A framework for understanding product market innovation paths – emergence of hybrid vehicles as an example

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Abstract: In the last few years, the automobile market witnessed a surprising rise in sales of a new type of engine: hybrid-electric engines. This is surprising, since the sector is typically averse to radical technological change of engines. The internal combustion engine has been around for more than 100 years after all.

Economists have explained the dominance of internal combustion (IC) technology mostly from processes of learning and scale economies, which lead to lock-in of an established technology. Those theories have however, difficulties in explaining more radical technological transformations, which typically interrelate with changes in the social and regulatory context.

In this article, we offer a framework for analysing the emergence of radical product innovation paths from a co-evolutionary perspective. The framework is applied for the case of emergence of electric and hybrid-electric engines on the automobile market after 1990.

Keywords: innovation path; technological competition; co-evolution; automobile market; car engine; path creation; hybrids.

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1 Introduction

Attention for HEV is booming. At a growing pace news magazines report on these partial electric drives. Consumers increasingly drive them, and car firms more and more explore them. Critics state that similar short-lived hypes appeared in the mid-1990s on electric vehicles and around 2000 on fuel cell vehicles, and they may be right. Still, today's momentum is distinctive in one important way: hybrid-electric engines have been sold 1.5 million times worldwide now. How could this happen in a sector that is typically risk-aversive and a classic example of 'lock-in' to a dominant technology?

Other researchers have studied this subject, but mostly with a narrower focus. Some focused on firms, whilst neglecting consumers. Pilkington et al. (2002), e.g., explore patenting of electric vehicles activity as an indicator of its technological development. Oltra and Saint Jean (2009b) present a patent data analysis on diversity in firm strategies around various low emission engines. Aggeri et al. (2009) and Beaume and Midler (2009) discuss firm innovation strategies for electric vehicles. Hekkert and Van den Hoed (2004) analyse firm competition of hybrid technology versus fuel cells, whilst Berggren et al. (2009) address hybrid versus diesel. Dijk and Montalvo (2009) analyse firm strategies on hydrogen vehicles. By contrast, other researchers focused on consumers, whilst disregarding car firms. De Haan et al. (2006) study why Swiss consumers like HEVs, and how they differ from conventional gasoline and diesel drivers. Gerard et al. (2006) do the same for US drivers. Few studies have an integrated character: incorporating consumers and firms, competition between technologies, and including technical, economic, social and regulatory aspects. Exceptions are Cowan and Hulten (1996) who address possibilities for escaping lock-in to internal combustion (IC) technology through electric vehicle development. They explicate the dominance of ICE technology in the automotive sector for more than a century with an evolutionary economic approach. Their analysis however ends in 1995 (excluding HEVs) and is not very specific on firm and consumer perspectives and behaviour. Another more integrated approach is Oltra and Saint Jean (2009a), who's sectoral system approach delivers a multi-faceted analysis of the automotive sector; but is restricted to France.

These studies have shown their value in explaining trends in consumer preferences, innovation at firm level (technological innovation, learning), and market and sector level (competition and diffusion), however, the conceptual approaches are less specific on the role of a changing social context and, accordingly, stakeholder perspectives. Popularity or social connotation of products, especially new emerging environmental products, may change alongside technological innovation. A chief example is HEV entering the car market since 1997. Many owners see their vehicle as 'socially responsible', as 'the right vehicle for society' (Heffner et al., 2006). Progression of such connotation will influence the further innovation and diffusion process of the technology, affecting both the consumer and the producer side. There are currently no theories in this field that incorporate this interaction of such social and technological aspects.

In this article, we offer a framework for describing and explaining the emergence of product innovation. We present the new product technology in the context of evolution of demand and supply, which results in a co-evolutionary analysis that highlights socio-technical innovation paths. We illustrate the framework by performing an explanatory case study of the emergence of (hybrid-) electric engines on the automobile market.

This article is structured as follows. In Section 2, we review economic and business theories of innovation to map out preceding (co-)evolutionary approaches. In Section 3, we present our framework of product innovation paths in a changing social context. Section 4 illustrates the framework for the case of emergence of electric and hybrid-electric engines on the automobile market after 1990. In Section 5, we appreciate the merits and drawbacks of the framework and suggest directions for future research on innovation paths.

2 From evolutionary to co-evolutionary approaches

Innovation refers to the *emergence of new products or practices*. Studies in various scientific fields have addressed emergence of new technology and innovation. The Austrian economist Joseph Schumpeter (1883–1950) is regarded a founding father of innovation theories, explaining why firms search for innovation. He described innovation as a shift in production function (of a firm, an industry or an entire country), that may be due to technical progress in a narrow sense – that is, product or process innovation – or the opening up of a new market, the acquisition of a new source of raw materials, or a structural reorganisation of an industry (Schumpeter, 1935). Written back in the 1930s, his concept is unusually broad and dynamic by considering product and process technology aspects together with industry and market aspects. The (neo-) classical economic school treats innovation essentially as an investment problem faced by rent-seeking agents. According to its view, if the costs of innovation (the costs of R&D, marketing and so on) match the benefits in terms of expected increased benefits, an investment of money and effort will be made. Therefore, price is seen as an essential driver (clearing markets).

In the footsteps of Schumpeter, especially in the last quarter of the 20th century, an evolutionary school of economics emerged. This school provides the basis for explaining why technology is so highly patterned and why it exhibits so much stability. Abernathy and Utterback (1978), in their book *Patterns of industrial innovation*, distinguish three phases in the emergence and development of a technology. In the first phase, when the technology emerges, product innovation is intense, and product variety widens. In the second, transitional phase competition between products takes place, competing for a dominant design. The emergence of this opens way to standardisation and mass production. The third phase is that of a mature technology, where innovation continues but only gradually. Following this line of enquiry, Freeman and Perez (1988) studied cycles in technological development and economic returns. They point to a cyclical pattern of *incremental* versus *radical* innovation. The first refers to a phase of continuous gradual improvement of many products, processes and services. By contrast, at discontinuous events the gradual process is punctuated by *radical innovation*, often involving a combined product, process and organisational innovation. Between such (rare) discontinuous events, technologies and systems exhibit a great amount of stability. As a simple illustration of a mature technology one may compare a car engine in 1950 with one produced in 2000, and see how remarkably similar they are.

One of the explanations for this great amount of stability of established technologies is that innovators operated within a ‘technological paradigm’. The choice of technical problems worth solving and the approaches used to solve them tend to restrict proposed solutions along particular avenues.

Following the same line of thought, Brian Arthur and Paul David developed models to study technological competition between competing designs. Their case studies and models have illustrated how an initial advantage of the existing path is self-reinforced through processes of increasing returns to adoption as a result of scale and learning or network effects. This is the notion of *path dependency* that is now widely acknowledged among scholars in technical change.

Business scholars have studied innovation from an entrepreneurial perspective.[1] These studies are mostly centred on finding effective firm strategies for successful innovation. Authors have argued that, apart from Research and Development (R&D) expenditures, some firms become persistent innovators due to dynamic economies of scale and learning by doing. Economies of scale may be utilised by any size firm expanding its scale of operation. It entails the fall of average cost per unit as scale is increased. Typically, benefits stem from purchasing, management and marketing. Economies of scale are also derived partially from learning by doing. This is the learning associated with accumulative production of a given item, improving the producers' skills, subsequently reducing production time and cost. Some authors in this field distinguish between technological and organisational capabilities, and have stressed the role of organisational learning (Leonard-Barton, 1992, 1995; Von Hippel and Tyre, 1995). Others have hinted at the importance of consumer involvement. Apart from direct consumer involvement in product development, firms learn from the market how much commercial potential a technology has. They learn about consumer preferences and how they evolve. The critical role of these user/producer interactions has been pointed out by Lundvall (1988) and Von Hippel (1988). Firms learn especially from emerging market niches with new technologies, their own customers but also customers of others. It will shape their business strategy and re-evaluate their current technological competences. The lessons will also direct future R&D investments toward better market application of technologies.

In their application evolutionary models have been focussing on firms and industries and to process innovations related to production efficiency. They have given less thought to the role of the social context, such as social institutions and demand structures. Some authors have been hinting at a co-evolutionary approach, which seeks to include such institutions in particular. Nelson (1994) works out the life-cycle of technology (Abernathy and Utterback, 1978) in terms of co-evolution of industry structure and supporting institutions with the technology. Nelson questions the universality of the original story of three-phases. He argues it will fit better for industries where the product is a 'system', and where customers have similar demands. For industries where consumer needs are divergent and specialised (such as the pharmaceutical industry) it is less likely applicable. Nelson also points attention to a third component to the co-evolution of technology and industry structure: supporting institutions. He argues they are not simply an outcome of the prevailing technology, but co-evolve with the technology and industry structure. Examples are industry associations and quality standards.

Other scholars have provided case-specific applications of a co-evolutionary approach. Rosenkopf and Tushman (1998) provide a case-study application on co-evolution of community of practitioner's networks and technology in the flight simulation industry. They work out how inter-organisational networks and communities socially construct technological change; in turn, technological outcomes determine the evolution of organisations and communities. Jacobides and Winter (2005) provide a framework on capabilities co-evolving with transaction cost, to understand how firms make choices with respect to vertical scope. This is done through the identification of the specific evolutionary mechanisms that determine vertical scope over time. They identify four key evolutionary mechanisms, which explain how capabilities affect scope, and how scope affects capability. Van den Bergh and Stagl (2003) propose a framework for studying the co-evolution between economic behaviour and institutions. They examine the interaction between social institutions and the behaviour of individuals and groups. They discuss mechanisms of how institutions influence, enable or constrain behaviour of individuals, and mechanisms of how interaction among individuals influences institutions: altruism, co-operation, individuals forming groups, etc. They conclude that, if one aims to formalise the entire set of two way interactions between individuals and institutions, then a multi-layered structure is required, and this would go beyond simple evolutionary game models. Windrum and Birchenhall (2005) present a formal a multi-agent model that explicitly includes consumers in addition to firms. In their model, the nature and direction of technological innovation is determined by the interaction of heterogeneous consumer preferences and heterogeneous firm knowledge bases at the micro level. Since the two populations exercise a strong selective force for each other, we can speak of a co-evolution between consumers and firms. Conceptually, the article resembles an argument of Saviotti (2005) to address co-evolution of demand and supply: *Demand is created gradually as an innovation diffuses and as various forms of learning take place, both on the consumer and of the producer side. These forms of learning are mutual (…). Thus we can say that demand and supply co-evolve during the life cycle of a technology (…), which means that their institutions co-evolve*.

In summary, co-evolutionary approaches are employed increasingly in economics, mostly to include the role of institutions in technological development. Our short overview confirms that co-evolution is useful as a framework to single out a small number of components of a complex innovation system in order to study their interacting evolution, since it gives us an analytically more tractable problem (Saviotti, 2005). Notions and mechanisms from various research fields can be drawn in and integrated. Many of the contributors above have done this. Nevertheless, the current understanding of co-evolving institutions and technologies is still poor. The notion of co-evolution is defined rather loosely in most publications. It tends to be used for any two or more variables that are partly dependent on each other; as a new term for all interaction phenomena. Van den Bergh et al. (2006) have provided a stricter definition, referring to co-evolution as *processes where two variation and selection processes, comprising two or more populations or systems, interact or mutual interfere*. This definition we follow in this article. We further stress that without explicating the processes or mechanisms that constitute co-evolution in a specific case, the term becomes merely a synonym for interaction or co-dynamics (where co-dynamics are simple dynamic changes reciprocally occurring between two or more identified systems).

There has emerged a more interdisciplinary co-evolutionary approach of innovation. In this approach, the emergence, transformation and decay of socio-technical systems is analysed as co-evolution of 'the social' and 'the technical' Rip and Kemp's (1998). Various retrospective analyses of the rise and fall of selected socio-technical systems have been developed, such as 'from sail to steam ships', 'from horse to car', 'from coal to gas' (Correlje and Verbong, 2004; Geels, 2005). Innovation is typically perceived as a transformation process by which a new sociotechnical ensemble or new technological regime grows out of the old regime. These studies have highlighted more than previous studies the patterns in which established technologies are sometimes abandoned and how new innovation paths emerge. They have been less explicit yet on key processes that underlie these patterns.

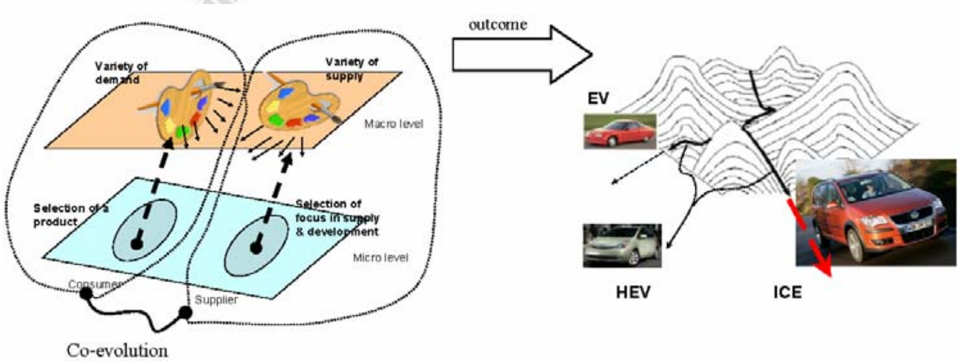
In summary, economic co-evolutionary models have started to address the role of the social embeddings, such as social institutions and demand structures. Little attention is given to the key processes that constitute co-evolution and the stakeholder perspectives. This deficiency may obscure the practical alternatives that individuals and organisations have, and consequently the potential of various directions of innovation. In the next section we develop a framework that responds to these issues.

3 A framework for product innovation paths

In our framework, we consider *demand* and *supply* as two populations of attributes that co-evolve (Saviotti, 2005; Windrum and Birchenhall, 2005). When we speak of demand and supply we thus mean the demand side and supply side. At the supply side, suppliers are creating technological *variety*. Of the possible options that emerge, some are *selected* on the market to the exclusion of others. At the demand side we have heterogeneous people of different income and lifestyles, equipped with needs and ways of thinking. The needs are to a certain degree socially structured.

Market price is important, but certainly not the whole story behind supply and demand. Markets are socially embedded (Rip and Kemp, 1998), and products are socially constructed (Bijker, 1995). Underlying supply and demand we find socio-economic actors, with ways of interpreting, expectations, capabilities, habits, etc. We therefore consider demand as more than actual sales, as including consumer attitudes towards various options. Supply is more than actual production, and involves capabilities, business opportunity, and future expectations towards the various options. The heterogeneity in potential adopters creates a *variety* of demand. In our scheme, there is present demand and future anticipated demand. Under influence of the latter, suppliers make decisions (*select* foci) about investment in R&D. By proposing solutions to problems, suppliers are viewed as creating technological variety (see Figure 1).

Figure 1 Trajectories as an outcome of co-evolution of demand and supply (see online version for colours)



Notes: Regime trajectory may co-exist with niche trajectory(s). A trajectory has its own level of momentum.

The social context in which technology is created and used is not stable, but undergoing change due to the introduction of novelty and institutional and material adaptations that go with it (Rip and Kemp, 1998). Both at the supplier and at the consumer side various forms of learning take place. These forms of learning are interrelated, in the sense that at the very beginning suppliers have to inform consumers about the innovation, but then suppliers themselves gradually learn how to evaluate demand as an innovation diffuses. Learning entails the availability of new skills and knowledge, new social connotations, changing future expectations, new supplier-user relationships, and changes in the regulatory framework. Consumers, by their different ways of interpreting, using and talking about technologies, further contribute to their social shaping. This is part of what some call the *domestication process* of product into daily life (Lie and Sorensen, 1996). Thus, both the technological hardware and the relevant social context change in a complex process with strong evolutionary traits.

The process of co-evolution is thus socially enacted, but not planned by actors. In the case of vehicle engines, e.g., the following actors are involved: car manufacturers, engine component suppliers, car users, car repair shops, sales persons, journalists, university researchers and teachers, banks, venture capitalists, shareholders, and policy makers. It is impossible to include all actors in a behavioural model of innovation diffusion. For the purposes of our framework, we include three types of actors on the micro level: consumers of the innovation (in the example: buyers of new cars), suppliers of the innovation (car manufacturers) and policy makers (regulators of the sector and sponsors of research and green products). In our scheme regulation adapts over time, but is not co-evolving in the same sense as demand and supply. Instead, we regard policymakers, and the regulation they impose, as a force that shapes the co-evolution of supply and demand.

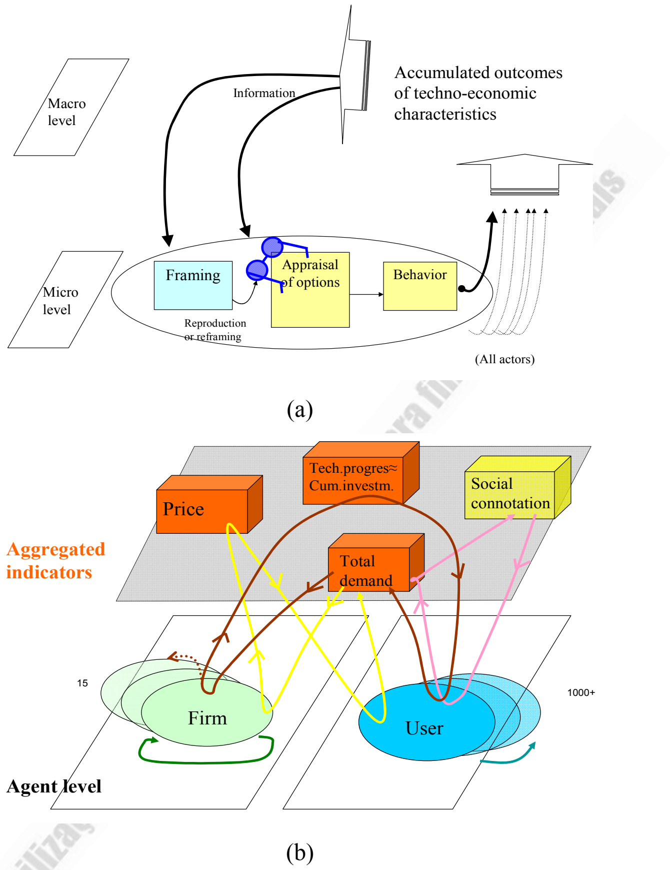
The actual behaviour of all actors aggregate into macro patterns, such as total sales of the various options, prices, technological progress of various options. These macro level indicators in return influence the individual agents on the actor level: it is a circular (micro-macro) process (see Figure 2a).

The studies of innovation we reviewed in Section 2 have identified various feedback mechanisms during the emergence of a product market or industry. Between the micro- and macro-level we distinguish (see Figure 2b):

- *Increasing returns to scale*: cost per unit fall as firms take advantage of economies of scale, allowing them to profitably sell products at lower prices, which stimulates sales and further scale economies (see Figure 2b yellow)
- *Learning about the market*: growing sales lead to better knowledge about the heterogeneity of demand (who prospective buyers are, their willing to pay for specific features, what is valued and less valued); knowledge which may be used for R&D and new product offerings, which will give rise to better products and more targetted marketing effort that will stimulate sales (see Figure 2b brown)
- *Social construction of meaning*: products obtain a social meaning, which will differ across groups; products may become more or less desirable because of this. The dynamics may stimulate sales (in case of positive stories and connotation) or discourage them (in case of negative stories and meanings) (see Figure 2b pink)
- *Network effects*: increases in usage lead to direct increases in value (as in the case of the telephone); increased usage of the product may also spawn the production of

complementary goods such as fuelling stations and assets such as skills which increase in the value of the original product; in case of competing technologies the one with the greatest installed base and compatibility with existing systems has an advantage over the other. (see Figure 2b purple)

Figure 2 (a) Innovation as a circular process involving two layers, where (b) various feedback mechanisms may be identified (see online version for colours)



(a)

(b)

Alongside these micro-macro processes, there are also micro-micro feedback loops:

- *Learning-by-doing*: production experiences leads to improved skills and helps to discover cost-efficiencies in production, allowing manufacturers to reduce prices and increase sales and production (see Figure 2.2b green).
- *Imitation of use*: potential adopters have a tendency to imitate peers (taste formation) (see Figure 2.2b blue) (at the supply side, producers may also imitate successful features of competitor products).

The velocity of the loops differs. Some loops are more rapid, such as falling prices in the course of a few years, or improvement of technological quality of new options. Other loops are slow or discontinuously changing, such as those involving social factors.

In our framework, actor groups have a mental perspective or *frame*. A *frame* is the structure in which the innovation is described or interpreted by an actor. The framing metaphor can be understood as a window or spectacles (worn by the actor group) that filters the total amount of information in a first impression (what it is about and what it important for them), and focuses attention on key elements and aspects within.

Using the example of an alternative engine, say electric propulsion, the user may perceive this as either a green engine, or just another engine, possibly an exciting new engine or something he finds hard to label (he or she may not give it any thought). For manufacturers, the engine may be perceived as a something that is of interest to their customers or to new customers, for which a clear or uncertain market is anticipated. For producers the profitability of an engine (the business case) is likely to be an essential component of the frame. Policy makers on the other hand may see the engine as a solution for air pollution problems or as something that is interesting from an employment point of view (new jobs).

Frames are devices for interpretation by accentuating certain attributes of the car (engine): maximum speed, power or fuel use, etc. It is being well established that goods and service hold symbolic as well as functional value (Douglas and Isherwood, 1979). So, besides *functional* attributes, there is an attribute of *social connotation*, symbolic meaning. The populations of (prospective) users and firms are heterogeneous: users and firms are highly different in terms of individual characteristics (such as preferences and technological capabilities). The frames are unconsciously applied by firms, consumers and policy makers when they deal with various opportunities and problems of vehicles.

To illustrate this framework we analyse the emergence of (hybrid-) electric engines in a changing social context as a dynamic process of co-evolution of demand and supply, mediated by feedback loops.

4 Emergence of hybrid vehicles

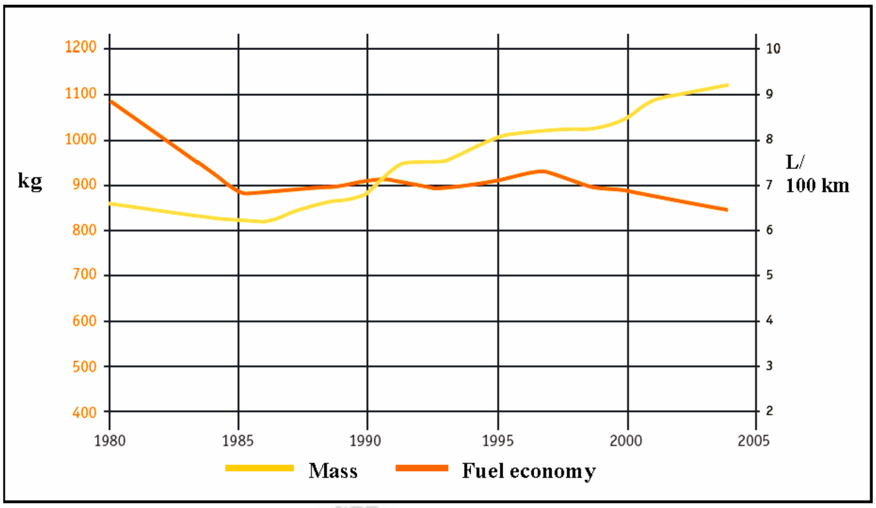
For more than a century now, vehicle engines are dominated by IC technology. The engines constructed by Otto, Daimler and Benz in the 1880s were greatly improved since then, though in principle surprisingly similar to today's engines.

4.1 Internal combustion engine (ICE)

After 1990, car firms continued to refine the ICEs, especially with respect to performance and emissions. In West-European countries, fuel consumption of the fleet typically decreased 25% between 1990 till 2003, while average horsepower highly increased. Figure 3 illustrates this trend for the Netherlands. Initially, average fuel economy remained fairly constant from 1990 until 1997. This was despite a trend of increasing average vehicle mass, and therefore only possible due to more efficient engines. After 1997 growth in engine fuel efficiency overtakes growth in vehicle mass, resulting in a decrease of average fuel use. The impressive rise in fuel efficiency was possibly through broader application of two new engine components in particular[2] DI and variable valve systems (Holt, 2005). Direct injection (DI) systems are the most recent generation of *fuel injection* (FI). FI systems have improved the precision of injecting fuel into an ICE, reducing incomplete combustion. *Variable valve timing* (VVT) optimises the timing of some or all of the valves of an ICE. It enables gas mileage improvements of up to 20% (Dresner and Barkan, 2005).

Production and sales levels of VVT and DI rose considerably after 1990 (see diffusion rates in the Netherlands as an example in Table 1). Beise and Rennings (2005) show that in Western Europe the growth of DI systems moved from 5 to 70% of the diesel market in only eight years time. By 2001 is had reached almost 80%. Application on the gasoline market is increasing as well after 2002 (reaching 13% in Europe in 2007). Diffusion of variable valve systems was also considerable, though initially mainly among larger engines (greater than 2.0 litres). We found it had reached 40%, 50% and 60% in Western Europe, USA and Germany respectively, by 2007.

Figure 3 Trends of average car mass and fuel consumption of the Dutch vehicle fleet from 1980 till 2005 (see online version for colours)



Source: Bovag-Rai (2005)

Table 1 Sales of diesel cars, battery electric vehicles and hybrid electric vehicles in the Netherlands 1995–2006

	EV	*HEV*	*DI diesel*	*Old diesel*
1995		0	8,500	76,500
1996	60	0	28,800	61,200
1997	10	0	33,250	61,750
1998	15	0	48,000	52,000
1999	13	0	66,000	54,000
2000	12	0	86,400	33,600
2001	0	50	93,600	26,400
2002	0	63	93,500	16,500
2003	25	17	92,650	16,350
2004	7	1,062	102,000	18,000
2005	0	2,800	104,550	18,450
2006	0	2,800	116,450	20,550

Source: www.avere.org, www.bovag.nl, Beise and Rennings (2005)

4.2 Electrical engines

From the mid 1990s onwards, electrical engines (re-) emerged as alternative technology for propelling vehicles. First, this was as pure electric vehicles (battery electric vehicle, BEV); later as hybrid-electric vehicles (HEV). Electric battery vehicles consist of an electric engine that moves the wheels, a battery for energy storage, and an electronic engine controller. Up to 1996, the production and sales of electrical vehicles was dominated by small companies outside the car manufacturing industry, most notably the Danish City Els. Sales were very low. Around 1995 though, car manufacturers showed an increasing interest in marketing their electric vehicles (just prior to California's ZEV requirements for 1996). After a time of showing prototypes at automobile shows, they now started to launch production vehicles. Most car manufacturers favoured electrifying existing models as an initial, low-cost strategy (Renault Clio, Peugeot 106, etc.). Around 2000 however, it was undeniable that EVs were unsuccessful as a product market (see sales levels in the Netherlands as an example in Table 1), mainly due to limited range, and a higher price relative to comparable IC vehicles. Not more than a few thousand were sold worldwide yearly between 1995 and 2000.

After 1997, a few car firms launched hybrid-electric versions (HEV). Hybrids have similar range as IC-vehicles and are cheaper than BEVs. Toyota presented its Prius on the Japanese market in 1997, and Honda followed with the launch of its Insight in California in 1998. Production cost for HEVs were significantly higher than ICEs by that time, but Toyota initially paid a premium of around 10% on each vehicle, to push down the price. It sold more than 15,000 HEVs annually in its first years. In 1999, Toyota's Prius was launched in California and later worldwide, followed by a 2nd generation Prius in 2004. By 2002, worldwide cumulated HEV sales exceeded the 100,000 mark, by 2008 one and a half million. Market shares reached around 0.5% in the Netherlands in 2005, and 2% in (first half of) 2008. In the USA, it was around 4% in USA in the first half of 2008.

4.3 Shifts in stakeholder perspectives

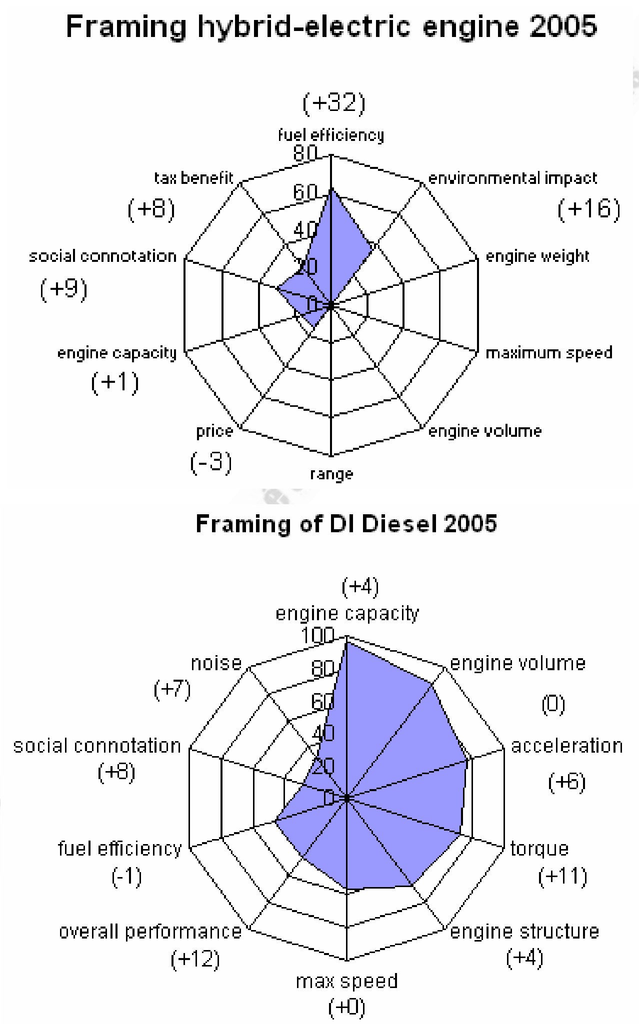
4.3.1 User perspective

Though many studies are performed on the social perception of automobiles (Steg et al., 2001; Heffner et al., 2006), few studies have examined perspectives on car *engines* specifically. Through analysis of news articles in the Dutch popular press we were able to gather data on the social frames of the technologies for our case study.[3] We determined what engine features obtained attention, and how such features were valued (as something positive or negative). Our analysis disclosed that for HEVs prominent attributes (by 2005) were: *fuel use* (63%) and *environmental impact* (37%), see Figure 4. The higher price, negatively appraised, had dropped in importance to 15% (in comparison to 2000). Fuel use was increasingly appraised: scoring +32 in 2005.[4] The score for *social connotation* was +9. In summary, our analysis of articles disclosed that hybrids were most referred for their low fuel use, while remarks on performance were few. *Acceleration*, an aspect of performance, was mentioned in only 17% of the accounts and appraised as +5 in 2005. This satisfaction was low in comparison to diesels.

For DI diesel vehicles performance attributes, such as *engine capacity* ('horsepower'), *acceleration* and *torque*, get most attention and are well appreciated, see Figure 4b. Performance was appraised +12 in 2005, social connotation scored +8. Only price was dissatisfying for most people: –2 in 2000 and –7 in 2005. Environmental impact is rarely referred to.

By comparing the years 2000 and 2005, we found that social frames of the technologies are not static. Framing of HEV changed quite substantially, and took place in the early stage of its diffusion process: in 2005, the percentage of HEV in new car sales was only 0.5%. Apparently the frame was fairly flexible by that time. Framing of diesel engines has been fairly stable between 1996 and 2005, despite progressive technological innovation.

Figure 4 Frames for HEV and DIDV in 2005 (see online version for colours)



Note: The spider diagram indicates the attention for attributes; the outer values indicate the appraisal score of that feature.

In addition, we analysed actual sales of engines for a number of high volume car types in The Netherlands (between 2003 and 2008), and interviewed car salesmen. For passenger cars consumers can usually choose between three to six engine models. We found that (about) 35% simply chooses the cheapest engine. Another part of the customers are willing to pay more for a stronger engine (about 60%). These customers like sporty driving, use a caravan, or value status. Customers paying more for a cleaner engine are an exception if such an option is available (7% or less); often such an option is not available, which makes the share in the whole population around 2% or 3%.

Combining the two analyses[5], we can estimate the specific frames of three consumer groups, see Table 2.

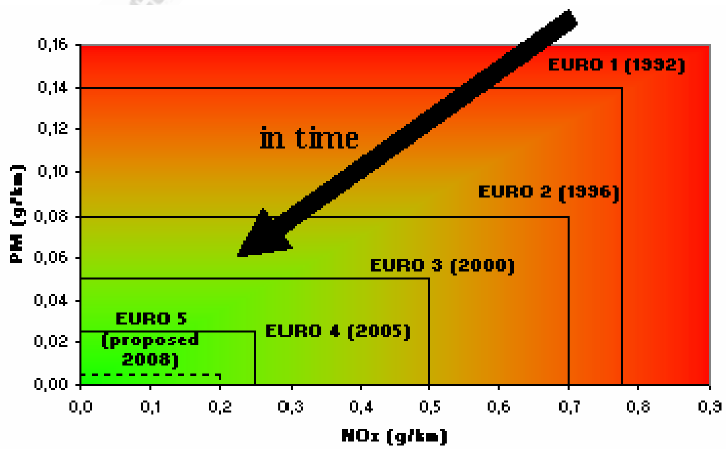
Table 2 Consumer sub-frames

Consumer sub-frame	Size	*Weights*			
		Functionality	*Social connotation*	*Price*	*Environm. impact*
1 ‘penny-pinchers’	35%	0.30	0.20	0.45	0.05
2 ‘power for convenience’	60%	0.50	0.20	0.30	0
3 ‘green’	5%	0.05	0.20	0.30	0.45

4.3.2 Policy perspective

Regulation in the automotive sector after 1990 built further upon initiatives in the 1970s (USA and Japan) and 1980s (Europe). There had been considerable debate among environmental and other policymakers on how the government should regulate this sector. This is a politicised debate, influenced by vested economic interests and ecological objectives, in Europe also between various member states (Jacob et al., 2005). The policy framing of the emission issue, the political discussions (what is the problem, what are alternative solutions? what is the ‘best’ solution?) and formation of majorities is a complicated matter. Here, we examine only what the outcomes were, such as decided emission standards and subsidies on R&D, with Europe and California as an example.

Figure 5 NOx and PM emission standards for diesel cars (1992–2005) (see online version for colours)



Source: www.wikipedia.org, 2006a

The regulation adopted in Europe in 1985 provided targets for around the year 1992. In addition, in the course of the 90s standards were defined in a series of EU directives laying down a time scheme of increasingly stringent standards for exhaust emissions. Emissions of NOx, HC, carbon monoxide (CO), and particulate matter are regulated. Figure 5 shows how requirements for diesel cars evolved, as an example. Similar progressive standards were set for gasoline vehicles.

The Euro-directives provided the industry with requirements on pollutants for five to eight years ahead. This gave vehicle manufacturers a focus point for their engine development work. From the beginning of the 1990s onwards, it became more and more apparent to policymakers that apart from polluting emissions, another type of vehicle emissions, CO_2, needed limitation as well. The EU chose a different strategy on this: a voluntary agreement between the EU and the automotive industry. In 1998, after two years of negotiation, the EU signed agreements with car manufacturer association of Europe (ACEA), Japan (JAMA) and Korea (KAMA), committing them to reaching 140 g/km by 2008/2009, which is a 22% reduction compared to 1995.

In order to support these emission requirements, governments on EU and national levels have regularly provided funds for R&D on cleaner engines. Also, to support this direction at the customer side, many national governments provided tax exemptions on the purchase of low emission vehicles, especially for BEVs and HEVs (mostly from the middle of the 1990s onwards). After 2000, many EU countries also implemented energy labelling schemes. These intend to provide information to the customer on the fuel efficiency of vehicles relative to other vehicles of the same (size) class.

Some governments found the European and US federal standards too weak. Initiated by severe health problems in the Los Angeles area, the California Air Resources Board (CARB) had the ambition to set stricter standards. When it learned about novel electric vehicles in 1990, it set new standards to trigger further development and sales of electric vehicles. It adopted the ZEV Mandate in 1990, requiring that by 1998, 2% of all new cars sold in California would be ‘zero emission’. In the year 2000, all new cars sold had to be either ‘low emission’, ‘ultra low emission’ or ‘zero emission’. The ZEV Mandate was a significant piece of legislation, not just for California but for the car industry worldwide: one out of nine cars in the US is sold in California, which represents 4% of the world market for cars. The Mandate was revised three times (in March 1996 when the 1998–2002 requirements were dropped, in 1998, when ZEV credits could be earned through partial electric vehicles and in 2001). By 1994, four additional states had adopted the California ZEV mandate (New York, Massachusetts, Vermont and Maine); eight more have joint the National Low Emissions Vehicle (NLEV) Program, approving stricter requirements than federal standards. In the Netherlands, the Prius car is exempted from a new car sales tax. If you lease the car you have to declare 14% instead of 20 or 25% of the value of the car as income. The total value of forgone tax revenues is about 75 million Euros a year (in 2008). The above examples show that government is part of the co-evolutionary story of green vehicles. The government involvement is not technology – neutral.

4.3.3 Firm perspective

For manufacturers, a novel engine may be perceived in various ways: as something that is of interest to their current customers, to new customers, as a product for which there is a future market when further developed. Market prospects may be clear or highly unclear.

For producers the profitability of an engine (the business case) is likely to be an essential component of their frame.

In order to survive in world of fierce competition, vehicle manufacturers define a certain *business strategy*, which contains a *technology strategy*. The business strategy defines the current and near-future product mix that should make the company profitable and competitive.

The technology strategy has two sides: an R&D strategy and a product launch strategy. The R&D strategy aims to develop technologies for future product launches. R&D delivers engine prototypes, most importantly as concept cars, which may be shown at international motor shows as 'study models', without the direct intention to be produced. R&D budgets are typically 5% to 15% of total firm turnover.

The product launch strategy defines the technology on the near-future products. Each new car or engine is seen as a project with revenues and cost. Revenues are from expected sales, and costs are from product engineering and manufacturing. Each project (product) should achieve a certain *return on investment* in order to be approved. Production volume is important for the developing firm, in order to get beyond break-even point. As long as production investments in a new product-technology have no profitable outlook, a firm will wait with launching the product. On the other hand firms are eager to achieve first-mover advantage. This is the temporary monopoly advantage that will accrue to the assembler first producing a reasonably priced improved engine, attractive to consumers. Perceived consumer demand is condition sine qua non for product launches; firms need to supply what the prospective buyers want, to obtain revenues. Emission requirements are a boundary condition for product launches: new vehicles have to comply with the regulation.

Firms differ in their precise strength and weakness of technological capabilities (Dijk and Montalvo, 2009). The examination of individual firm strategic activities (through patent data and new product launches) reveals that in the last 15 years firms have strongly focused R&D and engineering on incrementally improving their ICE engines. Up to 1996, some attention was spending on BEV technology, especially initiated by California's ZEV mandate. In 1996, when the mandate was relaxed, most firms shifted to fuel cell technology, as a more promising alternative for BEV (even before BEV proofed itself a market failure!). Exceptions were Toyota and Honda, shifting to both fuel cell and hybrid-electric technology. Toyota and Honda pioneered in launching hybrid vehicles, Ford followed (Ford Escape, 2006). Teske and Chanaron (2007), studying firm strategies towards HEV (by 2006), cluster the manufacturers in three groups: pro's, cautious pro's, and most reluctant. In group one they place Toyota, Honda, Ford, and GM. In group two, they put Hyundai, Kia, PSA, Nissan, D/C and BMW. In group three placed Renault, VW/Audi and Fiat. The product population is thus characterised by heterogeneity.

4.4 Co-evolution of demand and supply

Both demand and supply for car engines evolved over the last 20 years. We have hinted at developments at two levels: aggregate trends (Sections 4.1 and 4.2) and stakeholder perspectives (Section 4.3). Through feedback processes between and within these two layers two innovation trajectories have emerged: one of the established internal combustion engine (ICE) and a trajectory of electric propulsion (EP).

We found fast diffusion of DI and VVT systems for ICEs and slow diffusion of electric vehicle technologies. EP requires new capabilities at the supply side and positive appraisal from consumers. Suppliers created capabilities in electric vehicles and ICE in parallel, offering specially designed electric vehicles and new ICEs. We observed that while electric vehicles got improved, consumers still decided for an improved ICE vehicle. Consumers assessed and compared HEVs with ICEs, notably on their fuel economy (higher for non-highway drives), prices (higher), their engine capacity (sufficient, not spectacular), range (similar), and engine noise (more silent). Up until today electric vehicles have suffered from two unfavourable characteristics: low autonomy (kilometres per battery charge) and high battery costs. The modest sales levels of BEVs and HEVs (market share of less than 1%) slowed down both the development and further diffusion of electric vehicle technology (up to 2005). Due to the small market, firms were unable to take much advantage of scale and learning economies. Suppliers were reluctant to invest (much) in new models and capabilities up to 2005, which held back sales. All this is in strict contrast to new ICE components which benefited much from scale and learning economies.

Alongside, these techno-economic mechanisms (which have been studied relatively well) a social mechanism is found to play a role. Concerns about the climate enhanced environmental considerations of some consumers. Hybrid vehicles have been proposed as ‘the right vehicle for society’. Social meaning and image of this new type engine is not an ‘instant delivery’ phenomenon, but unfolds over time and with level of use. After 2000, HEVs are increasingly seen as green and trendy. Apart from influencing consumers, this social praise for hybrids also drives political support for tax discounts on HEVs in many countries. After 2005, actual purchases of HEVs went up considerably; much more than BEVs in the 1990s. This has stimulated car firms to give more priority to building up necessary EP capabilities. Thus, both techno-economic as well as the social mechanisms underlie the co-evolution of supply and demand.[6] The actual diffusion trends were the outcome of the co-evolutionary process.

4.5 Competition between ICE and electric vehicle trajectory

Development of electric technology took place alongside refinement and learning on ICE technology. The slow development of electric vehicles has a lot to do with the competition from ICE vehicles, which was a bigger profit maker and appealed more to consumers. In our analysis we found three sources of path dependency. One source was at the production side: it is economically not very attractive to invest much in a new, still immature technology. Those will not lead to more revenues in the short term. Competition on the present market is fierce, and it is (relatively) more attractive and necessary to invest in incremental innovation of the existing technology. We found a pattern in which car manufacturers continuously innovate the dominant design in order to improve environmental performance of ICEs. Since Ward (1967) innovation scholars refer to this as the ‘sailing-ship’ effect.

A second source of path dependency resided more at the consumer side: about 95% of consumers were satisfied with the way ICEs performed. They comprised two major consumer groups: those seeking sufficient performance engines at the lowest price, and those preferring more powerful engines at a slightly higher price. The remainder of about 5% (i.e., those who prefer clean and fuel efficient engines and who are willing to pay slightly higher purchase price for this) is the current niche market for hybrid technologies. For most consumers however, IC technology performed as they expected, at a predictable cost. They favoured innovations of ICE over electric engines.

A third source of path-dependency related to regulation. We found that the European Euro 1 to 5 regulations have mainly led to an impressive though incremental innovation of ICE, decreasing certain emissions step by step.[7]). They have not triggered radical innovations. In California, the air resources board used regulation to force market commercialisation of zero emissions and low-emission vehicles. Until 1996, the ZEV mandate put substantial pressure on firms to make R&D effort for alternative engines, enhancing technological competences on ULEV technologies (electric and fuel cells). After relaxation of the mandate in 1996, most firms relaxed efforts for radical innovations by putting them in a longer time-frame.

4.5.1 Path creation

In response to California's regulation, Toyota had made considerable advancement in electric vehicle technology (Yarime et al., 2008; Quandt, 1994), perhaps more than other manufacturers. While all manufactures where happy with ZEV relaxation, and lobbied for further reduction, Toyota saw a business opportunity for its electric engine technology, in the form of a hybrid-electric vehicle (Magnusson and Berggren, 2001). The Prius 1 (1997) was targeted at the 'green' niche in Japan, providing an extremely low fuel use (3.6 litres per 100 km), while compromising on acceleration and maximum speed. When the Japanese niche was captured successfully, the crossing of the Pacific to California was undertaken. The Prius 2 was launched there in 2000, though with a renewed trade-off of electric power (increasing fuel use to 5.1 litres per 100 km, but also increasing acceleration). This 'higher performance' Prius was received well in California, a state with a considerable amount of environmentally aware consumers. By 2004 the (improved) Prius 3 was launched worldwide, and was received well in most countries by the green consumer segment. Total global sales provided Toyota with a considerable scale level, which probably made the hybrid venture profitable by about 2005 (precise figures on this do not exist). Honda followed Toyota shortly in this endeavour, launching the insight already by 1998. Other firms were reluctant, expecting hybrids to be worthwhile for a small niche of the market only. After 2005 firms, observing the success of the Prius car, increased R&D attention for hybrids. The crucial question is whether and when hybrids will become attractive for consumers in segment two: those who seek sufficient performance at the lowest price. If fuel prices continue to rise, there may be reached a point soon where the extra purchase cost of hybrids will be recovered by lower fuel cost. Since this segment comprises around 35% of the market, this would mean an enormous boost to hybrid technology sales. Secondly, if the social connotation of hybrid continues to grow, taking over appreciation of cleaner and more fuel efficient ICEs, the amount of consumers that are willing to pay more for HEVs would grow. It will be interesting to see what policymakers will do: whether they will continue their support for HEV or will discontinue this. BEV may make a comeback, thanks to the HEV which generated an interest in electric drive among consumers, policy makers and companies, and the efforts of new companies such as Better Place.

5 Conclusions

The two-layered framework combines subjectivist notions of innovation (actor perspectives) with objectivist notions (aggregate trends and feedback mechanisms). It combines techno-economical mechanisms (such as learning and scale economies), with social and regulatory factors. In doing so it is psychologically and culturally richer than economic co-evolutionary innovation models (Nelson, 1994; Windrum and Birchenhall, 2005), and therefore suited also for studying the diffusion of consumer products in a changing social context. Combining different methods can compensate for one-sidedness.

In our cases, we can recognise these advantages. For example, objectivistic analyses of electric vehicles easily overlook the role of consumers. They often conclude that most drivers drive less than 100 km a day, so will be happy with an EV with a range of 120 km. A closer look at the consumer viewpoint, as in the subjectivist approach of Section 4.3, suggests that consumers do not make such a narrow trade-off. They have got used to the convenience of a range of 500 or 800 km. Moreover, many consumers choose their vehicle or engine for the most critical trip of the year: their summer holidays. If that requires a strong engine and long range, they are happy to drive with an oversized and over-ranged vehicle for the rest of the year. In other words, by incorporating these subjectivist notions thoroughly, our framework is better suited to explain the commercial potential of various technological innovation paths: why some niches are successful while others die?

The framework addresses competition between regime and niche trajectories, where innovation and diffusion of one product technology is at the expense of the diffusion of the other technology. The framework can be applied in principle to any diffusion process both retrospectively (historic analysis) and prospectively. The model cannot be used for prediction (because diffusion is not a deterministic process and because we lack data on certain variables) but can be used for exploration of future scenarios on the basis of proxy data.

The case of emergence of hybrid vehicles is illustrated with the help of our framework. We have identified a strong ICE regime over the whole period after 1990: car firms supplied (practically solely) ICEs to meet demand for two large consumer groups: those seeking sufficient performance engines at the lowest price, and those preferring more powerful engines at a slightly higher price. A third consumer segment is traditionally small in this sector: those who prefer clean and fuel efficient engines, and who are willing to pay extra for this. Various companies did explore this niche market from time to time by launching two types of engines: cleaner IC engines, and electric/hybrid-electric engines. Toyota was successful in addressing the green consumer segment around the globe with hybrid technology, creating and shaping the hybrid niche trajectory. The co-evolution perspective helps to understand better issues of lock-in and path creation.

For future research we propose two things. The first thing we propose is more thorough descriptive explanatory case studies on the emergence of niche markets in which subjectivist notions are combined with objectivistic notions. The second thing we propose is simulation analysis. The dynamics of techno-economic mechanisms on the one hand, and social factors on the other, can be usefully studied with the help of simulation analysis. Even a simplified but integrated model can provide useful insight in the principal dynamics of complex innovation issues. For both types of analysis the framework presented in this article can be a valuable starting point.

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Notes

1. Aggeri et al. (2009) and Beaume and Midler (2009) provide automotive sector examples of this in this Journal.
2. Other relevant innovations that were increasingly applied were turbo and intercooler for diesel engines, and multi-point injection systems for gasoline, and exhaust gas recirculation.
3. For simplicity and brevity we limit our description of the user perspective here to the Netherlands, implicitly addressing the world market as an extrapolating of the Dutch market. This is clearly a crude assumption that needs elaboration in future research.
4. Evaluation of attributes can be scored through analysis of actor stories. The storyteller may regard the attribute an improvement (+1), large improvement (+2), decline (–1), etc. For each year, the scores from stories are summed; see Dijk (2009). 'Dynamics in demand structures for cleaner car engines'. Industry and Innovation (submitted), for the complete analysis.
5. The rationale here is that when the three consumer groups (frames) are merged, accounting their sizes, they should deliver the (aggregate and averaged) socio-technical frame, such as in Figure 4.
6. For reasons of brevity the role of various feedback effects is not explicitly dealt with here. See complementary paper Dijk and Yarime (2009) for a more elaborate analysis on this.
7. Oltra and Saint Jean (2009a) reached similar conclusion.