performance can be substantial, but

[1] Assuming all other things are equal. Changes in driving behaviour are not studied in this thesis.

the CO_2 reduction potential of the existing system is limited in the long run, while some radical new technologies are potentially zero emission systems.

The observation that existing technologies rapidly adjust to changes in the selection environment is not new. It is often referred to as the sailing-ship effect (Harley, 1973; Geels, 2002). In our specific case, this sailing ship effect is strengthened by policy that stimulates improvements in the environmental performance of the existing system. So, this creates a difficult trade-off for policymakers who seek to improve the environmental performance of the transport sector between more certain but smaller improvements in sustainability in the short run and less certain but larger improvements in the long term.

7.2 Policy implications

1. The emergence of a large variety of radically new vehicle technologies that depend on a physical infrastructure may hamper the diffusion of each of the individual vehicle technologies. This conclusion has two major implications for policymakers who intend to accelerate technological change towards a more sustainable transport system. First, policymakers need to support technology providers in the creation of a limited number of vehicle technologies, which preferably make use of similar infrastructures. Second, each of the created vehicle technologies needs sufficient support for infrastructure build-up to stimulate consumer adoption and generate the critical mass needed to replace the existing technology.

Policymakers face a difficult task when composing a portfolio of technological options that will receive governmental support. Policymakers are not able to pick winners, but supporting different technological options is costly and should be done only when it is possible to benefit from this increased technological variety. For example, the model results of Chapter 2 illustrate that policymakers should only create technological variety when the government has the intention and the budget to support those technological options in later stages as well, including the roll out of a physical infrastructure, for example. Otherwise the probability of successful diffusion of any one of those technological options is very low, as they will not be able to gain critical mass.

When policymakers compose a portfolio of technological options for the future, they need to consider whether the diffusion of one technological option will harm the diffusion of another technological option. If this is the case and policymakers support both technological options, the consequence can be that none of the technological options successfully competes with the existing vehicle technology. The model results of Chapter 3 show that the diffusion of technological options increases when they make use of the same physical infrastructure. Standardisation of infrastructure is pivotal in this case. When technologies are compatible with respect to infrastructure the diffusion of one technological option does not necessarily harm the diffusion of the other technological option. Moreover, one vehicle technology may even serve as a stepping-stone for another, without the risk of early lock-in. In short, policymakers can increase technological variety without harming the diffusion of other technological options if the different technological options use the same infrastructure.

2. Incremental improvements in the environmental performance of the existing vehicle technology may hamper the diffusion of radically new technologies. Two critical implications for policymakers follow from this conclusion. First, policymakers need to set ambitious long-term goals to keep the option of zero emission vehicle systems open. These long-term goals provide incentives for technology providers to invest in radical innovations as well as in incremental improvements in environmental performance of the existing technology. Second, in order to attract market demand policymakers need to provide an advantage for those radically new technologies that have a large CO_2 reduction potential in the long term, but are not yet able to compete with the existing technology without help. The following will elaborate on these policy implications.

In the early stages of diffusion, the radically new vehicle technologies discussed in this thesis are often unable to compete with the existing system. While they score high on environmental performance, other characteristics such as driving range and purchase price are usually not yet aligned with consumer preferences. Financial carrots like tax exemptions or purchase price subsidies that also stimulate incremental improvements in the existing system may decrease the competitive position of radically new vehicle technologies even further. Their unique selling point, i.e., environmental performance, is diminished.

Chapter 5 empirically shows that all car manufacturers have significantly reduced the CO_2 emissions of their portfolio. These incremental improvements in environmental performance of the existing vehicle technology appeared to be rewarding for technology providers, as frontrunners in CO_2 reduction experienced the highest relative increase in sales on the Dutch market, while manufacturers who lagged behind performed relatively weak. Model results in Chapters 4 and 6 indicate that policy measures aimed at improving the environmental performance of existing vehicle technology effectively put pressure on technology providers to accelerate their rate of incremental innovations. Moreover, the models indicate that such short-term incentives successfully start a transition, as consumers develop preferences for more environmentally friendly vehicles and technology providers produce them. But the model results in Chapter 4 also illustrate that these same measures hardly generate any incentives for technology providers to invest in radically new vehicle technologies, as incremental innovation reinforces the competitive position of the existing vehicle technology. If parties with vested interests in the existing vehicle technology lobby for short-term incentives, such as financial carrot-and-stick instruments, this contributes to the legitimisation of the existing system. It even frustrates radical technological change. Therefore it would be better for policymakers to set ambitious long-term targets that provide incentives to invest in radical new vehicle technologies. If there is sufficient pressure from the emergence of the new vehicle technologies, sailing-ship effects may generate incremental improvements in the existing vehicle technology as well. Only if sufficient long-term incentives for radical innovation are present, these can be complemented with short-term incentives.

Samenvatting

De groeiende concentratie van broeikasgassen in de atmosfeer, zoals koolstofdioxide (CO_2), is de meest geaccepteerde verklaring voor klimaatverandering. De op één na grootste bron van broeikasgas emissies is het op fossiele brandstof rijdende wegtransport. Het verbranden van fossiele brandstof veroorzaakt CO_2 en andere broeikasgassen. Het wegtransport is verantwoordelijk voor 20% van de totale CO_2 emissies in de EU, terwijl de uitstoot van personenauto's alleen verantwoordelijk is voor ongeveer 12%.

In dit proefschrift bestudeer ik de transitie naar een duurzamer transportsysteem. Meer specifiek onderzoek ik de vergroening van personenauto's. Om zo'n transitie te realiseren is technologische verandering nodig. Nieuwe, milieuvriendelijkere autotechnologieën, zoals plug-in hybrides (PHEV), elektrische auto's (BEV) en brandstofcelauto's op waterstof (HFCV), zullen wellicht de dominante interne verbrandingsmotor technologie (ICEV) gaan vervangen.

Als we dit transitieproces willen versnellen dan is het belangrijk dat we de mechanismen van technologische verandering naar een duurzamer transportsysteem goed begrijpen. Mijn doel is daarom om door middel van dit proefschrift bij te dragen aan ons begrip van de mechanismen van technologische verandering, door de complexiteit van het transportsysteem in modellen van technologische verandering te vatten.

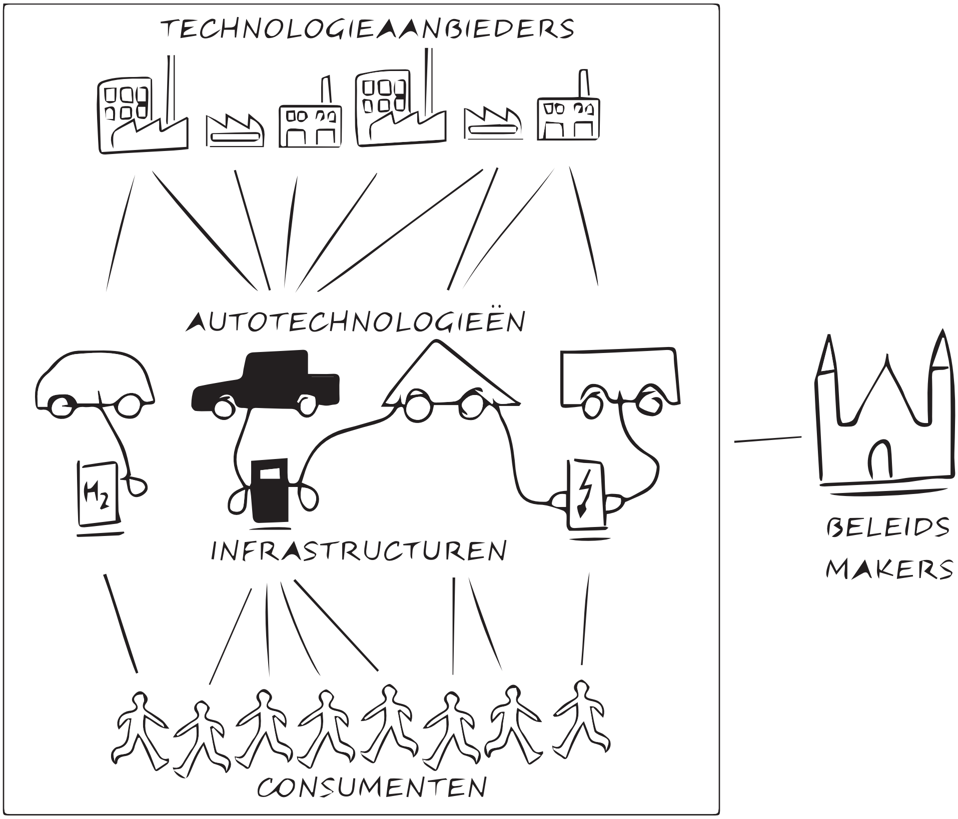
Aspecten die deze complexiteit veroorzaken en die in modellen van technologische verandering moeten worden gevat, zijn bijvoorbeeld: 1) de technologische afhankelijkheid van een fysieke infrastructuur; 2) de gelijktijdige opkomst van meerdere nieuwe technologieën; 3) de compatibiliteit tussen oude en/of nieuwe technologische systemen; 4) de substantiële verbeteringen die nog behaald kunnen worden in bestaande technologieën.

In dit proefschrift wordt de technologische verandering die noodzakelijk is voor een transitie beschreven als een evolutionair economisch proces waarbij nieuwe technologische systemen bestaande dominante systemen moeten vervangen. Ik heb de term 'technologisch systeem' gebruikt, omdat het gebruik van elke autotechnologie een uitgebreide infrastructuur vereist, zoals een netwerk van tankstations of oplaadpunten.

Evolutionair economen bestuderen dynamische processen die de economie veranderen. Technologische verandering is een belangrijk voorbeeld daarvan. De evolutionaire economie bouwt voort op inzichten van de evolutionaire biologie, maar gebruikt de biologische analogieën als variatie, selectie en overerving enkel als metafoor. De opkomst van nieuwe technologieën, ofwel innovatie, creëert technologische variatie. Wanneer deze nieuwe technologieën kleine verbeteringen zijn die voortbouwen op de bestaande technologie dan noemen we dat incrementele innovatie (overerving in de evolutionaire biologie). Radicale innovaties daarentegen worden beschouwd als een exogene schok die niet direct voortbouwt op de bestaande technologie en bovendien een heel nieuwe kennisbasis vereist. Om het evolutionaire selectieproces te overleven, concurreren technologieën om de adoptie door actoren aan de vraag- en aanbodzijde van de markt, zoals consumenten en producenten. Technologieën die in hoge mate zijn aangepast aan deze selectieomgeving hebben een grotere kans om het selectieproces te overleven.

Figuur S1 illustreert het conceptuele model dat ik heb gebruikt in deze studie. Het laat de belangrijkste actoren en componenten zien die samen het transportsysteem vormen dat ik bestudeer in dit proefschrift. Het toont een dominante autotechnologie en de bijbehorende infrastructuur. Met dominant wordt bedoeld dat de meeste aanbieders deze autotechnologie met bijbehorende infrastructuur ontwikkelen en verkopen en dat de meeste consumenten deze technologie gebruiken. Als de markt zodanig vastzit in de ontwikkeling en het gebruik van een bepaalde technologie dat dit de komst van nieuwe technologieën blokkeert dan spreken we van technologische *lock-in*. Daarnaast is in het figuur te zien dat een aantal nieuwe autotechnologieën op de markt wordt gebracht in een poging de dominante technologie te vervangen. Initieel worden deze nieuwe technologieën slechts geadopteerd door enkele technologieaanbieders en consumenten. Tot slot zien we dat beleidsmakers proberen de veranderingen in het transportsysteem te versnellen door beleidsmaatregelen te implementeren die de diffusie van deze nieuwe technologien stimuleren.

Om de competitie tussen de technologieën te simuleren, heb ik in dit onderzoek gebruik gemaakt van *agent-based modelling* (ABM). ABM is een steeds vaker gebruikte methode om acties van en interacties tussen autonome actoren over tijd te simuleren, om zo te bestuderen hoe mechanismen op microniveau leiden tot uitkomsten op macroniveau. Met andere woorden, met ABM heb ik kun-



Figuur S1: Model van technologische verandering in de transportsector.

nen simuleren hoe acties van en interacties tussen technologieaanbieders en consumenten de competitie tussen verschillende technologieën beïnvloeden en mogelijk leiden tot technologische verandering. Het gebruik van ABM als een rekenkundig laboratorium maakt het mogelijk om op systematische wijze patronen die bijdragen aan het begrip van technologische verandering te identificeren en te testen.

Dit proefschrift bestaat uit zeven hoofdstukken. In hoofdstuk 1 geef ik een overzicht van het onderzoek. In elk van de hoofdstukken 2 tot en met 6 richt ik me op een specifiek fenomeen dat technologische verandering in het transportsysteem karakteriseert. In het afsluitende hoofdstuk 7 presenteer ik de conclusies en aanbevelingen voor beleidsmakers die de diffusie van milieuvriendelijkere technologieën proberen te versnellen. Hieronder worden de belangrijkste bevindingen van ieder hoofdstuk gepresenteerd, gevolgd door de conclusie en beleidsaanbevelingen.

In hoofdstuk 2 introduceer ik een model van technologische substitutie aan de hand waarvan ik heb bestudeerd hoe de concurrentie tussen meerdere nieuwe technologieën bijdraagt aan het ontsnappen aan de *lock-in* van een bestaande technologie. De resultaten van de simulaties laten een *trade-off* zien tussen enerzijds het toewijzen van financiële middelen aan onderzoek, ontwikkeling en demonstratie (RD&D) van nieuwe technologieën, en anderzijds het toewijzen van financiële middelen aan de ontwikkeling van infrastructuur nodig voor marktimplementatie van de nieuwe technologieën. Het is bekend dat de opkomst van diverse technologische opties bijdraagt aan technologische verandering, maar dit onderzoek laat zien dat de diversiteit beperkt moet zijn omdat de kansen voor de nieuwe technologische opties kleiner worden als er te veel concurrentie is. De resultaten tonen verder aan dat overheidsondersteuning voor RD&D, bedoeld om meer variatie te creëren, het meest succesvol is als alle gecreëerde technologische opties ook substantieel worden ondersteund bij de ontwikkeling van infrastructuur ten behoeve van marktimplementatie. Beleidsmakers zijn namelijk niet in staat op voorhand te voorspellen wat de dominante technologie van de toekomst zal zijn. Zij kunnen echter wel proberen bepaalde technologieën (die tot minder CO_2-uitstoot leiden) te stimuleren door deze extra te ondersteunen. Maar als elk van de opties slechts beperkte ondersteuning krijgt voor de ontwikkeling van infrastructuur dan is het voor elk van deze opties moeilijk om voldoende kritische massa te realiseren om een vuist te maken tegen de bestaande technologie. Dus om voor technologieën die sterk afhankelijk zijn van een fysieke infrastructuur de kans op technologische substitutie te vergroten, moet de variëteit aan opties beperkt zijn. Bovendien moeten beleidsmakers niet alleen financiële middelen inzetten ten behoeve van het creëren van nieuwe variatie, maar ook voldoende middelen reserveren om de technologische opties te kunnen ondersteunen in latere fasen van ontwikkeling.

In hoofdstuk 3 wordt de competitie tussen drie potentiële technologische opties voor de toekomst (PHEV, BEV en HFCV) en de bestaande technologie (ICEV) bestudeerd. De resultaten van modelsimulaties illustreren dat afhankelijk van de beleidscondities verschillende technologische opties een kans maken. Zo is een snelle invoering van CO_2-taks veelal in het voordeel van de bestaande technologie, omdat technologieaanbieders in staat zijn deze technologie snel aan te passen aan de veranderde marktomstandigheden, terwijl de nieuwe technologische opties op dat moment vaak nog niet in staat zijn om op alle aspecten aan de wensen van de consument te voldoen. Latere introductie van een CO_2-taks creëert vooral kansen voor plug-in hybrides en elektrische auto's. Verder zien we dat technologische verandering er baat bij heeft als technologische opties gebruikmaken van dezelfde infrastructuur, zoals bij plug-in hybrides en de bestaande technologie en bij plug-in hybrides en elektrische auto's. Compatibiliteit van verschillende auto technologieën leidt tot zogenaamde *stepping-stone* effecten, waarbij de ene technologie het opstapje vormt naar de andere technologie. Zo kan bijvoorbeeld de opmars van de plug-in hybrides een opstap vormen voor de diffusie van elektrische auto's. De modelsimulaties illustreren dat als een portfolio van compatibele autotechnologieën zich aandient, het zelfs mogelijk is om specifiek één technologie te stimuleren zonder dat daarmee andere compatibele opties worden uitgesloten en kansloos zijn.

In hoofdstuk 4 bestudeer ik aan de hand van een model hoe combinaties van beleidsinstrumenten in een beleidsmix bijdragen aan technologische verandering. Simulaties laten zien dat een beleidsmix effectief kan zijn om additionele druk uit te oefenen om technologische verandering te versnellen. Maar tegelijkertijd zien we dat een beleidsmix ook kostbaar kan zijn voor de schatkist zonder dat enig positief additioneel effect ten aanzien van technologische verandering waarneembaar is. Neem bijvoorbeeld de introductie van een emissiestandaard voor de maximale CO_2-uitstoot in combinatie met een bonus-malus systeem voor de aanschaf van een auto. Dit genereert vooral kleine incrementele verbeteringen in de bestaande autotechnologie met als gevolg dat radicaal nieuwe technologische opties geen kans maken. Alleen voor enkele combinaties, waarbij de beleidsinstrumenten zich richten op zowel radicaal nieuwe als op de bestaande technologie, leidt dit tot gewenste synergie. Een voorbeeld is een aanschafsubsidie voor radicaal nieuwe technologieën in combinatie met de invoering van een CO_2-taks. De CO_2-taks stimuleert niet alleen incrementele vermindering van de milieubelasting van de bestaande technologie, maar verbetert ook de concurrentiepositie van nul-emissie-auto's. Het is dus van belang dat combinaties van beleidsinstrumenten weloverwogen zijn.

In hoofdstuk 5 bestudeer ik empirisch de incrementele verbeteringen en portfolio strategieën van autofabrikanten na de introductie van energielabels voor auto's. Alle autofabrikanten hebben sindsdien de CO_2-emissies van hun portfolio significant verlaagd. Maar de resultaten laten zien dat de fabrikanten die hierin voorop liepen in deze periode ook de hoogste relatieve toename in verkoopcijfers hadden, terwijl de achterblijvers ten aanzien van CO_2-reductie het ook in verkoopcijfers relatief slecht deden. Strakke regulering van de reductie van CO_2-emissies, zoals in Nederland, is dus effectief en beloont innovatief gedrag van fabrikanten.

In hoofdstuk 6 presenteer ik een model om technologische verandering in een productmarkt te bestuderen, waarbij de intensiteit van competitie varieert. De simulatieresultaten laten zien dat er een parabolisch verband bestaat tussen de verbetering van de milieuvriendelijkheid van producten en de intensiteit van de competitie. Dit is in overeenstemming met de theorie. Het is belangrijk voor technologische verandering dat zowel prikkels als mogelijkheden aanwezig zijn om milieuvriendelijkere producten te ontwikkelen en produceren. Deze kunnen worden gestimuleerd met beleidsinstrumenten die een technologie-*push* of technologie-*pull* karakter hebben. Uit dit hoofdstuk blijkt dat beleidsmakers die de transitie naar duurzamere producten willen versnellen er rekening mee moeten houden dat de effecten van deze beleidsinstrumenten afhangen van de intensiteit van de competitie in de sector.

De algemene conclusie van dit proefschrift is tweeledig. De eerste conclusie is dat overheidssteun voor de opkomst van een grote variëteit aan radicaal nieuwe autotechnologieën, die afhankelijk zijn van een eigen fysieke infrastructuur, de diffusie van elk van deze nieuwe technologieën afremt. Variatie is weliswaar belangrijk, omdat de kans op een succesvolle technologie dan groter is, maar bij te grote variatie blijft het bereiken van kritische massa die noodzakelijk is om de huidige technologie te vervangen vaak uit. De tweede conclusie is dat incrementele innovaties die de milieuvriendelijkheid van de bestaande technologie verbeteren, de diffusie van radicaal nieuwe technologieën, die de potentie hebben een stuk duurzamer te zijn, afremt.

Voor beleidsmakers zijn deze conclusies van belang. De eerste conclusie laat zien dat beleidsmakers het beste slechts een beperkt aantal technologische opties kunnen selecteren ter ondersteuning. Bij voorkeur kiezen zij daarbij voor technologische opties die dezelfde infrastructuur nodig hebben. Daarbij is het aan te raden dat zij deze technologische opties voldoende ondersteuning bieden, zodanig dat een infrastructuur kan worden ontwikkeld die adoptie door consumenten stimuleert en de kritische massa genereert die nodig is om de bestaande technologie te vervangen.

Ook de tweede conclusie leidt tot beleidsimplicaties. Uit deze conclusie blijkt dat de politiek er verstandig aan doet zichzelf ambitieuze langetermijndoelen te stellen om de transitie naar nul-emissie-auto's mogelijk te maken. De langetermijndoelen moeten technologieaanbieders voldoende prikkels geven om te investeren in zowel radicaal nieuwe technologieën als in incrementele verbeteringen in de bestaande technologie. Daarnaast is het belangrijk dat zij radicaal nieuwe technologische opties die een groot CO_2-reductiepotentieel hebben langdurig blijven ondersteunen, tenminste zolang ze nog onvoldoende in staat zijn om te concurreren met de bestaande technologie.

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A Appendix Chapter 2

Table A.1: Parameter values.

Parameter	Interpretation	Values
Stages		
B	Total budget for policy intervention	0.3
B_1	Budget allocated to variety creation (stage 1)	$< B$
B_2	Budget allocated to selection (stage 2)	$B - B_1$
I_1	Number of created technologies in stage 1	$\leq B/c$
I_2	Number of selected technologies in stage 2	$\leq I_1$
c	Costs of variety creation	$\in [0, 0.03]$
Consumers		
N	Number of consumers	$1,000$
φ_x	Consumer weights for characteristic x	$\sim N(x_{max}, 0.1)$
m	Budget constraint	$\sim N(0.4, 0.1)$
a	Infrastructure availability requirement	$\sim N(0.4, 0.2)$
ω	Replacement rate	$1/3$
U_i	Utility of consuming the set of char. of tech. i	$\in [0, 1]$
Technologies		
X_i	Set of service characteristics x of technology i	$\in [0, 1]$
x	Performance of characteristics	$\in [0, 1]$
x_{max}	Maximum observed performance on a characteristic x	$\in [0, 1]$
i	Index for technologies	
A_i	Infrastructure availability for technology i	$\in [0, 1]$
κ	Factor between financial resources and infrastructure development	$1/3$
γ	Incremental innovation rate	$\in [0.97, 1.02]$
α	Learning ability	0.05
P_i	Price of technology i	$\in [0, 0.5]$
$c_{i(t)}$	Cumulative number of adopters at time step t	
$S_{i(t)}$	Market share of technology i at time t	$\in [0, 1]$
Cum_{xi}	Cumulative number of innovations in char. x of the tech. i	
Cum_i	Cumulative number of innovations in all char. of the tech. i	
Incumbent technology		
$x_{e(0)}$	Initial performance of environmental characteristic	$\sim N(e_1, 0)$
$x_{t(0)}$	Initial performance of traditional characteristic	$\sim N(t_3, 0)$
e_2	Mean of initial performance of environmental characteristic	0.05
t_3	Mean of initial performance of traditional characteristic	0.2
$c_{i(0)}$	Initial number of cumulative adopters	900*
$P_{(0)}$	Initial price of incumbent technology	0.2
Emerging technologies		
$x_{e(0)}$	Initial performance of environmental characteristic	$\sim N(e_2, \sigma^2)$
$x_{t(0)}$	Initial performance of traditional characteristic	$\sim N(t_2, \sigma^2)$
e_1	Mean of initial performance of environmental characteristic	0.1
t_1	Mean of initial performance of traditional characteristic	0.1
σ^2	Disparity: variance of initial performance of characteristics	$\in [0, 0.06]$
c_{i0}	Initial number of cumulative adopters	1

Table A.1 – continued from previous page

Parameter	Interpretation	Values
ϵ	Random premium (price)	$\in [0.025, 0.125]$
ρ	Initial infrastructure investment by private firms	0.04

* Lock-in is defined as the situation where the incumbent technology is adopted by 90% of the consumers.

B Appendix Chapter 3

Table B.1: Parameter values.

Parameter	Interpretation	Values
Consumers		
N	Number of consumers	$1,000$
Φ	Set of consumer preferences	$\in [0,1]$
φ_x	Consumer preferences for characteristic x	$\sim N(x_{max}, 0.07)$
m	Budget constraint	$\sim N(0.4, 0.1)$
a	Infrastructure availability requirement	$\sim N(0.4, 0.2)$
β	Importance of price	$\sim N(0.6, 0.1)$
ω	Replacement rate	$1/3$
U_i	Utility of consuming the set of service characteristics of technology i	$\in [0,1]$
Vehicle technologies		
X_i	Set of service characteristics x of technology i	$\in [0,1]$
x	Performance of service characteristics	$\in [0,1]$
x_{max}	Maximum observed performance on a characteristic x	$\in [0,1]$
i	Index for technologies	
I	Number of different technologies	4
A_i	Infrastructure availability for technology i	$\in [0,1]$
A_g	Infrastructure availability of infrastructure g	$\in [0,1]$
g	Index for infrastructures	
G	Number of different infrastructures	3
γ	Incremental innovation rate	$\in [0.97, 1]$
α	Learning ability	0.1
P_i	Price of technology i	$\in [0, 0.5]$
$c_{i(t)}$	Cumulative number of adopters at time step t	
$S_{i(t)}$	Market share of technology i at time t	$\in [0,1]$
T1 & T2	Traditional characteristic 1 (Functionality) & 2 (Performance)	$\in [0,1]$
S1 & S2	Sustainability characteristic 1 (Fuel consumption) & 2 (Emissions)	$\in [0,1]$
Cum_{xi}	Cumulative number of innovations in characteristic x of technology i	
Cum_i	Cumulative number of innovations in all characteristics of technology i	
ICEV technology		
$c_{i(0)}$	Initial number of cumulative adopters	$22,500$*
$\kappa_{ICEV,fossilfuel}$	Dependency factor between ICEV and fossil fuel infra	1
Emerging technologies		
$c_{i(0)}$	Initial number of cumulative adopters	1
$\kappa_{PHEV,fossilfuel}$	Compatibility factor between PHEV and fossil fuel infra	0.25
$\kappa_{PHEV,electric}$	Compatibility factor between PHEV and electric infra	0.75
$\kappa_{BEV,electric}$	Compatibility factor between BEV and electric infra	1
$\kappa_{HFCV,hydrogen}$	Compatibility factor between HFCV and hydrogen infra	1**
Infrastructures		
$A_{fossilfuel(0)}$	Initial fossil fuel infrastructure	1
$A_{electric(0)}$	Initial electric infrastructure	0.05
$A_{hydrogen(0)}$	Initial hydrogen infrastructure	0.05

Table B.1 – continued from previous page

Parameter	Interpretation	Values
Policy measures		
Sub	Subsidy on the purchase price	0.05
Infra	Installation of additional initial infrastructure	0.1
Tax_i	Carbon tax on the purchase price	$\in [0, 0.05]$

* The incumbent technology is assumed to exist for fifty time steps already. Adoption was linear.
** All other combinations have a compatibility factor of 0.

C Appendix Chapter 4

Table C.1: Feebate calibration.

CO_2 emission (E)	Rebate	Fee
$E < 0.70 \times$Ebench	Feebate	
$0.70\times$ Ebench $\leq E < 0.85\times$ Ebench	$3/4\times$ Feebate	
$0.85\times$ Ebench $\leq E < 0.95\times$ Ebench	$2/4\times$ Feebate	
$0.95\times$ Ebench $\leq E < 1.00\times$ Ebench	$1/4\times$ Feebate	
$1.00\times$ Ebench $\leq E < 1.05\times$ Ebench		
$1.05\times$ Ebench $\leq E < 1.15\times$ Ebench		$1/4\times$ Feebate
$1.15\times$ Ebench $\leq E < 1.30\times$ Ebench		$2/4\times$ Feebate
$1.30\times$ Ebench $\leq E < 1.50\times$ Ebench		$3/4\times$ Feebate
$E \geq 1.50\times$ Ebench		Feebate

Calibration is based on the French "bonus-malus" system for internal combustion engine vehicles (2012).

Table C.2: Model calibration.

Parameter	Initial value	Description
T	40	Number of time steps
n	8	Number of firms on the market
n_c	2,000	Number of consumers
Vehicle features		
Calibration for Gas-tech vehicles is based on Renault Megane TCe 130 (2011)		
Calibration for Green-tech vehicles is based on Nissan Leaf (2011)		
We use a conversion rate gasoline-electricity from energy-facts.nl		
PC	$PC^{Gas} = 16,950$; $PC^{Green} = 27,356$	Unit production costs
EE	$EE^{Gas} = 15.9$; $EE^{Green} = 66.2$	Energy economy: the distance (km) the vehicle can travel per unit of energy consumed
EC	$EC^{Gas} = 60$; $EC^{Green} = 2.35$	Energy capacity: amount of energy units that can be stored in the vehicle
QL	$QL^{Gas} =$ $QL^{Green} = 0.5$	Quality level: performance measure for miscellaneous quality characteristics
PC_{min}	10,000	Minimum unit production costs
EE_{max}	66.2	Maximum energy economy
EC_{max}	60	Maximum energy capacity
QL_{max}	1	Maximum quality level
em	$em^{Gas} = 23.06$; $em^{Green} = 1$	Level of direct individual CO_2 emissions per energy unit
pe	$pe^{Gas} = 1.6$; $pe^{Green} = 1.12$	Costs per energy unit. Source: INSEE for Gas; EDF for Green
W	$W^{Gas} = 2$; $W^{Green} = 1$	Indicator of the availability of fuel or charging stations
VAT	0.196	Value added tax. Based on French VAT

Table C.2 – continued from previous page

Parameter	Initial value	Description
Firm characteristics		
B_0	$\in [0, 500000]$	Initial budget
F	25,000	Fixed costs
μ	$\in [0, 0.1]$	Part of budget used to finance R&D projects
RD_{min}	50,000	Minimum R&D investment
η	0.5	Distribution choice of R&D expenditure towards the technologies in portfolio
α_1 and α_2	1.0E-5 and 0.5	Scale parameters
ε	0.1	Parameter to trigger a firm to adopt the Green-tech if $MS^{Green} = 0$
ω	0.5	Parameter reflecting the general difficulty of perceiving the new technology
C^{Ad}	10,000	Adoption costs
T^{Ad}	10	Number of periods to wait after transition
λ	0.1	Firm mark-up
Consumer characteristics		
Pr^{Adopt}	0.25	Probability of adopting a new car
d_k	23% $\in [0, 99]$, 22% $\in [100, 249]$, 55% $\in [250, 953]$	Minimum required value for vehicles' drive range. Source: L'Observatoire Cetelems
$pmax$	$\sim N(29000, 5000)$	Reservation price. Based on the average car price of the C-segment in France and the Netherlands
Br	$\in [0, 1]$	Subjective value representing the emotion of the consumer
D	$\sim N(11755, 2500)$	Total distance (km) traveled over the period. Source: INRETS-ADEME, INSEE and SOeSP
Num_{ch}	2	Number of characteristics the consumer looks at in the purchase process
Regulation characteristics		
e	Low 90%, High 10%	Parameter reflecting the tightness of the CO_2 emission standards
Tax	Low 10, High 50	Sales tax on CO_2 emissions
Rebate	Low -2,000, High -6,000	Rebate to support the sales of the Green-tech vehicles. Based on the French ecological bonus (2012)
Feebate	Low -1,000, High -3,000	Maximum rebate (fee) for Gas-tech vehicles in a feebate system (details in table C.1). Based on the French "bonus-malus" (2012)

Table C.3: Simulation results without policy (benchmark). Average values over 100 simulations runs.

Total CO_2 emissions (kton CO_2)	Market share Green-tech (%)	Market share new firms (%)	Public finance (10^7)
1.60	9.17	32.55	7.26

Table C.4: Simulation results of stand-alone policy instruments. Average values over 100 simulations runs. A CO_2 reduction of 8.2% with *tax low* refers to an additional 8.2% CO_2 reduction w.r.t. the benchmark. Stars indicate whether average results are significantly different from the benchmark (no policy).

Stand-alone policy instrument		CO_2 emissions reduction %	Market share Green-tech increase %	Market share new firms increase %	Public income increase %
Tax	Low	0.4	- 4.2	32.6***	20.8***
	High	11.0***	28.1	103.4***	73.8***
Standards	Low	0.6	- 1.1	- 1.2	0.0
	High	21.8***	0.4	180.5***	- 0.9***
Feebate	Low	5.9***	3.8	35.3**	- 5.3***
	High	8.2***	- 1.5	71.3***	-18.6***
Rebate	Low	0.9	64.3***	8.4	- 3.3***
	High	11.8***	234.8***	- 23.0**	-23.1***

* significance at $p < .05$
** significance at $p < .025$
*** significance at $p < .01$

D Appendix Chapter 5

Box 1. Zooming in on car manufacturers' performance

Kia: Kia was a relative newcomer with minor activities on the Dutch car market. In 2001 its offer was limited to a small range of quite polluting car versions. However, the number of 'family' car versions offered on the Dutch market almost quadrupled between 2001 and 2010. Towards 2010 Kia expanded the price range by adding mainly cheaper and also lighter cars to its portfolio that produce less CO_2 emissions. In addition, Kia substantially reduced its CO_2 emissions over the whole range of versions. Kia's activities in more diverse segments appear to be successful as its sales quintupled between 2001 and 2010.

Peugeot and Citroën (PSA): Similar portfolio changes are observed for Peugeot and Citroën, which is not completely surprising as together they constitute PSA automotive group. Peugeot and Citroën are among the firms that increased the weight of their portfolio the most, with a median and below median change in CO_2 emissions. Most remarkable is the shared introduction of the cheap, light and low CO_2 emitting Citroën C1 and Peugeot 107. These car models account for almost half of their sales in 2010.*

Toyota: The data shows that Toyota's strategy was to specialise in relatively low emission vehicles and to discontinue most of its exclusive and polluting versions. This decreased range of versions, which includes the Toyota Prius, made them the second largest car manufacturer for the Netherlands in 2010. The hybridisation of Toyota is an example of a technological innovation strategy to reduce CO_2 emissions. Since hybrids are quite heavy this explains Toyota's poor performance in relative weight change.

Audi: Audi is another firm that reduced the CO_2 emissions of its portfolio through technological innovations. Audi showed an outstanding performance in the improvement of propulsion efficiency of its internal combustion engine. Audi doubled its portfolio of versions over the whole range and is among the best performing European car manufacturers in terms of relative sales.

*11,766 sales of the Citroën C1 in 2010 (source RDW), 24,908 total sales of Citroën in 2010. 18,247 sales of the Peugeot 107 in 2010 (source RDW), 39,659 total sales of Peugeot in 2010.

E Appendix Chapter 6

Table E.1: Parameter values.

Description	Parameter	Value
Number of consumers		10,000
Number of firms		$\in [1-25]$
Initial consumer preferences for general performance		$\sim N(0,50)$
Initial consumer preferences for environmental performance		$\sim N(5,50)$
Initial position of firms for general performance		0
Initial position of firms for environmental performance		0
Number of consumers necessary to continue production of a product	c	20
Radius in which firms search for new products	r	10
Maximum number of new product versions by a firm in a period	n	8

Curriculum vitae

Alexander van der Vooren (1985) obtained a Bachelor's degree in Economics and Law (2007) and a Master's degree in International Economics and Business (2008), both with the distinction Cum Laude, at the Utrecht School of Economics. For his master thesis he studied CO_2 reducing investment decisions with a real options approach. After graduation, Alexander started his PhD project at the Innovation Studies Group, Faculty of Geosciences, Utrecht University.

Alexander presented his research at various international conferences in Denmark (2010), Germany (2009), the Netherlands (2011, 2012), Spain (2013), Sweden (2011), United Kingdom (2012) and the United States (2011). He published in *Technological Forecasting and Social Change*, *Environmental Innovation and Societal Transitions*, *IEEE Transactions on Engineering Management*, and *Transportation Research Part A: Policy and Practice*.

In September 2013 Alexander started working as a policy researcher at PBL Netherlands Environmental Assessment Agency. His main research subject is sustainable development and innovation.

List of Publications

van der Vooren, A. and Brouillat, E. (in press). Evaluating CO2 reduction policy portfolios in the automotive sector. *Environmental Innovation and Societal Transitions*. Doi: 10.1016/j.eist.2013.10.001.

van der Vooren, A., Alkemade, F. and Hekkert, M.P. (2013). Environmental Performance and Firm Strategies in the Dutch Automotive Sector. *Transportation Research Part A: Policy and Practice* 54, 111 - 126.

van der Vooren, A. and Alkemade, F. (2012). Managing the diffusion of low emission vehicles. *IEEE Transactions on Engineering Management* 59(4):728 - 740.

Bakker, S. and van der Vooren, A. (2012). Challenging the portfolio of powertrains perspective: time to choose sides. *26th Electric Vehicle Symposium, May 6-9, Los Angeles* 2, 1306 - 1310.

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Huétink, F., van der Vooren, A. and Alkemade, F. (2010). Initial infrastructure development strategies for the transition to sustainable mobility. *Technological Forecasting & Social Change* 77(8), 1270 - 1281.

The transition towards a more sustainable transport system requires technological change. How can we accelerate this process? How should we allocate our financial resources, such as research and development budgets? Which policy instruments are effective? This thesis provides insights into the mechanisms of technological change by capturing the complexity that characterises the transport system into simulation models.