Cranfield University

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Depth or Breadth: Towards a contingency model of innovation strategy in the Automotive Sector

School of Management

PhD Thesis
Academic Year 2010 - 2011

Supervisor: Professor John Bessant
Revised, September 2010

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Abstract

The thesis explores the strategic choices made by automotive manufacturers in developing and deploying technology that is discontinuous and potentially disruptive. It studies the deployment of seat belts, airbags, hybrid vehicles and fuel cell electric vehicles, drawing on product deployment histories, patents and the opinions of industry experts. The thesis identifies two fundamental strategies called depth and breadth and shows how the different manufacturers' approach to these four technologies is arrayed along a continuum between these two choices.

The thesis contributes to the theory of the technology-based firm which focuses on the management of scale, scope, time and space by making operational the idea of scope with depth and breadth. It also explicitly links the theory to the literature on co-evolution and dynamic capabilities and adds to the understanding of the co-evolutionary dynamics at play in the automotive industry by applying the idea of technological pathways to the technologies under study. This discussion yields some potentially interesting insight for practitioners.

The thesis also reviews the literature concerning the potential changes to automotive power train technology and adds to it by using the theory of the technology-based firm as well as environmental literature and the non market strategy lens in order to develop a nonbiased view of the state of development of fuel cell and hybrid technology.

Finally, the thesis provides a rigorous review of the use of patents in management science over the last 50 years and makes one of the first attempts in the academic literature to study patents using a patent mapping tool to help make sense of the large amounts of data available in line with the new ideas concerning the importance of developing visualisation techniques in data intensive scientific enquiry.

About the Author

Mike Rosenberg lectures on Strategy at IESE Business School in Barcelona, Spain, where he is also involved in Executive Education and with work on alternative energy and scenario planning. Prior to joining the faculty at IESE, Mike taught on a part-time basis while he was the Practice Leader for Heidrick and Struggles' Global Automotive Practice, and before that was a Management Consultant to the automotive industry for A.T. Kearney and Arthur D. Little, involved in new product development, supplier management, and automotive distribution in Europe, the United States, Asia, and Latin America. Mike Rosenberg has an engineering Degree from the University of Michigan at Ann Arbor and a Masters in Business Administration from IESE Business School.

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NOTATION

The thesis employs a number of terms which are well known within the context of the automotive industry but which might not be as familiar to a wider readership, as follows:

Airbag	Inflatable device that protects vehicle occupants in the event of a crash
Battery Electric Vehicle	Electric vehicle which uses a large group of batteries as its primary source of energy storage
Cars and Light Trucks	Industry term for passenger vehicles which includes pickup trucks and sports utility vehicles (SUVs)
CARB	Abbreviation for the California Air and Resources Board, responsible for air quality in California
Component	Discrete part or group of parts later incorporated into a motor vehicle
Fuel Cell Electric Vehicle	Electric vehicle which uses a fuel cell to generate electricity on demand from liquid or gaseous feed stock
GM	Abbreviation for General Motors Corporation
Hybrid Electric Vehicle	Vehicle which has both electric and internal combustion propulsion systems
ICE	Abbreviation for internal combustion engine
Mild hybrid	Hybrid vehicle which relies primarily on its internal combustion engine
Module	Group of components that is delivered as a unit to the vehicle assembly plant
NHTSA	Abbreviation for the National Highway Traffic and Safety Administration, which regulates motor vehicles in the U.S.
OEM	Original Equipment Manufacturer, used to refer to the vehicle manufacturers. The thesis tends to use the term manufacturers.
Pretensioner	Pyrotechnic device which tightens a seat belt in the first moments of a collision
Power Train	The set of technologies used to store and convert energy and apply it to the wheels
Range Extender	Term coined by General Motors for a hybrid design in which an internal combustion engine acts as an electricity generator
Seat Belt	System of webbing which holds a vehicle occupant in place in the event of a collision or sudden stop
System	Group of components which together play a function in the vehicle
Suppliers	Term used to describe firms which make components, modules or systems which are then integrated into the vehicle by the OEMs

CHAPTER 1 INTRODUCTION

1.1 Background and the Research Question

Industry, government and academia are interested in the potential of very new technology which is often called radical, disruptive or discontinuous. There are a number of theoretical constructs which discuss the phenomena and retroactive case studies which document the emergence of new technology and explore in which cases such new technology caused disruption. There is, however, an important gap in the literature on how firms behave during what Tidd et al. (1997) referred to as the implementation phase of innovation in light of technology which is discontinuous and recognized as potentially disruptive.

The automotive industry has been the focus of intensive academic scrutiny over the last 50 years and has been a source for theoretical development and insights for practice in a number of areas including operations, new product development, and supplier relationships, to name some of the key areas of research. The area of potentially disruptive or discontinuous innovation is, however, less researched in the automotive context although there is a growing body of knowledge dealing with different aspects of the potential for change in automotive power train technology.

While there are several theories of the firm in the literature, Granstrand (1998) introduces the theory of the technology-based firm for those cases where technology and technological change have a substantial impact on firms which have an asset base that is heavily dependent on technology. In Granstrand's view, other existing theories do not sufficiently explain the co-evolutionary nature of technological development and diversification in modern multi-national and multi-product firms.

The thesis uses the automotive context and Granstrand's theory of the technology-based firm to contribute to filling the gap identified above and explore the choices in technology strategy (Ford, 1988) pursued by different vehicle manufacturers in the face of such discontinuous and potentially disruptive technologies.

The research question is: ***What strategies do automotive companies follow with respect to the investigation and deployment of discontinuous technologies?***

Within the broader research question, the thesis pursues two sub-objectives:

1. Explore how companies approach the development of different technologies
2. Assess how different companies develop the same technologies

1.2 Main Findings

The thesis explores how four automotive manufacturers introduced new technology by looking at four different technological innovations. By looking at four vehicle manufacturers and four technologies, the thesis develops eight complementary case studies based on data from technology deployment, U.S. patents, and the opinions of industry experts.

The case studies show that the manufacturer's strategies appear to array themselves along a spectrum the thesis refers to as "depth" and "breadth". This thesis applies the terms depth and breadth to the development and deployment of new technologies at the system level in cars and light trucks and defines them in Sub-section 6.2.2 in the following way: A broad strategy is defined as pursuing a number of parallel projects looking at different aspects of the new technology and/or seeking to implement the technology in a wide variety of applications. A deep technological strategy, on the other hand, is defined as focusing efforts on developing the technology in a single or limited number of applications prior to a potential or eventual roll out across the product line.

The concepts of depth and breadth have been used by other researchers to look at a firm's technological asset base (Prencipe, 2000; Wang and von Tunzelmann, 2000; Brusoni et al., 2005) and similar concepts have been looked at in the literature of automotive product development (Nobeoka and Cusumano, 1997). The contribution of the thesis is to apply the concepts to the development and deployment strategy for incorporating new technology into current products and contributing to the idea of managing scope which is one of the central aspects of Granstrand's (1998) theory of the technology-based firm. The thesis also finds that the deployment pattern seen appears to match the patent pattern in many cases and puts forward a construct in Sub-section 6.2.4 linking the deployment pattern of new technology and each firm's cumulative patent pattern in the technology.

Using these ideas, the thesis answers the research question by finding heterogeneity in the response of the different vehicle manufacturers for the different technologies and identifies factors related to the firms themselves and also the technologies which partially explain those differences. With respect to the technologies, the thesis applies Geels and Schot's (2007) technological pathways to the technologies and finds that the pathways can be combined with the ideas of depth and breadth to first develop a clear idea of the strategies employed and also give indications for practice in terms of what could be done in the face of discontinuous change adding to literature dealing with similar issues reviewed in Sub-section 2.2.1.

In addition to the contribution to Granstrand's idea of scope mentioned above, the thesis discusses three possible additions to the theory of the technology-based firm. The first addition is to explicitly link the theory of the technology-based firm with the co-evolutionary perspective and the multi-level perspective. The primary reason that Granstrand puts forward a new theory of the firm is that he feels that others theories do not adequately capture the co-evolutionary process between firms which develop technology and the environment in which those firms operate and compete, and if one were to link these three literatures, which have largely been separate, there might be much which can be applied from one stream to another, thus enriching all three.

The second addition is to link the theory to the dynamic capabilities literature of Teece et al. (1997) which deals with many of the same concepts, and appears to only differ from the theory of the technology-based firm in that Teece at al. and subsequent researchers use the model to identify capabilities which change over time in light of a changing environment but do not emphasize the other side of the co-evolutionary process.

The importance of linking these literatures lies in opening up an avenue to further develop the theory of the technology-based firm and breaking into what Granstrand (1998) calls the "dark box" (p.486) of management.

The third addition is to tighten the definition of what is and what is not a technology-based firm. Granstrand's definition of a technology-based firm is actually quite broad and could be applied to many if not most firms in today's' technologically advanced economy, and if, as suggested, literature from other perspectives can be used to complement the theory of the technology-based firm, a tighter definition could be useful in determining which studies are applicable and which are not. The thesis proposes three tests for the application of the theory which are further developed in Section 6.4:

1. That the firm must compete in a socio-technological regime which possesses the five properties of a co-evolutionary system (Lewin and Volberda, 1999).
2. That the firm in question has the requisite level of influence to affect its environment at the niche, regime or landscape level.
3. That the firm is primarily concerned with the development of technological artefacts or services, as opposed to marketing concepts, retail networks, etc.

In terms of method, the thesis uses an innovative text mapping tool to make sense of the patent data echoing Jim Gray's (2009) idea of the importance of visualization in data-intensive science, which he referred to as the fourth paradigm of scientific endeavour. While these tools are commonly used in practice (Blanchard, 2007) this thesis appears to be one of the first uses of the tools to inform management science and should be considered an early exploration of their potential.

Finally, the thesis suggests that using the theory of the technology-based firm as well as Baron's (1995) non-market strategy concept and Reinhardt's (2005) framework on how it pays to be green yields additional insight to that provided by institutional theory (Van den Hoed, 2004) in describing the evolution of fuel cell vehicles. Considering all the major automotive manufacturers as technology-based firms explains the heterogeneity in a more compelling way because it places technology and management at the centre, rather than at the periphery, of how the firm behaves. The combination of these perspectives appears to explain General Motor's apparent commitment to fuel cell electric vehicles as well as Toyota's apparently parallel commitment to hybrids and fuel cells, as well as Ford's choice to push for hybrids and Nissan's apparent choice to pursue neither one of the technologies.

1.3 Thesis Content

Table 1.1 shows the thesis content by chapter and makes explicit the purpose of each chapter.

Chapter	Contents	Purpose
1. Introduction	• Background • Research question • Main findings • Thesis content	To clearly situate the thesis in the field of discontinuous innovation and the automotive industry, highlight findings and explain content
2. Literature Review	• Literature review process • Literature concerning discontinuous and disruptive technology, the automotive industry, and the theory of the technology-based firm • Literature using patents	Review the literature review process, identify the gap in the literature that the thesis contributes to filling, as well as look deeply at the use of patents in management science
3. Research Methodology	• Philosophy & epistemology • Method • Site selection • Sources of data	Explain the philosophical and methodological choices made and highlight the limitations inherent in the approach taken
4. Industry Context	• Socio-technological model of the automotive industry • Examples of co-evolutionary dynamics	Establish the context for the research in a rigorous way to clarify case study limitations and avoid research bias
5. Case Studies	• Company case studies • Technology case studies	Show the empirical findings of the case studies
6. Discussion	• Development of the concepts of depth and breadth • Discussion of the implications of depth and breadth for the thesis • Discussion of theory • Discussion of alternative power train technology	Put forward ideas of depth and breadth and perform cross case analysis using the concepts as well as discussing their implications for theory and practice as well as commenting on the evolution of alternative power train technology.
7. Conclusions	• Contribution to knowledge • Limitations • Further research	State the contribution to knowledge made by the thesis as well as discuss its overall limitations and make suggestions for future research

Table 1.1 Thesis Content

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to place the thesis within a framework of existing management theory and methodology and to show those gaps in the literature which the thesis attempts to fill. According to Hart (1998), making a new contribution is not only "dependent upon knowledge of the subject" but also "requires a spirit of adventure" (Hart, 1998, p. 21). Section 2.2 will capture that spirit by briefly discussing the literature review process which has occurred in specific phases over the last six years. Eisenhardt discusses the importance of considering a "broad range of literature" (Eisenhardt, 1989, p. 544) and the researcher did just that prior to arriving at the specific literature in which to contribute.

Section 2.3 will explore the literature to which the thesis contributes. As discussed in Section 1.1, there is a gap in the literature that discusses how vehicle manufacturers in particular and firms in general deploy discontinuous and potentially disruptive technology, and this section will show the existence of that gap by looking at the literature focused on disruptive and discontinuous technology, the automotive literature dealing with such technologies, and Grandstand's (1998) theory of the technology-based firm. Other literatures which are used in the thesis will be introduced and reviewed as needed.

Section 2.4 will go into detail on the history of using patents in management research and show how patent analysis has informed management science over time. The key finding of Section 2.4 is that the development of digital tools has tremendously increased the power of patent analysis over the years yet brings new challenges including the need for visualization of the vast amounts of data. The role of Section 2.4 is primarily methodological and Chapter 3, which deals with the research methodology, will draw on the discussion of advantages and limitations to using patents and go past the normal litany of limitations and address some of the limitations inherent in using powerful digital databases and mapping tools.

2.2. The literature review process and methodology

More than a single activity, the literature review for the thesis was conducted in a series of six discrete phases in which different threads in the literature were read, analyzed and considered for use in the research. Hart (1998) presents a very clear and methodical flow chart of the literature search in which the researcher starts by choosing a topic and then focuses in on the topic through a combination of mapping and bibliographic analysis at finer and finer levels of detail. Tranfield et al. (2003) put forward the idea of the systematic literature review which entails looking for the connection between different literatures using key words and digital search tools such as ABI Proquest, Science Direct, Ebsco, etc. The thesis employed both concepts but did not experience the kind of step-by-step clarity implied by Hart (1998) but instead went through an iterative process during which different literatures were looked at in-depth, and even the same body of literature was reviewed at different times, as shown in Table 2.1.

Period	Focus	Application to thesis
Winter 2004	Long terms strategy, disruptive technologies, energy availability & climate change	Initial context developed and focus on heterogeneity of response by automotive manufacturers identified.
Summer 2004	Automotive, fuel cells, strategy, and innovation	A number of potential lenses identified as possible avenues of research.
Spring 2007	Strategy and innovation (2)	Lewin and Volberda's (1999) five properties of a co-evolutionary system used to analyze context and gap identified in innovation literature.
Summer 2008	Depth and breadth, the theory of the technology-based firm, the use of patents in management research	Focus of contribution changed to the theory of the technology-based firm. The analysis of the use of patents used to identify limits to using patents.
Summer 2009	Multi-level perspective and technology pathways	Geels' (2002) socio-technical model used in developing context and Geels and Schot's (2007) technology pathways adopted for technology case studies.
Winter 2010	Automotive (2), fuel cells in automotive (2), innovation (2)	Gap identified in automotive literature and overall tone of review made more critical with fewer concepts discussed in greater depth.

Table 2.1 Discrete phases in the literature review

Much of the impetus for these different phases of the literature review was feedback received during the Cranfield Review Process, which is designed to focus research efforts and assure that a researcher is making progress in line with the guidelines established by the School of Management, in this case for part-time PhD. students. (http://www.som.cranfield.ac.uk/som) The Viva also gave additional guidance and prompted an additional phase of the review. For the thesis, these reviews were conducted as shown in Table 2.2.

Review	Month, Year
1st Review	October, 2004
Addendum to 1st Review	December. 2004
2nd Review	July, 2007
3rd Review	September, 2008
Viva	March, 2010

Table 2.2 Review process timetable

This initial selection of literature was used to define the context of the research but was later not only refined but repeated in each of the iterations shown in Table 2.1. The first literature review, for example, found 1,743 journal articles by using the Proquest database and the 31 sets of key words shown in Appendix J.

Comment [A1]: figure 2.1 doesn't seem to exist

In the summer of 2004, the focus was sharpened and a search was made of the literature on disruptive technology in automotive, the application of fuel cells to transportation and the larger fields of strategy and innovation in order to explore different potential lenses which could be used in the research and are shown in Table 3.1. Part of this work was to look at the International Motor Vehicle Program as a possible source of applicable research, an example of which can be found in Steinemann (1999). In the Spring of 2007, the literature search was focused again and the fields of strategy and innovation were explored in more depth using citation searching and mapping techniques (Hart, 1998) to establish a chronological timeline in both literatures and to identify two broad threads in research into disruptive technology (Bower and Christensen, 1995) and discontinuous innovation (Abernathy and Clark, 1985, Tushman and Anderson, 1986) as well as looking at Pavitt's (1984) technological trajectories as a possibly important framework for the thesis. This effort also led to a deeper look at the co-evolutionary perspective (Lewin and Volberda, 1999).

In the summer of 2008, a fifth review of the literature was conducted along two parallel tracks. One track had to do with the use of the concepts of depth and breadth by other researchers which led to the identification of Granstrand's (1998) theory of the technology-based firm as a potential area in which to make a contribution, and the other with the use of patents in management science which is shown in Section 2.4. In the summer of 2009 the literature review focused on looking deeply at the multi-level perspective (Rip and Kemp, 1998) and Geels and Schot's (2007) technology pathways were identified as a potentially more robust framework for use at the product and component strategy level than Pavitt's (1984, 1997) trajectories which were done at the firm level. Finally, the literature review was expanded again by looking at the literature on automotive and fuel cells for a second time and also deepening the discussion of the two streams of innovation literature adding a more critical tone to the review while focussing on the intersection of the innovation literature and the automotive literature, shown in Figure 2.1, in which a gap had been identified and which is discussed in Section 2.3.

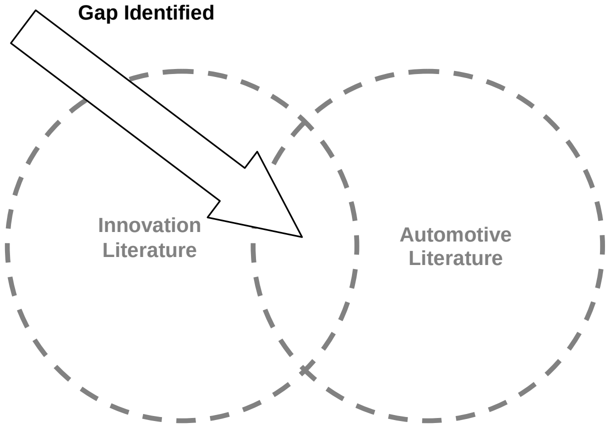

Figure 2.1 Locus of contribution

2.3 Gaps in the literature

As stated in Section 1.1, there is an important gap in the literature in looking at how firms deploy technology which is recognized as discontinuous and potentially disruptive, but in fact has not yet demonstrated that potential. This can be seen in both the innovation literature and that dealing with the automotive industry and potential changes to power train technology in the years ahead.

Sub-section 2.3.1 will review the innovation literature dealing with discontinuity and disruption by discussing several of the different definitions in use, exploring two major threads in the literature, and highlighting the relatively limited amount of literature which explores what companies ought to do in the face of such change. Sub-section 2.3.2 will look at the literature concerned with innovation in the automotive industry in general and that concerned with the transition to alternatives to the internal combustion engine in particular. Sub-section 2.3.3 will focus on Granstrand's (1998) concept of the technology-based firm and suggest that it could be expanded upon to inform the debate on what to do in the face of technological change of the type discussed in Sub-sections 2.3.1 and 2.3.2. Finally Sub-section 2.3.4 will summarize Section 2.3 and define the gap the thesis intends to address.

2.3.1 Technological innovation and technology strategy

There is an extensive literature dealing with innovation and the development of new technology which covers a wide range of topics, approaches, and theoretical frameworks. Essentially, the literature deals with three basic questions: what to do, how to do it, and how to classify different technology related activities.

- Definitions

In the literature, different researchers use different words to describe similar types of technological innovation, and sometimes use the same words to mean different things. This is also true in dealing with the type of technology of interest, i.e., those technological developments that present a true break with the past and can sometimes cause profound change or disruption in an industry (Garcia and Calantone, 2002; Noke, 2006; Daneels, 2004)

Garcia and Calantone (2002) look deeply at the marketing literature as well as the innovation literature identifying 15 constructs and 51 scale items in 21 empirical studies which seek to explore discontinuous and innovative technologies. In their view, the lack of common definitions and proliferation of typologies has led to a degree of theoretical confusion in the academic literature and this confusion has made it more difficult for the academic community to have as much of an impact on practice as could be possible. In their view the empirical studies are also confusing as they can be found at both the macro and micro levels of analysis, deal with technological and market discontinuities, explore single and multiple factors, and use categorical and continuous scales to evaluate levels of innovativeness and other measures.

Garcia and Calantone use the 1991 OECD definition of innovation as “an iterative process initiated by the perception of a new market and /or new service opportunity for a technology-based invention which leads to development, production, and marketing tasks striving for the commercial success of the invention” (Garcia and Calantone, 2002, p. 112). At issue is the definition of inventiveness which they understand as meaning newness and thus brings the question of new to whom i.e. the world, the firm, the consumer, etc. For Garcia and Calantone (2002) then, inventiveness is a measure of potential for discontinuity. What is striking is that after critiquing the proliferation of concepts concerning innovation, Garcia and Calantone go on to present an additional framework distinguishing between incremental, what they call really new, and radical based on whether a specific innovation represents discontinuity in the technology, market or both.

Noke (2006) resists the temptation to develop yet another framework but touches on the same theme that the proliferation of definitions, themes and frameworks is a hindrance to the development of theory and conducting meaningful empirical work. In her view, the proliferation of concepts is understandable because of the large number of academic disciplines involved and she attempts to tease out the common themes in different streams of research. For Noke, the difference between radical and discontinuous technologies has to do with whether or not a new technological paradigm is part of the development and in her view the creation of a new paradigm is central to what she called radical technology. Discontinuous innovation is often the result of an innovation being applied to a completely new field but without the introduction of a new technological paradigm. Such innovation does require a paradigm shift in the minds of the people involved in developing and introducing the technology but not in the technology as such.

Noke (2006) then looks at disruptive technologies and makes three observations. In the first place the appropriate unit of analysis for considering disruption is primarily the end-user or customer who, due to changing perception of value, will choose the new technology over the old; the resulting industry disruption is an effect of this shift. A second point is that disruption is context specific and that industry incumbents become disrupted when caught off guard or are surprised by the shift in perceived value. The third point is that there does appear to be some debate in the literature as to the pace of such disruption; changes in values might happen slowly or quickly, again depending on the context.

What appears to be the general consensus across these different streams of research, and which will be highlighted in the discussion of Bower and Christensen (1995) and later papers, is that discontinuous innovation might lead to disruption depending on the response by industry players, and that disruption is, like beauty, in the in the eye of the beholder (or in this case the disrupted players in an industry). For the purposes of the thesis Daneels’ (2004) definition will be used which states that “A disruptive technology is a technology that changes the basis of competition by changing the performance metrics by which firms compete” (p. 249).

- Two views of significant technological change

According to Pisano (2006), there are two distinct threads of research dealing with why leading firms fail to survive profound technological change. Pisano calls these threads the supply view and demand view, as the first has to do with what firms can offer and the second what customers ask for.

The first of these threads can be traced back to Schumpeter (1961) who argued that periods of evolutionary technological development were punctuated by waves of revolutionary technology change. Abernathy and Clark (1985) felt that research had not managed to provide frameworks useful for practice, and put forward four types of innovative activity based on the transilience concept in which architectural change would be the most impactful as it would have a profound impact on both technologies and markets. Tushman and Anderson (1986) set out to prove the concept empirically by looking at data from the airline, cement and semi-conductor industries. Tushman and Anderson then went on to classify discontinuous technologies in terms of competence destroying and competence enhancing, meaning the degree to which the core competences that incumbent players enjoyed prior to the technology's introduction were destroyed or sustained by that introduction. The main findings of Tushman and Anderson's study are that the competence destroying discontinuities create higher degrees of overall uncertainty in a particular industry and also that one can observe greater environmental munificence or growth potential after such discontinuities occur.

A second thread which attempts to explain the failure of incumbents was presented by Bower and Christensen (1995) and Christensen and Bower (1996). Drawing on the resource allocation literature of Bower (1970) and Burgelman (1983), as well as the concept of resource dependence as espoused by Pfeiffer and Salancik (1978), they show why it is that large successful firms are not able to deal with certain kinds of technological change. Christensen and Bower argue that the resource allocation process of well managed firms is beholden to developing products and services which appeal directly to their largest and most profitable customers.

According to Bower and Christensen (1995), when new technology comes out which is not explicitly requested by those customers, it is difficult to get adequate resources to pursue the technology inside successful organisations. Such technology often underperforms the existing technology, according to key performance metrics, while offering some other benefit which the market does not yet value. The engineers who developed the ideas often become frustrated and join new ventures which then begin to build expertise by supplying niche markets which do value some aspect of the new technology's performance such as smaller size, lower cost, etc. Over time, the new technology improves and eventually becomes good enough for widespread market acceptance on the key performance attributes. At the same time the previously unvalued attributes which do favour the new technology become more important and it eventually becomes the new dominant design (Utterback and Abernathy, 1975) or technological paradigm (Dosi, 1982).

Daneels (2004) sees merit in disruptive technology but argues that much work remains to be done to refine and develop the concepts. In his view there are five areas in which the theory needs further development and thus recommends further research. First, Daneels (2004) feels that the concept lacks rigorous definition and, besides offering the definition cited above, Daneels suggests that researchers look at the different types of technological change, the role of industry or market structure of a specific sector, how disruption can be measured and how to know when the process is complete. Second, Daneels asks "how can a disruptive technology be spotted in its early stages?" (Daneels, 2004, p. 248) and suggests research which will help develop predictive tools to make *ex ante* predictions and form the basis for managerial prescriptions for incumbents and new entrants alike. Third, Daneels recognizes how the theory explains why some incumbents fail to survive disruption but feels that significantly more work is needed to understand why others survive and even prosper during such a process. Fourth, recognizing the central role of the customer in the theory, Daneels suggests more research on how being customer oriented can help a firm survive disruption or, as argued by Bower and Christensen (1995), such a customer orientation actually leads to a firm being disrupted. In his view, a deep enough understanding of customer needs will allow a firm to invest in the features that customers might need but not even acknowledge and thus avoid disruption. Finally Daneels finds the idea of creating a spin-off to deal with new potential disruption worthwhile but again feels that much research and theoretical development is required to put this idea fully into operation.

In his account of Firestone's failure to switch to radial tyres, Sull (1999) actually supports both points of view although that does not appear to be his intent. When radial tyres were first brought into the market by a foreign firm looking to gain U.S. market share, Firestone and Goodyear both downplayed the new technology and pushed the belted bias tyre which was closer to their own technical competences and could be made in their existing plants. In Tushman and Anderson's terminology, the radial tyre was a competence-destroying technology, and Firestone and Goodyear resisted it in favour of their own competence-enhancing technological improvement. In 1972, Ford and Chrysler reportedly demanded that Firestone begin supplying them with radials and the company responded in record time, seemingly proving Christensen's basic thesis. Although the launch of Firestone's radials had serious quality problems, the company did eventually sort them out and retained a large portion of their customers' business. One way to read Sull's account is that Firestone's corporate crisis and later sale to Goodrich was not caused by its inability to acquire the skills needed to successfully manufacture radials but by its inability to close its outdated bias tyre plants and undertake what Teece et al. (1997) call the reconfiguration of the business required.

Both explanations discuss the potential of new technology to alter competition in a specific industry and the difficulties leading firms have in dealing with such technology. Another similar factor between the two threads mentioned above is that most of their examples and case studies look backward to show how a technology caused an industry to change. Both threads, however offer little advice as to what firms can do in the face of technologies which offer the potential of such change besides concluding that the best way around the problem is to have semi-autonomous units work on the new technology while the rest of the organisation does what it needs to do to incrementally improve existing technology.

While the theoretical foundation for both threads is well developed and continues to evolve in the discussions mentioned above, there still appears to be a gap in providing guidance to managers who find themselves at the edge of what might become disruptive or architectural change, and perhaps the most interesting aspect of looking at technological change from a practitioner's perspective is to be able to help firms decide what to do about it, before it is too late. One could argue that an important difference between Tushman and Anderson's (1988) view and that of Christensen and Bower (1996) lies in the causal explanation of incumbent firms' difficulty in embracing the new technology and the implications of the explanation for practice. For Tushman and Anderson it is the fact that the new technology requires a different set of competences to that possessed by incumbent firms. They blame organisational inertia on the apparent inability of such firms to acquire the needed capabilities. Christensen and Bower, however, offer examples of firms learning to cope with radical technology as long as there is clear interest on the part of their most important customers. If one's interest is to judge whether a specific technology were to become disruptive, then the different approaches would lead to very different constructs. Following Tushman and Anderson, one would look at the capabilities needed to develop, manufacture and market the new technology and compare them with those of the incumbents to determine if the technology was competence enhancing or competence destroying. Following Christensen's model, the key would be to look to the market and compare the performance attributes of the new technology with the present needs of key customers.

- What to do?

Within the innovation literature there appear to be four non-exclusive sets of ideas about what to do in the case of potential change. These appear to be: separate the organization into two parts, invest at the niche level for new technologies, develop a technology strategy which will guide investments and actions, and finally re-orient the innovation process itself.

1. Ambidextrous Organisation

The idea of separating the organization into two parts is best articulated in Tushman and O'Reilly's (1996) concept of the ambidextrous organisation which can make incremental improvements to existing technology for its most important customers and customer segments while also exploring revolutionary technologies in new and existing markets. Tushman and O'Reilly's focus is more on how to cope with the fact of disruptive change rather than the mechanics which cause it, and their ideas come from a series of case studies of firms which appear to have been successful in pursuing both aims simultaneously. At the heart of the ambidextrous concept is the idea that there are two, very different tasks facing management characterized by exploiting a firm's current resources and exploring new ones. Mirow et al. (2008) maintain that the concept goes back to March and Simon (1958). Benner and Tushman (2003) highlight some of the challenges that such an organization faces, while leadership is identified by several researchers as being critical to managing such an organization (Ben Mahmoud-Jovini et al., 2007; Jansen et al. 2008).

While there is a growing amount of empirical data based on different surveys to support the ambidextrous concept (He and Wong, 2004, Jensen et al 2006), Birkinshaw and Gibson (2004) challenge the idea that it is necessary to create autonomous units to achieve ambidexterity and that the right sort of individuals can, in fact, be ambidextrous in a single unit if they are sufficiently aligned with each other and focused on adaptation. For Birkinshaw and Gibson (2004) one must therefore distinguish between structural ambidexterity and contextual ambidexterity. An interesting point made by Jansen et al. (2008) is that at the senior management level there will have to be a management team acting in an ambidextrous manner even if there is structural ambidexterity below them, and that their success as a team is dependent on the degree of shared vision, social integration and contingent rewards across the management team.

1. Niche development and the multi-level perspective

Kemp et al. (1998) argues for strategic niche management in order to foster the replacement of current technology regimes, such as the internal combustion engine, by a more sustainable one based on fuel cells or electric vehicles. Key to the strategic niche concept is a deep understanding of all the barriers to such technology breaking through to the mainstream. For Kemp et al., the technology paradigm (Dosi, 1982) concept is incomplete because it does not take into account how changes in the economic and social environment impact on the research agenda of firms. Their definition, based on their analysis of the barriers mentioned above, is that a technology regime is “the whole complex of scientific knowledge, engineering practices, production process technologies, skills and procedures, and institutions and infrastructures that make up the totality of a technology” (Kemp et al., 1998, p. 182). One of the four common threads that Kemp et al. see in regime shifts is the importance of specialised applications where the technology is encouraged to flourish before its acceptance in the mainstream, and they cite Schot (1998), who has developed a list of such shifts which started in niche applications including radio, aircraft, computers and even clocks which were first developed for monasteries.

This thread of the literature is referred to as the multi-level perspective (Geels, 2002) and is based on the idea that firms exist in three nested levels defined as niches, socio technical regimes and a broader socio-technical landscape. Geels and Schot (2007) cite Berkhout et al. (2004) and Smith et al. (2005) as criticizing the perspective on the grounds that the three levels of analysis were hard to define empirically, that the perspective neglects agency theory, and that there was too much emphasis on niche markets as the source of novelty. On the first point Geels and Schot argue that the importance of the three levels is their nested characteristic and that researchers could, in fact, define the levels wherever they were the most useful. While the overall landscape remains the same, one could establish regimes at whatever level made the most sense and build niches within those regimes. The idea is to first establish the empirical level and then operationalize the multi-level perspective. On the second point, Geels and Schot make reference to DiMaggio and Powell’s (1983) *Organisational fields* idea and stress that both regime and niche level in the framework can be considered *organisational fields*, where all the actors involved in a technological application could be included in an analysis. The fundamental difference between regimes and niches is size and technological definition.

By invoking the *organisational fields* idea, Geels and Schot insist that agency is very much at the heart of the different actions by the actors at each level, and argue that the criticism has more to do with the misinterpretation of the diagrams used to explain the construct than its theoretical solidity. On the last issue of the perspective having a niche bias, Geels and Schot look to Suarez and Oliva's (2005) typology of environments as being applicable to the socio-technical landscapes discussed in the multi-level perspective. Van Driel and Schot (2005) had already defined three types of landscape changes but, by adapting Suarez and Oliva's typology, they are able to clearly define four paths of technological transition which deepen the multi-level Perspective and limit the observed niche bias.

3. Technology strategy

Ford (1988) defines technology strategy as "policies, plans, and procedures for acquiring knowledge and ability, managing that knowledge and ability within the company and exploiting them for profit" (Ford, 1988, p. 85), and there is a growing body of literature which looks at technology at either the corporate, or business unit level (Adler, 1989) and uses definitions similar to Ford's. Davenport et al. (2003), for example, use Soloman's (2001) definition of technology strategy: "Technology strategy encompasses the acquisition, management, and exploitation of technological knowledge and resources by the organization to achieve its business and technological goals" (Davenport et al., 2003, p. 483). The major distinction to Ford's definition is breaking down the activities of firms into acquisition, management and exploitation, as the literature dealing with technology strategy often focuses on one of these three aspects. Davenport el al, (2003) offer a long list of different ways of acquiring technology and references researchers who looked at different aspects such as in-house R&D, working with lead customers, and a large number of external sources and focused on networks and alliances as a particular area of interest for them. In terms of exploitation, their focus is on protecting competitive advantage and they cite three possible paths to do that including: the protection of intellectual property, achieving technological lock-in, and the idea of continuous innovation or staying ahead of the competition. What is less well developed is the idea of management which includes resource allocation and human resources management and "is inherently a part of the management of all of a firm's resources" (Davenport el al., 2003, p. 484). To this rather open-ended idea is added that of nurturing technological competences and capabilities.

There is a large body of literature which focuses on different aspects of a firm's technology strategy and all appear to take a relatively high-level view (Zahra, 1996; Zahra and Bogner, 2000;; Ryan, 1996; Hatfield et al., 2001). The contribution of such research is mainly to either develop generic technology strategies or list internal and external factors which technology strategies need to deal with, one of which is the degree of dynamism or technological uncertainty in the environment. Spital and Bickford (1992) built upon the elements of technology strategy put forward by Maidique and Patch (1978) and Burgelman and Rosenbloom (1989) to develop their own set of five aspects of a technology strategy including the selection of technologies, level of depth or competence in each one, the breadth or scope to be considered, sources of technological development and level of investment.

Zahra (1996) suggested that the technology strategy needs to be aligned with the firm's environment and put forward three environmental factors to look at including dynamism, hostility, and heterogeneity, and this idea is further developed in Zahra and Bogner (2000) in which dynamism is defined as the rate and level of continuity/discontinuity in the environment, while hostility or competitive intensity is separated into two categories of price on the one hand and service and quality on the other. For Zahra and Bogner (2000) a firm's technology strategy needs to be developed along five elements including its radicality, intensity of product upgrades, level of research and development spending, use of external sourcing and protection of intellectual property. Hatfield et al. (2001), in contrast, suggest that firms choose between four basic technology strategies which include waiting and entering at a later time, entering via joint venture or an alliance, seeking a leadership position by pursuing technological leadership, or hedging by investing in competing technologies simultaneously. Finally, Ryan (1996) offers a different set of choices framed as being first to market, second to market, pursuing cost leadership, or market segmentation developing different solutions for different segments. As can be seen in these examples, there are as many classifications of technology strategy as there are researchers and the term appears to be so widely used as to lose meaning.

Comment [A2]: please check - text states "four" but only lists three

4. Routines for discontinuous innovation

The fourth thread concerning what to do can be found in a series of research projects such as the Discontinuous Innovation Forum (Bessant and Tsekouras, 2001) which brought together 28 firms to develop exploratory case studies concerning how they were managing technological and market discontinuities, as well as others which included executive workshops and extensive interviews with practitioners. Phillips et al. (2006) gives partial findings of the first research project which highlights three aspects of dealing with discontinuous innovation beyond the normal best practice which is derived from the product development literature and also reviewed at length in Phillips et al. (2006). To summarize this thread in the literature, the researchers found three areas of critical import when dealing with discontinuous change: the need to look beyond a firm's existing technologies and markets in its scanning routines, a heightened importance of personal leadership first by project champions and most critically by Senior Management in obtaining resources for such projects, and finally the need to go outside an organization itself in order to bring such projects to fruition. This last theme can be done through different types of supplier relations which are further explored in Phillips et al. (2005) and in the development of networks (Birkinshaw et al., 2007, Bessant el at. 2008). Beyond these three specific areas, however, this thread indicates that, in order to be successful, firms must first recognize that discontinuities represent a special challenge, and that much of the improvement achieved by applying best practice to new product development has to be re-examined, and complementary or potentially incongruent practices adopted in order to be successful in discontinuous change.

- Gap in the innovation literature

Sub-section 2.3.1 has focused on the literature dealing with discontinuous, radical and disruptive innovation and found that, despite some differences in definitions and semantics, there is a clear consensus that profound change is part of the business landscape and dealing with it is of increasing interest to theory and practice. Much of the theoretical work is focused on understanding and classifying such change and less attention has been given to working out what to do in the face of discontinuous change which has the potential to cause disruption. The four threads identified which do deal with what to do are the idea of creating a separate unit to deal with such change, focus on niche markets, explicitly identify new technologies in an overarching technology strategy and in developing new routines to deal with disruptive innovation, including different ways of working with suppliers and even going beyond the supplier paradigm to create networks of firms which can work together to manage discontinuities.

Tidd et al. (1997) lay out a simplified five stage model of the innovation process which starts with scanning the environment, strategically selecting what to search for, resourcing a specific option, implementing its development, and finally reflecting and learning from experience. In discussing the research available on discontinuous innovation (DI), Phillips et al. (2006, p.193) write “Although there is growing research interest in the field, there is still relatively little guidance on the nature of generic routines for DI, nor how to configure them for particular circumstances”. In looking at the fourth stage of Tidd et al.’s (1997) model, implementation, there is even less research available. Implementation is the stage at which a firm has decided to do something and committed a certain amount of resources to the effort but still needs to develop specific programs to develop and introduce the technology to the market. Noke (2006) discusses only early prototyping (Mascitelli, 2000) as a specific routine or process for this phase, and Phillips et al. (2006) only identify working actively with users on co-evolution of innovation (Von Hippel, 1988; Prahalad, 2004) and building parallel resource networks (Leifer et al., 2000) in this area.

The thesis will address this gap by looking specifically at the issue of technology deployment, or the choice of where to introduce a new technology as part of the implementation phase in Tidd et al.’s (1997) model.

2.3.2 Disruptive technology in the automotive industry

The automotive industry has been the focus of intensive academic scrutiny for more than 50 years (Drucker, 1946) and has been a source for theoretical development and insights for practice in a number of areas including operations, new product development, and the relationship between vehicle manufacturers and their suppliers. *The Machine that Changed the World* by Womak et al. (1990) is widely considered the definitive text on lean manufacturing and overall, the industry has been a rich source of literature on operations. The literature concerning new product development has also used the industry as a context, and examples can be found in Beaume et al. (2009), Clark (1989), Clark and Fujimoto (1990,1991), Cosumano and Nobeoka (1992, 1997), and Kohn (2006). Other researchers including Kamath and Liker (1990), Lamming (1993), and Lettice et al. (2010) looked at supplier relationships.

- Systematic review

With respect to innovation, Fine and Raff (2001) classify management research in the industry into innovation dealing with product, process and organization.. The area of potentially disruptive or discontinuous innovation is however, less researched in the automotive context, although there is a growing body of knowledge dealing with different aspects of the potential for change in automotive power train technology. As discussed by Daneels (2004) and explored in depth in Sub-section 2.3.1, the terms technology and innovation are combined with the words discontinuous, disruptive and radical, with different and sometimes similar meanings in the literature. Thus a search was made combining these words with "automotive" using three different search engines; the results are shown in Table 2.3 and show that, while there are hundreds of papers dealing with innovation and technology, only 21 papers were found dealing with discontinuous/radical/disruptive technology/innovation, of which 6 are duplicates and 8 of 15 are directly concerned with alternative power trains.

Search string ("automotive" AND)	**ABI Proquest***	**EBSCO Business Source Premier****	**Science Direct*****
"technology"	1,266	1,802	63
"innovation"	280	398	28
"disruptive technology"	1	0	2
"disruptive innovation"	2	1	0
"discontinuous technology"	0	0	0
"discontinuous innovation"	0	2	0
"radical technology"	0	0	1
"radical innovation"	5	7	0

* Scholarly journals; citation & abstract
** Peer review; all fields
*** Journal articles; business and management; abstract, title, and key words

Table 2.3 Automotive search string results

Author (s)	Year	Context
Aggeri et al.	2009	EV's
Griffa	2008	Sensors
Barkenbus	2009	EV's
Vojak and Chambers	2004	Technology roadmapping
Ebrahimi and Holford	2009	Honda
Van den Hoed	2005	FCV's
Van den Hoed and Vergrat	2005	FCV's
Ben Mahmoud-Jovini and Caruc-Dubol	2008	Power train innovation in supplier
Beaume and Midler	2009	EV's
Canzler and Knie	2009	EV's and FCV's in China
Howell	2003	General Motors R&D
Chanaron	1998	EV's
Tan and Perrons	2009	Toyota and globalization
Story et al.	2008	FCV's
Stevens and Swogger	2009	Dow Chemical

Table 2.4 Results of key word search in automotive literature

Table 2.4 shows the 15 papers found which served as a starting point for an updated review of the literature dealing with the potential changes in automotive power train technology. What the bibliographic analysis shows is that there is a growing body of work in this area, and also that power train technology appears to be a relevant choice for studying potentially disruptive technology in automotive. Another possible choice could have been automotive telematics which Lenfle (2008) describes as being extremely innovative as neither technology or customer needs are fully understood at this time but do not appear to offer the same potential for disruption as power train technology and was not found during the systematic literature review shown in Table 2.3 and Table 2.4.

Expanding on the initial papers identified above, the review identified a total of 29 articles. Although a technology-oriented typology was considered which would look for articles focused on battery electric vehicles, hybrid vehicles, fuel cell vehicles, etc., it was felt that organizing the review using a topical typology would provide more insight and this typology is shown below and developed in Table 2.5.

Papers were grouped around the main purpose or theme of the paper as follows:

- History / Current Status
- In-Depth Modelling
- Technical Performance
- Supplier Involvement
- Clearly Favourable
- Clearly Sceptical

Topic	Focus	Papers reviewed
History / Current Status	Reviews history or current status of alternative technology vehicles	o Ahman, 2006 o Collantes & Sperling 2008 o Coup 1999 o Frenken et al., 2004 o Harborne et al., 2007 o Kemp et al, 1998 o Mikkola, 2001 o Schot et al., 1994 o Steinemann, 1999 o Van den Hoed, 2005, 2007
In-Depth Modelling	Uses advanced mathematical models to predict economic and environmental impact of the adoption of alternative technology vehicles	o Crabb and Johnson, 2010 o Karplus et al., 2009 o Kosugi et al., 2005 o Schwoon, 2006 o Struben and Sterman (2008)
Technical Performance	Looks at performance characteristics of competing technologies	o Weis et al. 2003
Supplier Involvement	Explores supplier involvement in alternative technology vehicles	o McGrath, 1999 o Story et al. 2008 o Williander, 2006
Clearly Favourable	Endeavours to demonstrate the benefits of making a transition to alternative technology vehicles often arguing for one or another of the potential technologies.	o Avadikyan and Llerena, 2010 o Barkenbus, 2009 o Canzler and Knie, 2009 o Fournier, 2009 o Hekkert and v.d. Hoed, 2004 o Johnston et al., 2005 o Suurs et al. 2010 o Zapata and Nieuwenhuis, 2010
Clearly Sceptical	Articulates rationale against the transition	o Carle et al., 2005 o Seidel et al., 2005

Table 2.5 Typology of papers dealing with alternative power train technology

What is striking about the literature found is that there appears to be no literature discussing what the vehicle manufacturers ought to be doing about the technology in terms of concrete recommendations based on sound academic theory. This gap reinforces that found in Sub-section 2.3.1 in which studies looking *ex ante* at potentially disruptive technologies are very rare and, while a number of studies refer to what different vehicle manufacturers are doing, they tend to fall into the typology shown in Table 2.5 and not deal explicitly with the heterogeneity of response by different manufactures in an attempt to inform practice and build theory in support of that recommendation. The following will describe the literature using the typology and then return to this apparent gap.

- History / Current Status

What is common in the papers classified in this category is that they attempt to summarize either what has happened or is happening in the area of alternative power train technologies and make an effort to remain neutral in terms of what is likely to happen. As part of the International Motor Vehicle Program, Steinemann (1999) described the state of fuel cell technology for automotive applications looking at the vehicle manufactures research and development approaches; the technical characteristics of fuel cells and their advantages and disadvantages, the history of fuel cell technology; early adopters such as Ballard and its eventual partners Daimler-Benz, and Ford, later entrants such as Toyota, General Motors, and Honda; patent counts by company; supply chain issues; and the challenges for the technology looking ahead. For Steinemann, the central challenge of the technology for the automotive industry is that the “The core knowledge required for the development of fuel cells is grounded in the electrochemistry of hydrogen and the electrocatalysis of hydrocarbon fuels, representing science that is fundamentally different from the experience acquired over decades of intensive research and development on internal combustion engines” (Steinemann, 1999, p.24). Steinemann’s work is frequently cited in the fuel cell literature and, in fact, his list of advantages and disadvantages is more or less repeated in most studies concerned with fuel cells.

Collantes and Sperling (2008), for example, perform a detailed stakeholder analysis and use it to document the emergence of the zero emission vehicle mandate imposed by CARB in 1990 and make the point that the mandate was driven by a desire to reduce pollution and not to reduce oil consumption or greenhouse gas emissions. Ahman (2006) takes a systems approach to look at the evolution of policy in Japan and is useful in developing a non-market context with which to better understand Coup’s (1999) account of Toyota’s commitment to alternative technology vehicles which in his view, was focused on the three goals of reducing pollution, the use of imported oil and greenhouse gases. Schot et al. (1994), contrasts the evolution of the California legislation with that of the Netherlands in support of natural gas as an automotive fuel, while Kemp et al. used a similar approach to look at the importance of developing electric vehicles in niche applications. Suurs et al. (2010) looked at the Netherlands case 16 years later and the clear conclusion that can be drawn from this thread is the critical role that government policy and intervention has in stimulating the investment in alternative power train technology. A similar point is made by Harborne et al. (2007) in their survey of the development of fuel cell buses which currently require pro-active government support due to the very high cost disadvantage that the buses have compared with conventional buses.

Mikkola (2001) also looks deeply at cost in its portfolio analysis of competing battery technologies for battery electric and hybrid vehicles. The portfolio analysis technique plots the different technologies on a two by two grid which considers competitive advantage and benefit to customer, and the fundamental issue for Mikkola is the life cycle cost of batteries as well as other issues such as energy density, re-charging infrastructure, re-charge compatibility, and the difficulty in predicting how customers will react.

Van den Hoed (2005) looks at patent counts for different vehicle manufacturers for battery electric, hybrid electric, and fuel cell electric vehicles over time and shows how hybrids and fuel cells displaced battery electric as the favoured option of the industry. Van den Hoed argues that there is simply too much effort going into fuel cells to dismiss it as "window dressing" but that fuel cell "optimists" are probably also overstating the readiness of the technology for the market. Frenken et al. (2004) looked at cumulative patents in the industry and measured the entropy of the patenting activity in order to determine the degree to which the industry had locked in on a dominant design. The concern expressed by the authors was that suboptimal lock-in could occur for non-technical and non-market reasons, and the study appears to find that the industry is still in the process of trying out new approaches and that lock-in has not yet occurred. Van den Hoed (2007) confirms Frenken et al.'s assertion that the preferred alternative to the internal combustion engine is not yet clear and again uses patent counts as proof that the emphasis has gone back and forth between the competing technologies. Van den Hoed also identifies five change factors that in his view have been driving the evolution of these technologies including new entrants such as Ballard in fuel cells, external shocks such as the ZEV mandate, the performance of the different technologies, market changes, and industry competition. What van den Hoed or the other researchers in this category do not do is try to forecast the future technologies.

- In-Depth Modelling

Studies which do attempt to look ahead use modelling techniques to explore different aspects of the potential such as technical performance of the different alternative technologies, government and fiscal policy, and consumer response. Crabb and Johnson (2010) develop a positive correlation between the rise in fuel prices and patenting activity by the vehicle manufacturers in what they call automotive energy efficient patents in which is included both improvements to internal combustion engine technology as well as its alternatives. Karplus et al. (2009), on the other hand, use the Massachusetts Institute of Technology's econometric model, EPPA, to look at the potential of plug-in hybrid technology in the United States in contrast with second generation biofuels, and finds that in all scenarios the largest impact on hybrid adoption will be seen if and only if the country adopts a nationwide limit on CO2 emissions. In their study, this factor has a much larger impact than other parameters such as gasoline and electricity cost, vehicle mark-up, hybrid usage factor, and even the availability of competitive, carbon neutral biofuels. Kosugi et al. (2005) assumed that Japan would impose this type of countrywide CO2 limit and found that, in that scenario, fuel cell vehicles would enjoy the highest economic investment of the different automotive technologies. Schwoon (2006) also found that government policy was the major driver for a change to fuel cell vehicles finding that tax incentives would drive faster penetration of the technology than massive infrastructure projects.

Struben and Sterman (2008) developed a behavioural, dynamic model to explore diffusion rates of the different alternative vehicle technologies and introduced the concept of willingness to consider as the key driver of such diffusion. In their model it will take anywhere from 20 to 50 years for consumers to consider alternatives to the internal combustion engine depending on issues such as technical parity, vehicle life and the critical importance of word-of-mouth communication.

- Supplier Involvement

A separate thread of research in the area of alternative technology vehicles has to do with the supply chain implications and particularly the potentially unique implications that the new technologies have for classic supplier relationships in the automotive industry. As discussed, much work has been done on supplier relationships and the basic question is what is different in the case of battery electric, hybrids and fuel cell technology. McGrath (1999) looks at the level of battery suppliers and uses morphological analysis to conclude that incumbent firms had overwhelmingly supported incremental innovation as opposed to more radical innovation in battery chemistry during the 1990s. Williander (2006) and Story et al. (2008) both make the point that broader networks are required to enable profound technological change than traditional OEM-supplier relationships and that only by involving additional actors such as government, infrastructure and fuel providers, etc., in focused efforts can such change be achieved.

- Technical Performance

Due to the fact that the systematic review was confined to management literature, papers dealing with purely technical issues were not identified, although there is a vast literature dealing with the performance and cost trade-offs associated with the different alternatives to internal combustion engines as well as deeper studies looking at variants within each alternative as well as the very large field of advanced diesel and gasoline engines. As these studies are often referenced by the other papers discussed in this review; Weis et al. (2003) was included as an example. The paper is an update to an earlier study by the same authors and looks at hybrid electric, fuel cell vehicles, natural gas vehicles and internal combustion engine vehicles in terms of current technology and the authors' best estimates of where the technology will be in ten years' time. This study, like all such studies, makes assumptions about the evolution of the different technologies as well as exogenous factors such as fuel prices, and attempts to construct what is called a well-to-wheel analysis in order to take into account all aspects of the production and supply of fuel and the vehicles themselves in addition to usage in order to measure the impact of each technology on greenhouse gas emissions. Based on their assumptions, Weis et al. (2003) find that fuel cells and advanced internal combustion will have similar greenhouse gas emissions mainly because of the assumption, common in the literature, that the hydrogen for fuel cells will be produced by reforming natural gas at filling stations and that the resulting carbon will not be sequestered. Weis et al. did find that hybrid vehicles have the potential to lower emissions of greenhouse gasses by 37-62% over the next 20 years but these figures are highly sensitive to their assumptions about the source of electricity production.

Studies such as that by Weis et al. (2003) illustrate that the debate about the benefits of the different technologies in environmental and economic terms are highly sensitive to assumptions about the rate of technological development and the source of different fuels and energy sources. In clearer language, it appears that one can find evidence supporting different points of view within the technical literature due to the uncertain nature of the technological developments and exogenous factors which will determine the actual merit of the different technologies.

- Clearly Favourable

Building on the point mentioned above, there appears to be a large body of literature which is clearly favourable to one or other of the alternatives to the internal combustion engine. Avadikyan and Llerena (2010) applied a real options approach to hybrid vehicles from the vehicle manufacturer's perspective. Taking into account that adoption will depend on the price premium with respect to internal combustion technology, fuel efficiency when corrected for the usage factor, and the short and long-term competitiveness of hybrid technology with advanced diesel engines and battery electric vehicles, they uncovered four possible justifications for investment in the technology despite the uncertainties. For Avadikyan and Llerena, vehicle manufacturers should invest in hybrid vehicles in parallel with their continuing investment in internal combustion engine technology in order to hedge against long-term risks, limit such risks by acting sequentially, invest in hybrid technology in order to diversify their technical asset base, or develop vehicle platforms with built-in flexibility.

Several studies go further than Avadikyan and Llerena, which at least attempts to argue rationally in favour of investments in hybrid vehicles and presents the transition to alternative technology vehicles as a *fait accompli*, an imperative or both. Barkenbus (2009) for example, starts with the assertion that "a transition to electric vehicles is underway" and that the transition is "inevitable" (p. 399). The paper provides a solid review of development in hybrid vehicles and the CO2 savings offered by electric vehicles in general and also lists potential developments such as neighbourhood electric vehicles, the possibility of low-priced Chinese and Indian imports and the Better Place experiments in Israel and Denmark as evidence of the transition. Canzler and Knie (2009) offer an equally unambiguous assessment asserting that the "era of cheap oil is over" (p. 892) and list a number of initiatives in China which in their view indicate that China will leapfrog the internal combustion engine and build a hydrogen infrastructure. Fournier (2009) takes a similar tone maintaining that the status quo "cannot continue" (p. 75) and, after reviewing different estimates which indicate that there might be as many as 2 billion cars on the road by 2050, argue that the only solution is second generation biofuels. Johnston et al. state that "pollution is threatening life on earth" (p. 569) and come to the conclusion that hydrogen offers the most commercially viable option after looking at both advantages and challenges as well as reviewing progress being made in Iceland, Canada, California, Japan and Germany.

What these studies have in common is the adoption of what Lomborg (2001) refers to as the litany or accepted vision of a world in serious ecological trouble which he maintains is not consistent with a broad view of the scientific evidence. One problem with these papers is that they accept this vision of the world without any apparent objectivity or balance. The ideas that we are running out of oil or that climate change will endanger life on earth are quite popular but in the first place are not necessarily proven and even if one does accept that climate change is a fact it is not at all clear that the governments around the world or even in the west will take the political action required to stop it. The other problem with these studies is that they tend to favour one of the competing technological options stressing its advantages and contrasting them with the disadvantages of others without necessarily presenting a balanced view.

Hekkert and Van den Hoed (2004) present a somewhat more rigorous look at hybrid vehicles and fuel cells using Jacobson and Johnson's (2000) technology systems framework to look at different vehicle power trains, and show how the implementation of hybrid technology requires substantially less disruption to the different forces making up the technology systems of conventional internal combustion engines than fuel cell electric vehicles; thus explaining their later success. Zapata and Nieuwenhuis also classify the Toyota Prius as incremental as they do Brazil's development of Ethanol as an automotive fuel and consider fuel cells to be a radical innovation accepting Daneels' (2004) assertion that disruption can only be discussed *ex post*.

- Clearly Sceptical

In contrast to the clearly positive papers, there are others which argue against the adoption of alternative fuel vehicles. Cable et al. (2005) apply Porter's (1980) five forces model to fuel cell vehicles and come to the conclusion that the cost of the technology is simply too high. Seidel (2005) takes a similar view and adds the relatively short system life of current generation fuel cell stacks and the lack of infrastructure as reasons why the technology will not make it. These studies come across as mirror images of the favourable studies, and what is striking is the apparent lack of true debate on the assumptions, technological and social trends, and competitive dynamics that will actually affect the evolution of the different alternatives in both of these groups of papers.

- Gap in the automotive literature

This review has endeavoured to look at the literature concerning the automotive industry which deals with discontinuous, radical, or disruptive change as opposed to more well-researched areas such as operations, new product development and supplier management which are well covered by management research. What was found was a limited but growing body of literature specifically dealing with the potential transition in power train technology away from the internal combustion engine running on petroleum distillates to alternative fuels and what are often called alternative technology vehicles mainly concerning battery electric vehicles, hybrid vehicles, plug-in hybrids and fuel cell vehicles.

This literature was reviewed and a typology presented of it grouping papers into those dealing with in historical analysis, in-depth modelling, technical performance, supplier involvement, and almost partisan research which appears to take an either favourable or sceptical view of the transition. What was not found in the literature were studies which attempted to look deeply at the heterogeneity of response by the different vehicle manufacturers in terms of technological deployment or which were focused on the larger issue of what strategic alternatives can be found for vehicle manufacturers when looking *ex ante* at potentially disruptive technology. Van den Hoed's assertion that the fact that several manufacturers are making significant efforts proves they are serious about fuel cells appears disingenuous given the relative size of these overall development activities of the companies involved and does not explain why some manufactures made significantly more efforts than others.

2.3.3 The technology-based firm

A relatively recent thread in the innovation literature looks at how there appears to be a connection between a firm's technological position and the degree of diversification it has across product groups and geographies (Granstrand et al. 1997, Gambardella and Torrisi 1998, Suzuki and Kodama 2004, Brusoni et al. 2005). A firm's technological position is often actually broader than the products and services it actually offers (Granstrand et al. 1997) and is not necessarily reduced by its decision to outsource production of key components (Prencipe, 2000).

In related work, Granstrand (1998) puts forward the theory of the technology-based firm in which technology and technological change have a substantial impact on a firm and in which its asset base (both tangible and intangible) is heavily dependent on technology. Building on Granstrand and Sjölander (1990), Granstrand reviews the way other theories of the firm have dealt with the role of technology and management and finds that they do not sufficiently explain the co-evolutionary nature of technological development and diversification in modern multinational and multiproduct firms. He rejects neo-classical economics because it limits technology to a factor input and, as a part of the mechanistic production function, loses the full scope of how technology can affect a firm's position and its evolutionary nature. For Granstrand, agency theory considers technology as just another source of asymmetries rather than a protagonist. He feels that the evolutionary perspective as espoused by Nelson and Winter (1977) places technology in the role of "randomiser" or "variety generator", thus losing the critical role of management in shaping its direction. In terms of the resource-based view, Granstrand did not review the dynamic capabilities framework (Teece et al. 1997) discussed above but felt that the resource-based view sees both technology and management as a particular competence without treating them in any special way.

For Granstrand, technology and management are the key resources around which technology-based firms are built, and thus the central aspect of his theory of the firm. Granstrand highlights the importance of management in the technology-based firm and says that it must exploit four types of economies that are inherent in technological capabilities: scale, scope, time and space. What he does not do, however, is go into what he refers to as the "big dark box" of practice (p. 486) nor does he try to unpack the processes that go into managing such firms beyond the four aspects mentioned above. Granstrand, for example, offers an explanation for one process of diversification which he calls "first pull then push". The idea is that customer requirements and/or technological innovation stimulate a firm to incorporate new technology into one of its products or services. Later, as the firm acquires competence in the new technology, it might find opportunities to use it in new areas; this results in technology-led product diversification. Here again, he does not explain how managers ought to do this.

The theory of the technology-based firm is compelling as far as it goes but falls short of laying out a framework which can assist in working out the most appropriate response to discontinuous and potentially disruptive technology. As the theory does acknowledge the co-evolutionary nature of firms' actions and a technology's developments it would appear that codifying the set of available responses would be of great value and the thesis endeavours to begin to address this gap.

2.3.4 Conclusions

This section has shown that there is an important gap in the literature in looking at how firms deploy technology which is recognized as discontinuous and potentially disruptive, but which has not yet demonstrated that potential. This can be seen in both the innovation literature and that dealing with the automotive industry and potential changes to power train technology in the years ahead.

Sub-section 2.3.1 reviewed the innovation literature dealing with discontinuity and disruption by discussing several of the different definitions in use, explored two major threads in the literature and the relatively limited amount of literature which examines what companies ought to do in the face of such change, and showed that Tidd et al.'s fourth phase in their simplified process of implementation receives even less coverage. Sub-section 2.3.2 looked at the literature concerned with the transition to alternatives to the internal combustion engine in the automotive industry and developed a typology for that literature which demonstrated that there was very little research done concerning the heterogeneity of response by the different vehicle manufacturers in terms of technological deployment. Finally the thesis reviewed Granstrand's (1998) concept of the technology-based firm and suggests that it could be expanded upon to fill this gap.

2.4 The use of patents in management science

Management researchers interested in the way that firms bring new technologies to market have often come up against a number of problems in obtaining reliable empirical data from the firms they are studying.

Often detailed data on projects, budgets, achievements, etc., are scattered across firms and difficult to assemble in one place. Other problems have to do with access, since much of a firms' competitive advantage is often linked to its technological edge and many firms are reluctant to share such data (if they actually had it in the first place) with outsiders. A third set of problems is the sheer volume of information that one would need in order to do any kind of industry-level analysis if it was required to go into each firm's detailed technological activities.

For these reasons a number of researchers have turned to patent data as a surrogate source of information from which a number of indications about technological activity can be drawn. Such use of patents dates back to Schmookler (1953), and, over the last 50 years, a number of researchers have taken advantage of patents for a broad range of theory-building work.

This section will develop a brief history of the use of patents in management research, discuss the reasons for using patents as well as their limitations, and review part of the extensive literature available with the goal of developing a typology of the use of patents in management science and informing the methodology of the thesis.

2.4.1 A History of Using Patents in Management Research

Understanding a firm's technological developments by looking at its pattern of patents is well established in the literature and has been done since the 1960's (Shmookler, 1966; Pavitt, 1982). Basberg (1987) refers to Schmookler as the Father of modern patent research, and explains how he used patents to argue that inventive activity is endogenously determined by economic variables such as economic growth. Griliches (1990) believes him to be the first researcher to try to link productivity growth to innovative activity by using patents. Unfortunately, with the limitations he faced, Schmookler was not able to prove the link.

Comment [A3]: please check – it seems that this should read "understanding" but "understating" may be your intention..?

In Griliches' view, Schmookler`s work was limited by the lack of data on R&D expenditures back in the 50's and 60's and that, over time, Schmookler narrowed his view of inventive activity excluding both research and development and focusing only on the application of technology. In this view, patents became an input indicator of innovation rather than an output indicator but even that assertion, according to Griliches, was of paramount importance.

Another thread of this early work was done by economists who were dealing with Schumpeter's (1961) assertion that large firms would do more research and development (R&D) than smaller firms and thus would come to dominate specific markets. Scherer (1965) in fact found a reverse correlation between firm size and patents produced and concluded that Schumpeter's assertion was invalid.

Soete (1978) found that, in some industries such as office equipment, chemicals, and personal products, Schumpeter's assertion was valid while in others it was not and in still others the data did not indicate either way. Part of his argument was that earlier studies including Scherer's were deeply flawed by relying on available data and using sales as a measure of size. In his view the total number of employees was a better metric of firm size, and R&D spending, as measured by Business Week, was a better measure of innovative activity.

Pavitt (1982) compared patent statistics with even more robust research and development spending statistics and found that patents do "underestimate innovative activity in large firms, and that R&D statistics do so in small firms" (p.33). He put forward four factors that explain the differences, including innovative behaviour, different degrees of specialisation, and variations across sectors and institutional factors in particular cases such as aerospace and defence. Perhaps the most important contribution of Pavitt is to correctly point out that patents only show one aspect of the larger innovative process, and, citing Schumpeter, he distinguished between innovation and invention. Patents are, in Pavitt's terms, only one way to protect innovations and obtain better rents from them but there are others such as keeping industrial secrets, leveraging market strength, imposing standards, or building on technological leadership and leaving competitors behind.

Scherer (1983) went deeper into the relationship between R&D spending and patenting and explored the concept of propensity to patent by looking for differences in the relationship across industry groups. He first established eight industry groups and then attempted regression analysis in 124 different industry categories seeking a clear relationship. Scherer not only confirms the relationship between overall spending and patent output but determines that the relationship or number of patents per million dollars of R&D spending is, in fact, fairly constant within a specific industry.

Griliches (1990) provides a fairly comprehensive review of the patent work done up to 1990 and uses the Knowledge Production Function, first introduced by Griliches and Pakes (1984), to classify the different research themes then going on in different parts of the academic world.

The Knowledge Production Function focuses on the net accretion of economically valuable knowledge or innovative output, and constructs a highly simplified model to explain what kind of inputs go into it and what kind of outputs come out. Essentially, R&D efforts drive the creation of such knowledge although there is a term to include other sources of innovation. Knowledge creation drives patent application and grants, with another term to provide for other sources of patentable ideas. Such accumulation of knowledge should then produce a set of outcomes such as growth, productivity, market capitalisation, etc. These in turn are affected by the accumulation of knowledge as well as other factors which Griliches and Pakes divide into measurable variables and random variables. What Griliches does in his survey is to classify the different streams of research into the different relationships between these variables. In this way he captures, for example, the work mentioned above in linking R&D expenditure to patent counts as well as other streams linking patents to different outcomes such as productivity growth, market capitalisation, etc.

For Griliches, patent research has been pursuing the "dream of getting hold of an output indicator of innovative activity" since the 1950's and goes back and forth across two questions: what aspects of economic activity do patents measure, and what would we like them to measure?

After a comprehensive review of dozens of papers, Griliches arrives at five conclusions. First, he felt that the larger issues of whether patents are an input or an output indicator and their link to the larger questions of productivity and economic growth were still open at the time of his writing. Second, he found a strong relationship between patents and R&D spending when done at the "cross-sectional" dimension or industry or cluster of industries level. Third, the propensity to patent is similar within an industry for firms of significant size. Fourth, the idea that smaller firms patent more is, in Griliches' view, a methodological artefact and he believes this question is, at best, still open. Finally Griliches concluded that time series of analysis at the firm level have not demonstrated consistent results and he feels there is too much noise in the data for meaningful conclusions.

Griliches concludes that "in the absence of detailed R&D data, the much more plentiful patent data can be used as an indicator of both input and output" and that "nothing else even comes close" (Griliches, 1990, p.1702) for the purposes of analysing technical change. At the same time he maintains that only in large numbers can they really say anything at all since each one is so different from the rest.

2.4.2 Advantages and limitations in the use of patents

In many ways, patents are used in researching innovation simply because many researchers agree with Griliches' assessment (Schiffel and Kitti 1978, Soete, 1987, Pavitt, 1984). These and other researchers discuss five reasons to use patents to inform management research. In the first place, patents are thought to be one of the best tools available to researchers considering the barriers to access, confidentiality and other methodological problems when trying to research in-depth the way companies bring out new technology (Pavitt 1982, 1988, Ernst, 1998). Second, patents offer a huge amount of rich data and allow for analysis by country, industry, company, technology, etc. They are also ubiquitous as they are used in most parts of the world. Third, the availability and the richness of patent data have increased remarkably with the advent of digital databases and powerful software. Trippe (2002) coined the term "patent informatics" to describe a whole set of methodologies and capabilities which the new digital databases and computer algorithms allow. The fourth reason to use patents is that they have a degree of both official validity and commercial value. While patent offices differ in different countries, at least there is a theoretically independent and objective assessment of each and every patent, and many researchers have cited patenting costs and renewal rates as a metric of their economic value. (Griliches, 1990) The fifth major advantage is that, while one could argue with what types of control variables are needed, there is a clear link between patent activities and innovation since one simply cannot win patents without some innovative idea.

In the literature there are three problems or problem areas stated again and again (Schiffel and Kitti 1978, Soete, 1987, Pavitt, 1985, Griliches, 1990).

The first problem is that not all inventions are patentable and much gets left out. The second issue is that not all inventions are patented, and propensity to patent varies by sector, company and even country and culture. Propensity to patent tries to get at how much of a firm's inventive activity is actually patented, and most findings correlate well at the industry level since, in a given sector, other sources of protecting rents vis-à-vis patents are often similar. Automotive, for example, is normally found to have a low propensity to patent (Arundel and Kabla, 1998). The third group of problems is that patents differ in "quality", meaning that they cover different aspects of innovative activity, have different value and are done in different legal systems with varying grant rates in each country.

2.4.3 Fifty years of research policy

A search on any of the most popular academic search sites for "patents" in title and abstract will produce literally thousands of papers. Starting with the most heavily cited works using patents, the journals in which those papers had appeared were looked at to understand the relative weight of each journal in the overall body of literature. Table 2.6 gives the results of this analysis and gives the total number of papers with patents in title and abstract in World Patent Information, Research Policy, Technovation, and the European Economic Review.

Journal Title (Search Engine)	**Nº Papers**
World Patent Information (Science Direct)	1,923
Research Policy (Science Direct)	237
Technovation (Science Direct)	74
European Economic Review (ABI Pro-Quest)	19

Table 2.6 Papers with "patents" in title, abstract and key words in leading journals

While having the largest number of papers, *World Patent Information* has as its primary focus "to provide a worldwide forum for the exchange of information between people working professionally in the field of Industrial Property information and documentation and to promote the widest possible use of the associated literature". It is not focused on management research using patents but on the patent system itself.

Research Policy is "a multi-disciplinary journal devoted to the policy and management problems posed by innovation, R&D, technology and science, and related activities concerned with the acquisition of knowledge (learning) and its exploitation" and it was thought that papers in it would be more directly linked to management science. In addition to the number of papers and focus discussed above, *Research Policy* has published many of the seminal papers in this field and was edited for many years by one of its most prolific and important researchers.

Research Policy is also considered by most leading academics in the field to be the leading journal, and the late Keith Pavitt as one of the strongest researchers whose multiyear partnership with Parimal Patel produced some of the cornerstones of the field. According to Meyers et al. (2004), Pavitt was "both a shaper of, and a bridge between, science and technology policy and bibliometric analysis."

Using Science Direct and searching in Research Policy, a search was conducted for papers using the word "patents" in title, abstract and keywords. The result gave 237 hits on June 22 2008. Another search engine, Pro-Quest, only found 211 since it only goes back as far as 1981. These positive hits were then sorted into four categories including: papers using patents to inform management science, papers with only tangential use of patents or primarily about public policy or university management, papers about patents themselves or the patent system, and references which were in fact not papers at all.

Classification of papers	**Nº Papers**
Papers using patents to inform management science	134
Tangential use / public policy or university management	50
About patents themselves or the patent system	48
Not papers	5
Total	237

Table 2.7 Papers with "patents" in title, abstract and key words in Research Policy

The 5 items which were not papers turned out to be a book review, an erratum, a letter, and two references which did appear in Research Policy. The other two categories were taken out of the review in order to focus on how management researchers use patents to inform management science echoing Griliches' (1990) review. The resulting list of 134 papers using patents was then compared to the 92 papers that had been found in an initial visual inspection of the Journal's table of contents, and 3 papers which had not come up using Science Direct (Pavitt and Patel, 1984, 1987; Prencipe, 1997) were then added to the sample. The results were a total of 137 papers. These papers were then classified by citation count, again using Science Direct. While one can argue whether Science Direct is complete, it does at least account well for references from *Research Policy* and *Technovation* and, since the same search engine was used for all papers, it gave a consistent reference point.

2.4.4 A typology of uses of patents

In the papers examined, researchers chose to look at different units of analysis. A typology was thus created in order to classify the patents in terms of the scope of the research's analysis as shown in Table 2.8 Within the sample of 137 papers, it was possible to classify 134 using the typology as 3 were literature reviews or otherwise did not fit into the typology. Table 2.8 also shows how the level of analysis has changed over the last fifty years and this phenomenon will be discussed in the next section which goes through the review in each of the categories outlined below.

	Global	**Country**	**Regional**	**Industry**	**Firm**	**Technology**	**Product**	**Inventor**
1970's	1	1	0	1	0	0	0	0
1980's	6	3	0	5	1	1	0	3
1990's	6	0	2	7	8	3	2	3
2000's	13	4	8	4	28	8	0	16
Total	26	8	10	17	37	12	2	22

Table 2.8 Time Series of Papers using patents by category

2.4.5 Review of papers using the scope of analysis typography

In the 1960's, patents were used mainly to look at global comparisons and perhaps the national or industry level of analysis. In the last 10 years or so there has been a sharp increase in work done at the firm and technology level, and in just the last few years there have been a number of very insightful papers focused at the inventor level. Over time, it appears that the databases and tools have improved and researchers have thus been able to use patents to inform issues concerned with increasingly finer levels of analysis, resulting in more papers than ever before concerned with looking deeper into issues at the firm level and looking at the inventor level, for example, during the last 8 years. What follows are examples of some of the earliest and most frequently cited papers in the review organised by the typology introduced above. A full listing of the papers included in the review and the number of citations each one received using Science Direct is included in Appendix A.

- Global level

In this typology, the global level is the research that compares the amount and quality of innovation in different countries and regions. An early example of this kind of research was done by Schiffel and Kitti (1978) who examined the apparent rise in foreign patenting in the Unites States looking at 8 countries over the time period 1963-1974. They concluded that there was a higher amount of innovation going on in general and that these trends explained the increase rather than a loss of competitiveness in the U.S. Schiffel and Kitti decided to focus on patents awarded to foreign firms in the U.S. as a way to get around the inherent variability of the different patent laws and rigor in different countries and proved the reliability of patents as an output indicator by finding a remarkably robust correlation with R&D spending at the aggregate, country level.

This idea of using U.S. patent data by other countries has been used by many researchers over the years (Soete, 1987; Tong and Frame, 1994; Furman et al., 2002) because of the reliability and stability of the U.S. patent office, the quality and depth of the data it provides, and the idea that firms will take the trouble to patent in the U.S. whenever the idea or invention is important enough.

In 1987 different papers published by Soete, Patel and Pavitt, and Fagerberg stand out as representing different streams of research looking at comparisons across different countries and regions and using patents as a primary source of data.

Soete (1987) was interested in explaining trade patterns and sought empirical evidence to prove that Factor Production Theory was inadequate. He was looking for an output indicator of technological innovation which he could then use to examine the link between technological innovation and national competitiveness. One of Soete's findings was that smaller countries seem to have a stronger technological output in terms of patents than larger countries. This idea is that it is similar to findings by Scherer (1983) when comparing firms. Soete's correlations get weaker when he drops down to the industry level and, while he does find a "close relationship" between technological performance and export performance for many industries, he also demonstrates that more data is needed.

Examples of Soete's mixed data include his findings on the aircraft industry and also on motorcycles and bicycles. He shows that while the United States has a very robust aircraft export sector, its technological position in aircraft is not so strong. Germany suffers from the opposite situation with a relatively strong situation in aircraft patents and not much of an export business. The U.K. had a more balanced situation with a significant technological position and strong exports in aircraft. In motorcycles and bicycles Japan had a low technological position but a thriving export sector, while the UK, Germany and France all had strong technological positions and relatively weak exports.

What Soete was using to determine a country's technological position was what he called "Revealed Technological Advantage" (RTA), defined as a particular country's share of the total U.S. patents in a given sector with the country's total share of U.S. patents. Thus, if a country had a higher share in a particular sector than their average share across all sectors, it would indicate some degree of technical specialisation.

Patel and Pavitt (1987) were trying to answer the question of whether Europe was falling behind Japan and the U.S. in the race for developing new technology, and used patents as one of a number of indicators including R&D expenditures. They also used Soete's RTA but did so using a more robust data set and at the aggregate level of Europe rather than at the country level, and also over three different time periods. What they found was that the data was stable over time and that, overall, Japan was more specialised. While their overall finding that Europe was not behind (or least not too far) is interesting, what was perhaps more striking was that they considered R&D spending and patents as indicators of innovative activity in its broadest sense and that "Their attribution to any one part of the process has no empirical foundation, nor has the assumption that patents are an intermediate "output" of R&D activities" (p. 62).

Fagerberg (1987) looked at data from 25 countries in his attempt to show that economic variables such as GDP per capita correlated with technological measures such as R&D spending or patent counts. As in the other papers discussed, the purpose of this global level research is to explain broad economic theory and properly account for innovation. The role of patents is generally as an output measure for that innovation. Over the next few years other authors pursued work in a similar direction including the following:

Archibugi and Pianta (1992) did a study with similar goals to Soete's and confirmed his assertion that smaller countries specialised more. One contribution of Archibugi and Pianta was to go a bit deeper into the "black box" and use the front page citations, done by the patent office, to add a quality or value factor to the analysis. Their idea was that patents which are cited more often must have a higher value and that the citations done by the patent office were more objective than those done by the patent authors themselves. They also looked at home country patents, looked at two time series, and did the analysis using both the 41 SIC codes and the 31 IPC codes.

Tong and Frame (1994) used claims instead of simply counting patents and looked at Japan, West Germany, the U.S., U.K. and France at three different time periods and determined that the apparent increase in innovation in Japan (Frame and Narin, 1990) was not, in fact, correct when looking deeper into what the patents were actually about.

Malerba and Orsenigo (1996, 1999) went deeper into the question of looking for technological differences between countries in an effort to find empirical evidence to support the two Schumpeterian ideas of technological regimes, referred to as Schumpeter Mark I and Schumpeter Mark II. Using 49 different classes and patents from 6 countries over time they were able to confirm what Schumpeter referred to as some technologies such as mechanical techniques which go through a "widening" process with new entrants joining and others such as chemicals and electronics which go through a "deepening" or concentration process. Malerba and Orsenigo confirmed that such different technology regimes do not only exist, but were also robust across countries with several explainable exceptions. The exceptions led them to look deeper into country-level explanations of what was going on.

Varsakelis (2001) follows in this tradition of using the patent data to develop an all-encompassing theory which explains how a country becomes innovative. He uses 50 countries and finds "that national culture, patent protection, and the degree of openness of an economy are determinants of the R&D intensity".

In a very similar vein, Furman, et al. (2002) introduce what they call a measure of National Innovative Capacity, taking into account a series of parameters and correlating them to R&D effectiveness, or patents produced per R&D expenditure. Furman et al. come to similar conclusions as Varsakelis; i.e., that patent protection, the openness of a country's economy, etc., all lead to a higher level of innovation. Perhaps what is additional in Furman et al. is to take into account the presence of industry clusters in the framework. This model was then applied by Hu and Mathews (2005) to five additional countries in East Asia.

Cohen et al. (2002) performed a detailed comparison between the U.S. and Japan, based on a survey sent to manufacturing companies which attempted to get at national differences between the two countries. Their overall findings were that Japanese companies appeared to give more weight to patents as a mechanism to appropriate returns on their inventive activity and as a source for monitoring rivals' activities. Cohen et al. is also an example of research where the focus of analysis is nominally at the level of global comparison but also provides insight at the country level as well, in this case Japan and the U.S.

- Country and regional level

At the country level it is important to highlight that, because of their size, the U.S. and Japan are often looked at as analogous to the European region as a whole and a number of studies are done at either the country level or the regional level with similar purposes and similar methodologies. Although this difference in scope has the potential to blur the different categories in the typology, it was decided to stay with the national level for the purposes of the review.

Looking at Table 2.4, there are far fewer studies done at the country level than the comparative studies covered above, and that might mean that there is either less research going on or that the editors of Research Policy simply feel that such research has additional outlets.

Basberg (1983) challenged Soete by looking at Norway's patents in the U.S. and her exports and called attention to the fact that they have little to do with one another. While it's true that there are some patents connected to its offshore oil infrastructure, Norway's exports are normally not technologically intensive and therefore require few, if any, patents. In terms of methodology, Basberg was able to take advantage of Norway's relatively small size to look deeply into the sectors under study and even the firms involved to back up his analysis.

Bosworth (1984) looked at U.K. patents by foreigners and foreign patents by U.K. firms in an attempt to understand international technology transfer, and looked at fifty data points taken from 1974 to test his mathematical construct.

Two papers published in 2001 by Hicks et al. (2001) and Trajtenberg (2001) are examples of researchers going well past simple patent counts in order to add depth to their analyses. Diana Hicks and her colleagues (2001) looked into U.S. patents to look at how healthcare and information systems were becoming more and more important, and also how the locus of innovative activity was moving to the west coast of the U.S., amongst other trends. Hicks et al. use a commercial database which tracks corporate ownership structures, thus allowing researchers to drill down to the corporate entity when analyzing patents and, using this tool, they were able to show how smaller, innovative firms, largely located on the west coast of the U.S., played such an important role in the innovation in information technology and healthcare.

Trajtenberg (2001) uses Israeli patents in the U.S. over 30 years as a way to better understand the development of the Israeli high-tech economy, and uses the methodology developed in Trajtenberg et al. (1997) which looks at the "detailed information contained in patents and in patent citations" to go beyond patent counts and get at their importance, generality and originality as a way of answering the fundamental question of patent quality.

Looking at the time series of papers in this category in Table 2.4, one can observe no papers published at the country level during the 1990's. One interpretation is that such research required the emergence of digital databases and associated bibliographic tools in order to obtain the kind of meaningful results found by Basberg with his knowledge of the Norwegian economy or Bosworth with his relatively narrow data set.

Using more information in patents and digital databases giving a finer level of data than ever before, researchers have also been able to go inside countries to the regional level. One of the most compelling examples of this work was done by Acs et al. (2002). Acs et al. set out to test whether patents provided a reliable measure of innovative activity at the level of 125 American cities. They compared patents with literature-based innovation output measures which focused on the new product sections of trade and technical journals, and applied Griliches' (1990) Knowledge Production Function at what is called the Metropolitan Statistical Area and came up with robust results. Zitt et al. (1999) undertook a similar analysis in the European Union, looking at the correlations between patent counts, publications measured by citations, GDP and R&D expenditure at the level of the 15 EU countries at that time, and also further subdivisions into 175 sub-regions and even 416 separate regions.

Other studies at the regional level include those by Noyons et al. (1998), who looked at the Flemish region in Belgium, and Zucker et al. (2007), who did a similar analysis using publications and patents on the spread of nanotechnology across the United States looking at the United States divided into 179 regions.

What makes all of this research possible is again, the development of powerful digital databases and analytical tools. Zucker et al., for instance, used a database called "nanobank" which provided the raw data for most of their analysis. Indeed, looking at Table 2.4, there were no papers published using patents at the regional level in *Research Policy* in the 70's and 80's and only two in the 90's. It is only recently that the data and tools have been available, enabling researchers to drill down to this level of patent analysis. Interest in the topic, of course, goes back many years but it is only recently that patents have been able to contribute at the empirical level.

- Cluster & sector level

Going past the country and regional level, researchers have also been interested in looking at industrial sectors or groups of such sectors often called clusters.

The first paper published by *Research Policy* which used patents as a primary source of data was Reekie (1973). Without the benefit of any digital technology, Reekie looked at all patents made in London from 1900 to 1966 in the pharmaceutical sector. By looking at one sector in particular he felt that he would control for the propensity to patent and was sure that, in pharmaceuticals, firms would patent whatever they could. He also felt that the U.K. market was important enough that even foreign companies would patent their inventions in the critical U.K. market. This is much like Soete (1987) and Patel and Pavitt (1987). Later using foreign patents in the U.S., Reekie maintains that, before 1935, doctors only used 6 medicines and that the number of different drugs grew exponentially after the introduction of penicillin in 1940, streptomycin in 1943 and antibiotics in 1949. Using patents as a complement to market share data and other measures, he was also able to show the evolving picture of multinationals in the industry and the eclipse of the U.K.-based companies in the industry.

Over the years, the chemical and pharmaceutical industries have repeatedly been used as a context with which to study patents, and patents used as a tool to look deeply into the industries themselves. This is largely due to the fact that, in study after study, both sectors were found to have a very high propensity to patent, which makes sense if one thinks about the possibility of reverse engineering virtually any chemical compound and the stakes at play in owning the next breakthrough drug or pesticide (Arundel and Kabla, 1998). Examples of such research include Palda and Pazderka (1982), Achilladelis et al. (1987, 1990), and Arora (1997).

Achilladelis et al. (1987, 1990) looked at the pesticide industry. In their first paper they undertook to develop a history of the industry from 1930 to 1980 to and contrast the historical record with new product introductions and patent counts to look at the fundamental dynamics of innovation in a specific industry. Their main finding was further explored in the second paper which highlights the role that radical innovation plays in driving company profitability and technological change.

Arora (1997) did a study similar to Reekie, but with vastly superior tools and focused on the European chemical industry. Using patents, he was able to highlight the trend toward technological licensing in the industry after World War II and identify a relatively new group of industry participants dedicated to R&D and the dissemination of knowledge based on business models focused on licensing rather than production. The idea of looking at the industry level goes back to the very first researchers who began using patents, such as Pavitt (1982) and Scherer (1983), who found that metrics such as R&D effectiveness, as measured by number of patents produced per unit spending of R&D, showed robust results at the industry level.

Palda and Pazderka (1982) made a similar finding in looking across Canadian industry, demonstrating that robust results for R&D effectiveness are only possible at the industry level. Kondo (1999) found that, in Japan, an industry level analysis also showed robust results in terms of the time lag between R&D investment and patenting.

Arundel and Kabla (1998) went deeper into the differences across industries in their analysis of two parallel surveys done in France and the Netherlands. By looking at the responses of hundreds of Europe's largest firms, they were able to drill deeply into the issue of propensity to patent and were able to weight patents by the kind of revenue they provide. Consistent with earlier work, they found that firms in different sectors had different levels of propensity to patent new products, but were also able to observe that process innovation was more heterogeneous across their samples and no such correlation was found at the industry level.

Jaffe (1989) reasoned, much as Pavitt (1984) had done in his paper on technology trajectories, that there are logical technological clusters that are more important than industry groups; he grouped the 328 U.S. patent classes into 49 groups and then took 500 companies over two time periods to determine 21 statistical clusters in which he felt there were enough technological links to perform robust analysis. Part of Jaffe's interest was to explore the so-called "spillover effects" which would indicate that there is transference of innovative ideas from one place to another through social networks.

The role of patents and other factors in the dissemination of knowledge is a common theme of research at this level of contextual analysis and can also be seen in Kumaresan and Miyazaki (1999) and Bekkers et al. (2002). The context for Bekkers et al. (2002) was the Global System for Mobile (GSM) industry and the role that patents played in developing the licensing model that is the basis for the industry, much as Arora had done for the chemical business.

Malerba and Orsenigo (1996) sorted the industrial patent codes provided by the European Patent Office into 49 classes for firms in 6 countries and were looking to link patenting activities to patterns in firms' entry into and exit from specific industries and countries. While their country level data was significant, its primary contribution was to determine that some industries are more turbulent than others in the sense of having higher degrees of entry and exit and less persistence in innovation by the firms in those industries. In some cases their data proves somewhat counterintuitive, with sectors such as multimedia systems and computers located in the stable industry group and agriculture and furniture located in the turbulent group.

From the point of view of the impact of digital databases and bibliographic research tools, the researchers looking at the industry level have clearly benefitted in much the same way as they have at other levels of contextual analysis. What is different at the industry level is however, that there has always been industry-level data provided by the different patent offices and, in fact, much of the early work in the field involved sorting through those industry codes and discussing to which degree they made sense or confused things further. For researchers interested in the sector level, it appears that digital databases and tools have made their lives fundamentally easier but have not changed the nature of what can be done with patents to inform innovation theory at that contextual level.

- Firm level

Many researchers have used patents to look at the firm and its innovation process. Although no papers were published in Research Policy at the firm level in the 70's, and only 5 % of the papers using patents were at this level in the 80's, 28% and 35% of all papers have been at this level during the 90's and from 2000-2007, respectively. There are, however, many papers placed into other categories which use firm-level data. These papers, such as Malerba and Orsenigo (1996), discussed above, use firm-level data to find patterns at the industry, country, or global level rather than look at the creation of knowledge or innovation in the firm.

As the volume of work at the firm level is so large in the sample, it was necessary to identify seven distinct threads including, R&D effectiveness, the role of in-house R&D, innovative persistence, the link between business and technological innovation, collaboration between firms, the internationalization of R&D, and the particular dynamics of start-ups and the so-called high-tech sector.

1. R&D effectiveness

In most of the work reviewed so far, the level of context is at the country or industry level and propensity to patent is found as a statistically relevant variable when looking across large numbers of firms. At the firm level, however, propensity to patent falls within the overall idea of how effective a firm's R&D activities are and to what degree a firm uses patenting as a strategy for appropriating value from its intellectual capital.

Ernst (1998), for example, looked at 25 Japanese and European electronics companies and did two things to get at his analysis of the different "strategies" for patenting at the firm level. One was to develop a measure of patent quality by looking at citations and other factors, and the other was to break out the R from R&D. Ernst is an advocate of corporate research and hoped to prove that it is a good idea. While his definition of quality might be questioned, his work is a good example of firm-level analysis as he shows different companies behaving differently. Some firms patent only a few high-quality patents, while others patent everything they can. What is very interesting about Ernst's work is that, while at the aggregate level the propensity to patent is fairly uniform in a given industry confirming earlier work; his data gives a heterogeneous result at the firm level.

Other papers also dealt with this theme. Frumau (1992) was one of the first studies to use bibliometric tools at this level of analysis and treated both patents and articles as an output indicator. Brouwer and Kleinknecht (1999) used the Community Innovation Survey (CIS) done in 1992 which gives hard data on new product introduction and thus attempted to separate out the effectiveness of firms' R&D activities from their decision to patent in the hope of getting a better measure of propensity to patent much as Arundel and Kabla (1998) did at a broader level of analysis. Blind et al. (2006) also looked deeply at why firms patent and, using data from Germany, tried to explore the increasing use of licensing as a rationale for the apparent upsurge in patenting observed in the 90's and early years of the new millennium.

2. The role of in-house R&D

Gambardella (1992) was interested in looking at the ability of firms to exploit publicly available information and in his study of 14 large pharmaceutical firms in the U.S. was able to determine that firms with large in-house R&D capabilities were able to generate more patents based on publicly available science. This research required going past simple patent counts and looking at the citations in the patents to establish the kind of research the patents were based on. Beneito (2006) developed a very sophisticated set of algorithms to measure not only radical new technology but also incremental improvements, and found in her research on Spanish companies that in-house research capabilities appeared better at radical innovation while contracted R&D was more effective at incremental improvements.

3. Innovative persistence

Geroski et al. (1997) took two different databases concerning U.K. firms: one with patents awarded in the U.S. and another with product innovation with overlapping timeframes to explore to what degree firms which are very innovative tend to remain persistently innovative. Their surprising results were that very few firms were innovative by these definitions over any length of time and the expected correlation that the most innovative firms at one time would remain innovative simply did not hold.

Cefis and Orsenigo (2001) however, did find evidence of persistence in looking at data from 6 different European countries when they compared patent applications to the European patent office. Their idea was that applications, not patent awards, are a better indication of innovative activity and did find evidence of persistence.

Roper and Hewlett-Dundas (2008) went even deeper in their analysis of persistence in firms in Northern Ireland and used survey data to find evidence of persistence, especially in process improvements at the plant level.

4. The link between business and technological innovation

The most cited paper in this debate in the sample was Gambardella and Torrisi (1998), who looked at a panel of U.S. and European electronics companies and found that the most successful companies simultaneously focused their business activities while keeping their innovation activities as measured by patents rather diverse.

Additional research in this area includes Breschi et al (2003), Suzuki and Kodama (2004), Garcia-Vega (2006), Rodriguez-Duarte et al (2007), and Quintana-Garcia and Benavides-Velasco (2008) and Ernst (2001). The question all of them are trying to answer in one way or another is whether business diversification leads to greater innovation, or does innovation, and the diversification of innovative activities, lead to opening up opportunities to diversify the business.

5. Collaboration between firms

The most widely cited paper was Mowery et al (1998), which looked for and found a relationship between technology overlap and partner selection, as defined by patent awards, and was able to show that this overlap increased over time after two firms started working together; supporting the idea that collaboration would increase the capabilities of both sides. Additional research in this area includes Santangelo (2000), Bas and Sierra (2002), and Katila and Mang (2003).

6. The internationalization of R&D

Two papers which were frequently cited and focused on looking at firms which did R&D activities outside their home market are Belderbos (2001) and Kumar (2001). While Belderbos (2001) tried to find a correlation between doing research abroad and obtaining more innovation as measured by patents, Kumar (2001) looked at where firms would endeavour to do their R&D. Bas and Sierra (2002) then postulated different strategies which matched their empirical findings and also found substantive differences between Japanese and Western firms. In all cases, patents were able to inform the research since the location of the original innovation is well documented as well as the corporate affiliation of the research centre.

Additional research concerning the internationalisation of R&D include Bergek and Berggren (2004), Iwasa and Odagiri (2004), Mariani (2004), and Singh (2008).

Singh (2008) is a good example of the level of complexity which is possible with modern databases, and he was able to dig deeply into the "black box" of patents to come up with statistically significant evidence that shows that geographically-distributed R&D actually has a negative correlation with R&D effectiveness. He also found that when such distributed R&D was effective it did produce patents of higher value (using his definitions and algorithms).

7. Start-ups and high-tech sectors

Relatively new research by Mann and Sager (2007) looked at software start-ups and determined that having a patent has a positive impact on the firm's ability to raise capital and make it through successive rounds of financing. Other research which focused on small firms and start-ups in sectors such as software, nanotechnology and biotech include Hicks and Hedge (2005), Avenel et al. (2007), Rothaermel and Thursby (2007), and Coad and Rao (2008).

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- Technology Level

While some researchers dug into the “black box” of patents to inform research into the way innovation occurs at the firm level, others were more interested in the way innovation disseminates across technologies. Some of this research clearly transcends the boundaries of the firm. In any case, research at the technology level using patents has also taken off relatively recently with the advent of more sophisticated databases and tools with which to study them.

One such study was Patel and Pavitt’s (1994), in which they used exclusively U.S. patent data to confirm Mowery and Rosenberg’s (1989) historical explanation of the development of technology in the U.S. during the twentieth century. Patel and Pavitt endeavoured to affirm the continuing importance of mechanical technologies in innovative activities despite the emergence of chemical engineering and electronics, and the patent data showed that fully 40% of new innovations were consistently based on mechanical and other traditional technologies as opposed to newer science-based technologies. The study produced robust evidence of the advantage of looking at patent data rather than aggregate R&D spending, and being able to drill down to the technology level and firm level.

Lanjouw and Mody (1996) stay firmly in the “black box” tradition and use patents as empirical evidence that rising concern about pollution control led to increased innovation on pollution control technologies. They re-enter the “technology push and market pull” debate and land squarely in the market pull camp. Nameroff et al. (2004) do a similar study looking at so-called “green chemistry”. What is interesting about their research is the need to dig a bit deeper into the patents themselves in order to separate out the “green” patents from total chemical patents.

At the other end of the spectrum, Von Wartburg (2005) looked at 4-stroke internal combustion engine technology using multi-stage citation analysis for both U.S. and European patents, and he develops algorithms and control variables which get at the economic value added of specific patents based on the number of citations received in a fairly complex network model.

Tijssen and Korevaar (1997) looked at the development of catalysis chemistry in the Netherlands as a way of getting at the informal organisations across inventors by using bibliographic techniques on patent citations. Murray (2002) looked at tissue engineering in the Netherlands to explore the idea that new technology is often found in both papers and patents, and used bibliometric tools to look for these patent-paper pairings and then to investigate the social network dynamics that were producing these innovations.

As researchers such as Murray (2002), Von Wartburg (2005) and Tijssen and Korevaar (1997) dug deeper and deeper into the evolution of the technology and explored networks of institutions, companies, and scientists, they naturally found themselves getting closer to the inventor level which will be covered in more detail below.

- Product & Product Category Level

There are only two papers in the sample of 134 papers which use patents at the product or product category level of analysis; Penan (1996) with 5 citations and Prencipe (1997) with 8 using the Science Direct database.

Penan (1996) was interested in competing strategies in the field of Alzheimer's disease therapy and went deeply into the network of researchers and companies in order to work out the apparent strategies of the different firms. To do this he used co-citation analysis of papers and patent co-word analysis.

Andrea Prencipe’s work closely examined Rolls Royce and the way it works at the technological level and is discussed in Section 2.3. His early work was at the subsystem level in jet engines and, in his 1997 paper, he uses patents as a proxy for understanding the actual technological profile of Rolls Royce. Prencipe’s point is that complex technological development requires deep technical know-how, and that traditional core competence theory is not enough. What is interesting is that, to reach this conclusion, Prencipe had to go deeply into the technology and the patents and look at 14 product and process technologies in order to develop a technology map for which to do his patent analysis.

- Inventor Level

There were six papers published in the first 28 years of *Research Policy* which used patents to inform research at the inventor level and 16 in the last 7 and a half years indicating either increased interest in the field or perhaps the opening up of this area in line with the availability of increasingly powerful tools and techniques.

Sirilli (1984) started the thread in a paper in which he interviewed inventors in order to gain their perspectives on innovation and the relevant inputs and outputs such as research papers and patents. Noyons et al. (1994) looked at Flemish inventors in laser technology, and was one of the first researchers to look at the link between papers and patents using bibliographic techniques. Tijssen (2001, 2002) and Balconi et al. (2004) built on Noyons’ ideas and used increasingly powerful bibliometric tools to go deeper and deeper into the social networks in which the inventors work.

Narin and Breitzman (1995) were on a slightly different track and looked at research scientists. They found that the number of patents per scientist followed the same inverse square distribution as found originally by Lotka in the 1920’s. If, for example, 100 researchers each had 1 patent, the number of patents per researcher would drop off rather quickly with only 25 having two patents, 11 having three, 6 having four, and so on.

Researchers now look at inventors’ career progressions (Dietz and Bozeman, 2005), where they live (Bettencourt and Strumsky, 2007) and where they work (Furukawa and Goto, 2006), and have done similar studies in different countries and in different technological areas, including tennis rackets (Dahlin, et al. 2004).

2.4.6 Conclusion

The purpose of this section was to review the history of management research which used patents as empirical data. Besides highlighting the fact that is well covered by other researchers that patents are a useful source of data when looking at innovation and the innovative process, the section developed a typology which makes it easier to classify based on the contextual nature of the research and the level of analysis.

Five conclusions come out of the survey:

1) In over 50 years of working with Patents (35 in *Research Policy*), researchers still find them a powerful tool across a widening spectrum of contexts and academic frameworks or lenses.

2) The level of contextual analysis has increased over time as more complete digital databases have become available to researchers and they have mastered more powerful analytical tools which can be used with the data.

3) Some contextual areas appear to be understudied such as product or product category level while others such as the inventor level are quite fashionable.

4) As the level of research goes deeper and deeper into the nature of the firm, the inherent advantages and limitations in the use of patents become even more critical to manage and increasing triangulation becomes necessary.

5) At the highly granular level made possible by the use of digital tools, the volume of information becomes exponentially large and there is a growing need of tools with which to be able to process that information.

2.5 Chapter Summary

This Chapter presents the literature review done for the thesis by first outlining the literature review process which is best described as an iterative one and covered a number of different literatures over a number of years. The chapter then goes on to look at the literature dealing with discontinuous and potentially disruptive technology discussing definitions and semantic debates, two major threads in this literature and the relatively limited research which looks at what firms do in the face of such change from either a theoretical or empirical perspective and no research directly dealing with technology deployment per se. The thesis then looks at the automotive literature dealing with one group of such technologies and finds that while there is much being written about the context, the issue of how to deploy is receiving little attention. In search of a theoretical perspective, the thesis reviews Granstrand’s theory of the technology-based firm and finds it falls short of covering this issue of technology deployment. Having identified a gap in the literature the thesis goes on to review management research using patents in order to develop a typology of such research and thus inform the method for the research which is partially based on using patent data. While not germane to the identification of the major area for the thesis’ contribution, this section is included in the review as the thesis does not make a contribution to method.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Introduction

The purpose of Chapter 3 is to explain in detail the research methodology used in the thesis and discuss the rationale for choosing it as well as highlighting its limitations.

Section 3.2 will briefly review three different philosophical approaches to the social sciences and show why the thesis adopts Bhaskar's (1975) Critical Realist Perspective, discuss the epistemological implications of that choice, and also why case studies were chosen as the research strategy applying Eisenhardt's (1989) ideas using case studies to develop theory.

Section 3.3 will go into the method itself describing the overall process used in arriving at the final research design, show how the thesis maps onto Eisenhardt's (1989) roadmap for developing case studies, discuss how the thesis will combine data from four sources to complete case studies for each of the manufacturers as well as each of the technologies under study, and finally present the *a priori* construct concerning technological deployment strategy that was used to guide the methodological choices in the thesis and which will be later refined in Chapter 6.

Section 3.4 will discuss the four companies and technologies selected and explain the logic behind this sample selection. Section 3.5, 3.6, and 3.7 will discuss the sources of empirical data for the thesis and the limitations of each data set. Section 3.5 will discuss the patent data as well as the mapping software applied to it. Section 3.6 will discuss sources used for the deployment data and Section 3.7 and Section 3.8 will discuss the interviews conducted with Industry experts and the use of the researcher's prior knowledge respectively. Section 3.9 will present a summary to Chapter 3 and place the thesis within the context of the research using patents presented in Chapter 2.3.

3.2 Philosophy of science, epistemology and method

According to Blaikie (1993), research needs to be clear in terms of its ontology, epistemology and method.

3.2.1 Philosophy of science and epistemology

According to Blaklie "over the past thirty years, the social sciences have been plagued by theoretical and methodological controversies" (Blaklie, 1993, p.1) and it seems that these controversies have continued. This section will summarize three different positions within that controversy and look at the advantages and disadvantages of each according to the researcher's viewpoint in the interest of explaining the choices made for the research in terms of ontology and epistemology. These choices will therefore drive the method chosen as there are many ways of looking at the research question formulated Section 1.1. To simplify a very complex set of debates and discussions there are two broad camps in the social sciences which Blaklie refers to as Positivism and Interpretivism. These will be explored as will Critical Realism (Bhaskar, 1975).

- Positivism

The positivist approach applies the positivist philosophy developed for the physical sciences to social science and is concerned with looking for causal relationships between observable phenomena. One important aspect of what Blaklie calls the "standard view" (Blaklie, 1993, p.16) of positivism is confidence in the scientific method and another is the idea that through the application of that method humanity will eventually be able to know the underlying laws which determine how the world works both in the physical world and the social sphere.

In management science, or the application of social sciences to the field of human organization concerned with business (as opposed to family life, social organizations, etc.) the positivist view has become very popular and even dominant in a number of universities and academic journals. A positivist world view and an empiricist epistemology would, in terms of method lead a researcher to posit a relationship between different phenomena and then develop a construct which links them together. Next the researcher will look for empirical data concerning the different components of the construct and then show through statistical analysis whether the construct is robust after controlling for exogenous factors and measuring the confidence level one can have in the findings. There are three aspects which make the positivist view deeply compelling. First, a positivist formulation has the potential to offer a prescriptive solution to problems facing practice. Second, the empiricist approach is conceptually straightforward even though it can lead to much methodological and mathematical complexity. Third, since much of the early management research was done using methodologies which fit into this epistemology and ontology, a body of knowledge has reached critical mass to which contribution can be made using methods for which there is precedent and pursuing lines of enquiry which have been opened.

For the researcher the positivist approach has an important disadvantage in addition to the philosophical objections cited by Blaklie and that has to do with the time lag inherent in such research which decreases its usefulness for practice. Management research in the positivist tradition will typically look at attempting to correlate some aspect of management such as early supplier involvement in new product development with some process or output indicator in an effort to determine the degree to which such activity will improve the process by a measurable amount. While such research is quite important for the development of theory and to add to the understanding of the phenomena, it is only possible when there is a statistically significant sample of instances when such an idea is applied which can be empirically compared to others where it is not applied. The dissemination of such ideas takes time and only when there is a sufficient sample available can such research be done. Research also takes time to complete and publish and the entire process suffers a significant time lag from the first time the new idea is tried out until publication of the research results. From a practitioner point of view however, the advantages and disadvantages of the approach might be well known with the result that such research is found not to be of interest to many practitioners although they might apply the methods in question.

- Interpretivism

Interpretivism, on the other hand, argues that the social sphere is fundamentally different than the physical world due to human interaction and therefore needs a fundamentally different epistemological approach. According to Blaklie (1993), who quotes Weber extensively, Interpretivism is an attempt to apply objective measurements to fundamentally subjective material and goes beyond the Negativist view which maintains that since everything is subjective there is little point in attempting generalizations. For the researcher, the attraction of Interpretivism is that it allows for great flexibility in method and encourages introspection and an exploration of the attitudes of social actors involved in a given phenomena. That people do not behave in a strictly predictable fashion, as would be maintained by a strict positivist, and that rationality is bounded is intuitively evident and the interpretivist tradition encourages the exploration of what lies outside of those boundaries. Blaklie (1993) gives a list of seven criticisms of Interpretivism many of which have to do with the challenge in recognizing that the way people think about things is not only part of what is being studied in the social sciences but also affects the study itself if one adopts an interpretive world view. From a strictly practical viewpoint, the researcher feels that very interpretive research with methods such as employing grounded theory and action research is difficult to accomplish. Section 3.1 will discuss the evolution of the design of the research during which the development of grounded theory with an interpretivist philosophy was considered and rejected.

- Critical realist ontology

The critical realist perspective was chosen for the research based on Bhaskar's original text (1975) and Blaikie's (1993) critique and review. Bhaskar takes a rational approach which can be considered as providing a pragmatic answer to the positivist-interpretivist debate (Benton, 1981). Bhaskar (1975) distinguishes between three levels of reality: the *empirical* that we can see and measure; the *actual*, events going on regardless of whether we can detect them with our present level of tools and understanding; and the *real,* the fundamental structures and mechanisms which produce these events. The approach encourages the search for causal relationships in open systems and thus responds, to a degree, to the recent history of both the physical and social sciences. In some of its most advanced disciplines, even the physical sciences are coming to understand that there are limits to the scientific method and what appeared to be fundamental laws to one generation of scientists are revealed to only being rough approximations and models to another as the quest for knowledge goes further and further, such as in the field of particle physics. Blaklie (1993) cites Benton (1981) in his examples of natural sciences such as evolutionary biology which also work in open systems and maintains that the differences between the natural sciences and social sciences ought to be methodological, not epistemological. While the purpose of this section is not to summarise Bhaskar or go into depth on the current debates in the critical realist tradition, the key idea relevant to this research is that we often cannot know in advance the rules and laws governing phenomena and will probably never uncover them all. The best science can hope for is to strive to understand phenomena and continually update its approximation of the underlying laws or, as Bhaskar called it, the *real*.

As explained by Blaikie (1993), realist epistemology is about building models of real mechanisms "such that if they were to exist and act in the postulated way, they would account for the phenomena being examined". In terms of the difficulties and disadvantages of Positivism and Interpretivism mentioned above, Critical Realism allows for the investigation of ideas before they are clearly part of the empirical fabric of the world and thus might still be interesting to practice while at the same time goes beyond the relativist idea and allows for reaching concrete conclusions on cause and effect at least at the approximate level.

3.2.2 Research strategy

As outlined in Section 1.1 the thesis is interested in understanding how firms respond to potentially disruptive or discontinuous technologies in terms of research & development and new product deployment and is focused on the context of the automotive industry. The thesis is thus built around the idea that managers in firms make an implicit or explicit strategic decision about how to deploy new technology and that identifying different patterns of that choice could help fill a gap in the literature which is discussed at length in Chapter 2.

- Retroductive approach

Within the critical realist tradition, Blaklie quotes Bhaskar (1975) as arguing for a retroductive research strategy and outlining three broad steps in performing such science. The idea is to first observe a phenomenon. Next an attempt is made to explain the phenomenon by postulating the existence of an overarching mechanism. Finally the researcher looks for evidence of the existence of the mechanism. What is elegant about the process is that it can be repeated for infinitely deeper levels of explanation.

In the first place such an approach fits better with the critical realist ontology than the classic inductive and deductive approaches to scientific inquiry. The inductive approach of the kind argued for by Durkheim (1964) is, according to Blaklie "now rejected by most natural and social scientists" (Blaklie, 1993, p. 140), and rejected for this research amongst other reasons because it requires the researcher to discard all pre-conceived ideas – something which was not felt to be either possible or useful for the research. The deductive approach as developed by Popper (1959) and summarized by Blaklie (1993, p.145) requires setting up a hypothesis as the central research question and then developing a set of propositions that can be logically derived from the hypothesis. These propositions can then be proven false or not and if not then the original hypothesis can be said to be corroborated although never quite proven to be true. Of the five criticisms levelled against the deductive approach by Blaklie (1993 p. 150-155), the one most compelling for the research is the question of where the hypothesis comes from. While potentially powerful for confirming existing theory or expanding on it, the approach appears destined to fail in developing fundamentally new ideas.

The advantage of the retroductive approach mentioned above is that one can start with a rough idea which is perhaps the fruit of an insight and then develop it into theory using the process. One of the differences between a retroductive approach and an inductive approach is the level of this starting point.

- Using case studies to build theory

In her seminal essay, Eisenhardt (1989) builds on earlier work by Yin (1984), Glaser and Straus (1967) and others to develop a roadmap for using case studies in order to build theory. While Eisenhardt positions her work as an inductive method, she does explicitly discuss the use of using a priori constructs as a possibility and in terms of Blaikie's definitions discussed above, the use of such *a priori* constructs would position such work as retroductive.

Yin defines a case study as "an empirical inquiry that investigates contemporary phenomena within its real life context especially when the boundaries between phenomena and context are not clearly evident" (Yin, 1994, p.13). Both Yin (1994) and Eisenhardt (1989) place great emphasis on the selection of the research question as it will drive the selection of the research strategy in general and the site selection and data collection methods for case study research if it is chosen.

As stated in Section 1.1 the research question for the thesis is ***What strategies do automotive companies follow with respect to the investigation and deployment of discontinuous technologies?*** In the case of the automotive industry in general as well as the particular potential transition to new power train technologies discussed in Section 1.1, the context is quite important and the boundaries between it and the larger issue of how firms approach potential disruptive or discontinuous technology is not evident.

For Eisenhardt "the case study is a research strategy which focuses on understanding the dynamics present in single settings", "can involve either single or multiple cases", and "typically combine data collection methods" (Eisenhardt, 1989, p. 534) and appear to be a sound approach to shedding light on the question above. As discussed in Section 1.1, the thesis pursues two sub-objectives within the broader research question:

Objective 1 Explore how companies approach the development of different technologies, for example, looking at the existence of path dependency in terms of technology strategy

Objective 2 Assess how different companies develop the same technologies, for example, looking for homogeneity or heterogeneity in terms of strategic response.

For these objectives, the development of case studies also appears to be a sound choice and in this case, the idea of developing multiple case studies from the same data set as done by Bourgeois and Eisenhardt (1988) showed promise. The final reason for choosing the case study method was that the researcher did have an *a priori* idea of what the answer to the research question might be and the case study approach, together with Eisenhardt's (1989) roadmap offered the possibility of exploring that construct while at the same time avoiding bias and assuring that the research would be robust in the sense of establishing internal validity and potentially developing good theory which Eisenhardt (1989) cites Pfeffer (1982) as defining as parsimonious, testable and logically coherent.

3.3. Method

The PhD. Process has been a journey of discovery for the researcher and in order to highlight the choices made in the research design, the following section will briefly cover the key points along that journey prior to discussing the research program itself and the *a priori* construct used in its design.

3.3.1 Thesis development

The starting point for the thesis was the apparent heterogeneity in the major vehicle manufacturers' response to the potentially profound changes to automotive power train technology that began to gather momentum towards the end of the 1990s due to concerns about air quality, environmental sustainability and the rising cost of oil based fuels. Van den Hoed (2004) argued that the fact that a number of vehicle manufacturers had embraced protein exchange membrane (PEM) fuel cells as a possible solution was evidence of mimetic homogeneity, yet the researcher was struck by the different levels of apparent investment and interest by the different vehicle manufactures and thus the first idea was to look at why the different companies appeared to be taking different approaches.

The first idea was to not adopt any lens, but develop qualitative case studies based on open-ended interviews with executives in the manufacturers and let the data speak for itself using a grounded theory methodology (Strauss and Corbin, 1998; Gummesson, 2000). The feedback received in a number of discussions with faculty and colleagues was that such an approach was highly risky. The first problem was identifying the key executives at each firm and gaining access to them. Next it would be necessary to get past the official explanations and uncover what really happened. Even if one was able to do that, another problem is the degree to which such people agree with each other or are retroactively truly honest with themselves about their individual and collective cognitive processes. To make things more difficult, many of the key people are Japanese and German and a working knowledge of both Japanese and German would have been useful as people are more comfortable in their own language.

As a result of this feedback this approach was abandoned and a process undertaken to look at 14 different approaches or lenses with which to look at the phenomena. This approach, shown in Table 3.1, shows the different lenses evaluated and an evaluation of each of them in looking at their fit with the researcher's interest, the potential contribution to theory, interest for practice, and a concept called "doability" which had to do with issues concerning access and the researcher's own assessment of his abilities.

As a result of this analysis, which was reviewed by a panel of Cranfield School of Management academics, the focus of the research was built around the idea of developing a new framework which would explain the heterogeneity around the ideas of depth and breadth. These ideas, which later became those defined in Sub-section 6.2.2, were still in an early stage of definition although a research program was designed for this approach and Nissan was selected as the site for a pilot study due to the researcher's access to specific executives within the Research & Development organization.

	Interest	Contribution	Practice	Doability
Causal Actors				
Alliances	-	++	++	+
Senior Management	++	?	+	--
Government	-	+	+	+
Strategic Planning	++	+	+	--
National Culture	--	+	+	--
Complementors	+	+	++	+
Christensen's model				
Initial Markets	++	+	+++	+
Improvement & Learning	+	++	++	+
Heterogeneity				
New framework	+	-	+	+
Ambidextrous Organization	-	+	+	+
Other Frameworks				
Dynamic Capabilities	++	+	+	+
Co-Evolution	+	+	--	-
Population Ecology	-	+	?	+
Nonmarket Strategy System	+	?	+	-

Table 3.1 Subjective evaluation of possible approaches

Over the course of six months the head of research and development for the company was brought into the process and, after the requisite non-disclosure forms had been signed, access was given to Nissan's current plans for product development in safety. Unfortunately, when presented with requests for information along the lines of Table 3.2, the Nissan executives were simply unable to comply. Not only would such an effort require a large amount of time, but the most difficult part would be to first identify where in the organization the data would exist i.e. engineering, strategic planning, public relations, regulatory affairs, finance, etc. and then work through internal channels to get access.

Concept	Indicators of Breadth	Indicators of Depth
Program length (years)	Longer (e.g. 15 years)	Shorter (e.g. 5 years)
Number of parallel applications	Many	Few
Total annual spending	High	Higher
Total program spending	Higher	High
# people involved	Many	Few
# sites involved	Several	One or two
Role of suppliers and collaborators	Large number of suppliers and collaborators involved	Small number of Key suppliers and collaborators involved
Patent generation	Higher	Lower
Strategic Timescale	Shorter term	Longer term

Table 3.2 Pilot study design

As a result of the failure of the pilot site, the research design was changed again to eliminate the need for direct access and to rely instead on publicly available patent data and new product introductions in order to infer the apparent strategies used by the different manufacturers and then to confirm those results by interviewing industry experts. At this time the scope of the project was expanded to look into additional technologies beyond hydrogen fuel cells, and hybrid vehicles, seat belts, airbags and catalytic converters were initially considered. The number of vehicle manufactures at the time was five including GM, Ford, Toyota, Nissan and what was called at the time DaimlerChrysler. Catalytic converters were later dropped due to problems in finding any interesting performance data, and DaimlerChrysler was dropped due to problems associated with its process of dissolution which was thought to cloud the data.

The research, however, continued to proceed along inductive lines with a narrow research question built around the idea of determining whether in fact there was heterogeneity in approach across the manufacturers using the ideas of depth and breadth. Three propositions were logically induced from the existence of the construct which involved the manufacturers showing a path dependency in terms of depth and breadth, deeper strategies leading to later but potentially more substantial technological progress and broad strategies leading to potentially more rapid introduction of less substantial technological leaps.

There were four problems with this approach. In the first place, the data for the propositions was not compelling and although they were downgraded to conjectures in the thesis submitted in December 2009, their role in the research was unclear. Second, the research question was considered too narrow by the examiners and the contribution to knowledge not clearly linked to it. Third, the overall linkage between the research question, gaps in the literature, method, data analysis, conclusions and contribution was thought to be unclear at best. Fourth, the thesis lacked a discussion chapter separate from the conclusion chapter and had a number of other omissions and deficiencies.

The research methodology has thus been modified again to reflect the input of the examiners and align it closer with established case study methodology in general and Eisenhardt (1989) in particular. A detailed mapping of the examiners' comments and changes to the thesis is shown in Appendix G.

3.3.2 Research programme

As a result of the process outlined in Sub-section 3.3.1, the thesis has been aligned with Eisenhardt's (1989) roadmap for performing case study research, and that alignment is shown in Table 3.3 in which the headings are taken directly from her paper and the thesis content and chapter and section reference are given for each heading. One of the key points made by Eisenhardt is that case study methodology can and should adapt during the study itself and research questions at the beginning of the research should be considered "tentative" and that it "may shift during the research" (Eisenhardt, 1989, p. 536). In this light the thesis has been able to embrace the recommendations made in the interest of producing a more robust study and not in the sense of retroactively justifying work that has already been done.

Web Site	Thesis content	Chapter-Section
Getting started	o Research question defined	1.1
	o A priori construct developed on depth and breadth	3.3.3
Selecting cases	o Site selection discussed in depth and alternatives discussed	3.4
Crafting instruments and protocols	o Research designed around four sources of data including patents, deployment data, expert interviews and prior knowledge	3.3.2
	o Patent data from Eureka database	3.5
	o Deployment data from variety of sources	3.6
	o Interview guides developed and methodology discussed	3.7, App. B1
Entering the field	o Write-up of case studies	Chapter 5
	o Write-up of interviews	App. B3
Analyzing data	o Data analysis presented in eight case studies (4 by vehicle manufacturer, 4 by technology)	Chapter 5
	o Cross case analysis performed	Chapter 6
Shaping hypothesis	o *A priori* construct refined in light of the data	Chapter 6
Enfolding literature	o Gaps in innovation and automotive literature	2.2
	o Use of patents in management science study	2.3
	o Concepts related to depth and breadth	6.2.1
	o Discussion of findings and links to literature	6.4, 6.5
Reaching closure	o Theoretical saturation	App. B2
	o Cross case comparisons	Chapter 6
	o Thesis conclusions	Chapter 7

Table 3.3 Application of Eisenhardt's (1989) roadmap

The research program for the thesis is shown in Figure 3.1 and involves triangulating data (Yin, 1994; Eisenhardt, 1989) from four different sources to develop two sets of case studies covering four companies and four technologies within the automotive industry. Miles and Huberman (1994) argue for such multiple-case sampling in order to add confidence to findings although they maintain that it does not necessarily add "generalizability" (p. 29) to the theory developed. Eisenhardt (1991) supports the idea and maintains that many of the most highly cited studies in sociology explicitly or implicitly consider multiple case studies although they might be at one location. For Yin (1994) multiple cases are like a series of experiments and he stresses the idea of "replication" (p. 45). The data sources are an analysis of the cumulative U.S. patents filed by the vehicle manufacturers in each of the four technologies (Section 3.5); an analysis of the deployment of those technologies by the manufacturers (Section 3.6); interviews with industry experts, who were selected for their knowledge of the technologies and companies under study, (Section 3.7); and the researcher's prior knowledge of the industry (Section 3.8). Figure 3.1 also shows how, using Eisenhardt's (1989) terminology, an *a priori* construct can be used with the case study methodology to provide a starting point for thinking through the sources of data and analytical tools.

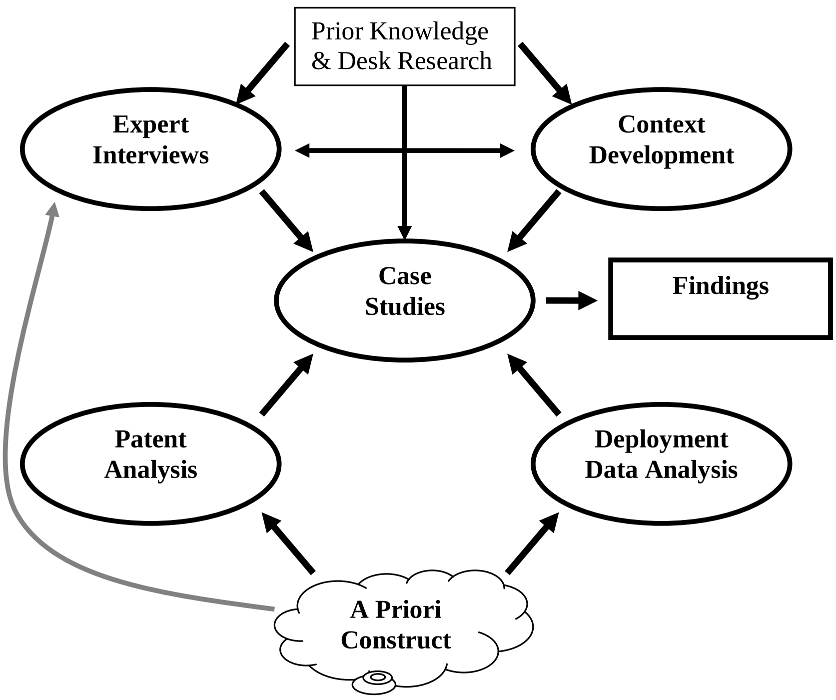


Figure 3.1 Research Methodology

Figure 3.1 also shows that much emphasis has been placed on developing the context for the research which is presented in Chapter 4. As discussed in Sub-section 3.2.2, part of Yin's definition of a case study is that the "boundaries between phenomena and context are not clearly evident" (Yin, 1994, p. 13) and it was felt that significant effort was required to ensure a rigorous coverage of the context for the research; this was done by using the researcher's prior knowledge as a base, organizing it using theory, supplementing it with additional desk research and then corroborating the result with three of the industry experts. For this effort the thesis applied Geels' (2002) socio-technical model to the automotive industry and explored its possible interpretation as a co-evolutionary system (Lewin and Volberda, 1999).

3.3.3 Depth and breadth as an *a priori* construct

One of the key recommendations made was to position the depth and breadth construct as emerging from the analysis of the case studies and discarding the inductive method discussed above. The key insight gained in the study of Eisenhardt (1989) is the role that an *a priori* construct can play in case study research. In fact, the relatively rough idea around the concepts of depth and breadth were in fact such an *a priori* construct and used as Eisenhardt recommends. Figure 3.2 gives an early version of the construct which was later simplified and is presented in Chapter 6 as Figure 6.2.

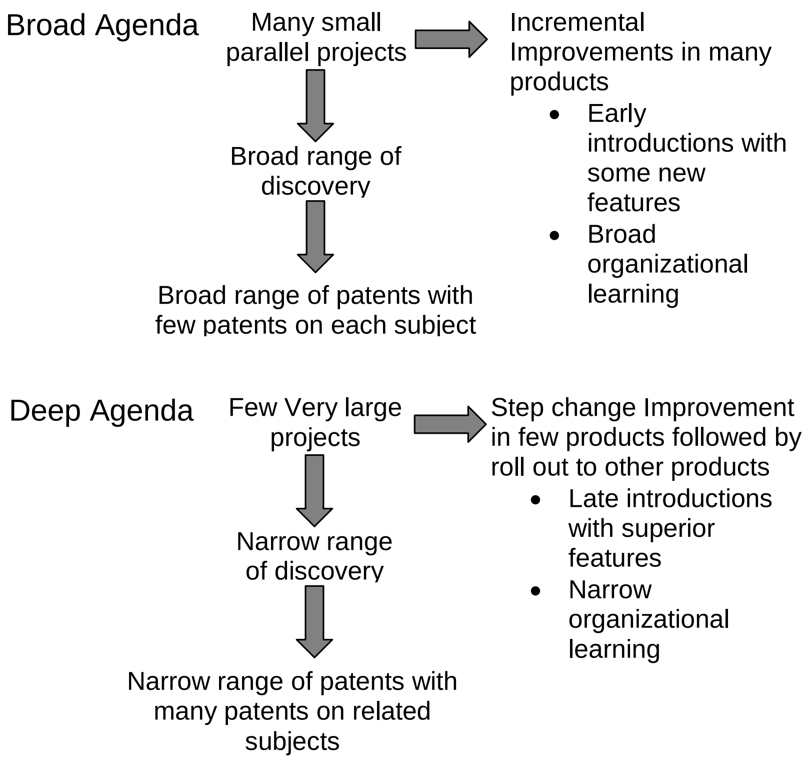


Figure 3.2 Preliminary construct for depth and breadth

As will be seen in Chapter 6, the main difference between the construct shown in Figure 6.2 and that finally found in the data is that the references to organizational learning were dropped during the research as lacking empirical evidence.

Eisenhardt (1989) discusses both the advantages and disadvantages of having an *a priori* idea of the constructs that might emerge from the data. On the one hand she explicitly talks about such constructs being able to "help shape the initial design" but also talks about the ideal of a "clean theoretical slate" and that "preordained theoretical perspectives or propositions may bias and limit the findings" (p. 536). Yin also stresses the importance of going into case study design with a "rich, theoretical framework" (Yin, 1994, p. 46). The thesis used the construct to inform the decisions about patent analysis and deployment data analysis which will be discussed further in Section 3.5 and 3.6 but did so only in a limited way in the expert interviews in order to limit the potential of biasing the research. As will be developed further in Section 3.7, the construct was not included in the interview guides but was discussed during the interviews as a possibility. Chapter 6 explores the evidence for and against the construct and highlights the comments from the experts both in support of it and when alternative explanations of the data were forthcoming.

3.4 Site selection

As discussed in Section 1.1, the potential radical evolution of automotive power train technology was chosen for the research due to the researcher’s personal experience in the industry, its importance to the world’s economy and the impact that the evolution of power train technology will have on environmental sustainability in the years ahead. The automotive industry has also proved to be a fruitful ground for management research as discussed in Sub-section 2.3.2.

According to Yin (1994), replication is the key point for multiple case studies and he recommends developing six to ten case studies which ought to be selected such that each case either “predict similar results” or “produce contrasting results for predictable reasons” (p. 46). Yin goes on to suggest that four to six cases are sufficient to see different patterns emerge. Building on Yin’s recommendations, the thesis develops a total of eight cases including four company case studies and four technology case studies. As the technologies are the same in each case, the thesis actually has a total of 16 nodes in the analysis.

Miles and Huberman (1994) stress the importance of setting a boundary around case design in order to drive sampling decisions and help focus the research although they also maintain that such boundaries can shift during the research. For the thesis, an initial decision was to focus on the United States (U.S.) as a geographic boundary for the research in terms of site selection and data analysis.

3.4.1 Company selection

U.S. market share was chosen as a measure of size, although other factors such as number of employees, revenue, etc. could have been chosen. Firms of sufficient size were thought to be in a position to dedicate sufficient funds to developing alternative power train technologies and thus could be classified as potentially showing similar results in Yin’s (1994) terms. Table 3.4 gives market share data for the United States in 2000 and 2008 from the industry trade publication, *Automotive News*.

Company	% U.S. Market Share 2000	% U.S. Market Share 2008
General Motors Group	28.3	22.3
Ford Group	24.1	15.1
Chrysler	14.0*	11.0
Toyota/Lexus	9.3	16.7
Honda/Acura	6.7	10.8
Nissan/Infiniti	4.0	7.2
VW Group	2.3	2.4
Hyundai/Kia	-	5.1

* 15.1% including Mercedes

Table 3.4 U.S. market share data for cars and light trucks (2000, 2008)

As shown in Table 3.4, the firms with the highest market share over time are GM, Ford, Chrysler, Toyota, Honda and Nissan. Chrysler was excluded from the sample due to complications arising from its aborted merger with Daimler. In 1998 Chrysler merged with Daimler and apparently combined its intellectual property efforts in the U.S. Daimler then sold Chrysler in August 2007, confusing the issue further, and it was decided to simply remove the company from the sample rather than attempt to purify the data. Honda has a significant presence in the U.S. but is a significantly smaller player in the global automotive business. Ernst (1998) recommends that patent analysis should also be done with companies which are somewhat homogenous in size, and thus Honda has been left out of the research. The Volkswagen Group (VW) and Hyundai have significantly smaller presence in the US but were also excluded from the sample for other reasons. VW is a very large global player but has struggled in the U.S. market over the years and was thought to have fundamentally different motivations due to its reliance on the European market. Hyundai not only has a very different global footprint to the other manufactures but is largely focused on a different segment of vehicles and thus was also thought to have different motivations from the other companies in the sample. As the interest was to find firms which could be predicted to show similar results, both of the firms were excluded.

3.4.2 Technology selection

As the purpose of the thesis is to explore the way vehicle manufacturers approached discontinuous and potentially disruptive technology, the primary consideration in choosing technologies for analysis was the degree to which they were considered as such at the time of their introduction.

As shown in Sub-section 2.3.2, a majority of studies focused on the automotive industry use changes to automotive power train technology as the context within which to do the research. One such technology, the hydrogen fuel cell has been the subject of increasing attention and investment (Dunn, 2002, Steinemann, 1999). Van den Hoed (2004) has documented how the automotive industry had, from 1998 to 2002, come to regard the fuel cell as the primary sustainable alternative to the internal combustion engine and this technology was the first selected to be part of the sample.

Due to their explosion in the automotive market, hybrid vehicles, which have both internal combustion and electrical drive train components, were also added to the scope of analysis. At the time of its introduction (in the Honda Insight and Toyota Prius), the technology was dismissed by many automotive executives as being too expensive for automotive applications and representing to sharp a break with current vehicle technology. Battery electric vehicles would, in hindsight, represent an interesting case study but were considered an unviable solution in 2003/2004 when the selection of technologies was being made and were thus not included in the scope of the thesis, although the technology is discussed together with fuel cell electric vehicles and hybrid vehicles even though the patent data for battery electric vehicles was not included. The problem with fuel cell and hybrid technologies in terms of academic research is that the technologies are still in development and it was recommended to add technologies further along in their life cycle as additional case studies in the research.

Four additional technologies were considered, as shown in Table 3.5, and each technology was considered regarding the degree to which the technology represented a discontinuity to automotive technology at the time of its introduction, the number of years between introduction and 2006, when these decisions were made, and the degree of patent and deployment data available.

	Discontinuity	**Years since introduction to 2006**	**Data Availability**
Fuel Cells Electric	Very High	10	Medium
Hybrid	High	10	High
Seat belts	Medium	40-50	Medium/Low
Airbags	High	25-30	Medium
Anti-lock brakes	Low	20-25	Low
Common rail diesel	Low	10-15	Low
Catalytic converter	Medium	15-20	Low

Table 3.5 Technology selection

The degree of discontinuity was determined by evaluating the technologies involved and comparing them with the researcher's prior knowledge of automotive engineering, as well as looking at criteria such as the novelty of the technologies under study to the industry or the world, the impact of the new technology on vehicle architecture, and the distance between the cost of the new technology and the targets that would have to be achieved for viability in automotive. Both fuel cell and hybrid technologies represent a sharp departure from traditional internal combustion engine technology, requiring the development of totally new power electronics in both cases and a completely new chemical-electric technology for fuel cell and battery chemistry as well as for the storage and delivery of new types of feed stock such as methane and hydrogen in the case of fuel cells. This last issue brought the vehicle manufacturers to cryogenic technology as well as other ways of storing hydrogen such as the use of metal oxides. While commonplace today, vehicle crash testing and the effects of crash dynamics on passengers was largely an unknown discipline back in the 1960's and represented an important discontinuity for the vehicle manufacturers (Johannessen, 1984). Airbags were, in the 1970's considered even more exotic and required the vehicle manufacturers to incorporate aerospace technology in the form of sensors, microprocessors and explosive devices on cars and, again, while the technology is accepted today, accounts such as that of Struble (1998) give a sense of the nature of the discontinuity perceived at the time. Anti-lock brakes also involved the application of sensors and microprocessors but the technology was better known by then and the challenge for anti-lock brakes was more about cost reduction of the systems already working in luxury cars and heavy trucks than dealing with technological discontinuity per se. The issue in common rail diesel engines was the pressure level required for the fuel system but this was thought to be a lower level of discontinuity as it only affected a limited number of components and did not involve any fundamentally different technology. Finally, although the catalytic converter involved very new technology and the development of completely new testing and analysis protocols, it was also limited in its impact on vehicle architecture.

Time since introduction was measured in an approximate way but its purpose was only to ensure an adequate level of historical data in order to determine the paths pursued by the different vehicle manufactures. While a more rigorous process of determining time frame could certainly be developed, it was not thought to add relevant depth.

Data availability was thought through in terms of both patent data and deployment data and while these topics will be discussed in depth in Sections 3.5 and 3.6, preliminary research was done prior to selecting the technologies. The problem with common rail diesel technology was that diesel engines are still not very popular in the United States and thus very few models have been introduced and therefore, it was thought that deployment rates and even patent counts would be lower than if the study was focused on European manufacturers. The patent patterns for catalytic converters were produced but when looking for deployment data the problem was that converter performance is not readily available in the public domain and thus the level of granularity is extremely limited. A similar problem existed for anti-lock brakes as cars were either equipped with them or not. For these reasons anti-lock brakes, common rail diesel technology and catalytic converters were dropped from the study. A similar problem concerning deployment data occurred in the seat belt data set despite initial indications that it would be possible to find richer seat belt data, and this issue is discussed in Sub-section 3.6.2.

These technologies were largely chosen based on their link to environmental and safety concerns as it was thought that such issues would be more analogous to the set of issues affecting fuel cell electric vehicles and hybrid vehicles and that other technologies which only had an impact on performance such as fuel injection, or passenger comfort, such as so-called “infotainment systems”. The technological development and product deployment of seat belts and airbags were largely driven by legislation, so perhaps one could argue for focusing on technologies that are more independent. According to interview subject number 6, however, the last major product innovation in automotive that was not the direct result of legislation was the V8 engine, and while this might be an exaggeration, the industry is heavily regulated and as will be seen in Chapter 4, the regulatory environment forms a critical part of the socio-technological regime and greater landscape. The disadvantage of focusing on safety and environmentally driven technologies is that it is difficult to determine the balance of competitive dynamics and regulation in the decisions of the vehicle manufactures to first develop and then deploy the technology. One aspect of this issue, which will be explored further in Section 6.4 is to consider when it makes sense for a firm to go beyond compliance (Reinhardt, 2005). Another is to consider the timing of the introduction of safety features and, while there is a class of safety-critical features for which no compromise can be made, the fact is that there are a large number of solutions for different problems and the cost benefit of them are routinely looked at in the industry.

A final issue concerning the choice of technologies is that two are largely linked to environmental issues and two to safety issues and the degree of comparability between these two sets of issues (Baron 1995) is not established. What is true is that both sets of issues are very high on the agendas of both the government regulators as well as consumer activists, but it is also true that the issues are different, fall under the responsibility of different agencies in the United States’ federal and local governments and are evolving along different time frames.

3.5 Patent data and mapping software

3.5.1 The choice of patents as a source of data

Understanding a firm's technological developments by looking at its pattern of patents is well established in the literature (Griliches, 1990; Pavitt, 1982). This type of analysis does have important limitations, covered below, but is nevertheless considered one of the best tools available to researchers considering the barriers to access, confidentiality and other methodological problems when trying to go deeply into the way companies bring out new technology (Pavitt 1982, 1988, Ernst, 1998). Due to its focus on the automotive industry, the use of patent data as a primary source of empirical evidence was thought to be reasonable as a surrogate for more detailed data on research and development expenditure. The ideas that specific industries engage in different levels of patenting and that, within a specific industry, the relation of overall R&D spending to the number of patents produced are well established in the literature, as is the idea that industry is far more important than national origin (Scherer 1983). While the automotive industry has propensity rates somewhat lower than other sectors (Arundel and Kabla, 1998), the critical finding from the discussion in Sub-section 2.4.2 appears to be to keep the data set homogeneous within an industry.

As patent data in the United States is quite accessible, it was decided to focus on the leading players in the U.S. market. This idea of looking at a critical market and the patents filed in it was first done by Reekie (1973) in his work on the international pharmaceuticals industry. As discussed in Section 2.4, many researchers including Soete (1987), Tong and Frame (1994) and Furman et al. (2002) used U.S. patent data because of the reliability and stability of the U.S. patent office, the quality and depth of the data it provides, and the idea that firms will take the trouble to patent in the U.S. whenever it is an important market for them. One of the main findings of Section 2.4 is that digital databases of patents and analytical tools have provided researchers with the ability to focus on increasingly granular aspects of the innovation process and the thesis follows in this direction by using patents to focus on the technological development level within the specific firms in the sample.

An initial search for patents was done using the USPTO Patent full-text and image database performing a search for each manufacturer using the keywords "seat belts", "airbag ", "fuel cell" and "hybrid" in the title and abstract. This approach did produce a collection of patents but had several problems. First the key words at times gave faulty results as not all patents concerning these technologies would have the keywords in their title and abstract and the term "hybrid" is found in common use for hybrid systems which have no relation to power train technology but do combine two technologies in other applications. Second, the total number of patents was low compared to other researchers such as Van den Hoed (2004, 2005), indicating that many patents were not being accounted for. For Ford, for example, only 15 patents were found for seat belts and 14 for fuel cells. Third, the volume of information provided by this initial effort was enormous and the issue of how to interpret this volume of data became critical. Gray (2007) suggests that science is in fact entering a new paradigm which he calls data intensive science where the central challenge is making sense of large amounts of data and thus the idea of visualization became central to the thesis.

3.5.2 Limitations in using patents

As developed in Sub-section 2.4.2, there are three problems with using patents in general and the methodology chosen raises others which will be discussed in Sub-section 3.5.3. These problems are discussed in depth by the pioneers in using patents and then repeated with minor variations by many others (Schiffel and Kitti 1978, Soete, 1987, Pavitt, 1985, Griliches, 1990).

Patents only cover a small part of innovative activity and much invention is not patented. Griliches' (1990) Knowledge Production function provides an analytical framework for this issue, and while Griliches does not develop a theoretical construct to explain why some inventions are patented and others are not, such a construct would logically include factors which are technology specific and related to technical architecture of the invention, as well as others which are firm-specific and have to do with the intellectual property strategy of a specific firm. The first problem is therefore that not all invention can be patented for a variety of technical reasons. By comparing data sets of patents within the same technological deployment, e.g., airbags to airbags or seat belts to seat belts, the expectation is that at least the technologically specific aspects of this effect will be similar across the data set.

The second problem cited is that not all patentable innovations are actually patented and that different firms have a different propensity to patent based on the options available for protecting their intellectual capital. Arundel and Kabla (1998) built on Soete's (1987) work in this area and found that, within industries, the propensity to patent was largely similar irrespective of other factors such as a firm's nationality. The thesis is confined to automotive manufacturers and therefore the propensity to patent could be considered as similar across the four firms selected.

The third problem is that patents have different levels of quality; meaning importance, value, depth, etc. This problem becomes even more acute when looking across different national patent systems. The thesis covers this problem in three ways: first, by looking at only U.S. patents, the thesis adopts a long tradition (Soete, 1987; Tong and Frame, 1994; Furman et al., 2002) in research using patents by relying to some degree on the U.S. patent office to impose a minimum level of quality on the sample. The second way that the methodology accounts for differences in quality is by looking at relatively large numbers of patents for each innovation and company following Griliches' (1990) finding that in large numbers the differences can become less critical. In the sample shown in Table 3.2 the smallest group of patents is found in Ford's patents concerning fuel cells with 40 patents which could be considered large enough to even out quality issues is difficult to say. The third and perhaps most important issue is that the thesis does not base its primary finding on the number of patents, which is where patent quality would have the largest impact but on the relationship between patents and their subject matter. This is done by using the free text analysis of the claims section and the *Themescape* maps which are described in Sub-section 3.5.3.

3.5.3 *Aureka* Database and *Themescape* Maps

To solve the problems associated with the initial effort to access patents, a specialist patent research company, InnovarIP (www.innovarip.com) was engaged to perform the relevant search of U.S. patents through 2006 using Thompson's *Aureka* database of all U.S. patents and Aureka's *Themescape* free text matching application. The findings of this effort in terms of patent counts are shown in Table 3.6, which also indicates in bold type the technologies and companies finally selected. InnovarIP was asked to find all patents for all major manufactures for the four technologies discussed above as well as catalytic converters and anti-lock brakes which were later dropped from the research as discussed in Sub-section 3.4.2.

Company Name	**Total US Patents**	**Airbags**	**Seat Belts**	**Hybrid Cars**	**Fuel cells**	**Catalytic Conv.**
General Motors	13078	**139**	**116**	**66**	**205**	222
Toyota	10588	**90**	**60**	**145**	**109**	515
Ford	10238	**46**	**63**	**142**	**40**	366
Volkswagen AG	568	18	3	-	3	179
DaimlerChrysler	3203	-	-	0	-	87
Honda Motor	10901	3	6	28	16	243
Nissan Motor	8519	**47**	**103**	**84**	**82**	410
Kia Motors	19	2	1	-	1	1
Renault	932	1	3	10	2	66
Suzuki Motor Co	688	-	14	27	2	38
Mitsubishi	98	6	12	22	70	113
Mazda Motors	2341	35	25	2	-	115
PSA	284	-	-	2		18

Table 3.6 Total U.S. patents through 2006

For the analysis itself, the thesis compares the claims section of the patents with each other, as did Tong and Frame (1994), rather than focusing on title and abstract. Patent writers and lawyers consider very carefully the words they use in titles and abstracts and do so with an eye to fulfilling internal company goals or external public relations objectives, regardless of the technical nature of the patents themselves. According to InnovarIP, the U.S. patent office gives only cursory review to titles and abstracts as they have no legal weight but do look very closely at the claims section which must be specifically related to the technical innovation of the patent. This makes the claims section more difficult to manipulate for legal or public relations purposes and also makes it a potentially more robust source of data for the thesis.

The problem with looking at the claims section is that the volume of information to read, code and analyze becomes very large and in line with Gray (2007), the thesis chose to use *Aureka*'s text matching algorithm and *Themescape* visualization tool to interpret the data. The application compares text fields in the patents themselves, finds words and phrases which come up in different patents, and groups them together. The algorithm is of a type called a naïve Bayesian classifier, which works with probabilities to determine the relationship between different documents. The use of databases such as *Aureka* and its free text analytical tools is becoming accepted practice in industry and has been called *Patent Informatics* by Trippe (2003) who considers such tools a robust way of looking at patents and their relationship to each other.

Once it has identified those words and phrases most commonly used in the patents, *Aureka* then groups those patents with statistically similar content. These groups are then graphically displayed in *Themescape* maps which represent the full set of patents as a topographical map of what looks like an island or group of islands. When there is more or less correlation between one set of patents and another, the software places them closer or farther away from each other on the map. When a number of patents share a phrase such as "detection shield substrate" or "glove box enclosure" the *Themescape* map will show them as hills or even mountain peaks. When there is little or no relation the system will create "islands" and separate groups by "water". The net result is an attractive and easy-to-use representation of the full set of patents which can be used to directly look at the issues of depth and breadth. A deep approach to introducing new technology would logically result in a map which resembles a volcanic island with relatively small land mass and high mountains grouped tightly together. A broader approach would show a larger, lower island with a number of peaks farther apart. A still broader strategy would resemble an archipelago with few peaks.

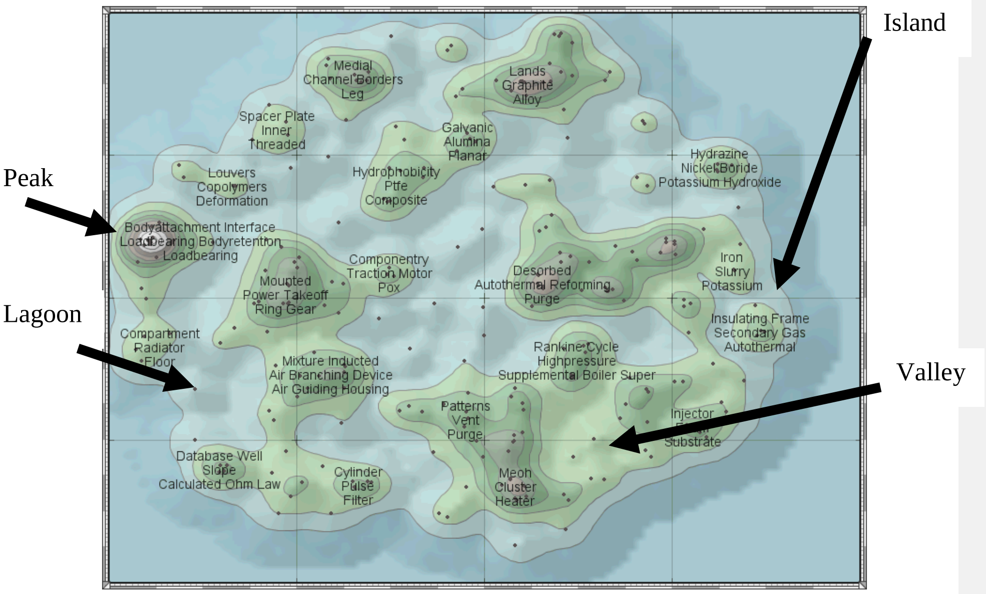


Fig 3.3 *Themescape* representation of General Motors U.S. patents in fuel cells

The thesis then performs an analysis of the different patent patterns by using the metaphor of a topographical map and counting and comparing ‘mountain peaks’, ‘small islands’, ‘lagoons’, etc. The *Themescape* representations of the U.S. patents for each of the technologies under study in each of the companies such as Figure 3.3 are shown in Section 5.2.

The use of the tools described above however does present a fourth problem, which is that it is unclear what exactly concepts such as “distance” and “height” in the topographical metaphor mean in terms of actual technology development, and that the text analysis software can identify false patterns in the data. For the *Themescape* maps, distance is an indication of the probability that two patterns deal with similar technology as calculated by the naïve Bayesian algorithm mentioned above. An analysis of patents filed by DaimlerChrysler, for example in the area of seat belts, produces a misleading picture with two large “islands” or areas of work due to the fact that a number of their patents use German words thereby causing the analysis to separate the patents into German and English areas; a deeper bilingual analysis would find more commonality between them. The idea that the powerful analytical tools that are increasingly being applied to patents can bring technological risks caused by the tools themselves is outlined in the conclusions to Section 2.4. In the case of the thesis, DaimlerChrysler was removed from the sample partly because of this problem as well as the issues of its de-merger discussed in Sub-section 3.4.1.Each of the 16 maps shown in Section 5.2 was analyzed for such false artefacts and no obvious problems were found. What is critical to consider, however, is that the use of visual patent mapping is quite new to academic research and further research will be required to fully operationalize it.

An important aspect of the analysis and mapping process, for example, is that the analysis ignores so called “stop words” such as “and”, “the”, “process”, etc., which are very common and thus distort the statistical analysis. Themescape has approximately 1,000 such stop words in its algorithm and Blanchard (2007) argues that small changes in the stop word list can make a big impact on the resulting maps. In his research, Blanchard refers to different mapping software such as Aureka, STN, AnaVistTM and OmniViz as “black box” (p.308) and shows how a skilled analyst can generate different maps for different purposes based on the careful selection of stop words.

Another issue is managing scale effects and calibrating the interpretation of the *Themescape* maps for the number of patents in a given sample. For example, the patterns of two manufacturers might appear similar but the number of patents in the sample range from 40 to 205. According to the senior patent specialist at Thompson scientific, Ric Snead (Telephone conference, May, 2010), the maps generate their own scale based on the number of documents under study and that the scale is logarithmic in that for any given order of magnitude, in terms of total number of documents, the scale should be similar; he did not see a major problem in comparing patterns based on 50 or 100 patents with others based on 200 patents. The thesis attempts to deal with this problem by commenting on each case separately. The analysis looks at factors such as the topography of the pattern, as well as its overall size, and highlights those cases where the number of patents is very small or very large.

A third issue is that by looking at all cumulative US patents up to 2006, there is no correction for time and major changes in strategy will simply not be captured. While parsing the data in time slices might be an attractive option, the advantage of this approach is that the data set becomes more robust by using a larger number of patents as suggested by Griliches (1990). The other temporal issue is that the different sets of patents were accumulated over long periods of time and the firms themselves have gone through significant changes during the period. As will be discussed in Sub-section 5.3.2, seat belts were first introduced in the 1950's and much of the early work was done in the 1960's. Airbag research started approximately ten years later, with fuel cells and hybrid research starting in the 1980's and 1990's respectively. The thesis attempts to deal with the second problem by taking this into account and attempting to factor in the evolution of the firms involved as required.

Finally there is a question as to whether the maps do in fact reflect the scope of technological development at all. In order to answer this question the *Themescape* maps generated for Ford's patents in airbags and fuel cells were compared with a manual coding of those patents found in the same categories in the initial patent search. Ford's airbag patents and fuel cell patents were chosen because both have relatively few patents (46 and 40, respectively) and the airbag pattern shows a very tight focused pattern while the fuel cell patents are very spread, as discussed in Sub-section 5.2.2 and shown in Figures 5.6b and 5.6d. While the total number of patents found in the preliminary study was less than in the final search, the patent counts for airbags and fuel cells were similar (15 and 14). The results of the analysis are shown in Table 3.7, in which it can be seen that the fuel cell patents fall into 10 categories compared to 8 in airbags and the categories appear to represent more disparate technologies and the albeit limited manual analysis confirms the direction shown in the *Themescape* maps.

	Ford Airbags Patents			**Ford Fuel Cell Patents**	
	Category	**Patent number**		**Category**	**Patent number**
1	Electronic circuits	4 262 931 4 366 465 5 544 914	1	Cell design -PEM	4 195 119
2	Integrated circuits	5 809 451	2	Cell design - solid oxide	7 014 934
3	Steering wheel housing	5 265 305 5 378 013 5 435 597	3	Cell design - Redox	4 396 687 4 407 902
4	Passenger side housing	5 669 626 5 810 338 5 489 116	4	Cell design - Alkali metal/sulfer	3 951 689
5	Door housing	5 447 326	5	Air system	6 716 546 6 896 095
6	Gas components	5 172 933 5 007 662	6	Power electronics	6 792 341 6 795 756
7	Igniter components	4 370 930	7	Energy dissipation / management	6 924 050 6 591 926
8	Complete system	4 262 931	8	Carbon monoxide removal	6 733 909
			9	Heating system	6 916 566
			10	Gas storage	6 736 229

Table 3.7 Manual coding of partial list of Ford's airbag and fuel cell patents

3.6 Deployment data

3.6.1 Data Sources

Data on the introduction of each of the four technologies comes from different sources, and the specific data sets used are discussed below for seat belts, airbags, and hybrid and fuel cell electric vehicles respectively. The method of research was to start with the manufacturer's web sites and cross-check data there with online resources, as shown in Table 3.8 indicating the sites, their descriptions, and the data provided for the thesis.

Web Site	Brief Description	Data Used in Thesis
www.gm.com	Corporate web site of General Motors	U.S. vehicle fleet, sustainability reports and future strategy
www.ford.com	Corporate web site of Ford Motor Company	As above
www.toyota.co.jp	Corporate web site of Toyota	Sustainability reports and future strategy
www.nissan-global.com	Corporate web site of Nissan	As above
www.toyota.com	U.S. web site of Toyota	Data on U.S. vehicle fleet
www.lexus.com	U.S. web site of Lexus	As above
www.nissanusa.com	U.S. web site of Nissan	As above
www.infinitiusa.com	U.S. web site of Infiniti	As above
www.autoliv.com	Autoliv company website	Detailed data on seat belts and airbags currently on the market
www.wikipedia.org	On line encyclopaedia	General information on technologies and links
www.sae.org	Web site of the Society of Automotive Engineers	Reports and technical articles
www.autonews.com	On line portal for automotive news	JATO specifications on all vehicles for sales in the U.S.
www.safercar.org	NHTSA Consumer portal	Safety data for many vehicles
www.nhtsa.dot.gov	NHTSA home page	Official U.S. Government safety studies and reports
www.fuelcells.org	Portal of fuel cells 2000	Access to semi-annual fuel cell Databook
www.conceptcarz.com	Webzine published by Daniel Vaughan	Data on prototypes and concept cars
www.autobloggreen.com	Webzine published by Weblogs, inc.	Data on prototypes and concept cars
www.hydrogencarsnow.com	Blog by Journalist Kevin Kantola	Prototype specifications

Table 3.8 Partial list of web sites providing deployment data

- Seat belts

With respect to seat belts, the technical data on the type of seat belts deployed by the manufacturers is irregular concerning which of the available components are actually incorporated onto which models. A company will, for example, boast about the pyrotechnic pretensioners on a specific model but will not specify which models do not have such devices. As such, comprehensive technical data was not readily available. As discussed in Sub-section 3.4.2, seat belts were selected in part because it was thought that deployment data would be readily available due to the interest in occupant safety and the fact that this assumption was incorrect led to serious consideration of taking seat belts out of the scope of the analysis.

Fortunately, data was found connected with two specific evolutions in seat belt deployment and these were used as a surrogate for the larger question of the manufacturers' deployment patterns: the introduction of rear seat belts and pyrotechnic pretensioners. Since January 1968, vehicle manufacturers have been required to install lap belt anchorages for each front and rear seating position and upper torso belt anchorages at each forward facing outboard seating position, but there was no requirement for installing rear seat belts. Saab and Volkswagen joined Volvo in putting seat belts on the rear seats in 1985, and in 1986 General Motors announced it would begin phasing in lap belts with shoulder restraints for the rear outboard seats of all of their vehicles. Over the next 3-4 years all manufacturers active in the U.S. market followed suit. In 1999, the United States' National Highway Traffic and Safety Administration (NHTSA) performed a study to evaluate the safety impact of the rear seat belts, and this gives a snapshot of seat belt deployment.

Pyrotechnic pretensioners were deployed by most manufacturers at the end of the 1990's and the beginning of the 2000's for front seats, and their deployment offers a second reference point. NHTSA provided a data set from model years 2001 to 2010 showing all models in the U.S. market and indicating which came with pretensioners as standard equipment. Unfortunately (for our purposes), both Toyota and Nissan had already equipped all of their U.S. models with pretensioners prior to model year 2001 but the data is useful when looking at General Motors and Ford.

An additional advantage of using NHTSA data for seat belts is that NHTSA assures that common definitions are used for the technologies under discussion and thus safeguards the rigor of the analysis. Data from the NHTSA rear seat belts report and the pretensioner data are provided in Appendix E.

Seat belt technology has been largely driven by a combination of developments at the niche level and legislation as opposed to ideas coming out of the major vehicle manufacturer's research efforts or market research; this idea of the origin of discontinuous innovation in the automotive industry will be discussed in greater depth in Section 6.4.

- Airbags

Appendix E provides a list of the type and number of airbags provided on cars introduced by the four firms under study from 1995 to 2006. As will be further developed in Sub-section 5.3.3, airbag development occurred in two dimensions over time. On the one hand, the deployment of airbags became increasingly sophisticated and tied into more complex electronic and mechanical components. On the other, cars were equipped with more and more airbags to protect more vehicle occupants from more types of collisions.

Along this first dimension, the thesis refers to *first generation* airbags as the kind described in Sub-section 5.3.3. *Second generation* airbags had superior designs, in that the overall airbag module was smaller, and more sophisticated electronic sensors were moved closer to the airbag and further from possible damage in a crash situation.

On/off switches were added so that the passenger side airbag could simply be switched off by the driver if travelling with a child or small person. Next, *smart airbags* were deployed which worked in conjunction with an *occupant sensor* and deployment algorithms, such as not allowing the airbag to deploy if it detects a small occupant based on that person's weight. Airbag manufacturers then developed *two stage airbags* or *advanced airbags* which could be deployed at different speeds and even to different bag volumes depending on the force of the collision and the size of the occupant.

The other dimension could be referred to as airbag proliferation. The first airbags installed only protected the driver. The passenger in the front seat was normally next with an airbag housed in the instrument panel. Side airbags were next introduced in the doors, and rear seats received airbags both in front of the passengers and along the side.

Additional airbags have been deployed recently for knee protection in the front seats and below the roof. Figure 3.4 shows Ford's *Safety Canopy* system which is a good example of the current level of airbag technology.

Figure 3.4 Ford's Safety Canopy system deployed on the Ford Edge
(From: www.fordvehicles.com/crossovers/edge/features/interior, accessed 15.6.09)

- Hybrid and fuel cell electric vehicles

In order to avoid issues of access and confidentiality, the thesis focuses on technical specifications which have been published by the manufacturers and other sources of data shown in Table 3.8. On the positive side, the manufacturers publicise these vehicles as a part of their overall public relations and marketing, so data is available for the commercially available hybrids and the fuel cell prototypes and concept cars. On the negative side, much of the technical data, such as cost, weight and volumetric size are either restricted by the manufacturers for competitive reasons or difficult to compare. For the comparison of the hybrid programs at each of the four manufacturers under study, the thesis focuses on five aspects of hybrid technology as follows:

1. The type of vehicle which is equipped, i.e., compact, SUV, etc.
2. The hybrid architecture used as discussed in Sub-section 5.3.5.
3. The battery technology employed.
4. Fuel economy measured in kilometres per litre.
5. Top speed on electric power when applicable.

For the comparison of the prototypes of fuel cell electric vehicles at each of the manufacturers, the thesis looked at five parameters as follows:

1. The type of vehicle which is equipped, i.e., compact, SUV, etc.
2. The fuel cell type and the fuel source it requires, such as methane, hydrogen, etc.
3. The storage medium for each fuel source.
4. Range as measured in kilometres.
5. Top speed as measured in kilometres per hour.

3.6.2 Limitations to deployment data

There are four limitations to the deployment data applicable to all of the technologies.

The first limitation, discussed in Section 3.3, is access to data. In a perfectly transparent world the opportunities for scientific investigation would be limitless, but in the real world, there are limits to the data that companies possess, are willing to share, and that a researcher can access. An example of this is seat belt and airbag data held by NHTSA. NHTSA tracks all aspects of vehicle safety in every vehicle sold in the United States and keeps all of this data in a central database. While the database is restricted to NHTSA investigations, NHTSA reports are published in the public domain so that data sets used in particular reports can still be accessed. Thus the rear seat belt data and pretensioner data used in Sub-section 5.2.1 comes from such reports.

A second important challenge from a methodological point of view is to ensure that the words used in specific sources are in fact comparable across the different companies and to ensure like-to-like comparisons. In some cases this is self evident as a vehicle either has one, two or multiple airbags, for instance but in other cases it is somewhat more complex, as Toyota might refer to “smart” electronics in a different way than Ford. Again, the advantage of using a government agency such as NHTSA is that it provides its own definitions and makes its own efforts to ensure a rigorous comparison.

The third problem is that verification of official web sites, webzines and blogs is extremely difficult. The official websites tend to support their own corporate agenda and might be biased. Bloggers and on-line journalists are also subject to exaggeration and often do not have the rigorous fact-checking approach required by traditional media, much less the analytical rigor required by social science.

The fourth limitation is that, although there are limits to data, the internet offers a huge amount of data and there is the danger of missing something. In reference to the seat belt data mentioned above, for example, while an effort was made to scan all the relevant publications by NHTSA and use their search engines, an exhaustive study of all of NHTSA's publications was not possible. This type of research is inevitably like looking for something in a dark attic using a flashlight. The problem is twofold. On the one hand one might miss interesting data by simply not shining a light on it and also might be pulled towards a certain type of analysis as a function of where the light is shining.

Specific problems associated with the data sets for each technology are as follows: The seat belt data is much more limited than desired but it has simply not been possible to obtain detailed deployment data for all models for the 50 years since the deployment of seat belts began. The choice to rely on partial data from NHTSA was made mainly due to the reliability and granularity of the data sets and the partial nature of the data, and limited time series were accepted as a trade off.

The airbag data set is better from all four points of view and the only main concern is the degree to which the definitions of each type of technology are in fact completely common across the four manufacturers. What is positive, however, is that the data sets are internally consistent within each manufacturer and, as the objective of the analysis was to understand the pattern of deployment, the importance of perfect consistency across the manufacturers in terms of definitions is not critical.

The choice was made to limit hybrid vehicles to those actually on the market in the United States in order to avoid the problems associated with fuel cell data as all vehicles on the market do, in fact, have to publish performance specifications which are checked by public and private groups such as the Environmental Protection Agency which publishes fuel economy data. The problem with the data on hybrids is that some of the most interesting technical information, such as detailed data on the type of transmissions and component performance, is not publicly available and has not been included. Keeping the analysis at a fairly broad level, however, does provide sufficient information for the purposes of the thesis and assures that the data set is sufficiently robust.

The main problems with the fuel cell data is that there might be concepts and prototypes developed by the manufacturers which are not in the public domain, and the performance characteristics of such vehicles is not independently verified in most cases. Nevertheless the interests of the manufacturers coincides with publicizing their progress in fuel cell vehicles for public relations reasons, and one would expect them to not excessively over-promise as the specialised press monitors their statements and looks for internal validity.

3.7 Interviews and triangulation

3.7.1 Purpose and approach

The purpose of the interview program is first to corroborate the contextual discussion in Chapter 4, second, to validate the results of Chapter 5 and third, explore to what degree the results found for the four technologies represent paths in the sense used by Teece et al. (1997). The overall idea is triangulate (Yin, 1994) the patent and deployment data and thus to make the thesis more robust. Miles and Huberman (1994) cite Rossman and Wilson (1984, 1991) as suggesting that in addition to triangulation linking qualitative and qualitative data can provide richer detail improving analysis and also open up "new lines of thinking" (p. 41) . Miles and Huberman (1994) offer criteria for determining the level of prior instrumentation needed for a study offering two extremes and a middle course, and Table 3.9 summarizes these arguments.

Little Prior Instrumentation	Much Prior Instrumentation	Middle course
o Instrumentation "can blind researcher to the site" o Instrumentation tends to "strip out context" o the statistical approach for large samples in unnecessary for case studies o instrumentation itself is a "misnomer" and all that is needed are some orientating questions	o No reason not to plan ahead o Instrumentation limits unnecessary information o Common instrumentation needed for comparable studies and theory building o Validated instruments are "the best guarantee of dependable and meaningful findings"	o Less instrumentation for exploratory research and more for confirmatory studies o Less instrumentation for single case studies and more for multiple case studies

Table 3.9 Guidelines for prior instrumentation
(adapted from Miles and Huberman, 1994, p. 35-36)

As discussed in Sub-section 3.2.2, the research is exploratory in nature and looks at a limited number of case studies. Therefore it was thought that less rather than more instrumentation would be appropriate but that a certain degree of preparation would be beneficial. Thus, the interviews were conducted using a semi-structured method as recommended by Easterby-Smith et al. (2002), and interview guides (Miles and Huberman, 1994) were used to assure a degree of validity and are shown in Appendix B1.

The interviews were not recorded for four reasons. In the first place it was thought that recording the interviews might limit the subject's willing to discuss firm-level issues, or at least might introduce anxiety (Easterby-smith et al., 2002). Second, the interviewer is experienced in remembering the salient facts and concepts, and third it was considered that detailed interview notes would be sufficient for the purposes of analysis in any case, and finally, as many of the interviews were conducted on the telephone it was thought that recording would be not only technically challenging but also make more difficult the issue of trust mentioned above. Notes were taken by hand and summaries of each interview were immediately written up and are also included in Appendix B2.

Interviews were conducted at both the firm level and technology level, and analysis was performed by cross-checking the interview notes with each case study and the discussion themes raised in Chapter 6 in an iterative way. A more formal coding system was not pursued due to the limited number of interviews and a sense that theoretical saturation (Glaser and Straus, 1967), had already been reached.

3.7.1 Interview Subjects

The advantage of looking at innovations which occurred in the past, such as seat belts and airbags, is that what has happened is part of historical record and the much of the data is clear and robust. One of the limitations of the approach is that the engineers and managers who were closest to developing the deployment strategy for these innovations have for the most part retired or moved on in their careers. The choice was made, therefore, to interview independent technologists and management consultants familiar with either the technologies or the companies under study or some combination thereof; the interview subjects are shown in Table 3.10.

#	Subject Name	Position	Companies /Technologies
1	A. Egglestone*	Independent Consultant, Formerly Marketing Director, Europe, Ford and Director, Intelligent Energy	Ford Fuel Cells, Hybrids
2	J. Olssen	R&D Director, Autoliv	Seat Belts, Airbags
3	M. Wiseman	Director, Alternative Powertrain, Ricardo	Fuel Cells, Hybrids
4	S. Parker*	Independent Consultant, Formerly Managing Director, Ricardo Strategic Consulting and advisor to Nissan	Nissan
5	L. Bailoni*	Vice President, Bright Automotive Former Management Consultant and Industry Analyst	Seat Belts, Fuel Cells, Hybrids
6	C. Oge	Director, PRTM	GM, Toyota
7	G. Mercer	Director, International Motor Vehicle Program Formerly, Senior Partner, McKinsey & Co.	Ford Fuel Cells, Hybrids
8	D. Struble	President, Struble Walsh Engineering	Seat Belts, Airbags

* Also reviewed Chapter 4

Table 3.10 Interview subjects

The advantage of using management consultants is that they might be more objective than current or past employees of the firms under study. Finally three of the experts were also asked to review a draft version of Chapter 4 in order to add validity to its description of the industry.

3.7.3 Limitations of interviews and triangulation

Two of the problems with using interviews discussed in the literature are the nature of the interaction between the interviewer and the interviewee, and the cognitive process in each of their minds. The primary issue in dealing with the first point is to build trust between the interviewer and interviewee (Easterby-Smith et al, 2002). Miles and Huberman (1994) argue that familiarity with the subject under study is of primary importance in establishing that trust. With respect to the behaviour and thinking of the interviewees, the key here is to avoid misinformation either deliberate, as in the case of Margaret Meade cited by Easterby-Smith et al. or accidental, as in the case where an interviewee is misinformed. In order to control for misinformation, interview subjects were selected based on their expertise, personal relationship or both. In order to avoid firm bias it was decided to rely on management consultants and independent suppliers who would not give a biased view of any one of the companies in the sample.

The danger of familiarity is that a subject might respond to what they understand is desired by the researcher and in order to limit this affect, i.e., the ability of the researcher to affect the outcome of the interview, the interview guides were designed in an open way and a conscious effort was made to avoid leading the interviewees during the interview. As pointed out by Miles and Huberman (1994), qualitative research requires a high degree of self knowledge. This conscious effort was critical in allowing the interviewees to give their views of the deployment strategies being pursued in the different firms despite the researcher's potential bias introduced by considering the *a priori* construct defined in Sub-section 3.3.3.

With regard to the specific set of interview subjects used for the thesis, the major danger was in establishing the validity of the sample and whether it is large enough to support the research. Janesick (2000, p. 393) defines validity in qualitative work as having to do with "description and explanation and whether or not the explanation fits the description". The program was designed to ensure at least one subject for each of the manufacturers and for each of the technologies and, as the interviews have provided explanations which are consistent with the patent and deployment data, the sample size could be considered sufficient for the purposes of the thesis.

Triangulation is designed to overcome the limitations of different sources of data by comparing them with one another. The challenge for the researcher is to maintain a critical perspective when going through this process, sifting through the empirical data and developing conclusions. Janesick (2000) has come to prefer the term crystallization to triangulation as, for her, the process has to do with choosing which facets of an issue to focus on while recognizing that there will be facets or aspects of reality that the researcher does not see at any point in time. When different streams of data point in the same direction it is tempting to only see the correlation and ignore any contrary explanations as to why the data points agree. When data does not correlate there is a strong temptation to look for alternative explanations rather than considering rejecting the main hypothesis. A conscious attempt was made to control for both of these problems and perhaps the most robust aspect of the critical realist ontology is the idea that it is normal to be only partially able to explain reality and therefore it is acceptable to have unexplained anomalies in the data (Blaiklie, 1993).

3.8 Prior knowledge

One of the debates currently underway in the area of qualitative research is the appropriate role of the researcher in influencing their research through their own experience. According to Fine et al. (2002, p. 108) there has been a "tendency to view the self of the social science observer as a potential contaminant" and they argue for a more reflexive paradigm in which the researcher's experience can be seen as part of the research. Gergen and Gergen (2002) also discuss reflexivity and refer to it as one of the major innovations in qualitative research. While the thesis does not take on a reflexive epistemology per se, prior knowledge does play a role in the research and is considered an asset to be exploited rather than a problem to be resolved.

This is not to underestimate the danger of bias which, in any case, must be managed. To do this the thesis first makes explicit the use of prior knowledge in informing the literature review and research methodology shown in Figure 3.1, including the expert interviews and case studies, and the development of Chapter 4, which establishes the context for the research. Second the thesis makes use of well-established frameworks such as Eisenhardt's (1989) roadmap for case study research and Geels'(2002) model of a socio-technological regime to ensure that the research is well structured and that the use of prior knowledge does not lower the level of academic rigor of the research. Finally the research is firmly grounded in the empirical data, and a conscious effort has been made to control for bias while at the same time taking advantage of prior knowledge of the sector and several of the firms and technologies under study.

3.9 Chapter summary

The purpose of this Chapter was to explain the research methodology used in the thesis and discuss the rationale for choosing it as well as highlighting its limitations. Bhaskar's (1975) Critical Realist Perspective was chosen due to its fit with the exploratory nature of the research which also led to the decision to base the research on case studies using Eisenhardt's (1989) roadmap for performing case study research with an *a priori* concept in mind at the start of the project. This approach was chosen after several false starts which are briefly reviewed. The final research design is shown in Figure 3.1, and each aspect of the research program is discussed in detail, highlighting its advantages and limitations and in some cases exploring avenues not taken.

In terms of the typology of research concerning new types of automotive power train technology presented in Sub-section 2.3.2, the research belongs in the category of understanding the history and current status of the transition without taking a biased view of it. In terms of the typology of research using patents in management science presented in Section 2.4, the thesis falls into the product and product category level and can be thought to be at a similar level of focus to work done by Penan (1996) and Prencipe (1997). The research is also an example of using patent informatics (Trippe, 2003) and goes further than other researchers in pioneering the use of mapping software, in this case Thompson's *Themescape maps* and, while using such a new tool brings about a number of interpretation issues which are discussed, it also gives an example of Jim Gray's (2007) idea of data intensive science which will become increasingly important as researchers attempt to deal with increasing amounts of data.

CHAPTER 4 CONTEXT

4.1 Introduction

The thesis develops case studies in the automotive industry as the context for studying how firms react to discontinuous and potentially disruptive technological change. Effort was made to look at the context in a rigorous way for three reasons. First, Yin (1994) argues that case studies are especially appropriate "when the boundaries between phenomenon and context are not clearly evident" (p. 13) and thus defining the industry clearly is necessary in order assist in the process of separating out the phenomena of interest. Second, as discussed in Section 3.8, the researcher possessed a degree of prior knowledge concerning the industry and it was considered necessary to make that knowledge explicit in order to avoid bias in the research. Third, the thesis contributes to the theory of the technology-based firm (Granstrand, 1998) and the reason that Granstrand put forward a separate theory for those firms affected by and involved with technology was due to the co-evolutionary interaction between such firms and their environment and it was therefore considered necessary to establish that such co-evolutionary effects occurred in the automotive industry.

The objective of Chapter 4 is thus to develop a rigorous definition of the automotive industry and uncover evidence for its consideration as a co-evolutionary system as described by Lewin and Volberda (1999). Section 4.2 will first review the theory which is used in the Chapter, and also discuss Pavitt's (1984, 1987) technology trajectories which were not used and explains why not, as this sheds some light on the complexity of the industry. It also explains why Geels and Schot's (2007) technology pathways were adopted to look deeper into the technologies in Section 5.3. Section 4.3 will use Geels' (2002) socio-technological model to describe the industry and Section 4.4 will apply Lewin and Volberda's (1999) five properties of co-evolutionary systems, and examples from the industry for each of the properties will be presented. As the examples are not comprehensive, the findings of this section will be limited to allowing for the consideration of the industry as co-evolutionary. As stated in Section 3.6, a draft of this Chapter was reviewed in depth by three of the industry experts who participated in the interviews for the thesis to assure the accuracy of the descriptions made and examples used as well as the validity of the findings.

4.2 Theory applied to context analysis

- Transition changes and the multi-level perspective

The work by Kemp et al. (1998) discussed in Sub-section 2.3.1 can be thought of as part of the multi-level perspective. According to Geels, Rip and Kemp first developed the multi-level perspective but Geels (2002) provides a very detailed look at the perspective at the same time as he enriches it. Citing Rip and Kemp (1998) and others, Geels defines the multi-level approach as looking simultaneously at three levels of analysis and uses the shift from sailing ships to steamships as an example.

The first level is the overall socio-technical landscape in which industries compete. The landscape changes relatively slowly and analysis of it includes social, economic, political and technological aspects. The second level of analysis is called Socio-technical regimes and, for this, Geels adds considerably to Nelson and Winter's (1982) concept of technological regime to include a total of seven dimensions which make up the web of actors and ideas around which Dosi's (1982) idea of dominant design would exist. The third level of the perspective is at the niche level where Geels, like Kemp et al. (1998) and the other researchers contributing to this area, believe that innovations truly occur. Geels' example focuses on England's dominant position in shipping in the 1700's and the tremendous changes which swept the world over the next 200 years, including the rise of the United States, shifts in world trade patterns and even geopolitical concerns. The sailing ship was the artefact at the centre of one regime which was eventually replaced by the coal powered steamship at the centre of another. Tug boats and short haul mail routes were niches in which the first steam powered vessels became popular. Geels also provides a rather comprehensive illustration of the regime concept and actually uses the automotive industry as a brief example. His framework is used to describe the overall context of the empirical evidence of the thesis. The seven dimensions Geels spells out in looking at a Socio-technical regime are:

1. The technology itself
2. User practices and application domains, by which Geels means markets
3. The symbolic meaning of the technology to the society at large
4. The infrastructure which is required to use it
5. The industry structure in which it is produced, including original equipment manufacturers (OEMs), suppliers, etc.
6. The set of rules and regulations or policy imposed by regulatory bodies
7. The sum of technological and scientific knowledge

The multi-level perspective is thus built around a macro landscape, which changes slowly over time, in which exist a number of socio-technical regimes representing the major elements of industrial society. Within each regime there are or could be a number of niches in which innovation or novelty, as Geels calls it, can occur. Profound transitions, such as sail to steam, occur because of what Geels calls niche accumulation. The process he describes is that the new technology is adopted in, or is used to create, several niches over time. Once a new technology is present in a large enough number of niches it can develop its own socio-technological regime which will then compete with the incumbent technology's regime. Often the adaptation process is done by employing the technology as an "add-on" to existing technology or developing hybrid solutions which combine elements of both. Steam power, for example was first introduced on ships for auxiliary power, and iron was used in combination with wood prior to the large scale construction of iron ships. Another mechanism which Geels cites as contributing to the emergence of a new regime is through explosive growth in those niches in which the new technology is successful. In his examples there were huge increases in transatlantic passenger traffic, which was one of the first transoceanic applications of steam ships. When a niche itself takes off, it pulls the new technology along with it potentially giving it enough scale to begin developing a new socio-technological regime.

- Co-Evolutionary perspective

In their seminal prolegomena on co-evolution (1999), Lewin and Volberda introduce this perspective and situate it at the centre of the intention-adaptation debate.

After reviewing population ecology, institutional theory, the industrial organisation perspective, transaction cost view, behavioural theory of the firm, evolutionary theory and the resource-based view, as well as contingency theory and what has been called the punctuated equilibrium view, Lewin and Volberda argue that all of the above lenses simplify the actual complexities of the world in which organisations adapt to their environment and at the same time affect that environment. Lewin and Volberda define co-evolution as the "joint outcome of managerial intentionality, environment, and institutional effect" (Lewin and Volberda, 1999, p. 526). Lewin and Volberda discuss the five properties of a co-evolutionary system as follows:

1. *Multi-levelness* has to do with the co-evolutionary process taking place within firms, between firms in a strategic niche, across industries and in fact in the greater environment.

2. *Multidirectional causalities* are where different actors affect each other; it is often quite complex to track which element in the complex system affects which others.

3. *Nonlinearity* has to do with the uneven and often unexpected impact that changes, in one part of what is in fact a complex system, have on other parts. These impacts can be non-linear in the sense that a small change in the environment can have a huge impact on organisations.

4. *Positive feedback* is the process of different changes reinforcing each other in a positive way (or negative, depending on one's point of view).

5. *Path and history dependence* is the idea that co-evolutionary changes happen over time and that what has happened previously has a direct impact on what will happen next. This is not to say that changes cannot be radical or disruptive but simply to acknowledge that there are patterns to change and that history does matter when looking at such phenomena.

- Technological trajectories

Pavitt (1984, 1997) developed a set of five major technological trajectories which include the main sources of technology and the main aspects of innovation strategy which he defines as positions, paths, and processes and refers to the automotive industry as scale intensive. The promise of Pavitt's framework is that by characterizing an industry as following one of the five trajectories, the researcher would have a clear set of concepts to work with to get at the technology strategy of firms in that sector. Table 4.1 shows Pavitt's (1984, 1997) 5 trajectories and the key characteristics of each.

Souitaris (2002) built on Pavitt's typologies by arguing that different managerial factors would drive innovation in the different trajectories such as marketing and strategy for supplier dominated firms, finance and R&D for scale intensive firms, growth and project management for specialized suppliers and R&D, profit growth, and licensing for science based firms. Souitaris did not comment on the information intensive trajectory. Souitaris did find Pavitt's trajectories compelling at the firm level with the addition of his discussion on management. For application to the thesis, the typologies would have to be adapted to the technology level from the firm level for which they were created, and this poses a potential challenge. Prior to undertaking that effort, however, it is necessary to consider which of the typologies presented by Pavitt do, in fact, best describe the modern automotive industry, as one could argue that its place as a scale-intensive business is not as clear today as it might have been in 1984 and even 1997.

	Supplier Dominated	Scale-Intensive	Science-Based	Information-Intensive	Specialised Suppliers
Main Task	Use 3rd party technology to reinforce competitive advantage	Incremental improvement and diffusion of best practice and design	Monitor and exploit advances from basic research	Develop and operate information systems to introduce new services	Match new technology to the needs of the most advanced users
Positions	Based on non-technical advantages	Cost effective and safe products and processes	Portfolio of products including pipeline	Depth of information infrastructure	Relationship with advanced users
Paths	Strategic purchasing & roll-out	Incremental integration of new knowledge	Major jumps	Customer needs analysis and service development	Optimisation of reliability and performance
Processes	Flexible response	Diffusion of best practice	Basic research & regulatory process	New service development	Interactions with users

Table 4.1 Summary of Pavitt's Technology Trajectories
(Adapted from Tidd et al., 1997)

Specifically, four industry trends blur the distinction in Pavitt's typology; the growing role of suppliers, increased government regulation, heavier use of information technology and shorter production runs. In the first place, automotive suppliers such as Bosch, Denso and others have assumed a growing role in developing and disseminating new technology. In areas such as common rail diesel technology and many others it has been the automotive suppliers and sometimes one firm who bring about an innovation and then progressively roll it out to its customers. In this regard the automotive industry sometimes behaves using the "supplier dominated" trajectory and it is the power of the purchasing department and engineering's ability to incorporate a supplier's module or component that is key.
Secondly, as government regulation increases in areas such as safety, pollution and fuel economy, the industry is increasingly obliged to follow the "science based" trajectory of

doing basic research and following government regulations in order to get its products "through" the system. Much of this basic research is in areas such as testing protocols that are not easily visible to the public but nevertheless have a huge impact on competitiveness. The third trend is the increasing importance of customer research and customer relationship management, as well as other applications of advanced information processing technology in such areas as automotive financing, warranty administration, parts and service, outbound logistics and vehicle design. The power of a company's information technology is becoming increasingly central to its competitive positioning; this could lead one to classify the industry as "information intensive".

Finally, the scale of automotive production is actually reducing with increasingly shorter production runs of new models. In fact the most profitable automotive company over these twenty years has been BMW with just a fraction of the scale of some of its rivals. While production runs of hundreds of thousands of units was the goal of every carmaker in the past, some of the industry's most exciting products are designed with volumes of only 50,000 units. Thus, the car companies are beginning to behave as specialised suppliers and are often most successful when appealing to very specific groups of advanced users. As Pavitt's trajectories cannot inform the research due to this ambiguity, and were in any case developed for the firm level, the thesis will apply Geels and Schot's technological pathways to inform the technology case studies and guide the analysis. Prior to exploring the technologies, however, it is first necessary to firmly establish at what level in the multi-level analytical framework, discussed in Sub-section 2.3.1, the automotive industry should be considered.

4.3 A Socio-technological model of the automotive industry

Geels' (2002) application of the model to personal transportation is shown in Figure 4.1.

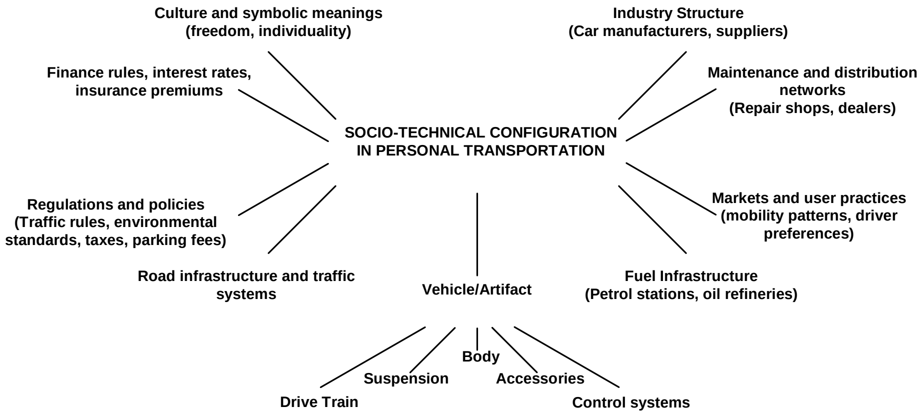


Figure 4.1 Geels' view of personal transportation (Geels, 2002, p. 1258)

The following discussion will develop Geels' ideas further and attempt to rigorously apply the seven elements discussed above to the industry drawing on research done in the academic and practitioner literature as well as the researcher's own knowledge of the industry.

- Technology

The first automobile was built by Karl Benz in 1885, based around a four-stroke cycle petrol engine which he patented the next year. Over the next 124 years the technology has steadily developed across a number of different technological areas. The modern automobile has over 10,000 parts and is generally considered to be made up of a number of different systems and modules. In Figure 1, Geels divides the vehicle into 5 major areas and, while this is the basis for most, if not all, vehicle breakdowns at the aggregate level, car manufacturers and suppliers go further at the operational level.

Comment [A4]: figure 4.1?

The term *system* is normally used to refer to groups of components which perform a specific function. The brake system is an example and consists of discs, callipers and friction pads on the wheel, an electronic control unit, hydraulic fluid, lines and pressure pump, and the brake actuator located behind the brake pedal. *Modules* have more to do with the assembly process of cars and light trucks and consist of subassemblies of components which are all placed on the assembly line together as a unit. The idea behind modules is that logistics and final assembly processes become much faster and dimensional quality control can be improved at lower cost (Sako and Warburton, 1999).

Systems and modules are not always mutually exclusive and a "front corner module", for example, has those brake components located on or around the wheel together with the steering knuckle, spring, and shock absorbers all bundled together for easy assembly. Figure 4.2 shows two types of front corner modules manufactured by Delphi.

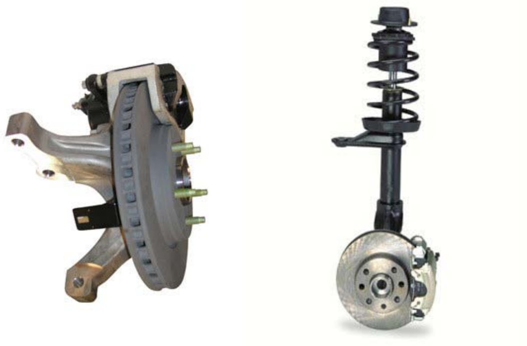


Figure 4.2 Front corner modules
(from www.delphi.com accessed 12.5.09)

In the industry, the term component is used to describe the pieces and devices that make up the systems and modules defined above. Brakes give an illustration of the range that components can have in terms of size, complexity, and number of parts. Automotive brakes work by pressing two pieces of material against a steel disc with hydraulic force. The disc itself is referred to as a component. The brake pads are relatively inexpensive components and consist of a piece of friction material attached to a steel or plastic housing so that they can be attached to the callipers. The electronic control unit is a small computer that is attached to sensors that monitor different aspects of a vehicle's motion and the brake's performance. The unit itself is referred to as a component, as are its sensors. Figure 4.3 shows the mechanical components of a typical brake system and a schematic view of the electronics associated with anti-lock brakes.

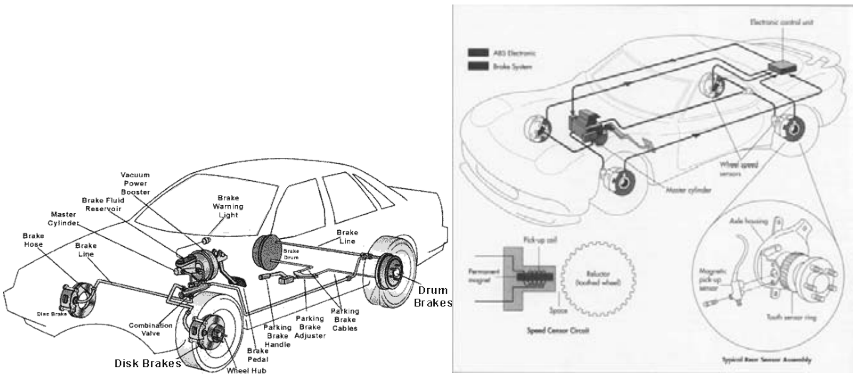


Figure 4.3 Brake system
(from www.mycarbox.com and www.madehow.com accessed 12.5.09)

Another example at the component level is a headlight which is sometimes integrated into a front end module. A headlight is made up of up to 30 parts as shown in Fig 4.4

Figure 4.4 Automotive headlight
(from www.expo21xx.com accessed 12.5.09)

- Markets

In many ways, General Motors' Alfred Sloan created the idea of market segmentation by developing vehicles for "every purse and pocket", and today the industry is normally segmented using five different concepts: geography, form, size and price, demographics, and psychographic profiles of drivers/owners.

1. Geography

Table 4.2 shows worldwide sales of cars and light trucks in 2007 according to Automotive News. At the time of writing, the industry is facing its worse slump in memory but, while the overall volume might fall sharply in 2008 and 2009, the basic geographic distribution will most likely remain similar.

Region	**Cars 07**	**Trucks 07**	**Total**
Asia-Pacific	14,727,330	6,692,764	21,420,094
Europe	19,198,854	3,728,731	22,927,585
North America	9,379,152	9,993,099	19,372,251
Central/S. America	3,336,011	1,072,092	4,408,103
Middle East	1,907,938	459,110	2,367,048
Africa	947,718	458,057	1,405,775
TOTAL	49,497,003	22,403,853	71,900,856

Table 4.2 Global Automotive Sales
(from Automotive News 2008 Global Market Databook)

Looking at the country level, the United States, China, Japan and the top 6 markets in Europe (Germany, the U.K., Italy, Russia, France and Spain) make up a total of 48,600,000 vehicles, or 68% of the total. While some companies in particular segments are able to successfully market the same vehicle all over the world, large manufacturers are struggling with the challenge of internationalisation (Freyssenet and Lung, 1999) and normally develop different vehicles for these different major markets as well as others. This is due primarily to five reasons.

First, people in the different markets have preferences about what kind of car they drive. Americans tend to prefer larger, more powerful vehicles. Europeans appreciate a different kind of styling, buy smaller cars due to regulatory and size restrictions, and enjoy responsive suspension. Japanese buy even smaller vehicles and appear to be happy with what North Americans and Europeans would consider underpowered engines.

Second, regulation is different in the different markets and, while there is a tendency to convergence, the fact is that safety and environmental standards remain different in the different regions.

Third, the automotive companies themselves have all developed from home markets and there is a degree of organisational inertia which tends to reinforce the idea that each region needs its own design, styling, and even engineering. Some OEMs, such as Honda, BMW and Mercedes, continue to focus R&D largely in their home markets which are staffed by nationals and long term employees who rarely move. Others, such as GM and Ford, have significant R&D assets located outside their home market and have experienced a degree of regional diversity as a result.

Fourth, in the researcher's experience, the regionalisation process plays out in the industry in the following way. In order to get closer to customers in Europe, a Japanese or American company, for example, will open a styling studio in London, Milan or Barcelona and staff it with creative people. These people will then develop ideas that they think will appeal to the European market and benchmark themselves against successful vehicles in the market. In the end the process reinforces the idea that each market is different since designers and engineers involved are being paid to develop and accentuate those differences.

The fifth and final reason for the difficulty in developing a truly "world" car is the tremendous complexity involved. The industry as a whole is very familiar with spectacular failures to produce such a vehicle such as the 1993 Ford Mondeo, also known as CDW27. Billed as a world car, the North American and European versions actually shared very few parts (wikipedia.org/wiki/Ford_Mondeo accessed 13.5.09). Some would argue that the 1996 Fiat Palio, or "178 project", was one of the more successful attempts at developing a world car (Camuffo, 2000). Luxury brands such as Mercedes and BMW have been successful selling the same cars all over the world by designing for specific key markets, such as Germany and the United States, and then making whatever changes are needed for legal issues in others.

2. Form

Within the industry, perhaps the strongest technological paradigm has to do with the basic forms that we all recognise in motor vehicles. Form refers to the traditional layouts or architectures called sedans (saloons), station wagons (estates), coupes (coupés), speedsters (sports cars), vans and pickup trucks. Over the last twenty years, innovative body styles such as mini-vans and the ubiquitous sports utility vehicles have been added to the mix, as have so-called "crossover" vehicles which combine different elements of the more classical body styles.

3. Size & price

Two other basic ideas are that bigger cars should cost more money than smaller cars and that there are different levels of quality and performance between brands. Our willingness to pay for motor vehicles has been found to correlate directly with these ideas. If one were to plot all of the cars on sale in a given market by price and basic size, one would find a fairly strong correlation within brands of similar prestige with people paying more money for larger vehicles.

4. Demographics

Different people have different needs and buy different cars. Men and women have different driving patterns and, in general, look for different things in their vehicles. Older and younger drivers have different tastes and people with different levels of affluence buy different types of cars. In general, this type of segmentation is referred to as demographics and is often done within a specific geographic market such as North America, Europe or Japan.

5. Psychographic profile of the driver/owner

The fifth way of segmenting the automotive market is by how people use and think about their cars, and market researchers have found correlations between car use and lifestyle. BMW buyers, for example, also appear to ski and play tennis; using this kind of data, automotive companies have developed psychographic profiles distinguishing between people who might have the same demographics but different lifestyles.

- Symbolic Meaning

Titles such as The Car Culture (Flink, 1976); The Automobile Age (Flink, 1990); The Automobile and American Culture (Lewis & Goldstien, 1983); A Nation on Wheels: The Automobile Culture in America Since 1945 (Foster, 2002); Two Billion Cars (Sperling and Gordon, 2009) and many others go into detail on the impact that the automobile has had on society and discuss three broad issues.

In the first place, cars have changed the way we live, where we live, and how we spend our free time. Having a car has become part of people's aspirations in many parts of the world for its association with personal freedom, economic progress and, in some places, as a sign of coming of age. People also define themselves publicly by what they drive. The choice of a large Sports Utility Vehicle (SUV) or bright red sports car says a lot about the person driving it, or at least about what that person wants to communicate, and in developed countries cars are often an important fashion statement.

Second, the idea that there is a causal link between our motorised lifestyle and climate change is now entering the cultural fabric and giving rise to an increasingly vocal and committed backlash against the automobile and the suburban lifestyle that it has allowed. Driving an energy-efficient vehicle, such as a hybrid car, has also become something of a statement about the politics of the driver.

Finally, industrial production of automobiles, their components, and the development of the infrastructure to support them has also played a key role in overall industrialisation and the dissemination of manufacturing know-how.

- Infrastructure

In his chart reproduced as Figure 4.1 above, Geels (2002) distinguishes between two aspects of automotive infrastructure: road and traffic infrastructure, and fuel infrastructure. A third element of the infrastructure surrounding the automotive industry is the network of restaurants and lodging facilities which have sprung up along the highway routes. The network of repair shops and retail outlets could also be considered part of the infrastructure due to its historical origin and its importance in any substantial shift in the socio-technical regime.

1. Road and traffic infrastructure

Without roads and parking facilities, cars and light trucks have extremely limited value. According to the popular website, about.com, there are over 2 million miles of asphalt roads in the United States. In the United States, the building of the interstate highway system in the 1950's led to a huge increase in vehicle traffic and economic growth (Rose, 1979) and country after country has undertaken similar programs over the years. India, for example, is currently building a series of highways running all around the subcontinent called the "golden quadrilateral" (www.nhai.org accessed 14.5.09).

The first traffic light was reportedly set up outside the houses of Parliament in the United Kingdom in 1868 and had gas lights for use at night. The first electric traffic light was deployed in Salt Lake City Utah in 1912 and the first four-way, three colour device in Detroit in 1920 (wikipedia.org, accessed 15.4.09). Since then, traffic control systems have become commonplace all over the world. Systems were first operated by manual switches and then pre-programmed using first electromechanical and then digital control systems. Today such systems are operated by integrated networks which allow local authorities to monitor and direct traffic patterns. Active management of road and highway networks is becoming increasingly common, and the latest innovation is to allow cars to communicate directly with the highway system using electronic toll-collection technology based on radio frequency identification technology.

Parking also plays an important role as it is no use to go somewhere in a car if you cannot park it. While there is a strong link between parking availability and regulation, which will be covered below, the need for parking has had an important impact on planning and architecture and can be tied directly to the rise of suburbs and shopping centres in the U.S. and other parts of the world. The first parking meters were reportedly installed in Oklahoma City in 1935 (wikipedia.org, accessed 15.4.09), and the infrastructure has developed remarkably since then with large parking lots and parking structures in virtually every city of the world. Parking structures have also become sophisticated, with electronic signage indicating the number and location of available spaces. Payment systems such as those discussed above have also been integrated into parking lots, eliminating the need to pay an attendant or an automated machine with cash or a credit card.

2. Fuel infrastructure

In conjunction with the rise of the automobile, the worldwide petroleum industry developed its enormous infrastructure to deliver the fuel that cars and trucks need. This worldwide network of production facilities, oil tankers, refineries, storage facilities, tank trucks, and filling stations represents an enormous investment. According to wikipedia.org (accessed 15.4.09), the world's first purposely built gas station was constructed in St. Louis, Missouri in 1905 and today there are thousands of such stations in every country of the world, with over 200,000 in the U.S. alone (wikipedia.org, accessed 15.4.09). Ford's Model T was able to go between 130 and 210 miles on a full tank of gasoline (wikipedia.org, accessed 15.4.09) so that, for longer trips, it became essential to have a refuelling point along the way.

As the highways were built up, gas stations became available along the routes and it soon became possible to drive continuously across the United States, and eventually most of the world, refuelling along the way. Most people can find a station within minutes of their home and office. Filling a tank of gasoline or diesel fuel can be done in just a few minutes and many gasoline stations are in fact self-service with automated billing machines allowing drivers to simply use their credit card at any time of day or night. One of the biggest hurdles in developing alternative power train technologies such as electric or hydrogen powered cars is the development of an infrastructure which is as convenient and permits such long trips.

3. Food and lodging

A third component of the infrastructure developed around the motor vehicle is the network of restaurants and lodging facilities located along most of the world's many highway routes.

Ray Kroc, a milkshake machine salesman, first saw the McDonald brothers' restaurant in California in 1954 and, convinced that the format would work well elsewhere, he opened his own McDonald's in Des Plaines, Illinois in 1955 (mcdonalds.com). Today there are over 31,000 McDonald's restaurants in the world (mcdonalds.com) and, to a large degree, the chain reached its prominence by offering Americans a standardised meal of reliable quality as they began making long car trips using the newly built interstate highway system in the 1950's.

Other entrepreneurs developed other chains, and hotel operators created the idea of the motor-hotel, or motel, which soon began to populate the places where the large highways intersected, providing travellers a place to stay. Eventually the entrepreneurs began developing destinations along the highway routes where people would actually go with their cars. Disneyland in Anaheim, California, was perhaps the most famous of these destinations, and today one can find a wide range of roadside activities and services on a "road trip".

4. Sales and Service

As the automotive manufacturers expanded their sales they looked to local mechanics and in some cases gas station operators to provide service to the vehicles. These workshops eventually grew into the authorised dealer networks we see today. This pattern was first seen in the United States, then in Canada and other countries around the world. The typical authorised dealer eventually provides four critical functions in the socio-technological system including: new car sales, used car sales, service and spare parts, and the sale of automotive finance and insurance. There are also independent mechanics that repair cars outside of the authorised system, and car owners typically take their cars to the dealership during its warranty period and then go to a more inexpensive independent after the warranty expires.

What have emerged over the last twenty to thirty years are independent players working to “unbundle” the classic role of the car dealerships. One group is the so called “fast fit” repair sector, which has large chains offering repairs of standardised items such as oil change, exhaust and muffler (silencer) replacement, brake system service, tyres, etc. Another group of companies is focused on selling used cars and, while again there have always been local independents in this side of the business, larger, well-financed companies are increasingly involved, such as Carmax, the United States' largest used-car retailer and a Fortune 500 company. Supporting the used car segment is a large network of business-to-business entities involved in the buying and selling of used cars. Many of these companies use live or internet auctions in which they buy large numbers of used cars from banks and finance companies and then resell them to used car outlets and traditional dealers at wholesale prices.

The financial services industry has also made efforts to break away from car dealerships, and many banks and insurance companies offer a full suite of services through their own branch networks and on-line platforms. All OEMs have also had their own finance companies which offer credit to both the dealer network and consumers, and for many years these divisions were often sources of much needed profitability for the OEMs. At the time of writing, however, the 2008 financial crisis has altered the situation in many firms causing huge losses for most automotive finance companies.

Companies have also been set up to sell new cars only and there has been much interest in doing so using the internet since 1999/2000. The problem that such on-line and direct sales organisations have had is the resistance of the car manufacturers themselves to support a multi-channel strategy and their active desire to prop up their dealer networks in the face of increasing pressure. The dealer networks have been consolidating with public companies acquiring large holding of dealerships in the United States, United Kingdom and other markets, and the manufacturers themselves have encouraged larger dealers to acquire smaller ones in the interest of generating scale economies around specific cities or “market areas”. This approach emerged naturally in the U.K. as publicly owned groups went through a process of buying and selling dealerships of the same brand until they owned all of the dealers in a specific town or district. Once a single entity has control of all of a brand’s dealers in the same area, they can achieve local economies of scale and, more importantly, can avoid bitter, intra-brand price competition.

A fifth component to the sales and service infrastructure is the large number of junkyards spread all across the United States and the world, which provide a critical disposal service to car owners since 65% of a modern automobile is made of steel; while the price of steel has fluctuated over time, its recovery has proven to be a viable business in its own right (www.recycle-steel.org, accessed 15.5.09).

- Industry structure

The modern automobile industry traces its roots to the pioneers of the automobile, and many of the leading companies still bear the names of those inventors such as Daimler, Benz, Peugeot and Ford. As the horse-drawn carriage gave way to the automobile, it was the engine manufacturers who became the system integrators and incorporated wheels, body components, interior components, etc., to make a complete motor car. Two trends are currently changing the structure of the industry i.e. globalization, and the emergence of the tiered system in the supply base.

Probably the most significant trend at the OEM level has been globalisation as automotive companies have been under increasing pressure to be active in larger markets around the world and at the same time reduce their cost base. In some cases the manufacturers have acquired each other in an attempt to gain the necessary scale and achieve synergies (Shimokawa, 1999).

Manufacturers assemble components into finished cars and although most of them also make their own engines or buy them from each other in some cases; most other components are outsourced to a large and complex supply base which has also been undergoing change. Pilorusso (1997) discusses the emergence of a tiered system of supply where tier 1 suppliers sell pre-assembled components, modules, or systems to the OEMs and they in turn buy subassemblies from second tier suppliers who buy from third tier suppliers.

Historically, the major automotive OEMs were vertically integrated; Ford's renowned plant in La Rouge, Michigan, reportedly made all of its own components and even had its own blast furnace for steel production (www.ford.com/about-ford/heritage accessed 14.5.09). This gave way to a policy called "tapered integration" where car companies made at least some of what they needed so that they would have deep firsthand knowledge of the technologies and costs involved and could selectively allow other suppliers to make part of their needs. This pattern also allowed the OEMs to keep their own component plants busy, even during economic slowdowns. It also led to an antagonistic and hostile relationship between the large profitable OEMs and their suppliers who seemed forever stuck in a cycle of boom and bust. Suppliers bid for contracts each year and "built to print" components designed by the OEMs engineering groups.

In the 1980's this strategy was seen as being inferior to the pattern that had developed in Japan, where the major OEMS would take ownership stakes in their closest suppliers and nurture those relationships over many years. This system is known as "*keiretsu*" and creates networks of companies with a shared future. Japanese companies would typically only have two suppliers for any given component, giving one the lion's share of their business but always awarding contracts for the life of a specific vehicle. The tiered structure came about in the West largely due to the OEMs' desire to emulate the Japanese example and thus reduce their own purchasing and logistics expenses by pushing increasingly complex and costly tasks to a reduced group of suppliers. One result of this trend has been an unprecedented concentration process in the supplier industry and the emergence of a small group of very large suppliers around the world.

Raw material suppliers had managed to stay out of the tiered system either by supplying high volume commodities such as steel directly to the OEMs, or by continuously advancing the technological sophistication of their products so that the OEMs will specify their use in the manufacture of components by other companies. This has changed with a move to commodity purchasing strategies by many OEMs that consolidate not only their own but also supplier commodities to get the best deal.

Other speciality suppliers have developed assembly capabilities for niche vehicles with relatively low production runs. Convertibles, for example, are typically built by independent manufacturers on contract to the OEMs who design and market the cars. Still other suppliers focus on developing the engineering talent needed in the industry and providing it on a variable cost or project basis to the OEMs.

One question that is often asked in looking ahead is the degree to which the emergence of very large and diversified suppliers might make it easier for fundamental change in the overall system. While the large OEMs have a vested interest in maintaining the pre-eminence of the internal combustion engine, due to their own investment in the technology and the prevailing paradigm in the minds of their engineers and executives, new entrants might not have this limitation. An electric motor or battery manufacturer could acquire all of the other needed components from these large suppliers and challenge the current socio-technical regime directly.

- Rules and regulations

Legislation plays a critical role in the automotive industry, and covers the vehicles themselves, how they are used by the driving public, and also the industry itself.

The regulations concerning the product itself start with the homologation process which allows vehicles to be driven in a particular country and are primarily focused on auto safety but also deal with atmospheric contamination, fuel economy, recyclability of parts, availability of solutions for the physically impaired, and so on. The role of regulation in the development of seat belts, airbags, fuel cell electric vehicles, and hybrid vehicles will be discussed further in Section 4.3.

Regulations concerning usage cover the rules of driving, including such basic ideas as whether a country stipulates driving on the left or right hand side of the road and speed limits, as well as licensing procedures and vehicle maintenance standards. Most developed countries have a regular inspection process such that all vehicles running must pass a regular maintenance inspection in order to be deemed roadworthy.

The third area are those regulations that affect the industry itself, and many countries have special rules for the automotive sector that affect the industry in five ways.

The first aspect is local content legislation that requires that some percentage of parts or even final assembly is done locally and this is common in developing countries. Locally produced components are often made by the same international parts suppliers, and the need to produce all over the world has been one of the drivers of concentration in the supplier industry. The industry's technique to accommodate local production in small markets has been to set up assembly plants where required and send all of the requisite modules and components to those plant for assembly into a car. Such plants are called Complete Knock-Down (CKD).

A second area which is legislated is the relationship between the OEMs and their dealer networks. In Europe, for example, the industry was given a block exemption from the 1957 Treaty of Rome, which pushed for open competition in Europe and allowed the OEMs to keep their networks more or less intact. The legislation was last amended in 2002 and will be again in 2010. The European Commission claims it is trying to find the right balance between encouraging competition while making sure that the industry has sufficient incentive to provide adequate service and guarantee public safety.

A third area is international commerce and the transfer prices of vehicles from country to country. Due to the complexity of local taxation policies, it might be advantageous for a company to sell cars in one country for use in another, or to play with its internal invoicing for components in order to move profits from place to place. Private entrepreneurs are often able to make profits through arbitrage across the different markets in what is known as the "grey" market. A common practice is to buy surplus new cars in one market at a sharp discount and physically move them to another distant market where they are sold again as new cars.

A fourth area are rules and regulations regarding the environmental sustainability of the industry itself, and a common issue is to oblige the OEMs to ensure the proper disposal and recycling of the vehicles, their batteries, tyres and other key components after the useful life of the vehicle is over.

The final area, very topical at the time of writing, are policies designed to support the automotive industry in times of economic slowdown or crisis. In many countries, the automotive industry represents a significant share of GDP and is often a measure of the state of the economy. One practice is to stimulate the purchase of new cars by offering cash incentives for the oldest vehicles still in circulation. Substituting newer cars for older cars has a very positive effect on pollution reduction, since newer cars are built to tougher environmental standards. Another is direct loans or investments in car companies in times of crisis; at the time of writing, the United States Treasury owns a majority stake in General Motors.

- Technological and scientific knowledge

At the beginning of the automotive age, the primary area of what Geels (2002) calls techno-scientific knowledge which created competitive advantage was concentrated on the engine and the mechanical and thermo-mechanical components that made up the power train system.

Henry Ford brought mass production technology to the forefront of the industry in the 1920's. Materials science evolved steadily throughout the industry's history, and the 1940's and 1950's were noted for the use of decorative chrome, faired body styles and the first uses of plastic. Around the same time, electro-mechanical devices became increasingly important in motor vehicles. The 1960's saw electronics come into play, and the Engine Control Unit was one of the first mass applications of microprocessors in the 1970's. According to The Economist (28/1/95) the value of the electronics in an average car has risen from $75 in 1970 to around $2,000-3,000, depending on the model. As even more sophisticated electronics are incorporated into cars for their operations and what has become known as "infotainment", or the combination of driver information systems and passenger entertainment, are added, this figure will continue to increase. Interest in safety technology and crash testing grew as a result of public campaigning and legislation in the 1970's, 80's, and 90's, and pollution control technology also saw a huge development at the same time. Figure 4.5 shows how the oil embargo of 1973 caused gasoline prices to rise by 64 % in the United States between 1972 and 1976, stimulating demand for smaller, more fuel-efficient cars.

European and especially Japanese carmakers have had more experience with this type of technology and, according to Halberstam (1986), their advantage over Detroit's "big three" in this area partially explained the rise of Nissan, Toyota, and Honda in the American market.

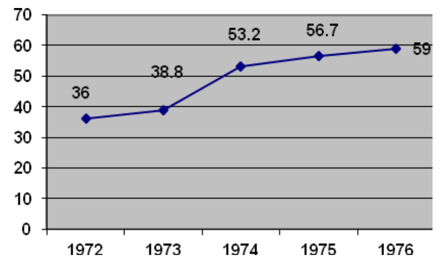


Figure 4.5 Average cost of gasoline in the U.S. (cents/gallon)
(From U.S. Energy Information Administration)

Another advantage the Japanese had was their production technology, and a new wave of effort was made around the world to adopt what became to be called "lean manufacturing" (Womack, 1990).

Although research into alternative power trains has been going on since the 1960's, heightened awareness of global warming has led to legislation, notably in California, that has stimulated the further development of the electric vehicle and the hybrid vehicle, which has both an electric and internal combustion engine. Work on alternative power train technology has concentrated mainly on battery and fuel cell technology, electronic control systems, vehicle architecture, and the issue of developing an alternative infrastructure to fuel the cars.

4.4 Examples of co-evolutionary dynamics in automotive

Lewin and Volberda (1999) discussed five properties that, in their view, would establish a system as being co-evolutionary. The five tests that such systems should possess are: multi-levelness, multi-directional causalities, non-linearity, feedback, and path and history dependence. The following section will discuss each of the five properties in turn and show examples from the automotive industry as defined in Section 4.3.

- Multi-levelness

The first test proposed by Lewin and Volberda (1999) is *Multi-levelness* or the idea that the co-evolutionary process takes place within firms, between firms in a strategic niche, across industries and, in fact, in the greater environment. In looking at the automotive industry, the property can be applied as it is possible to find different levels of analysis in all seven aspects of Geels' socio-technical system. The following examples are drawn from the technology and industry structure.

1. Seat belts and interior design

The section describing the automobile itself is presented in nested levels of analysis, starting with components and building up to modules, systems, and eventually the larger sections of the car such as chassis, body, etc., and finally to entire vehicles, classes of vehicles, etc. An innovation at the component level will have an impact on the system which can then have an impact on the overall vehicle architecture.

When the three point seat belt, for example, was first introduced, the anchor point for the shoulder strap was located on the B pillar, the steel beam between the front and rear side windows. The introduction of the modern tensioner device was finally incorporated into the B pillar and covered in plastic fairing. This arrangement has taken on what Dosi (1982) called a dominant design. It affects not only the seat belt arrangement but also the design of the seat and the interior design as a whole, as the passenger space in the rear seats needs to accommodate the more substantial B pillar in which the tensioner, reel, and other components can be housed. The latest trend, currently available in high end vehicles, is to have seat belts integrated into the seat itself and no longer connected to the B pillar. This frees interior designers from the constraint mentioned above but requires substantially more complex seat designs. One idea made possible by this innovation in larger vehicles is to allow the front passenger seat to swivel and face the rear seats.

1. Tiered supplier structure

In the supply base, there are also a number of levels which each affect the other. In the first place, the tiered structure discussed in Section 4.2.1 gives a natural set of levels nested within each other. The recent financial crisis has shown how interdependent the different levels can be and how first tier suppliers have had to struggle in those cases where their suppliers were in financial difficulties and how the OEMs themselves have had to offer financial support to critical suppliers in order to keep them operating and avoid disruptions in their assembly plants.

- Multi-directional causalities

The examples mentioned above focus on interactions between different levels within Geels' seven components of a socio-technical system such as the industry structure. Multi-directional causalities go beyond those dynamics and refer to the idea that one aspect of one part of the system can affect another one and that it might be very difficult to find clear causal relationships. An example of this phenomena in automotive is the trend toward modular assembly.

Assembly modules were first developed in the OEMs' factories as subassemblies. Such assemblies included seats, dashboards, and groups of chassis components. In the 1980's Ford was faced with the need to increase throughput in its assembly plants but had limits on capital expenditures and did not wish to make the plants larger. The solution was to ask suppliers to take on the assembly of specific modules and use the newly available space for vehicle assembly. The two largest seating suppliers, Lear Seating and Johnson Controls, quickly adopted the practice and sold other OEMs on the idea of buying fully built-up seats. This created an interest in the approach and it was later extended to other modules causing a number of changes in different parts of the socio technological system.

One impact has been to change the pattern of merger and acquisition within the supply base and several companies have been assembled around core competence in the logistics and assembly area, rather than with a technological or systems rationale. Suppliers who have moved into modular assembly have had to acquire capabilities in dimensional control and quality management of their second tier suppliers to a degree which was unheard of prior to these developments.

A second set of impacts has been on the OEMs themselves in terms of processes and positions to use Teece et al.'s (1997) terminology. One process which changed as a result of modular assembly, to give one example is in-bound logistics. The manufacture of modules as opposed to components has also changed the in-bound logistics patterns of many assembly plants, with small industrial parks springing up around the main assembly plant for modular assembly which are sometimes even integrated into the main plant by conveyor systems. These are found, for example at Ford's Valencia plant in Spain where a number of conveyors connect the plant to its supplier's factories located on the other side of the railway line.

An example of changes in position are in part a result of how Chrysler Corporation, in the late 1970's and early 1980's, undertook a fundamental re-think of the way it would approach component design as a result of its economic problems. In the past, Chrysler and other OEMs had teams of engineers devoted to practically every part of the car and would contract their suppliers to "build to print" or manufacture according to detailed specifications and blueprints. In order to emerge from its crisis, Chrysler was forced to furlough many of its engineers and pass most of the design responsibility to suppliers of systems and modules. Today, this trend has continued across many OEMs who now define their core competences (Prahalad and Hamel, 1990), as marketing, vehicle design, power train design and development and vehicle assembly, but no longer as the development of many of their systems and modules.

One interesting aspect to this trend is that the Japanese manufacturers did far less to take advantage of modular assembly than their Western counterparts due to the fact that they are quite capable in the area of dimensional control and quality management.

Finally, the switch to modular assembly has changed the way cars are maintained and repaired, as it has become more inexpensive to simply replace a certain module, such as a front corner unit, than to replace a damaged component within it. This of course creates its own effects in the logistics of spare parts as well as the repair and maintenance industry.

- Non-linearity

The third test has to do with the uneven and often unexpected impact that changes in one part of a complex system has on other parts. These impacts can be non-linear in the sense that a small change in the environment can have a huge impact on organisations and vice versa. A tragic and very topical example of nonlinearity is the faulty design of Firestone's Wilderness AT, Firestone ATX, and ATX II high performance tyres in the summer of 2000. This issue changed the course of the Ford Motor Company and, to a large degree, the structure of the industry itself. The design defect meant that the treads of the tyres separated at high speeds if under-inflated, and this could cause the large, heavy SUVs to roll over. According to the Firestone Tire Legal Information Center (www.firestone-tire-recall.com accessed 15.5.2009), there were a total of 119 deaths attributed to accidents on Ford Motor Company's flagship Explorer brand SUV in the United States.

Ford's CEO at the time, Jacques Nasser, had been working on an ambitious process to re-invent the company as a consumer-focused rather than engineering and finance driven firm and had a number of initiatives underway around the world to this end. Several such initiatives were focused on how cars were sold and involved an internet-based program called Ford Connect and a restructuring of the dealer network into larger, more cost effective dealers which would each dominate a market area. As part of Ford's response to the crisis, Nasser testified before the United States Congress on 20 June, 2001, and insisted that the "problem is with the tyres and not the vehicle" (www.justauto.com accessed 15.5.2009). This statement received a huge amount of bad publicity and, after Ford's reported heavy losses in the second and third quarter of 2001, Nasser was dismissed as CEO.

The aftermath of Nasser's dismissal was the promotion of a generation of executives who had been uncomfortable with his reforms. Bill Ford, grandson of Henry Ford, took over as CEO in order to return Ford Motor to its roots (Connelly, 2003). Under Ford's leadership, most of Nasser's reforms were scrapped and many of the executives he had hired to run them were dismissed. The nonlinearity of the example has to do with an engineering problem at a supplier which not only caused 119 fatalities and affected the careers of many auto industry executives but also brought to an abrupt halt a profound and potentially important change in the way business was done by the third largest player in the industry. Had this event not occurred, it's possible that Nasser would have been successful and the industry would have adopted his ideas, altering the socio-technological landscape.

- Feedback

The fourth test is the extent to which changes reinforce each other, either in a positive or perhaps negative way. The story of the diesel engine in the United States and Europe is a good example of feedback. After the rise in fuel prices in the 1970's, diesel engine technology was perceived by many to be part of the solution. While a bit more expensive to manufacture, diesel engines get approximately 30 - 50% better fuel economy than the equivalent gasoline engines.

Many OEMs launched diesel versions of their cars in the late 70's and early 80's, and today approximately 50% of new cars sold in Europe are powered by diesel engines. The European regulatory climate is better suited to the benefits of diesel technology and the price of diesel fuel is traditionally lower in Europe than unleaded gasoline as it has a lower fuel tax imposed on it. European consumers can therefore justify spending a bit more on a vehicle which will be substantially cheaper to fuel during the life of the car. European carmakers can also rely on a stable regulatory climate in which diesels do well (Diesel Technology Forum, 2001).

In the United States, diesel penetration is practically negligible as the technology was not accepted by the American consumer; diesel fuel is not subsidised in the United States as it is in Europe, and the Environmental Protection Agency's regulations are not favourable. Although opinions differ, the generally accepted explanation for the consumer's response was that the consumers rejected the first cars offered with diesel engines due to perceived slow acceleration and high noise. Engineers and product planning executives therefore did not invest in improving the technology for the U.S. market even while they were doing so in Europe. BMW, for example, developed a line of very quiet, powerful diesel engines which were offered in Europe but not promoted in the Unites States. Since the car company executives did not believe that people would buy the cars, they did not go to the trouble of marketing the improved engines or lobbying the EPA to adopt a more favourable regulatory climate. Present concerns over the environment and fuel economy are bringing the diesel back to the U.S. and, at the time of writing, BMW, Volkswagen and Mercedes are marketing 2009 models with modern, clean, and powerful diesel engines. Figure 4.6 gives an example.

	Diesel	Gasoline
City Fuel Economy (l/100km)	7.84	11.20
Highway Fuel Economy (l/100km)	5.74	8.11

Figure 4.6 2009 Volkswagen Jetta SportWagen TDI
(from www.dieselforum.org accessed 15.5.09)

o Path and history dependence

Co-evolutionary change happens over time, and what has happened previously has a direct impact on what will happen next. This is not to say that changes cannot be radical or disruptive, but simply acknowledges that there are patterns to change and that history does matter when looking at such phenomena. Despite the fact that it is a source of technological development, the automotive industry is quite conservative. Two examples of path dependence are automotive styling and the continued strength of independent dealers.

1. Design and styling cues

When developing a car company's model range, automotive stylists pay an enormous amount of attention to the history of a particular brand and run tremendous risks when they do not respect the brands identity. If one looks at Ford's *Mustang* cars over time or GM's *Corvette* one will see a natural progression from model to model. The popular Volkswagen Golf has also changed in an evolutionary way since its debut in 1974 and through the six different versions of the car that have been developed over 35 years. The Golf mark 6 was introduced in 2009 and will likely be in production until 2014 or 2015.

An example of the importance of continuity can be found in the related business of performance motorbikes. In 2002 Ducati launched the 998, a replacement for its very popular 996 top-of-the-line motorcycle, and made a fundamental change to the styling of the bike. Ducati motorcycles have always had a clear separation between the aerodynamic fairing around the engine and the fender over the front wheel. For the 998, Ducati chose to extend the fairing over the wheel to decrease the bike's drag coefficient. The response by the Ducati enthusiasts was very negative and sales of the new bike plummeted, driving the company into losses. The company later launched the 1098 which went back to Ducati's classic styling and was very well received by its market.

2. Independent dealer network

The dealer network is also a good example where one can see path dependency in action at the political level and in terms of change management. As briefly described in Section 4.3, the dealer network grew out of the need of the automobile manufacturers to provide service outlets and re-fuelling infrastructure at the beginning of the last century. Having proven to be successful, the same model was adopted as the OEMs expanded internationally and, today, most of the independent dealers around the world can trace their origins to a local mechanic or entrepreneur.

One of the manifestations of this model in the United States is that car dealers are often some of the largest and most successful local businessmen in many towns and cities across the country. At the local level, politicians look for funds and the auto dealers are a natural place to look. In the United States, they are often involved in supporting candidates for local office as well as representatives to the state government assembly and the U.S. Congress. Many states have legislation which supports independent car dealerships and attempts to limit the power of the OEMs with respect to their dealers, or block novel approaches to automotive retailing, such as internet sales across state lines.

In continental Europe the situation is a bit different, as most countries have a parliamentary system in which the political parties, not local voters, choose their representatives and, at the national level, the OEMs have more clout than local dealers. In both the U.S. and Europe however, the power of these local dealers has made it difficult for the OEMs to evolve at the speed they would have liked as they are constrained by the dealers' own priorities and their ability to fund new investment.

- Conclusion

The purpose of Section 4.3 was to explore to what degree the modern automotive industry could be considered as co-evolutionary as defined by Lewin and Volberda (1999). In looking at the five properties they discussed, this section demonstrates that examples can be found of the properties of multi-levelness, multi-directional causalities, positive feedback, non-linearity, and path and history dependence. These examples are listed in Table 4.3.

Property of Co-evolutionary System	Automotive Example
Multi-Levelness	o Seat Belts and Interior Design o Tiered Supplier Structure
Multi-directional Causalities	o Modular Assembly
Nonlinearity	o Firestone Tyre Tragedy
Feedback	o U.S. Diesel Engine Penetration
Path And History Dependence	o Design and Styling Cues o Independent Dealer Network

Table 4.3 Examples of co-evolutionary properties in automotive

<u>4.5 Chapter summary</u>

The purpose of Section 4 was to define the context for the thesis by applying. Geels' (2002) socio-technological model, and showing examples of its behaviour as a co-evolutionary system as described by Lewin and Volberda (1999). The chapter highlights the critical role that government regulation, suppliers, and consumer preferences play in determining the agenda of the vehicle manufacturers and also gives examples of the co-evolutionary dynamics that exist between these and other actors in the industry and the decisions and investments made by the vehicle manufactures in new technology. By defining the industry as a socio-technological regime (Geels, 2002), the use of Geels and Schot's (2007) technological pathways in Sub-section 5.3.1 becomes clearer and, by demonstrating that co-evolutionary processes do occur in the industry, it makes it possible to use the empirical data from the thesis to contribute to Granstrand's theory of the technology-based firm. This chapter therefore makes explicit the starting point for discussing the four technologies of interest and for performing further research into patents, deployment data, and the opinions of industry experts which is presented in Chapter 5. Finally by capturing what is known about the context in an explicit way, this Chapter will assist in controlling the researcher's prior knowledge from influencing the thesis through more subconscious ways.

CHAPTER 5. CASE STUDIES

5.1. Introduction

The purpose of Chapter 4 was to rigorously establish the context for the research at the industry level, defining the modern automotive industry as a socio-technological regime Geels (2002) and to show examples that indicate that the automotive industry can be considered as a co-evolutionary system (Lewin and Volberda, 1999). The purpose of this chapter is to explore the apparent strategy that the vehicle manufacturers made when introducing new technology into their products and to discuss the implications of those choices thus adding to the understanding of the research question stated in Section 1.1 which is "***What strategies do automotive companies follow with respect to the investigation and deployment of discontinuous technologies?"***

As outlined in Sub-section 3.3.2, the thesis developed case studies concerning the approach taken by four vehicle manufacturers with respect to four technologies and data is drawn from four sources including desk research and context development, patent analysis, a detailed look at the deployment data, and interviews with experts on the companies and technologies under study. The methodology is shown graphically in Figure 3.1 and reproduced as Figure 5.1 for convenience.

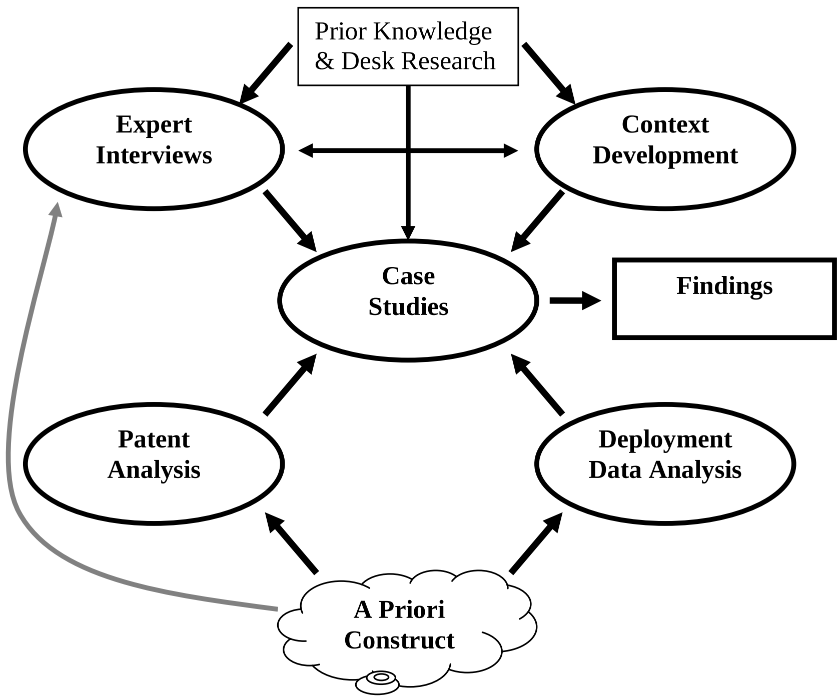


Figure 5.1 Research methodology

The selection of the vehicle manufacturers and technologies is discussed in Section 3.4 and shown in Table 5.1

Vehicle Manufacturers	Technologies
• General Motors (GM) • Ford • Toyota • Nissan	• Seat belts • Airbags • Fuel cell electric vehicles • Hybrid vehicles

Table 5.1 Research site selection

Section 5.2 will present the case studies for General Motors, Ford, Toyota and Nissan and will review the patent data, analyzing the deployment data and finally conclude with a discussion of each company's apparent technology strategy. Comments from the industry experts will be incorporated where appropriate and cited accordingly. Section 5.3 will thus present the case studies for seat belts, airbags, fuel cell electric and hybrid vehicles. For each technology, Section 5.3 will discuss the history and context of the technology, discuss the technology pathway it appears to be on using Geels and Schot's (2007) typology and perform cross case analysis on the patent and deployment data. Section 5.4 will conclude the chapter by exploring the degree to which the apparent strategies pursued by the different manufacturers in each of the technologies were heterogeneous and evaluate the degree to which any differences amongst them produced different results.

5.2 Company case studies

5.2.1 General Motors

- Patent analysis

Table 5.2 gives the total number of U.S. patents filed by General Motors up to 2006 as well as the number and relative percentage of patents filed in each of the four technologies under study. Table 5.2 shows that General Motors has produced a relatively large amount of patents in airbags and fuel cells, an average number in seat belts and a relatively low number of patents in hybrids.

	Total U.S. Patents	Seat Belt Patents	Airbag Patents	Hybrid Patents	Fuel Cell Patents
Total Patents	13,078	116	139	66	205
% General Motors	100%	0.89%	1.06%	0.50%	1.57%
Average % Across sample		0.81%	0.76%	1.03%	1.03%

Table 5.2 General Motors' patents

Figures 5.2a - 5.2d show the total number of patents for each technology plotted using the *Themescape* maps as described in Sub-section 3.5.3. The analysis compares different features of the patenting patterns by using the metaphor of a topographical map counting mountain peaks, small islands, inlets and lagoons, etc., of each of the representations as if they were islands or groups of islands in the sea.

General Motors' seat belt patents shown in Figure 5.2a appear to be spread out over a relatively large area with eleven peaks on three separate ridge lines. While there are no islands as such in the seat belts pattern, the valleys between these three areas appear quite deep indicating several different areas of research.

In airbags, on the other hand, General Motors' patents appear closer together in the representation. The airbag pattern has two adjacent peaks with one of them consisting of a large number of related patents and showing up as a large, broad mountain in the *Themescape* representation. The overall pattern is quite small with no islands. Taking into account that General Motors has more patents in airbags than in seat belts (139 vs. 116), the compact nature of the pattern is even more pronounced. As will be seen in Figure 5.19, however, airbag patterns were generally closer together for all of the manufacturers with the possible exception of Toyota, so that the pattern observed for General Motors might be explained by the history of airbag legislation and development discussed in Sub-section 5.3.3.

General Motors' hybrid patents shown in Figure 5.2c also show a focused pattern and are made up of 63 patents. The hybrid pattern has seven peaks separated by deep valleys. There are no islands and the entire set of patents covers a relatively small area.

The fuel cell patents for General Motors appear to be quite spread out in the *Themescape* representation. As shown in Table 5.2, General Motors filed 205 fuel cell patents representing 1.57% of all of its U.S. patents which appears to indicate a very large and ambitious program of research. The pattern depicts an eleven island archipelago spread out over a wide area with only one small peak. It is not the case, however, that more patents would automatically lead to a wider pattern, as can be seen in the above contrast between patents concerning seat belts and airbags. What does appear to be the case is that the scope of the fuel cell development efforts at General Motors far exceeded that of the hybrid program and, with a program more than three times the size, it stands to reason that the technological research would spread out.

Table 5.3 shows the salient features of the maps applying the topographical metaphor outlined in Sub-section 3.5.3.

	Seat Belts	**Airbags**	**Hybrid Vehicle**	**Fuel Cell Vehicle**
Relative area	Large	Small	Medium	Very large
Type of landmass	Contiguous with broad valleys	Contiguous	Contiguous with one Peninsula	Archipelago
Number of islands	0	0	0	13
Number of peaks	11	2	8	1

Table 5.3 Major features in GM patent visualizations

Figure 5.2a GM seat belt patent visualisation

Figure 5.2b GM airbag patent visualisation

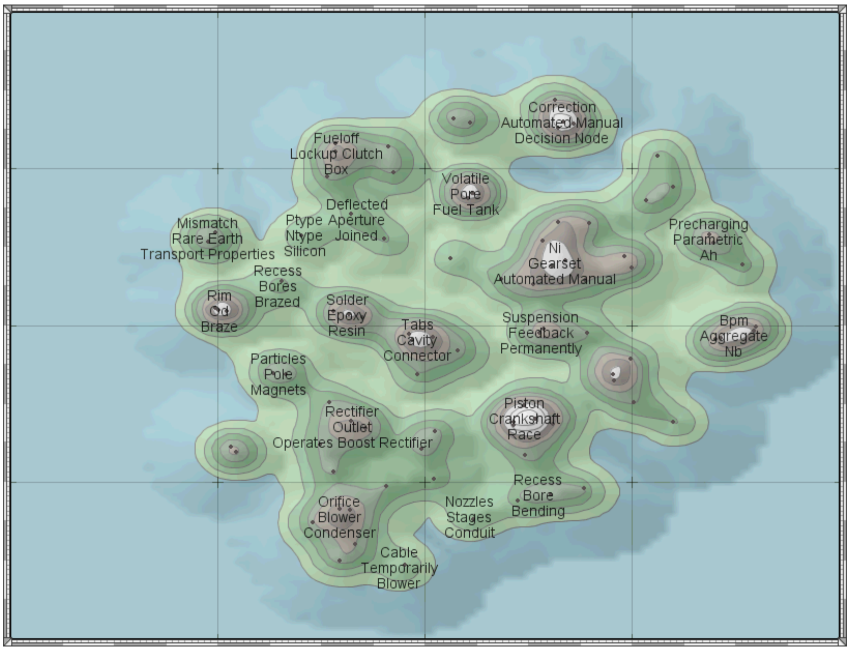


Figure 5.2c GM hybrid patent visualisation

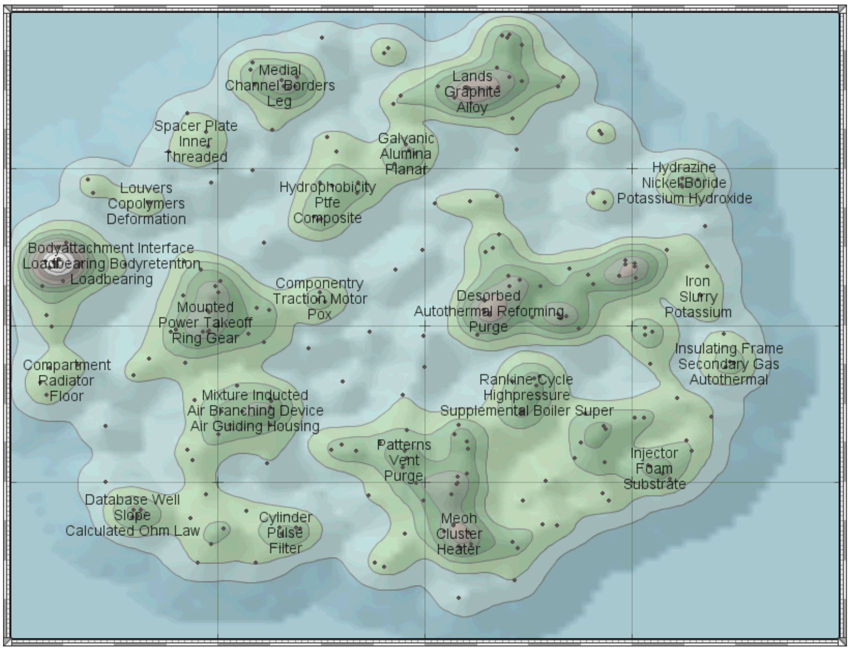


Figure 5.2d GM fuel cell patent visualisation

- Deployment data

1. Seat belts

Table 5.4 shows how GM put rear seat belts on 36 models over two years, possibly to live up to a public commitment it made in 1986, in one wave. In the case of pretensioners, however, General Motors appeared to follow a slower path. Pretensioners were rolled out over at least the seven years for which data was available. By 2007, GM had put pretensioners on its entire product range except for several versions of the GMC Sierra, which was in its run-out year, and two models of a 15 passenger minibus. GM did not actually have 100% coverage on all passenger cars until 2008, and never equipped the minibus with the devices even for the driver.

Model year	88	89	01	02	03	04	05	06	07
Models with rear seat belts	9	36	-	-	-	-	-	-	-
Total models with back seats	39	36	-	-	-	-	-	-	-
Percentage with rear belts	23%	100%	-	-	-	-	-	-	-
Percentage of models with pretensioners	-	-	13 %	9%	18%	33%	50%	86%	96%

Table 5.4 Rear seat belt and pretensioner penetration in General Motors

One possible explanation of the pretensioner data is that GM chose to gradually introduce the pretensioners due to their cost and waited until major restyling for each vehicle platform.

Interview subjects number 2 and number 5 offered a different reading of the data. In their view, what is important is obtaining a five star safety rating by NHTSA and other rating agencies and suggested that GM simply did not need the pretensioners to achieve this. The experts suggested that GM's older models were most likely built with heavier gauge steel and that maybe it took longer for lighter, more modern designs to make their way into GM's fleet. Heavier cars would perform well on the crash tests with or without the pretensioners and GM would only need to introduce the devices when models were re-designed using lighter steel.

U.S. crash tests are, according to interview subject number 2, less demanding than European and Japanese tests in terms of stressing the need for pretensioners, and thus it stands to reason that GM and Ford were slower than Toyota and Nissan to adopt the technology in the U.S. A final reason given by the same expert is that GM, like Ford, specifies seat belts quite early in their product development process and thus was locked in to a specific design. Pretensioners require some space next to the seat as well as electrical power and electronic connections; according to this logic, GM simply would not be able to place the devices into a specific model until its complete re-design.

2. Airbags

General Motors was a pioneer of airbag technology in the 1970's but only deployed airbags across its vehicle fleet in the early 1990's and appeared to be relatively slow to roll out the new technology. This can be seen in Figure 5.3, where each of the circles shown represents a specific new model and major innovations such as side airbags discussed are shown in their first year of deployment.

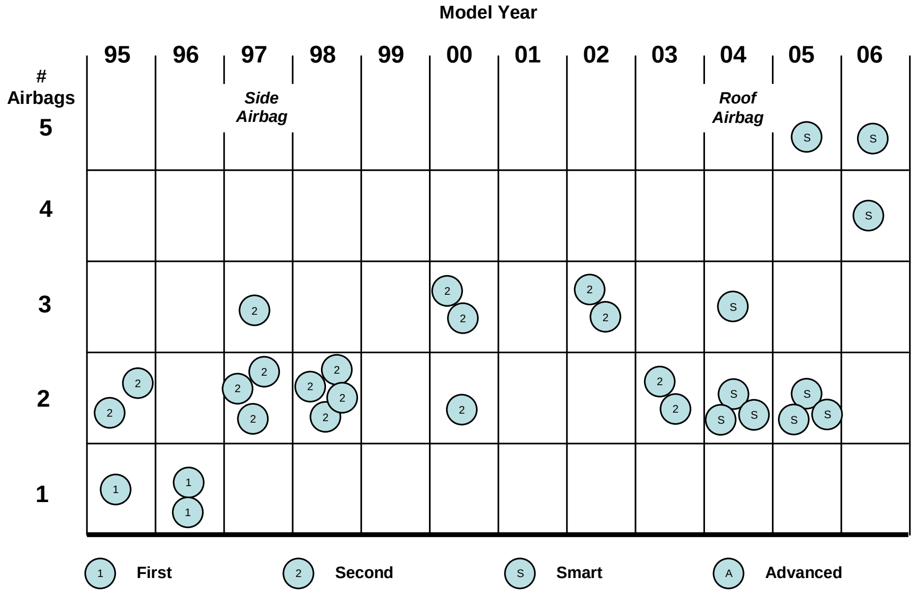


Figure 5.3 Airbag introductions by General Motors

GM, for example, put side airbags into the front doors of the Cadillac Seville in 1997, and was the first U.S. carmaker to do so, but then waited 8 years to extend the technology to other, less expensive vehicles. Interview subject number 6 explains that GM's internal accounting rules require a specific vehicle division, such as Cadillac, to fund the development of new technology, and this explains why airbags were first installed on Cadillac but does not explain the time it took to further deploy the technology to other models and divisions. A possible explanation is that GM did not see a competitive advantage in a faster roll-out and only started to put in the side airbags as a result of competitive pressure when the Japanese started deploying them in 2003. GM also introduced second generation airbags into its fleet gradually between 1995 and 2003 and did not install on/off switches in its vehicles.

On/off switches were a temporary fix for the child safety problem which will be discussed in Sub-section 5.3.3, and was solved by the new smart systems consisting of occupant sensors, smart electronics and a two-stage airbag. General Motors started deploying this technology in 2004 and was thought by interview subject number 8 to have made significant investments in it.

3. Hybrid and fuel cell electric vehicles

General Motors began testing fuel cells in 1964 and was the first manufacturer to produce a fuel cell electric vehicle in 1968 called the Electrovan 1. In 1969, GM developed the GM 512, a lightweight hybrid prototype which used a combination of batteries and a two-cylinder gasoline engine. General Motors led the industry launching the EV-1 in California in 1996 using lead acid batteries in its first two generations and switching to a nickel metal hydride (NiMH) battery in the third, steadily increasing the vehicle's range as shown in Figure 5.4.

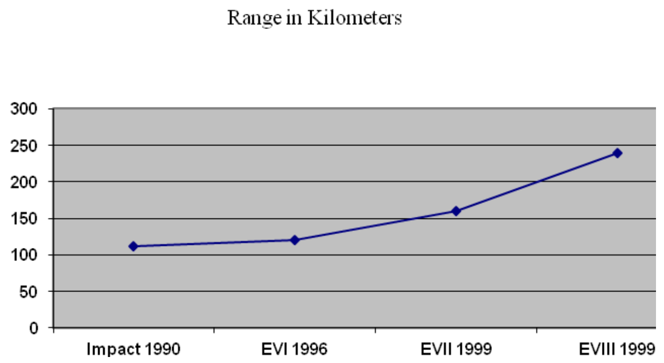


Figure 5.4 Range of General Motors' electric vehicles

In 1999, General Motors announced an agreement to develop hybrids and fuel cell vehicles together with Toyota, and there was talk of developing a Chevrolet model based on Toyota's Prius hybrid. In 2004, hybrid technology was taken out of the collaboration and in 2006 the fuel cell collaboration with Toyota also ended.

Looking ahead, GM's official position has been that the global automotive industry must develop alternative sources of propulsion, based on diverse sources of energy. In the International AMI Congress held in Leipzig on 31 March, 2009, GM showed a chart (Figure 5.5) to explain GM's advanced propulsion technology strategy, and in its 2009 Corporate Responsibility Report GM says that: "For the foreseeable future, this strategy calls for technology plans that support the co-existence of liquid fuels (conventional, synthetic and biofuels) as the primary in-vehicle energy carrier. In concert with liquid fuels, both electricity and hydrogen will play important roles as future transportation energy carriers. There will also be significant level of plug-in hybrids and electric vehicles as battery technology becomes more capable and affordable than it is today."

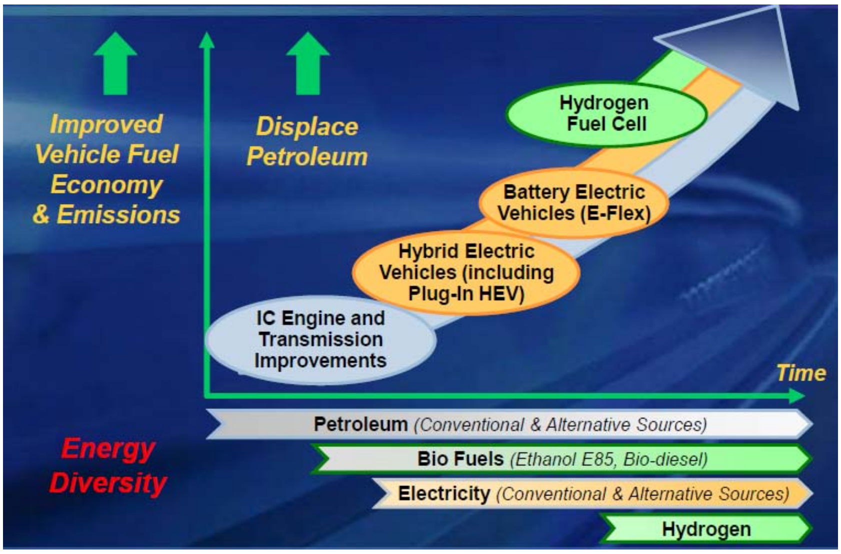


Figure 5.5 General Motors' technology vision

At the time of writing, General Motors has gone through bankruptcy and government intervention but has reiterated its commitment to sustainable transportation. According to the official press release dated 10 July, 2009, "GM also has moved aggressively to develop a full range of energy-saving technologies, including advanced internal combustion engines, biofuels, fuel cells and hybrids. The company is also a leader in the development of extended-range electric vehicles, with its first model, the Chevy Volt, currently undergoing road testing and scheduled for launch in 2010. The new GM is also taking steps to make advanced battery development a core competency, and expects to make additional announcements on this matter late this summer". The Chevy Volt is a hybrid vehicle in which a small internal combustion engine runs an electric generator to supplement the batteries and extend the vehicle's range. In the past, the degree to which GM's alternative energy programs were true strategic moves or substantial public relations investments was open to question (Doyle, 2000). However, with the U.S. Government owning 60.8% of the "New GM" and the environmental tone of the current U.S. administration, its commitment might increase.

With respect to hybrid vehicles, GM has had, over the last few years, four distinct hybrid systems, as shown in Table 5.5. GM put a pre-transmission hybrid on its Silverado pickup truck and then developed a power-split system which it placed on the Saturn Vue and Aura models in 2005 and 2006 respectively. In 2004, GM entered into a collaborative agreement with DaimlerChrysler, replacing the previously-mentioned arrangement with Toyota on hybrids. This collaboration led to a new, two-mode system which was then placed on the 2008 Saturn Vue, 2007 Chevrolet Tahoe and 2008/9 models of the Silverado and Sierra.

GM's latest system is called E-flex and will be used on the Chevy Volt. The system uses a small, 1 litre internal combustion engine running a generator which then powers the wheels when the battery is discharged. The E-flex architecture is designed to enable General Motors to build a range of electric power train options from a common platform, using the same electric motors, control systems, etc., but varying the size and configuration of the batteries and other energy sources such as fuel cells or, in this case, an internal combustion engine. As shown in Appendix C3, GM has 8 hybrids for 2010 which cover 23% of its fleet (if one excludes some of GM's body styles and the heavier trucks and passenger vans).

Model	Year	Vehicle Type	Architecture	Battery Type	Fuel Economy (km/l)	Top Speed Electric (km/hr)
Chevrolet Silverado FWD	2003 2005 2009	Pick Up	Pre-Transmission Pre-Transmission Two Mode	NiMH	7.1 7.3 8.9	n/a
Chevrolet Silverado 4WD	2003 2004 2008	Pick Up	Pre-Transmission Pre-Transmission Two Mode	NiMH	6.8 6.8 8.5	n/a
GMC Sierra	2003 2009	Pick Up	Pre-Transmission Two Mode	NiMH	7.3 8.9	n/a
Saturn Vue Green Line	2005 2008	SUV	Power Split Two Mode	NiMH	11.1 11.9	n/a
Saturn AURA Green Line	2006	Sedan	Power Split	NiMH	11.5	n/a
Chevrolet Tahoe 2WD	2007	SUV	Two Mode	NiMH	8.9	n/a
Chevrolet Malibu	2007 2009	Sedan	Power Split	NiMH	11.5 12.4	n/a
Chevy Volt E Flex	2011?	Compact	Range extension	Lithium Ion	21.3	40

Table 5.5 Performance characteristics of GM's Hybrid Vehicles

According to interview subject number 3, GM, like Ford, favoured the deployment of hybrid technology on its light trucks and SUV's in order to downplay the poor fuel economy of the vehicles.

In terms of fuel cells, GM waited almost 30 years after the Electrovan 1 to develop its second fuel cell electric vehicle, but then developed 14 such vehicles over 10 years using four distinct architectures. Table 5.6 shows GM's fuel cell program in which is it appears that GM pursued several different technological solutions in parallel.

Over the years, GM has placed different types of fuel cells on different models such as the Opel Zafira minivan and the Chevy S-10 pickup. GM also worked on developing new generations of its hydrogen vehicle, based on the Opel Zafira, improving the components and systems integration across four generations of the vehicle over 7 years.

In the case of the Autonomy concept car and subsequent Hy-wire prototype, GM worked on developing new vehicle architecture around the fuel cell. These two vehicles were built around a flat, skateboard-like platform upon which different passenger compartments could be fitted.

The fourth and current thread of GM's thinking is the Provoq concept which takes advantage of the same electric vehicle architecture as the Volt hybrid mentioned above but reduces the size of the battery and substitutes GM's fifth generation fuel cell stack for the small engine in the hybrid version.

Model	Year	Vehicle Type	Fuel Source	Storage	Range (km)	Top Speed (km/hr)
GM Electro Van	1968	Van	Liquid Hydrogen and Liquid Oxygen	Cryogenic tanks		
EV1 FCEV	1997	Sport Car	Methanol	n/a	n/a	n/a
Cintra	1997	Mini-van	n/a	n/a	n/a	n/a
Zafira	1998	Mini-van	Methanol	Pressurised Tank	483	120
HydroGen 1 (Zafira 2)	2000	Van	Liquid Hydrogen	n/a	400	140
Precept FCEV	2000	Compact	Compressed Hydrogen	Pressurised Tank	800	193
GM HydroGen 3 (Zafira 3)	2001	Van	Liquid Hydrogen	Cryogenic Tank	400	160
Chevy S-10	2001	Pickup truck	Low sulphur gasoline (CHF)	Gas Tank	386	113
Advanced GM HydroGen 3 (Zafira 4)	2002	Van	Compressed Hydrogen	Pressurised Tank	270	160
Autonomy	2002	n/a	n/a	n/a	n/a	n/a
Hy-wire	2002	Van	Compressed Hydrogen	Pressurised Tank	129	160
Chevrolet Sequel	2005	SUV	Compressed Hydrogen	Pressurised Tank	483	145
Chevrolet Equinox FC	2006	SUV	n/a	n/a	320	160
GM HydroGen 4 (Zafira 5)	2007	Van	n/a	n/a	320	160
Chevy Volt Fuel Cell	2007	Compact	Compressed Hydrogen	Pressurised Tank	483	120
Provoq	2008	SUV	Compressed Hydrogen	Pressurised Tank	483	160

Table 5.6 Performance characteristics of GM's Fuel Cell Vehicles

One explanation for the size and complexity of GM's fuel cell program has to do with the perceived strategic importance that the company placed on fuel cells during the late 1990's. According to Van den Hoed (2004), GM started late in the fuel cell race and only began its program in earnest after the collapse of its battery electric program. GM also made the decision to develop its own technology together with Toyota and chose not to invest in a fuel cell company, unlike Ford and Daimler which invested in Ballard power systems.

Perhaps because GM was in a hurry to catch up, they pursued several parallel tracks, rather than a sequential strategy. In any event, by the early 2000's GM was perceived by many as the leader in fuel cells with many projects and public relations activities.

The experts interviewed give other explanations for GM's fuel cell program. Interview subjects 3 and 6 maintained that GM's (and Ford's) fuel cell program was the result of an explicit agreement with the Bush administration to make a public show of fuel cell research in exchange for no further increase in the obligatory fuel economy legislation known as CAFE. The argument is that GM's estimated three hundred million dollars in annual spending was considered a small investment for such political relief. The same experts maintained that the choice to scrap its electric vehicle program in favour of fuel cells was also the result of political infighting in GM, and that Larry Burns, GM's head of R&D, pushed the fuel cell program due to his own belief in the technology and as a way to gain internal political advantage over rivals who favoured battery electric vehicles.

- Overview

Looking across the data set, it is difficult to find a consistent pattern in the data. General Motors patents show tight, contiguous patterns in airbags and hybrids, a very spread out pattern in fuel cells and something in between in seat belts. In terms of deployment the company also appears to have different approaches in the different technologies developing new generations of airbag and hybrid technologies sequentially while pursuing parallel tracks in fuel cells. The seat belt data is an example of the heterogeneity seen in General Motors as it appeared to follow a focused, fast program in its deployment in rear seat belts and a very slow program in pretensioners although the pretensioner data can be explained by design issues as discussed above.

According to interview subject number 7 General Motors' technology development and deployment can be explained by the company's deep belief in economies of scale and their position as the world's largest vehicle manufacturer. His view is that General Motors engineers would "polish the hairs of a doorknob" in a combination of "technological arrogance" and risk aversion to costly recalls. This view is characterised by a quote attributed to a GM executive concerning airbags, given by interview subject 8, that "there is not a problem we can't solve. The only question is which problems to solve". The term "technological arrogance" is also used by interview subject 6, who worked closely with General Motors' product development group for many years and maintains that the specific technological choices made by the company have much to do with the company's internal accounting process which required the vehicle programs to fund new technology resulting in Cadillac often being the only division to be able to invest.

General Motors appears to be able to generate large numbers of patents in different patterns when it needs to and can deploy technology in different ways. Sub-section 6.3.3 will discuss the General Motors data in more detail and attempt to draw more definitive conclusions.

5.2.2 Ford

- Patent analysis

Table 5.7 shows the total number of U.S. patents filed by Ford up to 2006 as well as the number and relative percentage of patents filed in each of the four technologies under study. The data shows an exceptional number of patents filed by Ford in the area of hybrid technology and relatively small numbers of patents in the other technologies and especially in the area of fuel cells.

	Total U.S. Patents	Seat Belt Patents	Airbag Patents	Hybrid Patents	Fuel Cell Patents
Total Patents	10,238	63	46	142	40
% Ford	100%	0.62%	0.45%	1.39%	0.39%
Average % Across sample		0.81%	0.76%	1.03%	1.03%

Table 5.7 Ford patents

Figure 5.6a – 5.6d shows Ford's patents in the same technologies. And Table 5.8 gives the salient features of the *Themescape* maps generated. The seat belt pattern does have several different contour lines separated by valleys but only one peak and one small island. The airbag pattern has three separate peaks, a much smaller land mass and no islands. Ford does, however, have fewer airbag patents than seat belts (46 vs. 63) so one would expect the land mass to be smaller. Ford's patents in hybrids and fuel cells, on the other hand, resemble each other even though Ford has more than three times as many patents in the hybrid area (142 vs. 40). In hybrids, Ford's patent pattern spreads out over a wide area with four islands, one very large lagoon and four peaks spread out over the topography. In fuel cells there is only one island, but the larger landmass has two lagoons separating its three peaks.

The most likely explanation of Ford's relatively small fuel cell program is its 1997 investment of $425 million in Ballard Power Systems, which had already developed a lead in developing PEM fuel cell technology and in which DaimlerChrylser had also invested. By making a direct investment in a fuel cell supplier, Ford appears to have chosen to outsource its fuel cell research although continued with its own development program as is seen below.

	Seat Belts	**Airbags**	**Hybrid Vehicle**	**Fuel Cell Vehicle**
Relative area	Small	Small	Large	Medium
Type of landmass	Contiguous with broad valleys	Contiguous	Spread out with two lagoons	Spread out with two deep lagoons
Number of islands	1	0	4	1
Number of peaks	6	6	6	3

Table 5.8 Major features in Ford patent visualizations

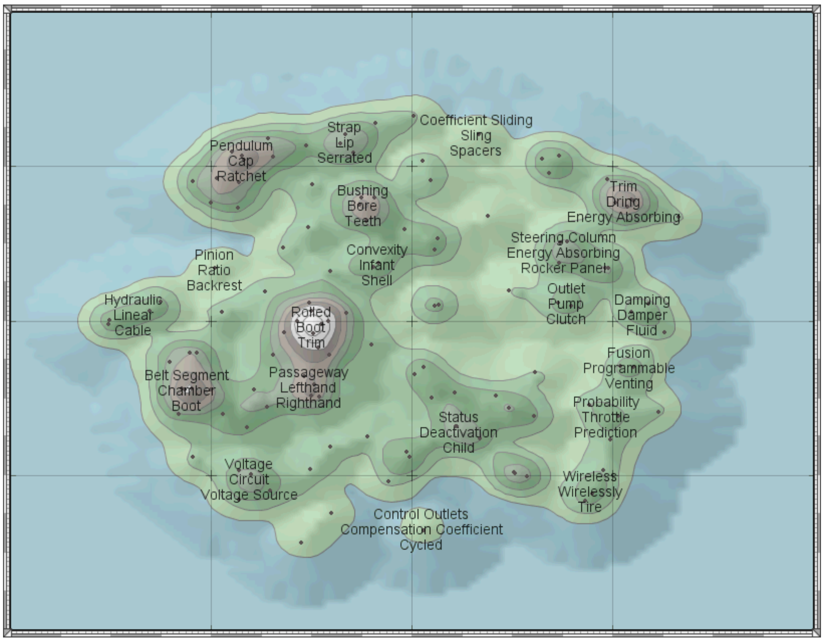


Figure 5.6a Ford seat belt patent visualisation

Figure 5.6b Ford airbag patent visualisation

Figure 5.6c Ford hybrid patent visualisation

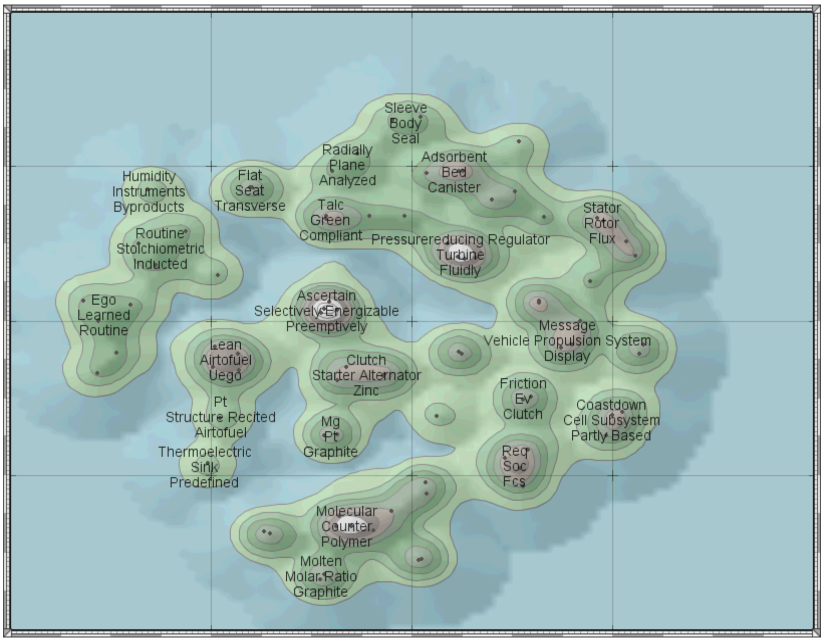


Figure 5.6d Ford fuel cell patent visualisation

- Deployment data

1. Seat belts

The data on Ford's rear seat belt deployment is shown in Table 5.9 Ford's deployed rear seat belts on five models over a two year period and then another 10 models in 1990. It is possible that Ford's back seat program was simply slower than GMs and that the deployment strategy was fundamentally the same. Ford also appears to have uncoupled the deployment of rear seat belts from major re-styling as did GM.

The pretensioner data for Ford is less clear, as Ford had already installed the devices on 70% of its models prior to 2001 when the NHTSA data set picks up. Ford did, however, take an additional five years to reach full deployment and appeared to place the pretensioners on models at the time of major re-styling efforts, echoing GM's very slow deployment.

Model year	88	89	90	91	01	02	03	04	05	06
Models with rear seat belts	3	5	15	16	-	-	-	-	-	-
Total models with rear seats	16	16	16	16	-	-	-	-	-	-
Percentage with rear belts	19%	31%	94%	100%	-	-	-	-	-	-
Percentage of models with pretensioners	-	-	-	-	77%	86%	86%	96%	84%	100%

Table 5.9 Rear seat belts and pretensioner penetration in Ford

As discussed for GM, the most likely explanation of Ford's pretensioner data is that the vehicles which were last to receive the technology were models in which the additional benefit of pretensioners, in terms of safety, did not outweigh the incremental cost due to other aspects of the overall crash dynamics such as heavier steel. In Ford's case the fact that it did put the devices quickly on 70% of its models could be interpreted to mean that Ford was ready to use pretensioners but delayed introduction on some models until they were fully re-designed and could make full use of the technology.

2. Airbags

Ford's airbag deployment shown in Figure 5.7 appears as a series of groups of models or waves. Ford first put both first and second generation airbags into 9 models in 1995, updated 16 models to second generation between 1997 and 2002, and then started bringing advanced airbags into 4 models in 2004/05.

There is some evidence which suggests that Ford chooses to follow the market and play catch-up, launching deep programs to equip its fleet just a few years behind the other manufacturers.

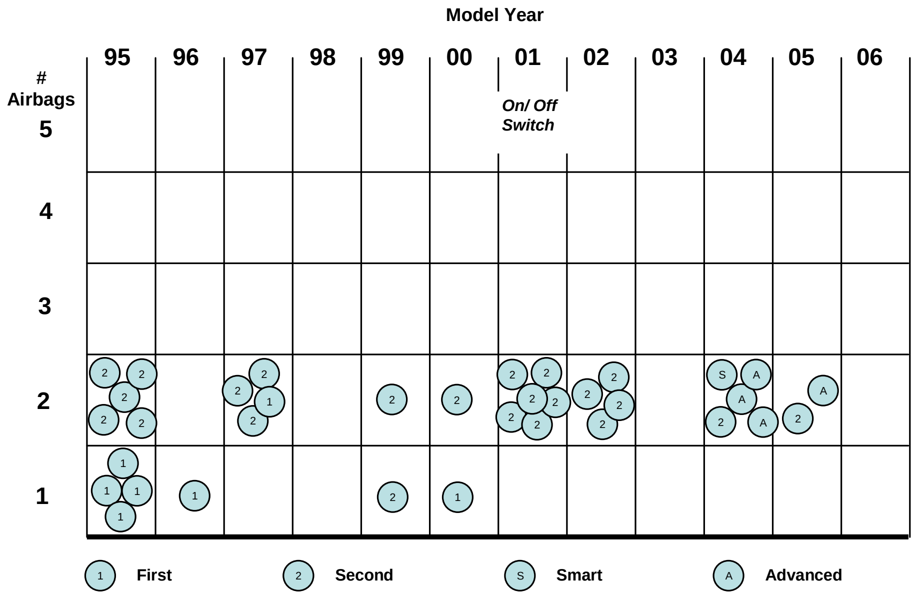


Figure 5.7 Airbag introductions by Ford

First, interview subject number 1 recalled how safety, driven by marketing research, became a major push at Ford of Europe and, while this strategy was executed in Europe, it still had not been extended to the U.S. market by 2006.

Second, Ford also appears to have delayed extending airbag technology to its fleet of vans and light trucks until required to do so by regulations. In 2000, for example, Ford put first generation technology on its E-250 Econoline van, while it had already installed second generation airbags on passenger cars 5 years before and had also used second generation technology on the smaller E 250 van.

Third, Ford appears to lag behind its competitors. Ford, for example, introduced smart airbags into one model in 2004 while Nissan had started deploying smart technology in 2003, and the data also shows GM and Toyota ahead of Ford. In 2004, GM had deployed smart airbags on 4 models and Toyota not only introduced 3 models with smart technology in the same year but also launched its advanced systems in one model.

Finally, since 1999, Ford has owned 100% of Volvo Cars, which according to interview subject number 2 is together with Mercedes Benz the market leader in safety technology. This leads to the conclusion that although Ford had access to advanced airbag technology it appears to have chosen to deploy airbags according to its own timetable.

3. Hybrid and fuel cell electric vehicles

The Ford Motor Company built two electric prototypes between 1913 and 1914. In 1966, Ford R&D built the Comuta demonstration vehicle with lead acid batteries, a top speed of 25 mph (41 km/hr) and a range of 40 miles (66 km). In 1979 Ford worked with Gould Inc., a battery manufacturer, to equip a Ford Fiesta with an experimental nickel-zinc battery which reached 65 mph (108 km/hr) and had a range of 100 miles (166 km).

In 1988 Ford won a DOE contract to fit an Aerostar van with a sodium-sulphur battery. Continuing with sodium-sulphur, in 1991 Ford developed the Connecta concept car, which had first plug-in capability, and went on to build a a fleet of 84 panel vans based on its Escort vehicle between 1992 and 1993. The two seat delivery vehicle had a top speed of 70 mph (km/hr) and a range of 100 miles (166 km). In 1998, Ford abandoned the sodium- sulphur batteries for lead-acid and nickel metal hydride batteries in a fleet of 2,000 postal delivery vehicles based on the Ford Ranger SUV. The cars had a top speed of 75 mph (125 km) and range of 30-70 miles (50-116 km). In 1999, Ford invested $150 million to take a controlling interest in a Norwegian company called TH!NK. TH!NK had developed its first generation TH!NK City in 1991, and was part of Ford until 2003 when Ford chose to discontinue its involvement.

With respect to hybrid vehicles, it took Ford four years after the U.S. launch of the Toyota Prius and Honda Insight in 2000 to launch the Escape Hybrid in 2004 with Toyota technology. The Escape Hybrid was the first hybrid sports utility vehicle on the market and Ford continued with the same technology in its hybrid program shown in Table 5.10. According to interview subject number 7, Ford is “pedalling quickly” to catch up in hybrids and is developing its own solution to replace the Toyota technology it is presently using. The Escape family of hybrids, for example, has shown increased fuel economy in 2007 and 2008 as compared to the initial launch in 2005 as shown in Table 5.10. For the Mercury Mariner, on the other hand, introduced in 2006, the hybrid power plant was not improved until a totally new vehicle was launched in model year 2010. At the time of this writing Ford has four hybrids on the market, counting the two versions of the Escape as one model and counting the Mercury Mariner and Mercury Milan as two additional models as shown in Appendix C3. These models represent 17% of Ford’s product line.

Model	Year	Vehicle Type	Architecture	Battery Type	Fuel Economy (km/l)	Top Speed Electric (km/hr)
Escape 4WD	2005	SUV	Power Split	NiMH	11.5	40
	2007				11.6	
	2008				11.9	
Escape FWD	2005	SUV	Power Split	NiMH	12.4	40
	2007				12.8	
	2008				13.5	
Mariner	2006	Compact	Power Split	NiMH	11.5	40
	2007				11.5	
	2010				11.9	
Fusion/Milan	2008	Compact	Power Split	NiMH	16.2	75

Table 5.10 Performance characteristics of Ford’s Hybrid Vehicles

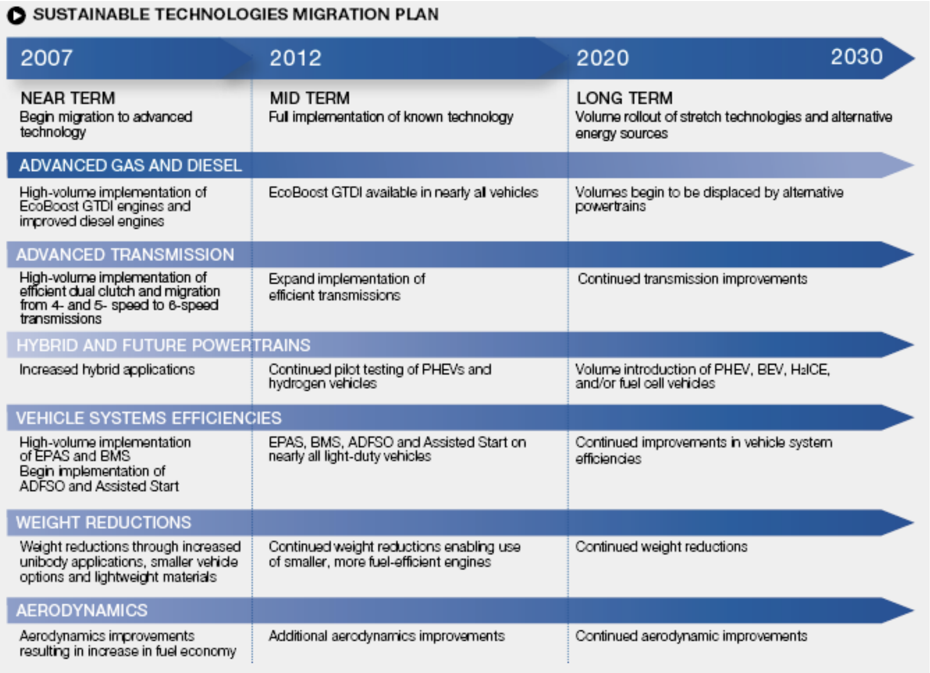
In fuel cells, Ford began development work in 1998 and in 1999 it produced its first working prototype on the Contour platform called the P2000 which used compressed hydrogen, as shown in Table 5.11. In 2001 Ford built a second prototype using compressed hydrogen on the Focus platform called the Ford Focus FCV CG H2. Also in 2001 Mazda, a Ford subsidiary put a methanol reform unit on the Premacy platform. In 2002 a new pre-production version of the Focus prototype was built, and in 2005 Ford built a number of the Focus FCV for testing and demonstrations such as that conducted at the North American Auto Show in Detroit in 2006. In 2007, Ford introduced a plug-in hybrid- hydrogen fuel cell prototype based on the Edge Platform and its new HySeries power train which had a range of 40 kilometres on battery power and then used the fuel cell. All of Ford's fuel cell vehicles to date have been test vehicles and prototypes, including its latest Fusion 999, with a 400kw fuel cell, which set a speed record for fuel cell vehicles by reaching 207 miles per hour. Ford has generally worked on one platform at a time and, with the exception of the Mazda Premacy project, is committed to compressed hydrogen as the fuel source.

FORD	Year	Vehicle Type	Fuel Source	Storage	Range (km)	Top Speed (km/hr)
P2000 FCEV	1998	Sedan	Compressed Hydrogen	Pressurised canister	160	128
Th!nk FC5	2000	Sub-compact	Compressed Hydrogen	Pressurised canister	n/a	128
Focus FCV	2000	Compact	Compressed Hydrogen	Pressurised canister	n/a	n/a
Premacy FCV	2001	Sedan	Reformatted methane	Pressurised canister	306	160
Focus FCV (2)	2001	Compact	Compressed Hydrogen	Pressurised canister	160	128
Advanced Focus FCV	2002	Compact	Compressed Hydrogen	Pressurised canister	306	160
Explorer FCV	2006	SUV	Compressed Hydrogen	Pressurised canister	560	140
Edge HySeries	2007	Compact	Compressed Hydrogen, Electricity	Pressurised canister, Battery	360	140
Fusion 999	2008	Compact	Compressed Hydrogen	Pressurised canister	n/a	345

Table 5.11 Performance characteristics of Ford's Fuel Cell Vehicles

The overall conclusion from Ford's fuel cell program, shown in Table 5.11, is that after a strong start it appears to have slowed down substantially; Ford developed a total of six prototypes between 1998 and 2002 and only three between 2003 and 2008. Ford's relatively weak fuel cell program appears to corroborate the idea expressed above that there was an explicit deal between GM and Ford and the Bush administration on fuel cells, in which Ford, according to interview subject number 6, agreed to spend one hundred and fifty million dollars per year or half of the commitment made by General Motors. A different reading of Ford's history in fuel cells and electric vehicles, provided by subject number 3, is that at one point in time Ford did actively pursue investments in alternative power train technologies, including its investment in Ballard, but simply had to pull back from non-essential activities due to financial constraints.

Figure 5.8 shows Ford's blueprint for sustainable technologies in which it clearly places fuel cell vehicles in the very long term. Ford places fuel cells as a possibility for 2020 together with battery electric vehicles, essentially ruling out any development on specific models at this time and thus restricting the technology to research projects, demonstration vehicles and concept cars.



SUSTAINABLE TECHNOLOGIES MIGRATION PLAN

2007	2012	2020 — 2030
NEAR TERM Begin migration to advanced technology	MID TERM Full implementation of known technology	LONG TERM Volume rollout of stretch technologies and alternative energy sources
ADVANCED GAS AND DIESEL		
High-volume implementation of EcoBoost GTDI engines and improved diesel engines	EcoBoost GTDI available in nearly all vehicles	Volumes begin to be displaced by alternative powertrains
ADVANCED TRANSMISSION		
High-volume implementation of efficient dual clutch and migration from 4- and 5- speed to 6-speed transmissions	Expand implementation of efficient transmissions	Continued transmission improvements
HYBRID AND FUTURE POWERTRAINS		
Increased hybrid applications	Continued pilot testing of PHEVs and hydrogen vehicles	Volume introduction of PHEV, BEV, H_2ICE, and/or fuel cell vehicles
VEHICLE SYSTEMS EFFICIENCIES		
High-volume implementation of EPAS and BMS Begin implementation of ADFSO and Assisted Start	EPAS, BMS, ADFSO and Assisted Start on nearly all light-duty vehicles	Continued improvements in vehicle system efficiencies
WEIGHT REDUCTIONS		
Weight reductions through increased unibody applications, smaller vehicle options and lightweight materials	Continued weight reductions enabling use of smaller, more fuel-efficient engines	Continued weight reductions
AERODYNAMICS		
Aerodynamics improvements resulting in increase in fuel economy	Additional aerodynamics improvements	Continued aerodynamic improvements

Figure 5.8 Ford's sustainable technologies migration plan
(from Ford Motor Company's *2007/8 Blueprint for Sustainability Report*)

- Overview

It is also difficult to see any broad pattern in the Ford data as its approach appears to vary with the technology in question. Ford's patent patterns as shown appear to be spread out in hybrids and fuel cells and more focused in seat belts and even more so in airbags. In a similar way Ford appears to be developing technologies in parallel in hybrids and fuel cells and pursued more focused technological development in seat belts and airbags. One explanation for the Ford data is that Ford approaches each technology in whatever way makes the most sense for it. Interview subject number 5 maintained that the key drivers for technological introduction were cost and perceived value and interview subject number 7 thought that strategy was driven by the size of the financial commitments. Subject number 8 felt that Ford's culture was all about analysis again supporting this interpretation of the different patterns seen in the data. Subject number 7 also gives an alternative view insisting that Ford "lurches back and forth" in terms of technology strategy according to the personality and agenda of the CEO at the time.

5.2.3 Toyota

- Patent analysis

Table 5.12 shows the total number of U.S. patents filed by Toyota up to 2006 as well as the number and relative percentage of patents filed in each of the four technologies under study. The data shows a very large output of patents in both hybrids both in absolute and relative terms and a major effort in fuel cells.

	Total U.S. Patents	Seat Belt Patents	Airbag Patents	Hybrid Patents	Fuel Cell Patents
Total Patents	10, 588	60	90	145	109
%	100%	0.57%	0.85%	1.37%	1.03%
Average % Across sample		0.81%	0.76%	1.03%	1.03%

Table 5.12 Toyota patents

The *Themescape* representations of Toyota's patents are shown in Figure 5.9a -5.9d. In seat belts, Toyota has only two islands but also two large peninsulas. There is a central core area with two large, contiguous peaks but this is surrounded by hills spread out across the landmass. Toyota's airbag patents resemble the seat belt pattern even though there are 30% more patents in the sample. This gives the airbag picture a higher elevation in the representation and six peaks. Toyota's hybrid patents represented in Figure 5.9d appear as an eight island archipelago with four peaks, and covers a relatively large area in the representation. Toyota also has the largest number of patents in hybrids (145).

Toyota's fuel cell patents, on the other hand, cover a smaller area with a central land mass characterized by a large peninsula and a small island. The representation has only one peak but does have a central ridge line running like a cross dividing the landmass upon which most of the patents appear to be concentrated.

Table 5.13 shows the salient features of the maps applying the topographical metaphor outlined in Sub-section 3.3.3

	Seat Belts	**Airbags**	**Hybrid Vehicle**	**Fuel Cell Vehicle**
Relative area	Large	Medium	Medium	Medium
Type of landmass	Major central landmass two peninsulas	Central landmass	Archipelago	Contiguous with one Peninsula
Number of islands	2	4	8	1
Number of peaks	2	6	4	2

Table 5.13 Major features in Toyota patent visualizations

Figure 5.9a Toyota seat belt patent visualisation

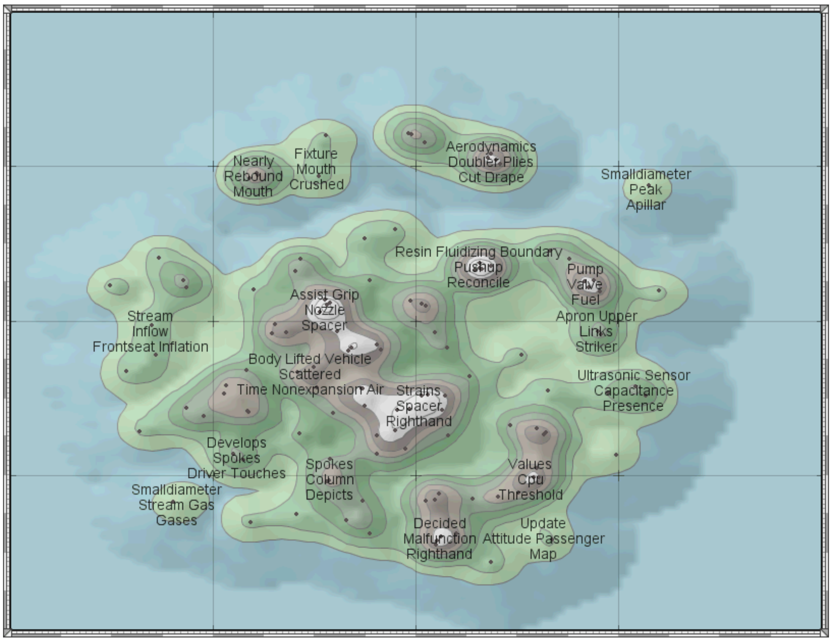


Figure 5.9b Toyota airbag patent visualisation

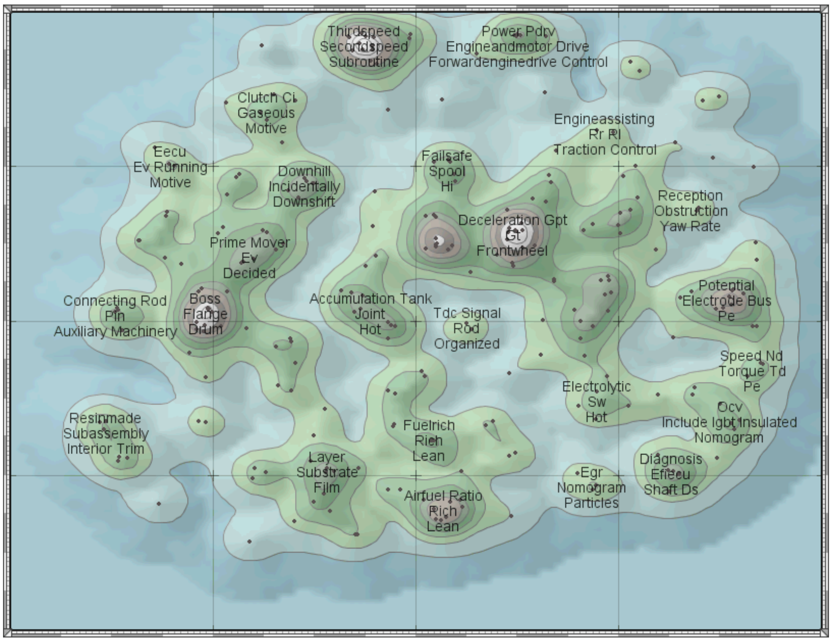


Figure 5.9c Toyota hybrid patent visualisation

Figure 5.9d Toyota fuel cell patent visualisation

- Deployment data

1. Seat belts

The deployment data in Table 5.14 shows Toyota introducing the rear seat belts in one model in 1988 and then extending them a year later to its other 5 models.

Model Year	1988	1989
Models with rear seat belts	1	6
Total Models with rear seats	6	6
Percentage with rear belts	17%	100%

Table 5.14 Rear seat belt penetration in Toyota

2. Airbags

In airbags, Toyota's deployment is presented in Figure 5.10 and two ideas stand out. First, Toyota appears to bring out the new technology in selected models and then roll it out to the rest of its fleet. The time lag in roll-out from the first application to the second was six years in side impact, five years in smart technology, and just one year in the case of the advanced system. Second, Toyota deploys different generation technologies at the same time as it does in 2004 where it deploys second generation technology as well as smart airbags and advanced airbags. Like GM, Toyota shows a large time lag between its first introduction of side impact protection in 1998 and the next deployment in 2004 and, while this might be evidence of the technological difficulties associated with the technology, it might also indicate less market demand.

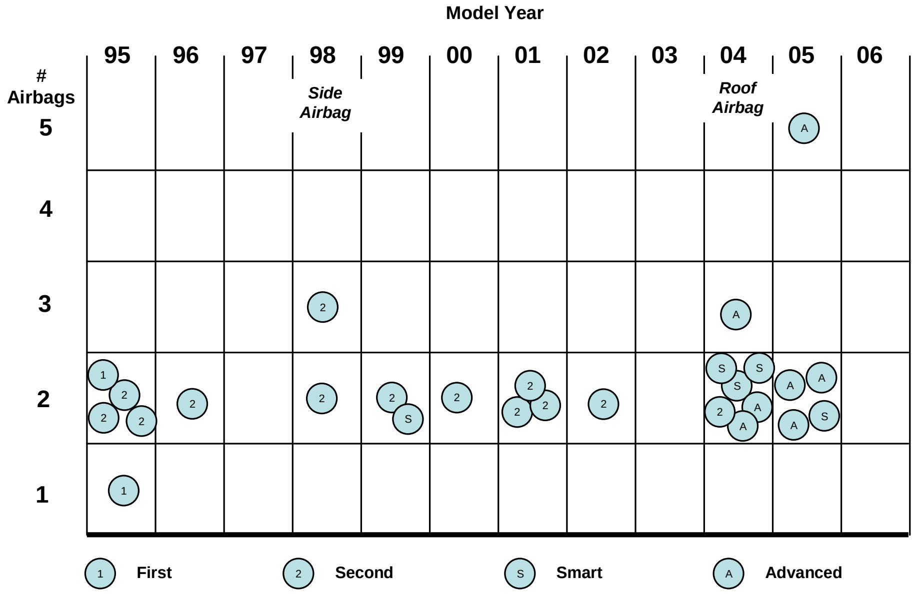


Figure 5.10 Airbag introductions by Toyota

Interview subject number 2 believed that the Japanese manufacturers including Toyota chose to make safety an issue in the late 1980's and in this light Toyota's rapid deployment of rear seat belts and its deployment of airbag technology was an effort to catch up and then get ahead of its American and European competition.

3. Hybrid and fuel cell electric vehicles

In 1992 Toyota adopted the Toyota Earth Charter and created an environmental committee chaired by its president to develop and then implement a series of four-year plans. Toyota refers to the need to reduce the environmental burden caused by cars as the only way to protect its future core business and has placed the development of environmentally friendly technologies at the top of its corporate agenda.

Toyota's view of sustainable transportation in shown in Figure 5.11 and is that all vehicles will become hybrids in the not-too-distant future and sees hybrid technology as the precursor for whatever types of ultimate eco-car will finally emerge. One of the points that Toyota makes is that "well to wheel" energy efficiency of different types of vehicles depends on the energy mix of a particular country and this supports the idea of developing the right car for the right place, at the right time. If electricity is produced from coal in conventional power plants, for example, an electric car might actually pollute more than a very efficient internal combustion engine vehicle.

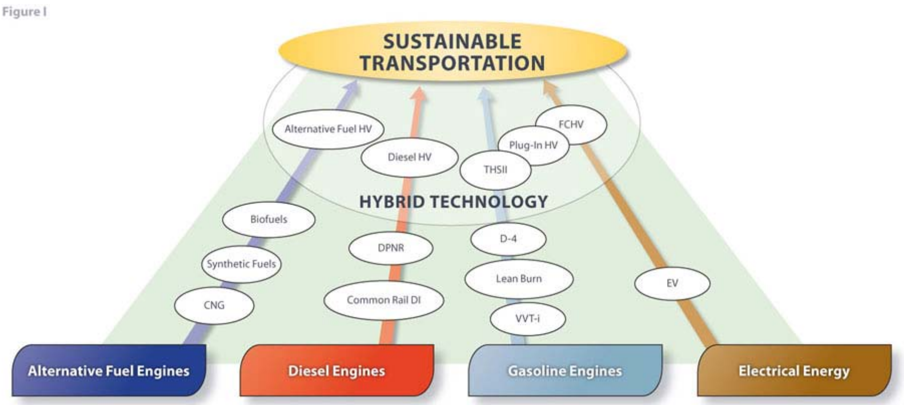


Figure 5.11 Toyota's view of sustainability
(from Toyota's 2007 North American Environmental Report)

Partly in response to California's zero emissions legislation discussed in Sub-section 5.3.4 and also due to the Earth Charter, Toyota developed an electric version of its RAV4 SUV in 1996 with a nickel-metal hydride battery pack, a range of 152 km and a top speed of 126 km/hr. According to interview subject number 3, Toyota was directly requested to build the RAV4 vehicle by California officials but sold only a few hundred cars and then went through a costly, but quiet, recall program. In 1997, Toyota produced the Toyota e-com which was a small city car concept with a 100 km range and top speed of 100 km/hr. A second version of the e-com was shown in 2001.

What proved to be the real breakthrough for Toyota however was the launch in 1997 of the Toyota Prius. At that time, much of the automotive industry's attention was focused on fuel cell electric vehicles (Hoed, 2004) and hybrids were seen only as a technological forerunner to fuel cell vehicles as many of the components, such as the electric motors, inverter and control systems, are potentially compatible. Table 5.15 gives a sense of Toyota's commitment to hybrid technology and its apparent two pronged strategy, one part of Toyota's strategy appears to be focused on improving the Prius product by updating its styling and performance every few years. The other part seems to about placing hybrid power trains on more models. Toyota offers 7 hybrids out of a total of 24 models in the United States or 29% of its product range, as shown in Appendix C3. Lexus has half of its 8 models available as hybrids

Toyota	Year	Vehicle Type	Architecture	Battery Type	Fuel Economy (km/l)	Top Speed Electric (km/hr)
Prius	1997	Sedan	Power Split	NiMH	n/a	n/a
	2000				n/a	n/a
	2003				17.5	n/a
	2008				19.6	n/a
	2010				21.3	50
Camry Hybrid	2007	Sedan	Power Split	NiMH	14.5	n/a
Highlander Hybrid 2wd	2006	SUV	Power Split	NiMH	14.5	n/a
	2008				11.1	
Highlander Hybrid 4wd	2006	SUV	Power Split	NiMH	11.1	n/a
RX400H	2005	SUV	Power Split	NiMH	11.5	n/a
RX450H	2010	SUV	Power Split	NiMH	11.9	n/a
GS450H	2006	Sedan	Power Split	NiMH	9.8	n/a
	2009				10.6	
LS600H	2007	Sedan	Power Split	NiMH	8.9	n/a
	2009				9.4	

Table 5.15 Performance characteristics of Toyota's Hybrid Vehicles

Another example of pursuing parallel tracks was in Japan, where cars have a three year warranty, the Prius was equipped with an all-electric running mode while in the U.S. this feature was never offered. On balance, Toyota's program should be considered broad as the Prius was just one of the options it was developing and Toyota continues to pursue a broad strategy at the component level as shown for batteries in Figure 5.12.

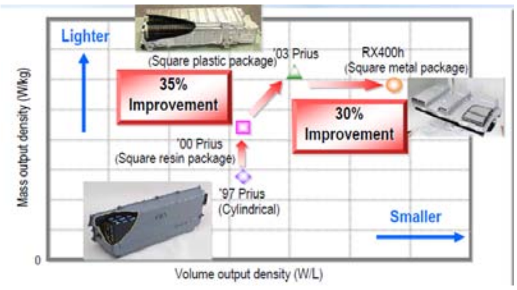


Figure 5.12 Toyota Battery Improvements
(from Toyota Environmental Forum, June 2008)

In hybrids, Toyota is considered the technological leader and, according to interview subject number 6 who has particular expertise in the area of new product development, Toyota's position is largely due to its disciplined approach to technology management. One element of the strategy is that Toyota will not allow a vehicle program to use completely new technology and will instead have new ideas worked out and tested and only then be allowed into a new vehicle program. Once a technology is "on the shelf" however, all programs are encouraged to use it and Toyota's managerial accounting spreads the costs of the new technology out across the company. Toyota also reportedly takes a portfolio approach to technology management and thinks through where it hopes to see new technology well in advance. Finally, Toyota makes major power train innovations only at the 2 year re-styling and not at the 4 year new product launch, in a deliberate attempt to limit the technological risk of a new model.

Toyota's fuel cell program, shown in Table 5.16, has largely been focused on the FCEV / FCHV program with one notable departure in the development of the FINE prototypes using the same technology. Toyota's first fuel cell electric prototype was built at the same time and on the same platform as the RAV4 electric vehicle and used a hydrogen absorbing alloy as the fuel source. The next year, Toyota improved the vehicle's range and speed by adding an on-board reformer which converted methanol. As for the fuel cell itself, Toyota took the decision to keep its fuel cell technology in-house and is now producing its fifth generation fuel cell.

Toyota	Year	Vehicle Type	Fuel Source	Storage	Range (km)	Top Speed (km/hr)
RAV4 FCEV	1996	SUV	Hydrogen	Metal Alloy	250	100
RAV4 FCEV (2)	1997	SUV	Reformed Methanol	Gas tank	500	125
FCHV-3	2001	SUV	n/a	Pressurised canister	300	150
FCHV-4	2001	SUV	Compressed Hydrogen	Pressurised canister	250	152
FCHV-5	2001	SUV	Compressed Hydrogen	Pressurised canister	n/a	n/a
FCHV 2002	2002	SUV	Compressed Hydrogen	Pressurised canister	290	155
FINE-S	2003	Coupe	Compressed Hydrogen	Pressurised canister	n/a	n/a
FINE-N	2003	Coupe	Compressed Hydrogen	Pressurised canister	500	n/a
FCHV-adv	2008	SUV	Compressed Hydrogen	Pressurised canister	830	155

Table 5.16 Performance characteristics of Toyota's Fuel Cell Vehicles

According to Toyota it has "made great strides in overcoming many of the technical challenges. We have increased the on-board hydrogen storage capacity and the vehicle range, increased the durability and reliability of the fuel cell stack, and have succeeded in subzero operation to as low as -34.5° F (-37° C)" (from Toyota's 2008 North American Environmental Report).

The latest FCHV has actually been leased to several universities and a power company in Japan, allowing Toyota to argue that the cars are commercially available. While this claim is technically correct, these vehicles are still prototypes and the experts interviewed for the thesis concur that commercially-viable fuel cells electric vehicles are still 10-20 years away.

- Overview

With the exception of the pattern shown for hybrid vehicles, Toyota's patents fall into fairly tight patterns with a central land mass and a couple of outliers. In terms of deployment, Toyota also appears to be very focused and consistent.

While the interview subjects agreed with Toyota's leadership position in hybrids, there was disagreement over the overall competitive position of Toyota in the area of alternative power trains in general. Subject number 7 was convinced that Toyota was "on the right track" and that the underlying technology developed for Prius will give it competitive advantage in whatever evolution the industry takes. The same subject argued that Toyota's problems at the time of writing were only "chinks in its armour" and that it was still enjoying a dominant position in production technology.

On the other hand, subject number 6 felt that Toyota was in trouble and had gone too far with an over-engineered hybrid system. Despite his respect for its development process, he felt strongly that Toyota's consensus-based management team will not be able to "make the tough decisions" needed to compete in a world which will become battery electric. Their hybrid drive is expensive and the underlying component technology is not as useful as initially thought. Battery technology, for example, is moving to lithium-ion while Toyota uses nickel-metal hydride batteries in its hybrids.

According to subject number 4, Toyota itself acknowledges that it needs to change and be "less boring". In this view Toyota's ability to plan and the discipline it has to stick to the plan is considered a weakness rather than strength.

5.2.4 Nissan

- Patent analysis

Table 5.17 shows the total number of U.S. patents filed by Nissan up to 2006 as well as the number and relative percentage of patents filed in each of the four technologies under study. The data shows a very large output of patents in hybrids and fuel cells both in absolute and relative terms.

Nissan	Total U.S. Patents	Seat Belt Patents	Airbag Patents	Hybrid Patents	Fuel Cell Patents
Total Patents	8,519	103	47	84	82
% Nissan patents	100%	1.21%	0.55%	0.99%	0.96%
Average % Across sample		0.81%	0.76%	1.03%	1.03%

Table 5.17 Nissan patents

Table 5.18 shows the salient features of Nissan's patent patterns shown in Figure 5.13a-d and applying the topographical metaphor outlined in Sub-section 3.3.3, it appears that Nissan has a fairly consistent approach.

Both the seat belt and airbag patterns have no islands, 4 peaks, and present a smaller landmass than the other manufacturers. The airbag representation is smaller than that of seat belts indicated a more focused group of patents. Nissan does have less than half as many patents in airbags as in seat belts (47 vs. 103) but, as explained in Sub-section 3.5.3, the number of patents should not drive the map scale as long as the total number of patents is within the same order of magnitude; thus, if there were a partial scalar effect, it would not explain the difference in area.

In hybrids, Nissan's pattern appears quite concentrated and, although it does have three islands, its central feature is a very large mountain with three contiguous peaks.

In fuel cells, Nissan's pattern appears more spread out than in the other areas but still covers a largely contiguous, large landmass with only one small island. It does have three peaks along a central ridge but, with close to the same number of patents as for hybrids (82 vs. 84). This might have to do with the nature of fuel cell technology which is significantly less developed than the other areas under study.

	Seat Belts	**Airbags**	**Hybrid Vehicle**	**Fuel Cell Vehicle**
Relative area	Small	Very Small	Very Small	Very Large
Type of landmass	Contiguous with two inlets	Contiguous with one Peninsula	Contiguous with two Peninsula	Contiguous with two lagoons
Number of islands	0	0	2	2
Number of peaks	4	4	3	3

Table 5.18 Major features in Nissan patent visualizations

Figure 5.13a Nissan seat belt patent visualisation

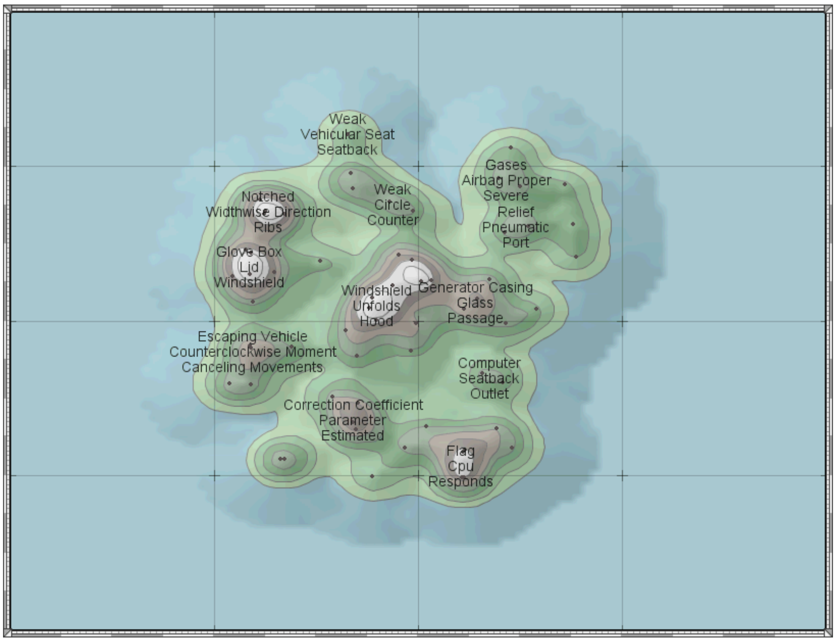


Figure 5.13b Nissan airbag patent visualisation

Figure 5.13c Nissan hybrid patent visualisation

Figure 5.13d Nissan fuel cell patent visualisation

- Deployment data

As outlined in Section 3.7, the deployment data covers each technology in turn.

1. Seat belts

Table 5.19 shows the deployment of back seat belts by Nissan and shows that Nissan put the belts on only one vehicle in 1987 and then waited until 1989/1990 to deploy the belts across its product range. Nissan was the first of the four manufacturers under study to install rear seat belts and did so in its Maxima model in 1987. Nissan then waited until 1989 to install the belts on the 200, 240 SX and Stanza, and the rest of its fleet only in 1990. The Pulsar was re-styled in 1990 and equipped with the rear belts at that time, but this is the only such example for Nissan. One interpretation of the data could be that the delay was deliberate and that perhaps Nissan chose to perfect the system before rolling it out across the fleet.

Model Year	1987	1988	1989	1990
Models with rear seat belts	1	1	3	7
Total models with rear seats	6	6	6	7
Percentage with rear belts	17%	17%	50%	100%

Table 5.19 Rear seat belt penetration in Nissan

2. Airbags

Figure 5.14 shows Nissan’s airbag deployment which reveals the company making no new deployment over a four year period and then engaging in a massive 5 year program to upgrade the systems on its entire model range.

As shown in Figure 5.14, Nissan fit both first and second generation technology on its entire product offering in 1995, placing the more expensive second generation technology on the higher end Maxima and Altima models while at the same time equipping the 200, 240 and 300 models with first generation technology. Nissan had more models with side impact protection, was one of the first in the market to install on/off switches and was the first with advanced systems and roof airbags. Nissan then appeared to redesign its airbag systems deploying new systems on new vehicles in 1999 and 2000 and then updating its entire fleet after 2002. During this deployment Nissan went ahead with new airbags and, as can be seen in Appendix E, in some cases did not wait for a major facelift and changed airbags systems from one model year to another.

As stated above, Interview subject number 2 characterised Nissan and the other Japanese manufacturers as fast followers in safety, and attributes both the seat belt and airbag data as evidence of its efforts to catch up on safety.

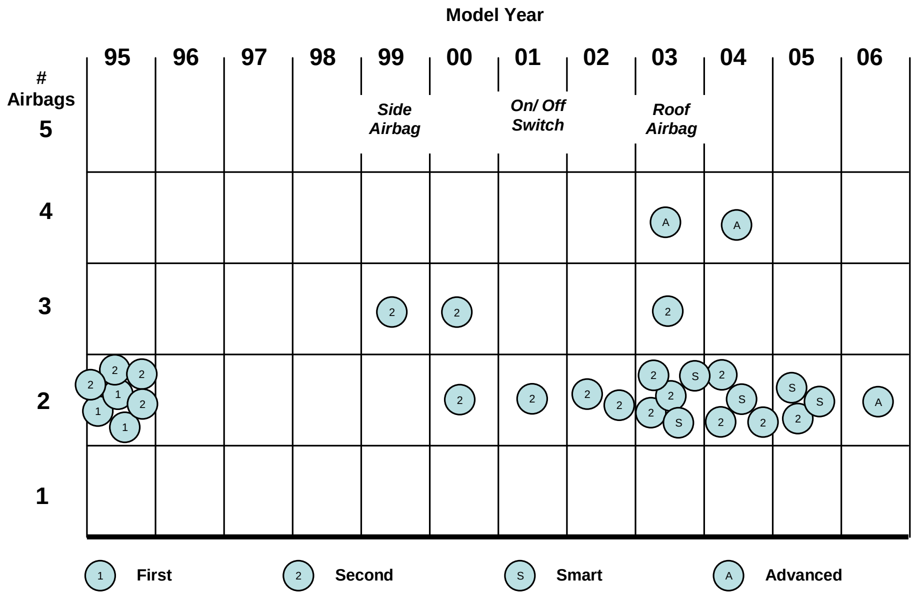


Figure 5.14 Airbag introductions by Nissan

3. Hybrid and fuel cell electric vehicles

Although Nissan reportedly released its first electric vehicle in 1947 and has had a research program going on for some time, Nissan's CEO Carlos Ghosn has been sceptical of alternative energy technology. In 2005 Reuters reported that, in an address to the National Automobile Dealers Association, Ghosn said: "They make a nice story, but they're not a good business story yet because the value is lower than their costs". In the same speech Ghosn said that Nissan was only getting into hybrids to comply with fuel economy legislation in certain markets, that they were a niche product, and that they had written off fuel cell vehicles because they cost on the order of $800,000 each to build.

Nissan's hybrid program consists of only one vehicle, the Altima, and is shown in Table 5.20. Interview subject number 3 did assign some importance to the Tino hybrid program which preceded Nissan's adoption of Toyota technology but saw it as a road not taken by the company. As Nissan has a total of 19 models including Infiniti on the market in the US, its hybrid coverage is 5%, reflecting the scepticism shown by Nissan Management discussed above.

Nissan	Year	Vehicle Type	Architecture	Battery Type	Fuel Economy (km/l)	Top Speed Electric (km/hr)
Altima	2007	Sedan	Power split	NiMH	14.5	n/a

Table 5.20 Performance characteristics of Nissan Hybrid Vehicle

- Fuel Cells

Table 5.21 shows Nissan's fuel cell program, which produced a series of prototypes based on the X trail SUV.

Nissan	Year	Vehicle Type	Fuel Source	Storage	Range (km)	Top Speed (km/hr)
Altra FCV	1999	Estate	Methanol	Reformer	n/a	n/a
R"Nessa	1999	Estate	Methanol	Pressurised Tank	n/a	70
EFFIS	2003	Sub compact	n/a	Pressurised Tank	n/a	n/a
X-Terra	2000	SUV	Compressed Hydrogen	Pressurised Tank	160	120
X-Trail FCV	2002	SUV	Compressed Hydrogen	Pressurised Tank	200	125
X-Trail FCV (2)	2003	SUV	Compressed Hydrogen	Pressurised Tank	350	145
X-Trail FCV (3)	2005	SUV	Compressed Hydrogen	Pressurised Tank	500	150

Table 5.21 Performance characteristics of Nissan Fuel cell Vehicles

- Overview

The interview subjects gave opinions on Nissan's overall situation with subject number 4 maintaining that Nissan has made impressive financial returns over the last 10 years but has been in permanent "turnaround" mode, subordinating all decisions to the achievement of the financial goals in a series of three year plans. Subject number 7 maintained that Nissan was still "thrashing around" looking for a basic strategic direction as it emerges from its recovery phase.

With respect to Nissan's relatively new electric vehicle program the experts interviewed had different views about its chances of success. Subject number 4 understands that Nissan has committed virtually its entire research budget to the program and considers it as a "throw of the dice" and supports the view that Nissan was so far behind Toyota on hybrids that it was not worthwhile to try and catch up. Subject number 7 refereed to the program as a "Hail Mary" strategy making a reference to American football where the offensive team might throw the ball far forward in the closing moments of a game and pray that it will result in turning a loss into a win. Subject number 1 was also sceptical of the program, pointing out that it is dangerous to be "too soon" with new technology and that the infrastructure for electric vehicles was hard to imagine in urban environments.

Subject number 6, however, is convinced that the future of personal transportation will be electric and that Nissan will successfully leapfrog Toyota's lead in hybrids because its multicultural team was "pragmatic and determined to succeed". For subject number 5, Nissan recognizes the critical issues around consumer finance and will keep the purchase price of the vehicle competitive by leasing the batteries but is, at the same time, concerned about lithium-ion batteries which are actually thousands of small cells wired together with a huge potential for failure.

In July, 2008, the New York Times quoted Mr. Ghosn as making a firm commitment to putting 1 million electric vehicles on the road starting in 2012. “I want a pure electric car. I don’t want a range extender. I don’t want another hybrid.”

Nissan has made a serious commitment to lithium-ion batteries as the cornerstone of its electric vehicle plans and built a series of prototypes around the technology over the last 10 years, which led to its announcement in August 2009 of the launch of the Nissan Leaf, a medium-size hatchback that comfortably seats five adults and has a range of more than 160km and is shown in Figure 5.15.

Figure 5.15 Nissan Leaf

Figure 5.16 shows Nissan’s view of the future in which all cars will have a much lower CO2 footprint but where the internal combustion engine still makes up the majority share of the market in 2050.

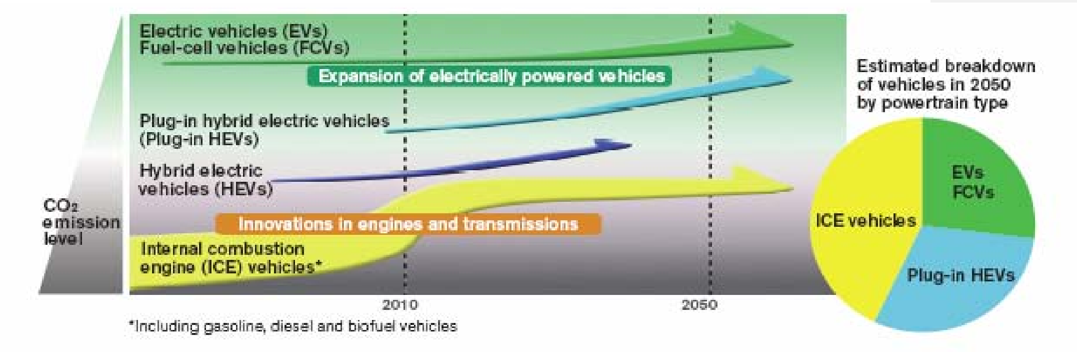


Figure 5.16 Nissan’s technology roadmap
(from Sustainability Report 2007 of Nissan Motor Company)

5.3 Technology case studies

Section 5.2 presented case studies of each of the four manufacturers and discussed how they looked at the four technologies under consideration. Section 5.3 takes an orthogonal look at the data by discussing each technology in turn and evaluating the response of the four manufacturers. Sub-section 5.3.1 will discuss Geels and Schot's (2007) typology of technological pathways. Sub-sections 5.3.2 – 5.3.5 will present the case studies for seat belts, airbags, fuel cell electric and hybrid vehicles. Each sub-section will discuss the history and context of the technology, discuss the technology pathway it appears to be on using Geels and Schot's (2007) typology and then explore how the four manufactures appear to have approached the technology by looking at the patent data, deployment data and the opinions of the experts interviewed.

5.3.1 Technology pathways

As discussed in Sub-section 2.2.2, Geels and Schot (2007) develop the mult-level perspective and combine it with Suarez and Olivia's (2005) typology of environmental change to define four pathways for technological transitions.

Suarez and Olivia's typology is based on evaluating the frequency, amplitude, speed, and scope of changes to the environment and combining these concepts to develop five different types of change: A *regular* environment is one in which few things change over time, the changes themselves are small and happen slowly and are normally confined to specific parts of the environment or landscape. A *hyperturbulent* environment has a large number of very low impact changes happening very quickly in different parts of the landscape. An environment might suffer from a once-in-a-lifetime, high amplitude, high speed *specific shock* which affects one aspect of the landscape. If the same change happens slowly it could be described as *disruptive*. Finally a high impact, high speed change with wide impact is described as an *avalanche*. After reviewing Suarez and Olivia's typology, Geels and Schot throw out the hyperturbulent mode for change and then go on to introduce two additional ideas to the perspective in order to come up with their four pathways. One idea is the timing of change pressure with respect to the level of development or readiness of a new technology at the niche level. The other is the degree to which the new technology is complimentary or competitive with respect to the existing technology regime. In order to operationalize the idea of readiness Geels and Schot propose four tests of readiness as follows:

1. If the technology has emerged as the dominant design within its niche or niches
2. If powerful actors have joined the technology's development or deployment
3. If scale effects are already being felt or, in other words, if the learning curve is providing measurable reductions in cost
4. If the niche or niches amount to at least 5% of the total market

Geels and Schot consider the degree to which the new technology is complementary or competitive with respect to incumbent technology and define four pathways for technological transitions as follows:

1. Transformation

Transformation occurs when there is moderate pressure from the landscape for change but the technology is not ready in its niche application. In this case regime actors will change what they are doing to respond to the changes. Social pressure groups, for example, might demand changes to a set of services and, if the current set of industry participants do not make those changes, new entrants might come in.

2. De-alignment, re-alignment

In the face of far reaching and sudden landscape change, a regime can begin to fall apart even if there is no clear alternative developing in niche markets. What happens next is that different alternatives compete and eventually a new dominant design can emerge. Geels (2005) discusses the change from horse-drawn carriages to the modern automotive regime as an example of this kind of change.

3. Technological substitution

If there is a moderate to high degree of landscape pressure in any one of the categories discussed above, and the niche technology is ready, then what happens is technological substitution.

4. Re-configuration

Sometimes, with very moderate landscape pressure, new applications develop sufficiently, and are also symbiotic with the incumbent technology regime such that they can be adopted into it as add-ons or in a hybrid form. In some cases the new technology allows new configurations to emerge and, when this in turn causes substantial changes to the overall socio-technical regime, Geels and Schot refer to this pathway as re-configuration.

5.3.2 Seat Belts

- History and context

Although simple seat belts had been used since 1885 (Johannessen, 1984), serious interest in them for cars did not occur till the 1950's. Hugh De Haven is credited with the first serious study of what he called the second collision (De Haven, 1952). According to Nash (2009), De Haven put forward the fundamental principles of safety research still in use today. De Haven, together with Roger Griswold, also invented the first three point seat belt in 1952. Ford offered the first seat belts on a production car in 1956 as part of an optional "lifeguard safety package" on its Crown Victoria sedan, and Saab became the first manufacturer to install front seat belts as standard equipment in Sweden in 1958 and brought them to the United States in 1962.

Saab used a two point seat belt and Volvo followed with Nils Bohlin's patented three point system in Sweden in 1959 and the United States in 1963. By the early 1960's, concern over automotive safety had been building in the United States and other markets, but was still considered a relatively minor issue. Using Geels and Schot's terminology, at the time of their introduction there was mild environmental pressure. Effective 1 January, 1964, 23 state governments enacted legislation requiring seat belt anchor points in the front outboard positions in response to public pressure of the kind shown in Ralph Nader's seminal book, *"Unsafe at any speed"* (Nader, 1965).

As it was not considered economic to only install seat belts on cars destined for sale in the states that required them, most manufacturers placed front seat belts or at least anchor points as standard equipment in 1964. In 1966, The U.S. government passed the Highway Safety Act, which created the National Highway Safety Bureau (NHBS) and paved the way for the introduction of a series of safety regulations including Standard 208 which required cars to have seat belts, which took effect on 1 January, 1968. The NHBS later became the National Highway Traffic Safety Administration (NHTSA).

Johannessen (1984) charts the technological development of seat belts in subsequent years showing a time lag between the appearance of superior technology in European brands, particularly Volvo, and the adoption of those improvements by Ford, Chrysler and General Motors. Volvo appealed to a segment of consumers who were especially concerned about safety, and as legislation continued to evolve technology has been available. The fact that seat belts were already being offered by Ford, Volvo and Saab facilitated the incorporation of the technology by the rest of the industry, which was faced with increasing pressure from consumers and regulatory bodies. Volvo, for example began installing seat belts in rear seats in 1967 and introduced pretensioners in 1987. (from www.volvocars.com/us/footer/about/NewsAndEvents/Pages/Volvo_Safety_Firsts accessed 20.12.09)

There has been, and still is, a segment of the market that is concerned about automotive safety. In the spring of 2009, for example, Volvo offered its "technology package" to its XC60 for $1,695 with five new active safety features as follows:

- Adaptive Cruise Control
- Collision Warning with Auto Brake
- Distance Alert
- Driver Alert Control
- Lane Departure Warning

(from www.volvocars.com accessed 13.4.09)

- Technology Pathway Analysis

If there is a moderate to high degree of landscape pressure and the niche technology is ready, then Geels and Schot call the pathway *technological substitution*. In the case of seat belts, of course, the seat belt did not substitute an alternate passenger restraint device so its substitution is, in fact, an addition. The thesis, however, maintains Geels and Schot's nomenclature.

As over 50 years have gone by since the first production of automotive seat belts, the technology has advanced substantially, as shown in Table 5.22. All of the features shown in Table 5.22 are currently available as standard equipment or options on the top-of-the-line Volvos, Mercedes and some other brands.

In summary, it appears that the *technological substitution* pathway holds some validity for seat belts because, there was moderate environmental pressure leading up to federal legislation, the technology was ready at the niche level and actively supported by the supply base, and seat belts required little technical adjustment to the vehicle or the socio-technological regime. Where seat belts have struggled and are still struggling in some markets is on the social adaptation required to get people to use them.

Component	**Description**
Buckle	standard item which has also undergone technological development in order to be easy to open and close but also withstands crash forces
Belt Grabber	first introduced in 1986, this device which pulls up seat belt slack has become standard on most vehicles
Height Adjuster	relatively standard in manual form but also available with built in motor and even memory capability for automatic adjustment
Retractors	standard device since 1967, the retractor not only pulls up slack but also locks in place against sudden acceleration
Active Seat belts	seat belts equipped with a high speed motor which tightens just before crash and/or vibrates in order to advise the driver of an emergency
Belt in Seat	also referred to an integrated seat belt and discussed above
Pretensioner	pyrotechnic device which tightens seat belt sharply at the moment of impact
Load Limiter	First introduced in 1995, acts to adjust the force of the restraint to a steady load during crash dynamics in balance with the airbag
Smart Belt	system quipped with a 2-gear pretensioner which allows a lighter restraint immediately after initial impact or if occupant is smaller or lighter
Trunk Belt	new application of technology which acts to hold items in the trunk secure during an accident keeping them from impacting the passenger space
Electronic Control Unit	central processor for seat belt and airbag system

Table 5.22 Selected Seat Belt Components
(from Autoliv.com accessed 10.5.2009)

- Empirical data

Table 5.23 shows the absolute and relative patent counts for seat belts at the different manufacturers. In terms of filings, GM has filed many patents but is only slightly higher than the average for the sample in relative terms. Nissan, in contrast, has almost as many patents as GM but a much greater relative effort with seat belts representing 1.21% of all of its patents or about twice the output seen from Ford and Toyota and 36% higher than GM.

Nissan's large number of seat belt patents could be interpreted as evidence of what interview subject number 2 referred to as the efforts of both Nissan and Toyota to push safety in order to develop competitive advantage. Toyota's relatively small number of patents however, does not support this idea although one could argue that it is not necessary to perform extensive in-house research in a specific component area in order to seek rapid roll out or even relative technological superiority as the supply base is capable of supplying leading edge technology to the vehicle manufacturers in seat belts.

Seat Belts	Total U.S. patents	Seat Belt Patents	% of Total	% of four firms
General Motors	13,078	116	0.89%	34%
Ford	10,238	63	0.62%	18%
Toyota	10,588	60	0.57%	18%
Nissan	8,519	103	1.21%	30%
Total	**42,423**	**342**	**0.81%**	**100%**

Table 5.23 Total seat belt patents by manufacturer

Figure 5.17 Seat belt patent visualisation

Figure 5.17 show the *Themescape* maps from each manufacturer (Figures 5.2a, 5.6a, 5.9a, and 5.13a) reproduced in a smaller scale for convenience and Table 5.24 shows a comparison of the salient features of the different patent patterns.

Toyota General Motors Nissan Ford

Feature	GM	Ford	Toyota	Nissan
Overall Size	Large	Small	Large	Small
Landmass	Contiguous with broad valleys	Contiguous with broad valleys	Major central landmass two peninsulas	Contiguous with two inlets
Islands	0	1	2	0
Peaks	11	6	2	4

Table 5.24 Major features in seat belt patent visualization

The General Motors pattern is much wider than the other manufacturers and shows 11 peaks or focal points indicating that their patenting pattern covered a number of related but disparate topics. Ford's pattern is similar to General Motors but much smaller and lower reflecting the lower elevation appears to reflect the overall lower level of activity. This relationship appear so to hold up in comparing the Nissan pattern with that of Toyota as they also have a similar shape with Toyota showing lower elevation and fewer patents.

Table 5.25 shows the number of years required for rear seat belt deployment and the year when all of each manufacturer's passenger cars had been equipped with pretensioners, in the front seats.

Technology	GM	Ford	Toyota	Nissan
Years to deploy rear seat belts on all models	2	4	2	4
Model year with standard pretensioners on passenger cars and light trucks	2008	2005	2001	2001

Table 5.25 Seat Belt deployment summary

One explanation for the pretensioner data might be that the rate of deployment is a function of the numbers of models and since GM has more models than Ford and both of them have more models than Nissan or Toyota. This would explain how Nissan and Toyota were able to equip their entire fleet relatively quickly while it took Ford and GM longer but does not explain GM's fast deployment of rear seat belts. A more likely explanation of the difference in the pretensioner data is discussed in Sub-sections 5.21 and 5,22 and has to do with other aspects of GM and Ford vehicles which could have made the pretensioner devices unnecessary to achieve acceptable levels of crash dynamics.

Interview subject number 8 felt that the response of the US manufactures to changing safety regulations was to lobby the government for more relaxed rules while the Japanese companies would "figure out what to do" in order to comply. While this idea is certainly tempting, neither the deployment data nor the patent data appear to be sufficiently compelling to support it. In fact two manufacturers, General Motors and Toyota appear to have done a significant amount of seat belt research while Ford and Toyota did substantially less.

5.3.3 Automatic seat belts and airbags

- History and context

Airbags are one of two technological solutions for the issue of passive restraint systems and a discussion of them requires looking first at automatic seat belts which were eventually rejected by the public and the industry in their favour. After years of false starts and court challenges starting in 1970, NHTSA first mandated the use of passive restraints in 1984 for implementation in cars between 1987 and 1990 (Kratzke, 1995). The problem was that, despite years of public awareness campaigns and increasingly vigorous laws and enforcement, many people continued to drive without fastening their seat belts and still do so today. The regulations were designed to oblige the vehicle manufacturers to develop a solution to this problem, although some would argue it is a social, not technical, one. Nevertheless, the key issue in Detroit was how to protect people who would not protect themselves.

In the late 1970's and early 1980's, however, there was no clear technological solution and neither airbags nor automatic belts were sufficiently developed. In terms of the environmental stimulus classification put forward by Suarez and Oliva (2005), the new law was felt as a specific shock by the vehicle manufacturers.

1. Automatic Seat Belts

Many companies favoured automatic seat belts over airbags, arguing that airbags were dangerous in themselves and that seat belts were better protection. Johannessen (1987) provides a comprehensive account of the development of the automatic seat belt which lost the passive restraint battle to the airbag in the late 1980's.The first production car with automatic belts was the VW Rabbit in 1975. This was a two point shoulder belt attached to a track on the top of the door. The anchor point was motorised and would travel up the track thus securing the occupant when the door was closed. Upon opening the door, the anchor point would slide down the track allowing egress. A separate lap belt was buckled manually by the occupant. GM launched a different 2-point system in its Chevette in 1978, in which the belt remained anchored above the door but was pulled out of the way by a secondary belt when the door was open. This system was upgraded to a 3-point system in 1980. Toyota launched its own 2-point system in 1981.

Three conclusions can be drawn: The first is that all three systems were different and that what Dosi (1982) called "the dominant design" had not emerged. This is an indication of there not being a sufficiently developed niche market.

A second issue is that they were launched during a time of legislative turmoil. Kratzke (1995) provides a detailed account of the legal battles between the automakers, insurance groups, activists and NHTSA over the passive safety legislation. In August 1973, for example, a federal law was passed requiring all cars to have either automatic seat belts, airbags, or an interlock system which would not allow the car to operate if the driver seat belt was not fastened. This law created a huge public outcry and was eventually eliminated by a subsequent law in October the following year.

The third issue is that, rather than place the automatic belts on their top-of-the-line models, all three manufacturers placed them on relatively small, inexpensive cars. This could be seen as an indication that the efforts of carmakers were focused on influencing the public debate and developing low cost solutions to the problem. By 1987, Johannessen counts 11 models equipped with automatic belts in 1987 out of the approximately 100-150 models on sale in the U.S.

2. Airbags

While the automatic seat belts were in development, parallel work was being done on airbags which would also satisfy the U.S. Government's legislation on passive safety, keep the passenger in the vehicle and protect him or her from the "second collision" with the dashboard and windshield.

An airbag system is made up of crash sensors and an airbag module which is made up of an inflator, housing, and inflatable bag. For the driver side airbag, the steering wheel and steering column interact with the airbag and driver during crash dynamics and their design becomes a critical element in the system. The key issues in airbag design are the "time budget", or the time available for the airbag to deploy, and the force that the airbag should exert on the occupant in order to restrain them.

Struble (1998) documents the history of airbag technology and credits Volkswagen with the first development work and Ford with the first working system in a fleet of 1972 Mercury Montereys. These first units used compressed gas to fill the airbag and Struble credits General Motors engineers with the idea of using the combustion of sodium azide to produce the gas used to fill the airbags. The history of airbag deployment is one of technological uncertainty as different suppliers and OEMs used different variations on the GM system and suffered some significant problems with tragic consequences.

One set of problems was with airbag deployment. A modern system has a series of sensors to ensure that not only do airbags deploy when required but also that they do not deploy when not needed. Typical systems connect sensors which detect accidents with others which test for no accident to a microprocessor which combines the information and makes the decision on whether to deploy or not.

Another set of problems concerned small people and children who could be injured or killed by the force of airbag deployment. The early airbags could prove fatal and, according to NHTSA, 92 people were killed by passenger side airbags between 1986 and 1 March, 2000, either because of being too small or out of position at the time of deployment. The two problems also happened at the same time, with the airbag deploying in a non-critical situation against an unbelted or out of position passenger. In the same time period as these fatalities, NHTSA estimates that airbags saved over 6,000 people's lives. In 1991, legislation was written to require that all passenger cars be equipped with driver and passenger airbags by 1998 (Kratzke, 1995).

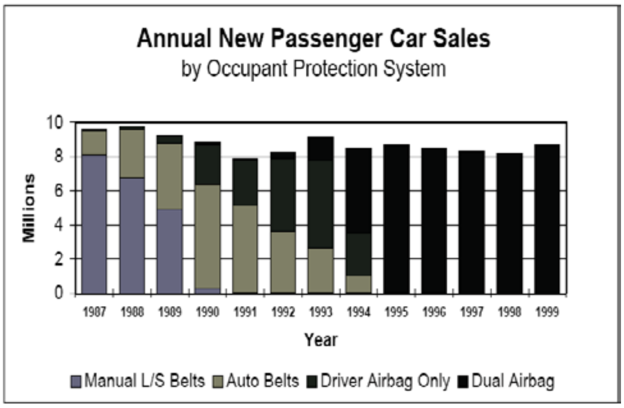


Figure 5.18 U.S. Airbag penetration
(from Department of Transportation document NHTSA 00-7013)

Over the next decade, auto makers became engaged in an airbag competition which was partially based on increasingly tight regulations but also on public perceptions about safety. Airbags were considered good, and the more the better. Figure 5.18 shows that, by 1995, airbags had become standard equipment and the automatic seat belt had faded away.

During the same years as this proliferation in the number of airbags per vehicle, a number of additional innovations were introduced. Side airbags were introduced to protect people from side impacts. Airbags were introduced for rear seats and even the so-called "curtain" or roof airbag became common on top end vehicles. An on/off switch was provided in many cars so that the passenger side airbag could be switched off if a child or smaller person was in the passenger seat. Later so-called "second generation airbags" replaced the first units and in recent years "smart" systems were introduced. Smart airbags incorporate additional features such as two stage airbags which can inflate to different sizes and different speeds depending on the severity of the crash, and can even be linked to sensors which determine the size of the occupant such that the force of the airbag is changed accordingly.

- Technology pathway analysis

In terms of Geels and Schot's (2007) pathways, airbags appear to have followed the *de-alignment, re-alignment* path as landscape change requiring passive restraint systems occurred in a relatively sudden way although there were indications that such legislation would eventually be enacted, the niche market was not yet developed with no dominant design, powerful actors or clearly identified segment of the market which supported the airbags, and the combination of advanced sensor electronics, explosives, and materials technologies was thought to be beyond the scope of the vehicle manufacturers at the time of the first airbag introductions and the early cost estimates made the devices prohibitive.

- Empirical data

While General Motors was often first to market in airbags with a number of innovations, Table 5.26 shows how Nissan and to a lesser extent Toyota managed to take the lead in airbag technology. As discussed in Section 5.3, GM was first in several areas such as side airbags but then lost the initiative over time as the Japanese manufacturers first caught up and were then able to deploy faster across a larger portion of their albeit smaller vehicle fleet. According to interview subjects 2 and 8, it appears that the Japanese companies were committed to getting ahead on airbag technologies while the U.S. manufacturers took a slower, steadier deployment.

Technology	**GM**	**Ford**	**Toyota**	**Nissan**
1st Generation	1995 - 1996	1995 - 2000	1995	1995
2nd Generation	1995 - 2002	1995 - 2005	1995 - 2004	1995 - 2005
Smart Airbags	2004 -	2004 -	2004 -	2003 - 2005
Advanced Airbags	-	2004 -	2004 -	2003 -
Side Airbags	1997 -	-	1998 -	1999 -
On/Off Switch	-	2001	-	2001
Roof Airbags	2004 -	-	2004 -	2003

Table 5.26 Airbag deployment time line

Table 5.27 shows the relative patent counts for airbags and the data shows little to no correlation with the deployment data. Nissan, which was in a leadership position, has very few airbag patents in both absolute and relative terms. The answer to this apparent paradox might lie in the role that suppliers of airbag technology, such as Autoliv, play in the industry and the possibility for a company like Nissan to get ahead by simply buying the best technology available from such a supplier. General Motors, on the other hand has the largest patent count in both absolute and relative terms but shows little to no advantage in terms of the state of its technology deployed by 2006. What is true is that GM had managed to be first in several instances and perhaps its patent position has more to do with its cumulative effort over the years in airbag technology than its current level of activity.

	Total U.S. patents	Airbag Patents	% of each firm	% of four firms
General Motors	13,078	139	1.06%	43%
Ford	10,238	46	0.45%	14%
Toyota	10,588	90	0.85%	28%
Nissan	8,519	47	0.55%	15%
Total	**42,423**	**322**	**0.76%**	**100%**

Table 5.27 Total airbag patents by manufacturer

Figure 5.19 shows the patent patterns of the four manufacturers in their US airbag patents up to 2006 reproducing the *Themescape* maps shown in Figures 5.2b, 5.6b, 5.9b, and 5.13b. In the graphical representation a certain degree of homogeneity can be observed, although all of the airbag patterns appear to cover a relatively small area compared to the other technologies under study.

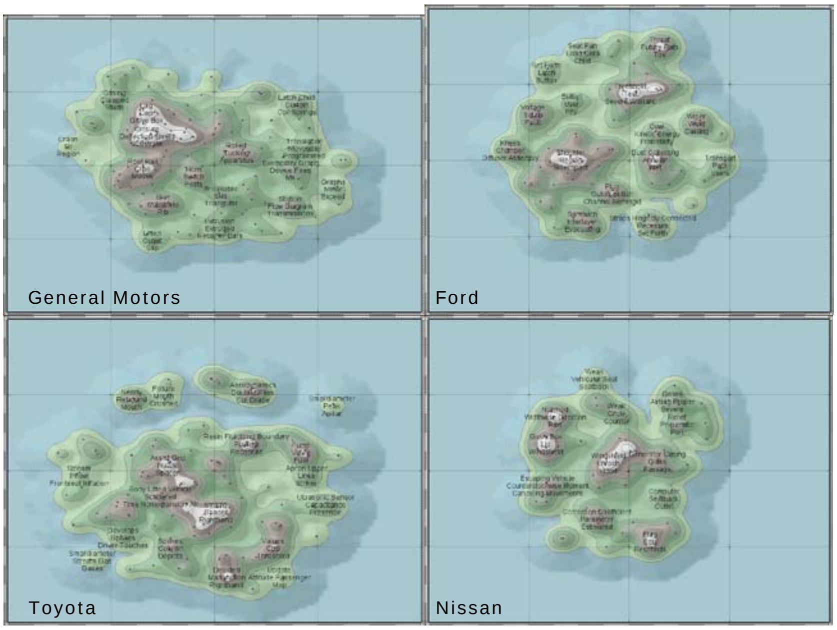


Figure 5.19 Airbag patent visualisation

Table 5.28 gives the salient features of Figure 5.19 and shows that only Toyota appears to have pursued separate lines of inquiry as shown by the islands in the *Themescape* representations and also covers the widest area.

Feature	**GM**	**Ford**	**Toyota**	**Nissan**
Overall Size	Small	Small	Medium	Very Small
Landmass	Contiguous	Contiguous	Central landmass	Contiguous with one Peninsula
Islands	0	0	4	0
Peaks	2	6	6	4

Table 5.28 Major features in airbag patent visualization

One aspect that seems critical is the idea put forward by interview subject number 2 that the Japanese companies are able to specify their choice of safety components including airbags late in the vehicle development process which allows them to take advantage of the latest innovations from the supply base.

The case study appears to point to the critical role that the supply base can have in deploying new technology and also the importance of having a product development process of sufficient flexibility to take advantage of technological improvements. In periods of rapid change such as would be expected on the *de-alignment, re-alignment* pathway this aspect of the product development process appears to offer an advantage in terms of deployment.

5.3.4 Fuel cell electric vehicles

- History and context

The fuel cell electric vehicle is part of the broader potential transition to electric vehicles and it will be helpful to develop the context prior to looking at the degree to which technological pathway best describes the evolution of fuel cell electric vehicles.

The power train is that part of the vehicle which provides motor force to the wheels. A traditional power train has four fundamental elements. At the heart of the system is the internal combustion engine which converts fuel into kinetic energy. The fuel is stored in a steel or plastic tank, and then pumped into the engine which transforms its latent chemical energy into kinetic energy. The energy is then transferred from the engine to a transmission via the crankshaft. The transmission then reduces the revolutions of the crankshaft and transfers the energy to a slower driveshaft which then goes through a differential and powers the wheels. Figure 5.20 shows a simplified view of a rear wheel drive vehicle. There are also a number of very complex subsystems required, such as the fuel system, exhaust system, control system, etc.

Over the last 80-100 years, this system has been the dominant design in the automotive industry. In 1940, General Motors introduced the first fully automatic gearbox, but besides front wheel drive cars and incremental developments in the engine, transmission and fuel system, the power train has remained relatively unchanged.

Figure 5.20 ICE Power train schematic

A German engineer, Felix Wankel, for example, developed a very compact and smooth-running 4-stroke engine, which Mazda introduced in its 1967 Cosmo vehicle and produced until 2000 in its RX line of sports cars. The “rotary engine”, however, never made it past a few models due to its relatively high fuel consumption.

During the 1970's and 1980's a number of university projects, environmentally committed hobbyists, and some entrepreneurs began developing alternative power trains including engines which ran on different fuels, battery electric cars, flywheel vehicles, and fuel cell electric vehicles (Hoffman, 2001). Today there are two major strands of development in this area. One involves replacing gasoline or diesel fuel with a new type of fuel which is partially or totally made from biological materials as opposed to fossil fuels, and the other is to replace the combustion-mechanical power train with a chemical-electric one either using a battery to store the electrical energy or using a fuel cell to produce energy from feedstock such as pure hydrogen, methane, etc.

Although only fuel cell electric vehicles are considered as part of the scope of the thesis, a brief discussion of battery electric vehicles is appropriate as they do help in defining the overall context and indeed come up in the company case studies particularly in the case of Nissan. Alternative fuel vehicles are not discussed and considered out of scope.

1. Battery electric vehicles

At the end of the 19th century it became clear that the socio-technical system developed around horse-based personal transportation was drawing to a close, and the electrical vehicle was a strong contender during the process which eventually led to the dominance of the internal combustion engine. Geels (2005) discusses the change from horse-drawn carriages to the modern automotive regime as an example of the *de-alignment, re-alignment* pathway, and argues that the horse and carriage regime was already failing to satisfy societal needs long before the internal combustion engine and passenger car emerged as the dominant design. After being surpassed by the internal combustion engine, the electric vehicle was regulated to very specific niche applications such as golf carts and forklifts, until the 1970's and 1980's when, for environmental reasons, they became popular again with a small group of ecologists and university research groups (Hoffman, 2001).

In an electric vehicle, one or several electric motors replace the internal combustion engine. Energy storage is provided by batteries and an electronic control unit takes the place of the transmission. Electric vehicles can be more efficient due to several factors. One is that there is less need for the mechanical transfer of kinetic energy, as electric motors can be placed directly on the wheels. Another is that electric vehicles not only transfer energy to the wheels but can also recover energy by "regenerative braking" in which the electric motors can be used to slow the car and charge the batteries.

The primary problem with electric vehicles has been the high cost and poor performance of battery technology. In terms of range, for example, the difference can be as high as 400% and, in terms of cost, a $20 plastic fuel tank costs a small fraction of the approximate $10-30,000 needed for a nickel metal hydride or lithium-ion battery pack (Alexander, 2006). Additional problems include power density and weight, cycle life and calendar life, as well as safety and disposal concerns as some of the more exotic chemical agents used in batteries are toxic and require complex handling and disposal.

Electric vehicles came into the mainstream in 1990, when the California Air and Resource Board (CARB) decreed that manufacturers which sold significant volumes of cars in California would have to sell a percentage of zero-emission vehicles in the total fleet that they sell. Doyle (2000) provides an account of the industry's response which essentially involved spending tens of millions of dollars on developing such vehicles and also extensive lobbying to persuade California to relax its requirements. GM led the industry with the battery electric Impact in 1990 and the EV-1 in 1996. GM, however, only sold or leased 500 units in two years (Buss, 2001) and eventually abandoned the EV series after developing a third generation vehicle with a nickel metal hydride battery in 1999. Chrysler, Ford, Honda, Toyota and Nissan also offered electric versions of some of their vehicles, but the EV-1 was the only vehicle designed to be electric with an iconic body style offering very low aerodynamic drag. The argument made by the carmakers was that their efforts were made in "good faith" but that the technology was simply not available. A recent documentary released by Sony pictures, on the other hand, entitled "Who Killed The Electric Car", makes the case that the GM project was deliberately designed to fail by Detroit and the major oil companies (www.whokilledtheelectriccar.com accessed 18.5.09)

Van den Hoed (2004, 2005) shows how the battery electric vehicle lost out to fuel cells and hybrids in the mid 1990's by showing cumulative patent counts across all three technologies in the U.S. each year from 1990 to 2003. His data shows that hybrid and fuel cell patents exceeded battery electric patents in 1997 and 1998 respectively. If one adds a reasonable time lag of 2-3 years from the allocation of funding to patents being granted, it would seem that the tide turned away from battery electric cars around 1995.

Today the battery electric vehicle appears to be coming back with small players aiming at niche markets such as TH!NK, Tesla Motors, and Bright Automotive. Also Nissan has made a public commitment to launch the all electric Nissan Leaf in 2011 and also developing battery electric cars due to ever increasing pressure on environmental issues and potentially improved performance from lithium ion batteries

2. Fuel cell electric vehicles

Based largely on the failure of the launches in the 1990s and the lack of progress on batteries, fuel cell electric vehicles emerged as the preferred alternative for both carmakers and the State of California. In 1996, CARB relaxed its mandate, both in terms of timing and number of zero emission vehicles, and took steps to actively encourage fuel cells (Collantes and Sperling, 2008, Doyle, 2000; Van den Hoed, 2004). Fuel cell vehicles solve the battery problem by creating electricity directly from a source of fuel such as hydrogen. This technology has advanced significantly over the last 20 years and solves the range problem outlined above, although costs are still at least two orders of magnitude above a traditional power train. By 2005, almost all of the automotive manufacturers, with the notable exception of Volkswagen and BMW, had fuel cell programs underway. DaimlerChrysler, Toyota and General Motors, for example, made considerable investments in the technology and a number of partnerships were started between carmakers, carmakers and different combinations of government agencies, energy companies, component suppliers, and public and private research laboratories (Steinemann, 1999, Van den Hoed, 2004).

One of the lines of research which has been pursued by major oil companies and vehicle manufacturers is to store liquid fuels such as ethanol or gasoline in the vehicle and to produce hydrogen from that fuel in an on-board reformer. This of course adds cost and complexity to an already complex system but solves the infrastructure and on-board storage problems.

- Technology pathway analysis

Fuel cell electric vehicles are best described as being on the *Transformation* pathway as defined by Geels and Schot (2007) as the landscape pressure could be described as moderate, there is not large niche market, and fuel cells are not compatible with major elements of the current socio-technological regime,

The pressure from the overall social and political environment towards a fundamental change in vehicle power trains has been building for some time. This pressure has been gradually growing as a segment of consumers are becoming concerned about the environment and oil prices continue to fluctuate. At the time of writing, the pressure appears to be far from sufficient to trigger a change from the internal combustion engine, mainly because none of the new technologies are cost competitive without changing the way externalities such as air pollution and climate change impacts are included in the cost of using cars. (Weis et al., 2003; Carle et al., 2005; Seidel et al., 2005)

Despite some specific applications such as space exploration, remote power generation and some forklifts, fuel cells have not found a large niche market and no dominant design has emerged despite the efforts of powerful industry players to support them. Buses are a potential niche application but have not yet gone beyond limited demonstration vehicles (Harborne et al., 2007).

Unless reformer technology is used, fuel cell vehicles are not complimentary to the current socio-technological regime. In the first place, vehicle architecture will change sharply, as will the types of suppliers. Service and repair will also need to change. Perhaps the biggest change will need to come from the refuelling infrastructure, which would need to be rebuilt; hydrogen sceptics point to the estimated cost of replacing our entire fuel delivery infrastructure as the major factor which will inhibit this transformation. (Karplus et al., 2009; Siegel et al., 2005)

- Empirical data

Table 5.29 gives a summary of the deployment data discussed in Section 5.2 for each of the four manufacturers. General Motors has made the largest apparent commitment to the technology with four partially simultaneous threads. By contrast, Toyota also has a large fuel cell program in terms of patent counts and the number of prototypes, and even worked with GM, but has approached the technology in a much more focused way. Ford appears to be only monitoring fuel cell technology and Nissan appeared to have a similar approach to Ford but has not built a new prototype since 2005, and appears to have at least reduced its interest in the technology in favour of battery electric cars powered by lithium ion batteries.

Technology	GM	Ford	Toyota	Nissan
1st Prototype	1968	1998	1996	1999
Latest Prototype	2008	2008	2008	2005
Number of Prototypes	16	9	9	7
Number of Concepts	4	2	3	2

Table 5.29 Summary of fuel cell development programmes

Table 5.30 shows the total number of fuel cell patents for each manufacturer and General Motors again has the highest number of patents in this technology (205) and also the highest overall commitment to the technology of any of the firms in any of the technologies, with 1.57% of its total U.S. patents involving fuel cells. General Motors has almost twice as many patents as Toyota (109), 2.5 times as many as Nissan (82) and more than 5 times as many as Ford (40).

Fuel cells	Total U.S. patents	Airbag Patents	% of each firm	% of four firms
General Motors	13,078	205	1.57%	47%
Ford	10,238	40	0.39%	9%
Toyota	10,588	109	1.03%	25%
Nissan	8,519	82	0.96%	19%
Total	**42,423**	**436**	**1.03%**	**100%**

Table 5.30 Total fuel cell patents by manufacturer

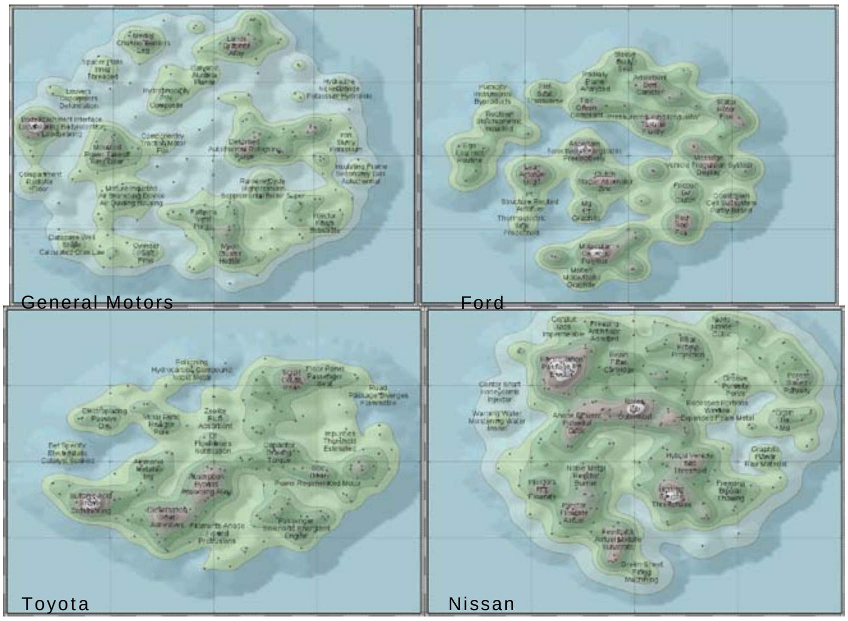


Figure 5.21 Fuel cell patent visualisation

Figure 5.21 reproduces the *Themescape* maps generated for the U.S. fuel cell patents of the manufactures (Figures 5.2d, 5.6d, 5.9d, and 5.13d) for convenience and shows the very different patterns across the sample indicating that the research programs of the manufacturers were also quite different in approach. These differences are called out in Table 5.31 which analyzes the topographies showing, for example, the large extent of GM's patent pattern which resembles an archipelago in the *Themescape* representation.

Feature	**GM**	**Ford**	**Toyota**	**Nissan**
Overall Size	Very large	Medium	Medium	Very Large
Landmass	Archipelago	Spread out with two deep lagoons	Contiguous with one Peninsula	Contiguous with two lagoons
Islands	13	1	1	2
Peaks	1	3	2	3

Table 5.31 Major features in fuel cell patent visualization

The data appear to show that General Motor's large program, with the most number of prototypes covering different concepts, was supported by an equally ambitious research program with the largest number of patents covering different topics. The experts interviewed confirmed the large amount of government funds available for fuel cell research and raised the possibility, discussed in Sub-sections 5.2.1 and 5.2.2, that the U.S. manufacturers had actually struck a deal with the Bush administration to pursue fuel cell research in exchange for having no increase in CAFE standards.

Considering the characterization of Fuel cell electric vehicles being on the *transformation* pathway in Geels and Schot's (2007) terminology brings a perspective on the programs of each manufacturer. General Motors large program only makes sense if it truly believed it could bring about the transformation to the socio-technological regime. As such an outcome is unlikely in a time frame which would make any degree of investment profitable; the assertion that the program had non market and political drivers appears the most likely. Toyota's large program must be seen in the context of its even larger commitment to hybrids and its overall corporate strategy, discussed in Sub-section 5.2.3, that there will be changes to the socio-technological regime sooner or later, as well as Toyota's very different corporate culture which focused on the medium to long term. Ford and Nissan's apparent strategies also appear to make sense as it would seem that both were using a hedging strategy (Avadikyan and Llerena, 2010) to assure that they would not be left too far behind just in case the transformation did come about. What can also be gleaned from the example, however, is the enormous political and industrial power that a firm would need to lead such a transformation. Fuel cells did receive support from the Californian and U.S. governments but was not able to keep the rest of the industry focused on this relatively long-term solution.

At the time of writing it appears that interest in fuel cell vehicles is increasing and one manufacturer which is not in the sample, Honda, is commercializing a fuel cell electric vehicle in the Unites States.

5.3.5 Hybrid electric vehicles

- History and context

In 1996 and 1997 Honda and Toyota launched hybrid vehicles in Japan, called the Insight and Prius respectively. Hybrid vehicles have both an internal combustion engine running on standard automotive fuel as well as a battery and one or several electric motors, and come in a wide variety of configurations. Hybrids have a cost disadvantage compared to traditional vehicles but get as much as 50% better fuel economy and do not suffer the range problem associated with battery electric vehicles. Toyota has sold more than one million of the cars around the world and has rolled out its hybrid technology to an additional 5 models in its fleet (www.toyota.co.jp, accessed 18.5.2009), and its success has inspired hybrid programs in most manufacturers.

Hybrid vehicles are designed with one of three architectures which determine how the internal combustion engine and the electric motors work with each other. One solution is to add an electric motor to the vehicle which can provide additional power to the transmission when needed. Another solution is called "power-split" in which either power plant or both can drive the wheels. A third solution is to have the engine act as a generator of electricity which can re-charge the battery and/or power the wheels. This is the idea behind the new Chevy Volt concept being developed by General Motors.

At the heart of all types of hybrids is the control system which manages the flow of electrical energy to and from the wheels, and governs the use of the two power trains which are either linked in parallel or in series with each other. Table 5.32 shows examples the first two types of hybrids introduced to the market.

Hybrid Architecture	**Car Models**
Pre-transmission electric motor hybrids	Honda Accord, Honda Civic, Chevy Silverado, Saturn VUE
Power-Split Hybrids	Ford Escape, Ford Fusion, Mercury Mariner, Lexus RX 400h, Lexus GS 450h, Toyota Highlander, Toyota Prius

Table 5.32 Hybrid Vehicles Architecture (Alexander, 2006)

Other recent models use what is called a "two mode hybrid system" which operates in one way at low speeds or low torque requirements and another at higher loads. At the heart of the two mode system is a transmission which has two electric motors incorporated into it such that the motors can add power directly to the transmission and the car can run without the internal combustion engine, like power split hybrids, but can also add additional power to the gears while the engine is running, like pre-transmission hybrids. The control system is arguably even more complex as it must govern the electric motors, the internal combustion engine, and also the planetary gears which resemble an automatic transmission to some extent. Figure 5.22 shows a sketch of the Chrysler system which was introduced in the 2009 Chrysler Aspen and Dodge Durango. General Motors has developed a similar system for the 2008 Chevrolet Tahoe and GMC Yukon.

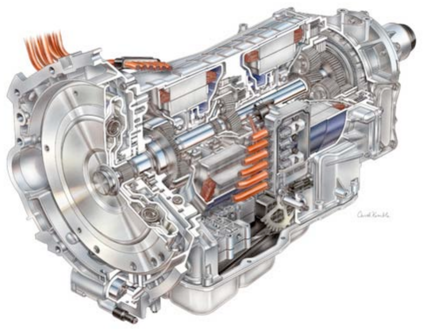


Figure 5.22 Two Mode Hybrid Transmission
(from http://alternativefuels.about.com/od/hybridvehicles Accessed 24.6.09)

Four issues came together to push hybrid technology to the forefront and required a fundamental re-think by the industry as a whole. One was the sudden emergence of a segment of the car-buying public which was genuinely interested in making a personal statement about environmental sustainability (Buss, 2000; Reinhardt, 2005). A second issue was the steady rise of oil prices from 2000, reaching a peak of $147 per barrel in the summer of 2008, which drove gasoline prices to record levels and improved the cost benefit analysis of buying a hybrid car. The third issue is the competitive dynamics of the car business which pushes each company to “keep up” with one another - a phenomenon known as “mimetic homogeneity”, which Van den Hoed (2004) put at the centre of his thesis explaining the high level of activity in fuel cell electric vehicles. As can be seen in Appendix C, Honda, Toyota, General Motors, Ford and Chrysler all have hybrid models on the market. The fourth issue is that the U.S. Presidential election of 2008 changed the level of discourse concerning the environment, and eventually both John McCain and Barak Obama embraced the twin goals of reducing emissions and seeking energy independence. President Obama recently scrapped the Bush Administration’s Fuel Cell program in favour of more immediate focused support for hybrid vehicles which are perceived to offer a much faster implementation timetable (Roland, 2009).

Hybrids today represent about 3% of the automotive market with some analysts projecting 17% by 2010 (Giliberti, 2008).

One interesting development is the emergence of so called “plug-in hybrids”. Plug-in hybrids are designed to overcome the limited all electric range of many of the hybrid vehicles currently on the market, which is perceived as a major shortcoming. The battery pack of the Toyota Prius, for example, can only be charged by running its internal combustion engine and through regenerative braking. The car is programmed to run all electric only in parking and other limited applications such as stop and go traffic jams. In the last few years, enthusiasts and hobbyists began breaking into Toyota’s operating system and electrical hardware to allow for more use of the all electric option and also to allow for recharging of the battery directly from the power grid.

At the time of writing, a number of companies are working on the launch of plug-in hybrids which would have 10, 20 or even 40 km range when running on batteries, allowing for all-electric operation in some cases such as for commuters or to qualify for inner city smog abatement programs, which limit traffic within the city limits to all but zero emission vehicles. Duvall and Alexander (2005) affirm that the widespread use of plug-in hybrids will result in much lower greenhouse gas emissions than either conventional internal combustion engines or hybrid vehicles, and Alexander (2006) quantified that amount as ranging from a 40% to 65% improvement over the conventional vehicle to a 7% to 46% improvement over the hybrid electric vehicle. Duvall (2004) quantifies the willingness to pay of American consumers for different types of electric vehicles, and shows in Table 5.33 that consumers who are interested in the technology will pay more for a similarly equipped vehicle, and that the amount increases with vehicle size and with all electric capability. The expectation that consumers are willing to pay more for hybrid technology is the basis of the development of hybrid vehicles, as the vehicle manufacturers simply do not yet enjoy sufficient margins to be able to absorb the extra cost inherent in hybrids.

Vehicle Type	**Incremental price vs. conventional model**
Midsize Hybrid Electric	$2,250
Full size or SUV Hybrid Electric	$3,000
Mid Size Plug-in Hybrid with 20 Miles electric range	$3,600 – $4,000
Full Size / SUV Plug-in Hybrid with 20 Miles electric range	$5,500

Table 5.33 Willingness to pay for electric vehicles in the United States

- Technology pathway analysis

The trajectory of hybrids and plug-in hybrids appear to be following the *re-configuration* pathway. In the first place, there is moderate environmental pressure in terms of fuel price. Secondly, hybrids have not yet reached the 5% level as established by Geels and Schot (2007) to consider a niche segment fully developed, and, despite its best efforts, Toyota has not managed to make its Hybrid Synergy Drive the dominant design which is another indication of the niche market not reaching sufficient readiness. Hybrids are, however, complementary to the current socio-technological system and can run on ubiquitous gasoline and even plug-ins are being designed to take advantage of the electrical infrastructure and suburban nature of many American households.

- Empirical data

Table 5.34 shows the differences in the hybrid programs of the four manufacturers where Toyota's lead is again apparent in terms of the number of models and percentage of models in their fleet as detailed in Appendix C3 and shows not only Toyota's leading position but Nissan's apparent lack of interest in the technology. General Motors and Ford have both made important efforts in Hybrids with General Motors having 10 models on the market in the 2010 model year.

Technology	GM	Ford	Toyota	Nissan
1st Model	2003	2004	1997	2007
Number of models (2010)	10	4	7	1
% Hybridization	23%	17%	29%	5%

Table 5.34 Summary of hybrid deployment

According to interview subject number 3, the General Motors percentage is overstated and hybridization should be calculated on sales and not model line-up. The model calculation is used because it is a measure of the manufacturer's intention and reflects development commitments. Ford reaches four models due to counting the Mercury Mariner and Milan as separate vehicles, but this could also be challenged as the vehicles are actually very similar to the Ford Fusion and Escape. Removing the two models and changing Ford's overall number of models by removing the Mercury nameplate would give Ford 10% hybridization.

Table 5.35 shows the total U.S. patents for hybrids up to 2006 for the four firms in the sample and shows the very large number of patents filed by Toyota and Ford with significantly less effort on the part of General Motors and Nissan. In relative terms the efforts of Toyota and Ford appear even greater with even Nissan filing more patents as a percentage of its total than General Motors.

Hybrids	Total U.S. patents	Hybrid Patents	% of each firm	% of four firms
General Motors	13,078	66	0.50%	15%
Ford	10,238	142	1.39%	32%
Toyota	10,588	145	1.37%	33%
Nissan	8,519	84	0.99%	19%
Total	**42,423**	**437**	**1.03%**	**100%**

Table 5.35 Total hybrid patents by manufacturer

Table 5.36 gives the salient features of the *Themescape* maps generated for the U.S. hybrid patents of General Motors, Ford, Toyota and Nissan shown in Figures 5.2c, 5.6c, 5.9c, and 5.13c and Figure 5.23 for convenience. Again Toyota and Ford show very broad patterns spread out over a wide area and General Motors and Nissan appear to have much more focused programs.

Feature	GM	Ford	Toyota	Nissan
Overall Size	Medium	Large	Medium	Very Small
Landmass	Contiguous with one Peninsula	Spread out with two lagoons	Archipelago	Contiguous with two Peninsula
Islands	0	4	7	2
Peaks	8	6	4	3

Table 5.36 Major features in hybrid patent visualization

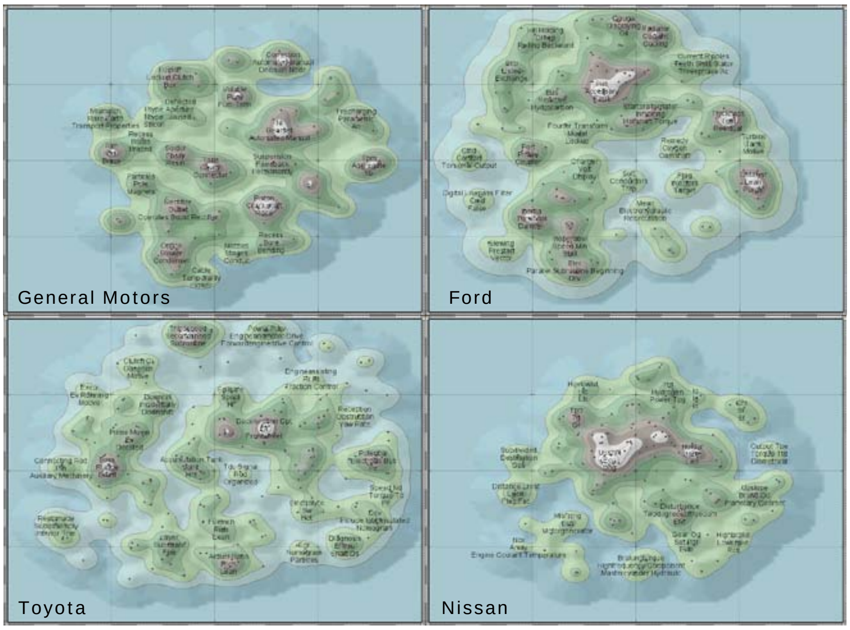


Figure 5.23 Hybrid patent visualisation

Toyota is the undisputed leader in hybrid vehicles at the time of writing and had pursued a broad deployment strategy pursuing both Prius and other technologies in Japan until focusing on Prius after its runaway success. Toyota is now rolling out the same technology across its fleet and its patents pattern resembles an archipelago of islands in the *Themescape* representation, indicating that its research efforts dealt with a number of issues related to hybrid vehicles.

Toyota Nissan

Ford's approach most resembles Toyota's and has a similar number of patents and also has them in a wider pattern. Ford, however, shows a different deployment pattern and based its hybrid strategy on the early introduction of a hybrid version of its Escape SUV, rather than a specially designed vehicle such as the Prius or Honda's Insight.

According to Geels and Schot (2002), one of the features of the *re-configuration* pathway ought to be a large degree of technological variation, and this can be seen in the case of hybrids with the different companies following heterogeneous strategies not only in terms of their deployment and patent pattern but also in the technologies being pursued. General Motors is, for example, promoting its Chevy Volt range extension vehicle, while Toyota continues to develop the Hybrid Synergy drive which is at the heart of the Prius, and Ford is in the process of moving away from Toyota technology to its own hybrid solution.

5.4 Chapter summary

The purpose of Chapter 5 was to review the empirical data in order to inform the research question and sub-objectives presented in Section 1.1 and reproduced below:

Research Question***: What strategies do automotive companies follow with respect to the investigation and deployment of discontinuous technologies?***

Sub-objective 1: Explore how companies approach the development of different technologies
Sub-objective 2: Assess how different companies develop the same technologies

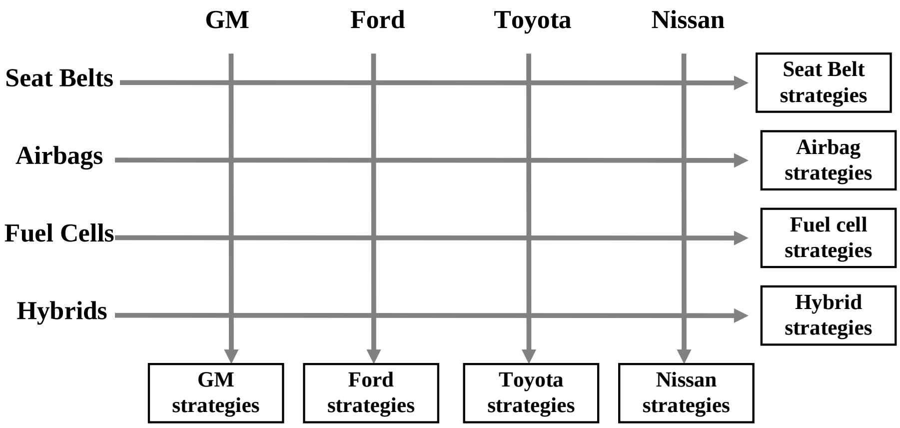


Figure 5.24 Conceptual view of empirical results

Figure 5.24 gives a conceptual view of the results presented in Chapter 5 and shows how the thesis approached the two sub-objectives and thus informed the research question. In terms of the manufacturer's strategies, General Motors and Ford showed heterogeneity in their strategies in the different technologies, while Toyota and Nissan appear to be somewhat more consistent. General Motors' response appears to indicate a tremendous capability to invest resources if and when it chooses to do so and this can be seen in their very large fuel cell program, pioneering work in seat belts and airbag technology, and their response in deploying rear seat belts and hybrid technology. Ford appears to pick its battles very carefully either as the result of in-depth analysis or political issues and is, for example, making a major effort in developing its own hybrid technology but has not appeared to make the same level of commitment to the other technologies in the sample. Toyota appears to follow a very consistent and focused technological deployment strategy and also has relatively concentrated pattern patterns in all cases other than in hybrids, in which it is said (interview subjects #1,3) to have developed a leadership position in the technology and which is protected by its patents although is also over-engineered (interview subjects #6,7). In all cases Nissan appears to follow a focused strategy consistent with the idea of being a fast follower in the market and it appears that, in hybrids, Nissan chose not to try and catch up and this might explain its recent commitment to the battery electric Nissan Leaf.

With respect to the analysis of the data by technology, Sub-section 5.3.1 introduced Geels and Schot's (2007) technology pathway framework which was used to position each technology along one of the pathways in the hope of gaining additional insight into the strategies pursued by the manufacturers. The results of the pathway analysis is summarized in Table 5.37 and shows how each technology can be positioned along a different one of the four pathways. This result was serendipitous as the pathways were not part of the technology selection criteria discussed in Sub-section 3.4.2.

	Seat Belts	**Airbags**	**Hybrid Vehicles**	**Fuel Cell Vehicles**
Environmental Pressure	Moderate pressure building up to federal legislation	Sudden landscape change due to legislation (1973)	Moderate pressure for fuel efficiency and sustainability	Moderate pressure for medium term sustainability
"Readiness" at the Niche level	• 3 point system already common • Active supply base and adoption by Daimler Benz • Clearly defined niche market	• No dominant design • No powerful actors • No penetration in niche markets	• No dominant design • Toyota first powerful player • Prius and Insight define new market niche	• No dominant design • GM, Daimler, and Toyota establish apparent consensus • Slow development of niche markets
Degree to which new technology is Complementary	Seat belts required little technical adjustment but fundamental behavioural change	At the time the technological complexity and cost were seen as insurmountable	Potentially complementary to ICE engines but at high cost	Not complimentary (unless reformer solution is pursued)
Pathway	Technological substitution	De-alignment, re-alignment	Re-Configuration	Transformation

Table 5.37 Summary of technology pathway analysis

With respect to seatbelts, its position on the *technological substitution* pathway is based on the development of a niche market by Volvo and Saab, which first developed and deployed the technologies, and a segment of consumers who appear to value safety and in some cases are willing to pay for it. The case study on seat belts also shows the impact of the supply base as well as path dependency in technology deployment as Toyota and Nissan were able to catch up to General Motors in seat belts despite its very large and multifaceted research program, and Toyota was able to do so without much of its own research as shown in the patent counts. The pretensioner data, while incomplete, does give an indication of the role of path dependencies by limiting the ability or perhaps the necessity of both General Motors and Ford in deploying the technology due to the design of their current models. The seat belt data also shows co-evolution in the industry as Volvo and Saab's early introduction of seat belts gave the technology legitimacy at the niche level and, much later, General Motor's decision to install rear seat belts in advance of legislation made them standard.

Air bags are positioned along the *de-alignment*, *re-alignment* pathway mainly due to the high degree of technological and legislative turmoil which existed around passive restraint technology during the late 1970s and 1980s. General Motors again invested heavily in the technology but then seemed to slow down in its deployment while Ford, Toyota and Nissan all accelerated their airbag deployments once the technological paradigm became clear in the early 1990s. The role of the supply base appears to have been critical as well as the early investment of Volvo and Chrysler's decision, discussed in Sub-section 5.3.2, to deploy the airbags again demonstrating co-evolution.

Fuel cells are considered to be on the *transformation* pathway and the main finding from the data is that while General Motors did appear to make a very large investment in the technology it other manufacturers such as Nissan did very little demonstrating heterogeneity in response as to the homogeneity found by Van den Hoed (2004). Three possible explanations for this heterogeneity emerge from the data. One is that the different manufacturers came to different conclusions as to the scope of the transformation required and time frame needed for it and that in hindsight General Motors either wasted effort doing too much or perhaps did not invest enough to actually produce the transformation it was betting on. Had its efforts been successful, General Motors would have changed its competitive environment through its technology development. A different explanation has to do with the non market hypothesis that General Motors and Ford were well compensated by their investment in fuel cell technology by the Bush administration's inaction on CAFÉ standards (interview subjects #3, 6, and 7). A third possible explanation is political and has to do with the reported political infighting at General Motors (interview subject #6), Ford's leadership crisis (discussed in Sub-section 4.4), Toyota's commitment to its earth charter (discussed in Sub-section 5.2.3), and the opposition of Nissan's president Carlos Ghosn to alternative power train technology (discussed in Sub-section 5.2.4).

Hybrid vehicles are considered to be on the *re-Configuration* pathway primarily because of their compatibility with the socio-technological regime which has been built around the internal combustion engine. Toyota's leadership position in hybrids is clear in the data and appears to show the success of Toyota's apparent hedging strategy (Avadikyan and Llerena, 2010) based on its "earth charter", in which it made a corporate decision to make considerable investments in a number of alternatives in parallel to the internal combustion engine. Ahman (2006) describes the support of the Japanese Government for the development of hybrid technology, and it is also interesting to note that while Toyota and Honda did take advantage of that support, Nissan did not. Hybrids have also benefited from increasing changes in the overall socio-technical landscape both in the spike in fuel prices which occurred over the summer of 2009 as well as the changing political agenda in the United States in favour of the twin goals of energy security and a reduction in CO2. Hybrids also show that the actions of Toyota and Honda helped create the climate in which they were successful again demonstrating co-evolution. In the case of hybrid technology mimetic homogeneity (Van den Hoed, 2004) can be seen in the response of General Motors and Ford with Nissan being the only major company to limit its hybrid program. At the time of writing no dominant design has emerged and, in this period, Nissan appears to be attempting to leapfrog the technology with its battery electric vehicle while General Motors attempts to change the game with its Chevy Volt range extension programme.

CHAPTER 6 DISCUSSION

6.1 Introduction

Chapter 5 gives the empirical evidence of the thesis and looks at the deployment data and patent pattern for each of the four companies in the sample as well as the four technologies under investigation. The purpose of this chapter is to synthesise and discuss the findings from the data, show how the findings relate to the literature and explore different explanations of those findings.

This chapter will first explore what appears to be a consistent pattern in the data and use the ideas of depth and breadth, first introduced in Sub-section 3.3.3, to perform cross-case analysis of the case studies presented in Chapter 5. This discussion will be presented in Section 6.2. The terms depth and breadth have been used by several researchers to illustrate issues of scope at a number of levels, and Sub-section 6.2.1 will review that literature and discuss those definitions which are the most relevant to the thesis. Sub-section 6.2.2 will put forward a definition of depth and breadth and this definition will then be applied to the data in Chapter 5 and discussed in Sub-section 6.2.3. Sub-section 6.2.4 will put forward a construct relating the deployment data and patent data sets refining the ideas originally put forward in Sub-section 3.3.3.

Section 6.3 will discuss the implications of the ideas of depth and breadth with Sub-section 6.3.1 focussing on the company case studies and Sub-section 6.3.2 giving a consolidated view of the case studies incorporating the concepts of depth and breadth as well as Geels and Schot's (2007) technology pathways, which were discussed for each technology under consideration in Chapter 5. Sub-section 6.3.3 will then take the empirical data one step further and explore what could be some implications for practice based on the research.

Section 6.4 will look at how these findings can be related to the innovation management literature discussed in Sub-section 2.2.1; Section 6.5 will position the findings in light of the current debate concerning the evolution of automotive power train technology discussed in Sub-section 2.2.2; and Section 6.6 will summarize the Chapter.

6.2 Depth and breadth

The ideas of depth and breadth are first introduced in the thesis in Sub-section 3.3.3 as what Eisenhardt (1989) refers to as an *a priori* construct. The original construct is shown in Figure 3.2 and explores the degree to which a firm's technology development path as shown in its patent record might be linked to its technology deployment strategy as shown in the introduction of a specific new technology across its product line. The limitations of both sets of data are explored in Sections 3.5 and 3.6 respectively and the terms depth and breadth are used to develop two aspects of scope. In order to be more precise in their use the following will first review how the literature uses these terms and then offer a definition of depth and breadth for the thesis.

6.2.1 Depth and breadth in the literature

Teece et al. (1997) use the concepts of depth and width in their dynamic capabilities framework to qualify the set of technology opportunities that a firm might have based on its research and development path. Teece et al. argue that if there are technologies with market potential "in the neighbourhood of a firm's prior research activities" (p. 524) then firms are more likely to work on them than other subjects.

Granstrand et al. (1997) discuss the importance of firms having a technological base that is broader than the product line, challenging Prahalad and Hamel's (1990) concept of core competencies. For Granstrand et al. "management in large firms needs to sustain a broader (if less deep) set of technological competencies" (p. 18). Broader appears to refer to the 34 technological classifications used in the research and, while "less deep" is not explicitly defined, it appears to refer to the range of technological competence discussed in the paper, running from full design capability to systems integration, applied research, and exploratory research.

Prencipe (2000) uses depth and breadth in his work which applies the dynamic capabilities framework to describe the different positions that different aircraft engine manufacturers enjoy with respect to engine control systems. Prencipe (2000) shows how one competitor re-configures its technological capabilities to manage the transition from electromechanical to digital control systems and uses the concepts of breadth and depth to discuss the technological abilities of the engine manufacturers. For Prencipe, breadth is defined as the number of different technologies possessed, such as incorporating digital electronics and software development to what had formerly been hydro-mechanical control systems. By depth, Prencipe means different levels of knowledge such as components or systems architecture. Depth is also used to describe the level of knowledge a firm has concerning a particular component or system, including the ability to define requirements, do the design work, manufacture the part or parts, perform different levels of testing, and integrate the component or system into increasingly larger and complex assemblies and devices. One of the main findings of Prencipe's work is that, in the particular case of control systems for aircraft engines, one manufacturer, Rolls Royce, enjoyed a much broader and deeper set of technological capabilities than was strictly needed in its primary role of systems integrator and that this "boundary overlap", as he calls it, has been a source of competitive advantage.

Cusumano and Nobeoka (1997) look at similar concepts in their study of 210 product launches in the automotive industry between 1980 and 1991. Looking at the total vehicle level, Cusumano and Nobeoka were interested in exploring the degree and speed of new technology transfer across new project launches and determined that firms which engaged in what they called rapid design transfer were able to introduce more new models faster than those which took a more step by step approach. In many ways the concepts of depth and breadth mirror Cusumano and Nobeoka's typology of new design, and rapid design transfer mirrors the concepts of depth and breadth as used by Prencipe.

Wang and Von Tunzelmann (2000) also used the terms breadth and depth to describe the complexity with which firms are faced. For Wang and Von Tunzelmann, breadth is the range of areas that have to be investigated while depth is the analytical sophistication of the subject. They also introduce the idea that specific processes can be coactive or conflicting in terms of adding complexity to one or both dimensions. Conflicting processes reinforce the idea that there is a trade-off between depth and breadth, while coactive processes are ones that actually allow processes to add complexity in both directions.

Brusoni et al. (2005) build on Prencipe's work and attempt to operationalize Wang and von Tunzelmann's concepts in such a way as to look broadly over a firm's knowledge base using patents and bibliometric data, rather than the detailed case study approach followed by Prencipe. For Brusoni et al., breadth for firms is defined as the "range of scientific and technological knowledge that impinge upon the development of the specific product market in which they compete" and depth as the degree of "integration across different typologies of research (i.e., basic, applied and development oriented)" (p. 397). While useful in characterizing the overall knowledge base, Brusoni et al. (2005) appear to lift the vantage point quite high, making it difficult to see clearly how firms actually go about diversifying the knowledge base itself.

6.2.2 Definition of depth and breadth

While Brusoni et al. attempt to expand the concepts of depth and breadth in a firm's knowledge base so that they can be more readily investigated with the data intensive bibliometric methodology they employ, the thesis uses the terms to reach a finer level of granularity and explore the technology level as it relates to specific products, features and components. Thus the focus of the thesis is not on a firm's knowledge base, as in the work cited above, but on its product program - specifically in the context of developing and deploying new technology.

For the thesis, a broad strategy is defined as: *pursuing a number of parallel projects looking at different aspects of the new technology and/or seeking to implement the technology in a wide variety of applications*. A deep technological strategy, on the other hand, is defined as: *focusing efforts on developing the technology in a single or limited number of applications prior to a potential or eventual roll out across the product line.*

These definitions of depth and breadth are a logical extension of the use of the concepts by other researchers to the higher level of granularity that is of interest, i.e., specific technologies.

Research	Level of Analysis
Brusoni et al. (2005)	Knowledge base at the firm level
Wang and Von Tunzelmann (2000)	Technological complexity
Prencipe (2000)	Technological capabilities in specific field
Cusumano and Nobeoka (1997)	Complex product level (vehicles)
Thesis	Technology level

Table 6.1 Levels of analysis for breadth and depth in the literature

6.2.3 Application of depth and breadth

The following section will review the case study data presented in Chapter 5 in light of the concepts of depth and breadth defined in Sub-section 6.2.2. These concepts appear to manifest themselves both in the patent data and the deployment data as shown in Table 6.2 which gives a framework for application of the concepts.

Concept	Patent Data	Deployment Data
Depth	• Patents are grouped around a relatively small number of key concepts • Relatively large numbers of patents are found on the same topics	• New technology is seen first in a limited part of the product line and only deployed in a wider application after a time delay • Alternate technical solutions are pursued in sequence
Breadth	• Patents are seen on a large number of topics • Relatively few patents are found on the same topics	• New technology appears simultaneously across the product line • Alternate technological solutions are pursued in parallel

Table 6.2 Depth and breadth framework

In the patent data, it is necessary to interpret the *Themescape* maps in order to see the patterns of depth and breadth. In this interpretation one must take care to control for the particular problems associated with the algorithm discussed in Section 3.5 which primarily have to do with correctly interpreting the scale of the maps and controlling for the overall number of patents when analyzing them. Nevertheless, the topographic metaphor introduced in Section 3.5 and used in Chapter 5 can help in identifying depth and breadth as shown in the analysis guidelines shown in Table 6.3.

Feature	Indicator(s) of depth	Indicator(s) of breadth
Overall Size	• Smaller area	• Larger Area
Landmass	• Contiguous with few inlets or lagoons	• Non-contiguous showing an Archipelago and/or deep inlets and lagoons
Islands	• Fewer islands • Smaller islands	• More islands • Larger islands
Peaks	• Fewer peaks • Peaks grouped together • Higher peaks and generally higher topography	• More peaks • Peaks located apart from each other • Lower peaks and generally lower topography

Table 6.3 Analysis guidelines for depth and breadth in *Themescape* maps

Thus an extremely deep strategy would appear in the *Themescape* maps as an isolated mountain rising up from the sea like a volcanic island in the South Pacific. It would have a small area and consist of one land mass rising up to a single high peak. An extremely broad strategy would resemble an archipelago and consist of a number of low-lying islands spread out over a wide area. As the actual representations discussed in Chapter 5 rarely conform to these two simplistic ideals, it is necessary to interpret the patterns and also to evaluate them with respect to each other indicating that the concepts of depth and breadth are not black and white extremes but ends of a continuum along which strategies can be found. With respect to the deployment data discussed in the case studies in Chapter 5, depth and breadth would manifest themselves directly in the timing and characteristics of the seat belts, airbags, fuel cell vehicles, and hybrid vehicles deployed by the manufacturers. As this data also requires interpretation the same concept of a continuum will be applied and is shown in Figure 6.1.

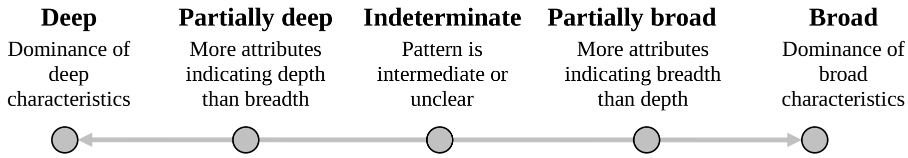


Figure 6.1 Classification scale for depth and breadth

- General Motors

Figure 5.2a shows the cumulative seat belt patents of General Motors using the *Themescape* representation. The pattern shows a single, large, contiguous land mass with no islands and 11 peaks located on three distinct ridge lines. Applying the guidelines in Table 6.3 would thus classify the pattern as broad, based on the number of peaks and overall size of the pattern, but also as deep, since there is only one land mass and no islands. GM has 116 patents in seat belts so one could interpret the pattern as being fundamentally broad but the sheer volume of patents acts to raise the elevation of the entire land mass essentially connecting the disparate peaks which might have shown up as islands with a lower overall elevation. Using the classification scale in Figure 6.1, GM's seat belt patents appear partially broad.

GM's airbag pattern shown in Figure 5.2b has a much smaller land mass and two very high adjacent peaks. Using the guidelines in Table 6.3, this pattern should be characterized as deep especially considering the GM has 139 airbag patents or 20% more patents than in seat belts.

GM's hybrid patent pattern, shown in Figure 5.2c, also appears to cover a relative small area and has no islands but does have seven separate peaks one of which is located on a small peninsula indicating a broader approach than in airbags. With only 66 hybrid patents, the large number of peaks appears to indicate a relatively concentrated pattern of discovery which would lead to classification of the pattern as deep.

GM's fuel cell patents, shown in Figure 5.2d depicts an eleven island archipelago spread out over a wide area with only one small peak and, given the fact that GM had 205 fuel cell patents, such a spread out pattern should be classified as broad using the guidelines in Table 6.3.

Table 5.4 gives the rear seat and pretensioner penetration in GM over time and shows how GM rolled out rear seat belts in one wave between 1988 and 1999 but took seven years to gradually increase the penetration of pretensioners from 13% of its fleet in 2001 to 96% in 2007. Using the definition of depth and breadth given in Sub-section 6.2.2 and the framework provided in Table 6.2, it would appear that the rear seat belt data indicates a broad strategy as GM endeavoured to implement the technology across its product line very quickly while the pretensioner data would indicate a deep strategy. The explanations offered for the pretensioner roll out in Sub-section 5.2.1, however, suggests that the timing had little to do with the technology itself and more to do with the safety system in which it is embedded. Using the classification scale in Figure 6.1, the deployment data for seat belts should be classified as indeterminate.

In airbags, General Motors' deployment shows features associated with a deep strategy in Table 6.2. GM introduced new generations of airbag technology in selected models and then, after several years, rolled the technology out to more models in the fleet.

GM's hybrid vehicles program is summarized in Table 5.5 and shows GM developing four hybrid systems sequentially and perfecting the technology in one model before rolling it out to others during a major restyling or model change. Applying the framework in Table 6.2, GM's hybrid deployment could be characterized as deep.

GM's fuel cell program is summarized in Table 5.6 and shows how GM pursued several technologies in parallel which is a characteristic of a broad program as defined in Sub-section 6.2.2 and elaborated in Table 6.2. The problem with GM's fuel cell program is the sheer size of the effort which naturally produced a large number of prototypes. Rather than consider it a broad strategy, interview subject number 7 characterized GM's fuel cell program as a series of deep deployments and see the entire program as evidence of what this expert called General Motor's "technological arrogance". While this idea has some validity, the definition provided considers parallel activities as aspects of broad strategy regardless of the funding level.

Table 6.4 shows a summary chart for GM indicating how the ideas of depth and breadth apply to the case study developed in Sub-section 5.2.1 based on the definition provided in Sub-section 6.2.2 and developed further in Tables 6.2 and 6.3 and then classified according to the scale put forward in Figure 6.1.

	Deep	**Partially Deep**	**Indeterminate**	**Partially broad**	**Broad**
Patent Analyses	o Airbags o Hybrids			o Seat belts	o Fuel cells
Deployment Data Analysis	o Airbags o Hybrids		o Seat belts		o Fuel cells

Table 6.4 Summary chart for General Motors

There does not seem to be evidence of path dependence in the GM data as it appears to follow deep strategies in airbags and hybrids and a broad strategy in fuel cells as well as pursuing different strategies in different aspects of seat belt deployment. What does come across, especially in the interviews, is the idea mentioned above of “technological arrogance”. This view is characterised by a quote attributed to a GM executive concerning airbags, given by interview subject 8, that “there is not a problem we can’t solve. The only question is which problems to solve”. According to subject number 7, General Motors’ managers and executives had a firm belief in their role as the largest car company in the world, with the most resources and the highest economies of scale. GM would naturally do whatever it felt like and would be successful as soon as the volume kicked in.

Such an attitude appears to have resulted in large, well-funded, game-changing programs which can then be classified as deep or broad depending on the factors listed in Table 6.2. In the case of rear seat belts and fuel cells it appears that political considerations led GM to deploy the rear seats quickly and initiate a parallel set of fuel cell activities which the thesis classifies as broad. In the case of airbags and hybrids GM appears to have sought to perfect the technology in one application before rolling it out to more vehicles in its fleet. As discussed in Sub-section 5.2.1, interview subject number 6 pointed out how new technologies would often be first developed for GM’s Cadillac division, as Cadillac was one of the only divisions with sufficient financial resources to pay for new technology, and then rolled out across the wider fleet following what the thesis refers to as a deep strategy.

GM’s choice of depth or breadth appears, in summary, to be the result of cultural and political factors and the way the managerial accounts were managed as much as anything else.

- Ford

Applying the analysis guidelines shown in Table 6.3 to Ford’s patent data shown in Figures 5.6a - 5.6d yields the following conclusions. Ford’s 63 seat belt patents appear on the *Themescape* representation as a low-lying land mass of medium size with one peak and one small island. While there does appear to be a broad valley separating the land mass, the overall pattern should be classified as deep using the guidelines shown in Table 6.3. The seat belt pattern does have several different contour lines separated by valleys but only one peak and one small island. Using the classification scale shown in Figure 6.1, it appears that the best characterization of Ford’s airbag patents would be partially deep.

The more focused airbag representation has three separate peaks, a much smaller land mass and no islands. Ford does, however, have fewer airbag patents than seat belts (46 vs. 63) so one would expect the land mass to be smaller. The fact that it is also higher implies a deeper technology deployment strategy and it should be classified as deep.

Ford's relatively large number of hybrid patents (Table 5.7) and the *Themescape* representation shown in Figure 5.6c yield a large land mass with four separate peaks, a deep lagoon and four islands. This pattern should be characterized as broad using the guidelines in Table 6.3 and the classification scale shown in Figure 6.1.

In fuel cells, Ford has only 40 patents which is the lowest number of fuel cell patents of any of the manufacturers and also the lowest percentage of its own patents in fuel cells (Table 5.7). The possible reasons for this are discussed in Sub-section 5.2.2 and might be linked to Ford's investment in Bollard as its fuel cell supplier. As discussed this would logically lead Ford to only develop its own technology in specific areas where it thought it needed to complement Bollard's. Figure 5.6d shows a medium sized land mass with two deep lagoons and a large island and three widely separated peaks and should be characterized as broad.

The data on Ford's rear seat belt deployment is shown in Table 5.9 and indicates a deep pattern, as Ford appears to have deployed the seat belts on just five models in 1988 and 1989 and then another 10 models in 1990. It is, however, possible that Ford's back seat program was simply slower than GMs and that the deployment strategy was fundamentally the same. The fact that Ford uncoupled the deployment of rear seat belts from major re-styling, however, supports the hypothesis that Ford engineers and product planners chose to wait and evaluate the deployment on the first few vehicles before committing to the entire fleet. This kind of trial-and error approach is consistent with the idea that the deployment strategy was fundamentally deep.

The pretensioner data for Ford is less clear, as Ford had already installed the devices on 70% of its models prior to 2001. Ford did, however, take an additional five years to reach full deployment and appeared to place the pretensioners on models at the time of major re-styling efforts, echoing GM's very slow deployment. Taken together one could argue for characterizing the seat belt deployment as partially deep using the scale given in Figure 6.1, although the case could also be made for indeterminate due to the pretensioner data.

Ford's airbag deployment shown in Figure 5.7 was introduced in waves. Ford, for example wait for 2-7 years between installing second generation airbags on the first 9 models and then rolling out the technology across the rest of the fleet. This type of pattern is consistent with a deep strategy as shown in Table 6.2.

Ford's hybrid program is shown in Table 5.10 and can be interpreted in different ways. On the one hand Ford has been dividing its efforts between two technological solutions in its effort to develop an alternative to its reliance on Toyota's technology, as discussed by interview subject 7, and this kind of parallel effort would be considered as broad using the definition in Sub-section 6.2.2. In addition Ford has been pursuing hybrids on multiple body styles since 2006 and this type of diversification would be classified as a feature of a broad strategy. One could also argue that the program is still not that broad and, although Ford has 4 hybrid models on the market, it has essentially developed only two hybrid vehicles (Fusion/Milan, Escape/Mariner each of which are badged for both the Ford and Mercury brands). On balance, Ford's hybrid program is classified as partially broad using the scale in Figure 6.1.

Ford's fuel cell program (Table 5.11) has largely been focused on using Ballard's compressed hydrogen fuel cell stacks although there have been exceptions to this idea, such as the Mazda Premacy project which used reformatted methane as the feed stock and, while the technology platform has been stable, Ford has experimented with a larger number of body styles and configurations. In terms of body styles Ford has put fuel cells in sedans, sub-compacts, compacts, and SUVs and, in terms of configuration, is developing the Edge HySeries hybrid fuel cell/plug-in vehicle and supported the high speed Fusion 999 prototype. Considering the range of the relatively small program, Ford's fuel cells could be characterized as partially broad using the scale put forward in Figure 6.1, although one could argue for its placement as indeterminate as well.

Table 6.5 shows a summary of the classification applied to the patent representations and deployment data for Ford.

	Deep	**Partially deep**	**Indeterminate**	**Partially broad**	**Broad**
Patent Analyses	o Airbags	o Seat belts			o Hybrids o Fuel cells
Deployment Data Analysis	o Airbags	o Seat belts		o Hybrids o Fuel cells	

Table 6.5 Summary chart for Ford

In terms of path dependence it is difficult to draw a conclusion from the Ford data, although the seat belts and airbags would lead one to assume that, at least at one point in time, Ford favoured deep strategies. While interview subject number 1 recognized a tendency in both General Motors and Ford for deep strategies that represented a "silver bullet" to solve particular problems, subject number 7 felt that the CEO plays a pivotal role in technology strategy and that Ford "lurches back and forth" according to the personality and agenda of the CEO at the time.

The Ford data also makes clear that there are a large number of variables that affect what a company will do concerning new technology at a given point in time including its overall economic situation and the management issue mentioned above. Ford's hybrid and fuel cell deployment clearly appear to have been heavily influenced by the fortunes of Bill Ford, an environmental enthusiast, and by the economic difficulties the company faced in the early 2000's which appear to have led it to scale back its efforts on fuel cells.

- Toyota

Toyota has 60 patents in seat belts as shown in Table 5.12 and the *Themescape* representation of them (Figure 5.9a) , shows features associated with deep and broad strategies. There is a central core area with two large, contiguous peaks but this is surrounded by hills spread out across the landmass. The two peaks could be used to classify the strategy as deep while the large peninsulas and two small islands would be an indication of a broader strategy. A balanced application of the guidelines shown in Table 6.3 and the classification scale in Figure 6.1 places the pattern as partially deep.

In the *Themescape* representation shown in Figure 5.9b, Toyota's airbag patents also have both broad and deep characteristics. The main land mass has a total of six peaks but the two largest are adjacent to each other and form the central feature of the representation. There are also four small islands. In airbags, Toyota filed 90 patents (Table 5.12) which gives the representation a generally higher elevation than in the case of the seat belt representation. Overall the pattern again appears to be partially deep using the classification scale in Figure 6.1.

In Hybrids Toyota has filed 145 patents through 2006, as shown in Table 5.12, and these patents are shown as an eight island archipelago in the *Themescape* representation shown in Figure 5.9c. While there are four peaks and two are adjacent to each other, the pattern should be classified as broad using the classification scale.

The representation of Toyota's fuel cell patents shown in Figure 5.9d shows a medium size land mass with a small island, a large peninsula and only one peak. While some of these features would appear to indicate breadth, most of the patents appear to fall along a central ridge line in the representation and the relatively high elevation of this ridge could be interpreted as a sign of depth as would the overall smaller area of the representation. Using the classification scale in Figure 6.1 it would appear that the best classification would be partially deep.

Toyota's rear seat belt deployment is shown in Table 5.14; Toyota deployed the technology across its fleet in two years. Toyota had only 6 models with rear seats in its U.S. fleet in 1989 and one could argue that the pattern was either broad or deep depending on the interpretation. GM's deployment over its much larger fleet over two years was considered, as shown in Sub-section 6.3.1, as a very fast, broad deployment, yet one could also argue that Toyota perfected the deployment on one model in 1988 and then deployed to the other 5 following the deep deployment pattern shown in Table 6.2. Because Toyota had already equipped its entire fleet with pretensioners by 2001, the pretensioner data is not useful. On balance the deployment data for seat belts is considered indeterminate.

In airbags, Toyota's deployment is presented in Figure 5.10 and shows elements of both a deep and a broad strategy. As discussed in Sub-section 5.3.3, Toyota appears to bring out the new technology in selected models and deploys to the rest of its vehicles after a time delay in line with a deep strategy. On the other hand, Toyota deployed different generation technologies at the same time in 2004. This second trend, however, appears to have more to do with the increased pace of technological change, and in fact Toyota finds itself deploying smart airbags to selected models while still bringing the last models up to second generation airbags. In an effort to account for both ideas, Toyota can be classified as partially deep using the scale shown in Figure 6.1.

Toyota's hybrid program is summarized in Table 5.15 and again requires interpretation. While the U.S. data presented shows Toyota pursuing a deep strategy focused around the Prius and its hybrid synergy drive, interview subject number 3 placed the Prius program in context and maintained that Toyota pursued different electric vehicles and also launched a minivan hybrid called the Estima in Japan in 2001 and only increasingly centred its efforts on Prius as it became a runaway success.

What does characterize Toyota's hybrid program is the large number of variants and body styles currently in development and production. This deployment, however, only occurred after three generations of the Toyota Prius were developed and the technology refined; such a program is classified as deep using the definition in Sub-section 6.2.2. Finally there is evidence of Toyota pursuing parallel tracks both at the vehicle level, such as offering electric running mode in Japan but not in the United States, and in developing multiple battery technologies. On balance it would appear that Toyota's program is more deep than broad due to its reliance on the hybrid synergy drive and the way it first developed the technology for the Prius.

Toyota's fuel cell program, appears to fall in the more deep than broad classification as most of its efforts, shown in Table 5.16, have been focused around the continuous development of its proprietary fuel cell technology and the FCV series of vehicles, but it has also developed the FINE-S and FINE-N vehicles which use radical vehicle architectures.

Table 6.6 presents a summary of the analysis of the Toyota patent and deployment data using the classification scale shown in Figure 6.1.

	Deep	**Partially deep**	**Indeterminate**	**Partially broad**	**Broad**
Patent Analyses		o Seat belts o Airbags o Fuel cells			o Hybrids
Deployment Data Analysis		o Airbags o Hybrids o Fuel cells	o Seat belts		

Table 6.6 Summary chart for Toyota

In terms of path dependence, Toyota appears to favour deeper strategies but the evidence is not compelling. Interview subject number 2 felt that "fast follower" was a more accurate description of Toyota's technology strategy and that he did not see a tendency towards depth or breadth. Insisting on the strength of Toyota in the safety area, subject number 8 remarked on its ability to mobilise its people and said that "once in motion, everyone gets on board".

Toyota's culture of continuous improvement and the managerial processes discussed in Sub-section 5.2.3 appear to allow it to place relatively large bets on technology and then push for rapid roll out when a decision is finally taken. This idea is consistent with the literature on automotive product development, discussed in Sub-section 2.2.1, including Clark and Fujimoto (1989,1991) on Japanese new product development in general and also Coup's (1999) account of the history of Toyota's developments of alternative power train technology.

- Nissan

The *Themescape* representation of Nissan's seat belt patents are shown in Figure 5.13a and show a single, small land mass with four peaks, two of which are adjacent and form a central massif. The pattern also has two small inlets. Nissan filed 103 seat belt patents (Table 5.17) and this gives the small land mass a high elevation. It appears that the pattern can be characterized as deep using the classification scale shown in Figure 6.1.

The airbag representation shows a similar pattern, although it covers an even smaller area; this is probably due to Nissan having only 47 patents in airbags, as shown in Table 5.17. The representation has one large peak and three smaller peaks and a large peninsula but should be classified as deep to its overall elevation and small size.

The representation of the Nissan's hybrid patents shown in Figure 5.13c has three contiguous peaks rising out of a small central land mass which has three islands and two peninsulas. Table 5.17 shows Nissan with 84 patents, giving the land mass a relatively high elevation. On balance it appears that Nissan's hybrid pattern is partially deep using the classification scale in Figure 6.1.

The representation of Nissan's fuel cell patents is shown in Figure 5.13d and, while the large land mass only has one island, it does have two deep lagoons and three peaks spread out along a central ridge line. Broad characteristics include the overall size of the land mass and the lagoons and island while deep characteristics include the peaks and the ridge line. As seen in Table 5.17, however, Nissan has close to the same number of patents as for hybrids (82 vs. 84) and the overall elevation of the pattern is much lower leading to a characterization of the pattern as partially broad.

Nissan's deployment of rear seat belts matches that of Toyota and can also be characterized as deep using the framework put forward in Table 6.2, because the rear seat belts were placed on one of the six models with rear seats in 1988 and then deployed to two others in 1989 and the remaining four in 1990.

Nissan's airbag deployment is depicted in Figure 5.14 and shows a deep pattern in the deployment of second generation airbag technology. Four models were fitted with this technology in 1995, and then Nissan waited between 4 and 9 years to deploy the airbags to the rest of its fleet. Nissan also appears to show the simultaneous introduction of different systems in different models which would normally indicate a broad strategy. As in the case of Toyota, the most likely explanation is that Nissan was again introducing smart and advanced systems in selected models and will eventually deploy them across the fleet in another wave.

Table 5.20 shows Nissan's one hybrid vehicle. As discussed in Sub-section 6.3.1, at issue is not the size of the program but its degree of focus. Nissan has invested only on the Altima hybrid program and has now, according to interview subject number 4, committed all available funds to the battery electric Nissan Leaf. Despite its investment in lithium ion battery technology for the Leaf, it appears that Nissan is still using nickel metal hydride battery in the Altima Hybrid.

Table 5.21 shows Nissan's fuel cell program, which produced a series of prototypes based on the X trail SUV after developing two prototypes using reformed methane and a small city car for the 2003 Tokyo auto show. With the exception of the show car Nissan worked on the two technologies sequentially and thus, using the framework shown in Figure 6.1, its fuel cell strategy can also be classified as deep.

Table 6.7 shows a summary chart for Nissan's patent analysis based on the *Themescape* representations and the deployment data discussed in Sub-section 5.2.4. Alone among the manufacturers, Nissan offers evidence of path dependence with all of its deployment data showing deep strategies and only its fuel cell patents being classified as broad. Interview subject number 4 confirmed that, in his opinion, Nissan consistently worked on large, game-changing programs and would perfect a technology before deploying it.

	Deep	**Partially deep**	**Indeterminate**	**Partially broad**	**Broad**
Patent Analyses	o Seat belts o Airbags	o Hybrids		o Fuel cells	
Deployment Data Analysis	o Seat belts o Airbags o Hybrids o Fuel cells				

Table 6.7 Summary chart for Nissan

- **Summary**

The purpose of this section was to apply the ideas of depth and breadth, introduced in Section 6.3 to the empirical data in Chapter 5 using a clear definition of depth and breadth as a framework for its application. Table 6.8 shows the results for all four manufacturers and all four technologies.

	GM	**Ford**	**Toyota**	**Nissan**
Seat belts	Patent pattern: Partially broad Deployment data: Indeterminate	Patent pattern: Partially deep Deployment data: Partially deep	Patent pattern: Partially deep Deployment data: Indeterminate	Patent pattern: Deep Deployment data: Deep
Airbags	Patent pattern: Deep Deployment data: Deep	Patent pattern: Deep Deployment data: Deep	Patent pattern: Partially deep Deployment data: Partially deep	Patent pattern: Deep Deployment data: Deep
Hybrids	Patent pattern: Deep Deployment data: Deep	Patent pattern: Broad Deployment data: Partially broad	Patent pattern: Broad Deployment data: Partially deep	Patent pattern: Partially deep Deployment data: Deep
Fuel Cells	Patent pattern: Broad Deployment data: Broad	Patent pattern: Broad Deployment data: Partially broad	Patent pattern: Partially deep Deployment data: Partially deep	Patent pattern: Partially broad Deployment data: Deep

Table 6.8 Summary of strategies in terms of depth and breadth

As the conclusions for each company case study were discussed in Sub-sections 6.3.1-6.3.4, the following will discuss the analysis summarized in Table 6.8 for each of the four technology case studies.

In seat belts, the patent patters for Ford, Toyota and Nissan are classified as partially deep or deep and only GM has a partially broad pattern, perhaps reflecting some of GM's early work on seat belts and the idea, discussed in Sub-section 5.3.1, that these vehicle manufacturers pursued relatively focused programs for seat belt development. The deployment data for seat belts shows no evident pattern; the deployment data only shows a relatively narrow part of the overall seat belt strategy of the firms involved and could be considered inconclusive.

In the case of airbags all patent patterns are deep, with the exception of Toyota which was considered partially deep, indicating a somewhat focused research program in all of the manufacturers. The deployment pattern appears to be similar with GM, Ford and Nissan, following what is characterized as deep strategies while Toyota's deployment is only classified as partially deep.

With respect to Hybrid vehicles the patent patterns show heterogeneity across the sample, with Ford and Toyota pursuing what appear to be broad strategies and GM and Nissan pursuing deep and partially deep strategies respectively. The deployment data shows all manufacturers pursuing deep or partially deep strategies. While apparently homogenous, the actual pattern of deployment of the different manufactures discussed in section 5.2 and Sub-section 5.3.3 is actually quite different and care should be taken to calibrate the findings for the very different size of the hybrid programs at the different manufacturers. These differences come out strongly in the patent representations while all manufactures appear to be following essentially deep strategies for deployment, although of course Toyota is leading the industry and Nissan is doing very little.

With respect to fuel cell electric vehicles, all of the manufacturers, with the exception of Toyota, appear to follow broad strategies based on the patent representations. In the deployment data there appears to be a split between GM and Ford, which appear to be pursuing broad and partially broad deployments respectively, and Toyota and Nissan, which appear to be on a deep and partially deep track.

Overall, the analysis summarized in Table 6.8 appears to indicate that there is both heterogeneity and homogeneity in approach in terms of the ideas of depth and breadth across the sample. In the case of the company analysis, only Nissan shows signs of homogeneity which could be interpreted as path dependence (Teece et al., 1997). In the case of the technologies, only airbags gave consistent results across both data sets and all four vehicle manufacturers. What does appear to emerge in Table 6.8, however, is a certain relationship between the two data sets which will be discussed in Sub-section 6.2.4.

6.2.4 A construct relating patents and technology deployment

In looking across the 16 data points shown in Table 6.6, the classification made through interpretation of the patent pattern appears to match that made in looking at the deployment data in 9 of the 16 cases (56%), indicating the possibility of a causal relationship between them. If one collapses the partially broad and partially deep classifications into deep and broad, the correlation goes up to 75 % with the two indeterminate cases. Table 6.9 shows this correlation.

Deep and partially deep	Broad and partially broad
• Ford and Nissan in seat belts • All manufactures in airbags • GM and Nissan in hybrids • Toyota in fuel cells	• Ford in hybrids • GM, Ford, and Nissan in fuel cells

Table 6.9 Instances supporting the depth and breadth construct

While the correlation shown above does appear compelling, inductive research of the type pursued by the thesis carries with it the danger of finding those patterns one is looking for and, due to the qualitative nature of the cross-case analysis presented in Section 6.3, the correlation between the two data sets must be qualified to some extent. To address this possible bias, the construct shown in Figure 6.2 attempts to explain these results by taking the position, supported by Leonard-Burton (1995), that there is a constant process of two-way technology transfer between research and development activities which would result in patents and product development directed at deploying new technology in products and services.

As stated in Sub-section 6.2.2, a broad strategy is defined as pursuing a number of parallel projects looking at different aspects of the new technology and/or seeking to implement the technology in a wide variety of applications. Assuming some constant level of two-way technology transfer, such a strategy ought to lead to a broad range of scientific and engineering discoveries which in turn ought to lead to a wide distribution of patents. The mechanism at work is that, since engineers are doing more different things, they will logically find a diverse range of potentially patentable innovations. A broad strategy also ought to lead to incremental improvements in a number of applications, products and services.

A deep technological strategy is defined as focusing efforts on developing the technology in a single or limited number of applications prior to a potential or eventual roll out across the product line. In this case the scientists and engineers involved with the effort will all be working on tasks related to achieving a smaller number of projects' stated objectives. Patents resulting from such efforts ought to be more related to each other. A deep strategy would also be more likely to produce major leaps of innovation, perhaps from one product generation to the next, with little or no incremental improvement. Major new platforms would be added as a block to products or services once they were fully ready and the improvement in performance would be significant.

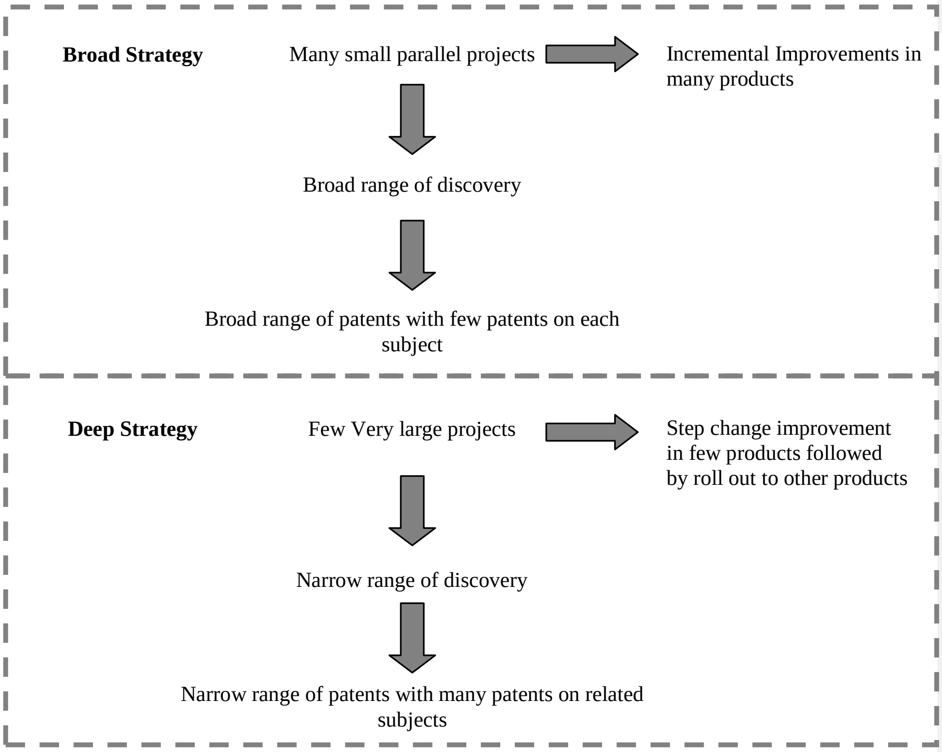
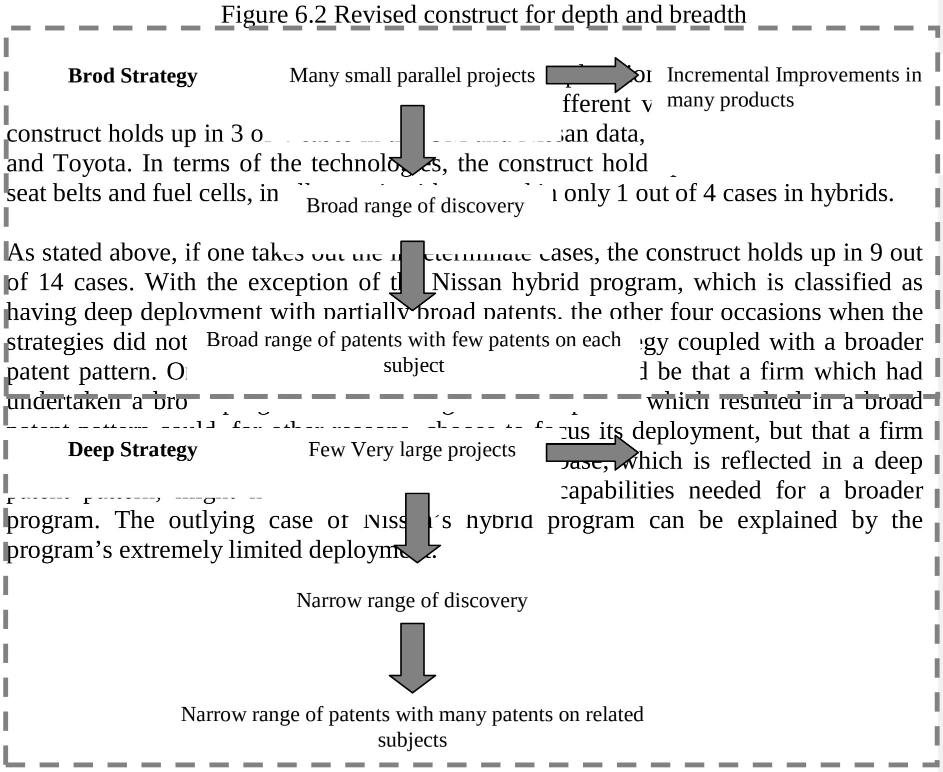


Figure 6.2 Revised construct for depth and breadth



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construct holds up in 3 o … san data, and Toyota. In terms of the technolo…es, the construct hold … seat belts and fuel cells, in … only 1 out of 4 cases in hybrids.

As stated above, if one take… cases, the construct holds up in 9 out of 14 cases. With the exception of th… Nissan hybrid program, which is classified as having deep deployment with partially broad patents, the other four occasions when the strategies did not … gy coupled with a broader patent pattern. O… d be that a firm which had undertaken a bro… which resulted in a broad patent pattern could, for other reasons, choose to f…cus its deployment, but that a firm … ase, which is reflected in a deep patent pattern, might … capabilities needed for a broader program. The outlying case of Niss…'s hybrid program can be explained by the program's extremely limited deployment.

6.3 Implications of depth and breadth

Section 6.3 will discuss the implications of the ideas of depth and breadth within the empirical data, combine the results of the cross-case analysis in Section 6.2 with the technology pathways discussed for each technology under consideration in Chapter 5, and explore what could be some implications for practice based on the research.

6.3.1 Implications within the data set

Having classified the strategies employed by the four vehicle manufactures under consideration in each of the four technologies in the sample, and also explored the degree to which the patent data and deployment data can be related in terms of depth and breadth, the next step in the analysis is to attempt to determine what, if any, generalizations can be drawn regarding the application of depth and breadth within the data set. The three areas where generalizations might be found using the data in the case studies are path dependence within the manufacturers, medium-term penetration or adoption, and impact on technical performance. Other issues which would be of interest but are beyond the scope of this analysis would be the total program cost of choosing different strategies, the unit cost of the solutions deployed, and the profitability of that deployment, taking into account any ability for margin improvement and the impact on market share.

- Path dependence

While there is some evidence to suggest that Nissan and Toyota favoured deep and partially deep strategies, the GM and Ford data do not support such a conclusion. Toyota appears to favour partially deep strategies although it does have a broad patenting pattern in fuel cells, and the deployment data in seat belt is classified as indeterminate. Nissan appears to use deep strategies, with the exception of its patent pattern in fuel cells which was classified as partially broad. General Motors had deep strategies in airbags and hybrids, a broad strategy in fuel cells, and, as stated above, the data for seat belts is somewhat contradictory but, whether the product deployment data is considered deep (rear seat belts) or broad (pretensioners), there is little to indicate a preferred path for GM. Although Ford appeared to have a deep or partially deep strategy in seat belts and airbags, there is also no evidence of a favoured path.

There was also no clear consensus concerning path dependency amongst the industry experts. According to interview subject number 2, the issue was being a technology leader or a follower, and suggested that there might be a clearer distinction in those terms. Subject number 1 felt that Nissan always pursued a deep strategy and pointed to Nissan’s Leaf battery electric vehicle as an example. For this expert the idea of there being a “silver bullet” which would solve all problems is also very much an American concept and he could also see evidence that Ford and GM also tended to deep strategies. Subject number 5 maintained that each technology was different and that the different manufacturers will pursue different patterns based on the imperatives of the technology, which in turn are driven by issues of price and consumer value. According to interview subject number 7 Ford “lurches back and forth” depending on its CEO.

- Medium-term deployment

As stated in Sub-section 6.2.2, a broad strategy is defined as pursuing a number of parallel projects looking at different aspects of the new technology and/or seeking to implement the technology in a wide variety of applications. Thus, one would expect deployment to be faster in broad strategies than deep strategies. Over time, however, deep strategies ought to result in a technology's rollout and an interesting question is therefore which type of strategy will result in increased deployment over the medium term. Taking out the 3 instances in which the deployment data does not match the patent pattern leaves 13 samples, of which 9 are classified as deep strategies and 4 as broad.

Comparing the three broad programs in the fuel cell area, with that of Toyota, which was classified as deep, the data is inconclusive. In the first place all fuel cell vehicles are, for these manufacturers, still in the prototype phase so that all that can be done is to count the number of prototypes - an incomplete measure of deployment at best. In any case, GM's program produced 16 fuel cell prototypes followed by Ford and Toyota with 9 each and Nissan with 7. Assuming that the overall size of the program would be proportional to the number of patents as well as the total number of prototypes, one would expect a rough correlation to exist between the two measures of innovative output. In fact such a correlation does exist between the programs of GM, Toyota and Nissan but breaks down in the case of Ford (Table 6.10). As mentioned in Sub-section 5.2.2, a likely explanation for Ford's low volume of patents is its link with Ballard Power Systems through the Automotive Fuel Cell Cooperation Corp (AFCC). For the purposes of the exploration of depth and breadth, however, no appreciable difference is found between Toyota's deep program and the broad programs of the other manufacturers.

	Number of fuel cell prototypes (See Tables 5.6, 5.11, 5.16, 5.21)	Number of fuel cell patents (See Table 3.2)	Ratio of patents to prototypes
GM	16	205	12.8
Ford	9	40	4.4
Toyota	9	109	12.1
Nissan	7	82	11.7

Table 6.10 Ratio of patents to prototypes

In the case of hybrids, Toyota's program achieved the highest fleet coverage, 30%, but does not match the depth and breadth construct, as its patent pattern appears to be broad while its deployment is classified as partially deep. A comparison can be made between GM and Ford which did pursue deep and partially broad strategies respectively. As shown in Appendix C3, General Motors had achieved 23% coverage by model year 2009/2010 and Ford has only achieved 16% which would indicate that its deep strategy had paid off. Interview subject number 3 felt, however, that this data point was misleading and suggested that, if one were to look at the percentage of hybrid in terms of sales, rather than models, the Ford number would be higher. In any case the data appears inconclusive in linking depth or breadth with medium term deployment.

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- Impact on technical performance

In fuel cells, the differences between broad and deep strategies could be explored by contrasting the results of Toyota's apparently deeper strategies with those of the other manufacturers. The problem with the fuel cell performance data is that, according to the manufacturers as well as the industry experts interviewed for the thesis, the technology is still in flux and commercialisation is still at least 10 to 20 years distant. Moreover, the data set on fuel cells gives only range and top speed; more technical data such as the fuel cell output characteristics, cost data and fuel consumption are either not available, difficult to compare or both. The problem with range and top speed is that they are inputs into the design process rather than outputs, and manufacturers have been designing their vehicles for a range of approximately 500 km and a top speed of 150-160 km/hr. Of these, Toyota's new FCHV prototype might achieve a range of 830 km because it was designed to do so, but the trade-offs made to reach that target in terms of cost, for example, are not known. In this sense, fuel cell data will only be robust once vehicles are in the market and real design tradeoffs are made.

The hybrid programs of Ford and GM offer a more robust comparison as Ford's partially broad pattern appears to achieve better performance than GM's deeper strategy in fuel economy. Table 6.9 shows a comparison of fuel economy in the hybrid programs of GM and Ford. One can compare, for example, the Escape hybrid with front wheel drive to the similar Chevrolet Tahoe in the 2007 model year. Ford's Escape achieved fuel economy of 12.8 km/l while Tahoe managed only 8.9 km/l. GM's passenger cars are achieving 11.9 – 12.4 km/l while Ford's Fusion/Milan is rated at 16.2 km/l. This data is, however, considered far from conclusive as it deals with only one aspect of performance and represents only one data point.

General Motors	Year	Fuel Economy (km/l)	**Ford**	Year	Fuel Economy (km/l)
Chevrolet Silverado FWD	2003 2005 2009	7.1 7.3 8.9	Escape 4WD	2005 2007 2008	11.5 11.6 11.9
Chevrolet Silverado 4WD	2003 2004 2008	6.8 6.8 8.5	Escape FWD	2005 2007 2008	12.4 12.8 13.5
GMC Sierra	2003 2009	7.3 8.9	Mariner	2006 2007 2010	11.5 11.5 11.9
Saturn Vue Green Line	2005 2008	11.1 11.9	Fusion/Milan	2008	16.2
Saturn AURA Green Line	2006	11.5			
Chevrolet Tahoe 2WD	2007	8.9			
Chevrolet Malibu	2007 2009	11.5 12.4			
Chevy Volt E Flex	2011 ?	21.3			

Table 6.11 Hybrid fuel economy of GM and Ford

6.3.2 Depth and breadth and technology trajectories

As discussed in Section 5.3, the different technologies under consideration have been or are part of different pathways of technological change using the framework put forward by Geels and Schot (2007). The emergence of seat belts could be considered an example of what Geels and Schot called *technological substitution*. Although there were early adopters of airbag technology, the early devices were rather crude, and a number of serious safety issues both at the manufacturing and usage level needed to be ironed out before the technology became acceptable. Geels and Schot's *de-alignment, re-alignment* might therefore be considered as an adequate choice for airbags. Electric vehicle technology including fuel cell powered vehicles appear to be following the *transformation* pathway and is still very much underway and finally hybrid vehicles were thought to be best described by the *re-configuration* pathway.

Geels and Schot (2007) applied the pathways to higher level artefacts and entire socio-technological regimes yet the approach, described in Sub-section 5.3.1, appears robust at the level of component and drive train technology. Table 6.12 adds the depth and breadth discussion from Section 6.2 and maps it onto the technological pathways analysis developed in Section 5.3 and shown in Figure 5.25

Technological Pathway	***Technological substitution***	***De-alignment, re-alignment***	***Re-Configuration***	***Transformation***
Technology	**Seat Belts**	**Airbags**	**Hybrid Vehicles**	**Fuel Cells**
Broad Strategies	na	na	Ford	GM
Deep Strategies	Ford Nissan	GM Ford Toyota Nissan	GM Nissan	Toyota

Table 6.12 Manufacturers strategies by technology pathway

While the implications for theory will be discussed in Section 6.4, some comments can be made from the data about what appears to be critical in each of the technology pathways represented in the sample.

The most important aspects of product deployment in the *technological substitution* pathway appear to be deploying quickly and having sufficient marketing resources and capabilities to take advantage of that deployment in the market. As the data only gives clear evidence of two manufacturers pursuing deep strategies, it is difficult to make a comparison with the results of a broad strategy. Examples of making such commitments and also marketing them are found in GM's back seat program and in Toyota and Nissan pretensioners' deployment.

Airbags followed the *de-alignment, re-alignment* pathway and it appears that Toyota's broad strategy proved to be the most effective, although it might also be that Ford and GM simply lacked the commitment to pursue the technology across its product line.

The electric vehicle situation is still very fluid but, according to sales data and the expert interviews, hybrids are gaining ground and fuel cell research is sharply reduced. In both hybrids and fuel cells it appears that broad strategies have done better than deep strategies as they have given a better chance of achieving technological leadership and this can be seen both in Toyota's hybrid program and in GM's fuel cell program. In hybrids, it appears that it was also important to be in the right place at the right time or have the ability to see where the market is going in advance. Toyota appears to have been right to bet on hybrids, and today they have become a corporate priority, although it appears that their original intention was to only invest in hybrids as a bridge to fuel cells. The main advantage of hybrids is that their sales do not require any fundamental change in the infrastructure or any other part of the socio-technical regime. With GM's financial collapse and the change of administration in Washington, GM no longer can stop the electric tide turning and is being directed by its new owners to join the hybrid bandwagon.

6.3.3 Implications for practice

Managers of technology-based firms might find this combination of ***depth*** and ***breadth*** with technology pathways useful in reviewing their current portfolio of technological development. The following summarizes the apparent advantages and disadvantages of choosing either depth or breadth in the different technology pathways based on the data presented in Chapter 5 and discussed in Section 6.2. Inconclusive examples, including Toyota's seat belt deployment and Nissan's and Ford's fuel cell program, were not included.

- Technological substitution

According to Geels and Schot (2007) both threads in the innovation literature dealing with discontinuous and potentially disruptive technology are largely dealing with the technological substitution pathway. One of the salient characteristics of the disruptive literature also discussed in Sub-section 2.2.2 is that most of it is retrospective in nature and disruptions which seem obvious in hindsight often do not look so clear to industry actors in the years leading up to such transitions.

While the thesis has no clear examples of companies pursuing a broad technological strategy in the face of technological substitution, such a strategy could consist of monitoring developments in a number of different possibilities in the way that Roussel et al. (1991) described as pacing technologies. Such a strategy might have three advantages. First, from a political point of view, the strategy would not require forging a clear consensus - something which might be difficult depending on the cognitive bias of specific executives and perhaps a lack of compelling evidence from the market. The second advantage is that not all expected transitions do, in fact, occur and the level of expenditure for a broad exploratory strategy could be contained. The third advantage is that if the transition does occur, at least the firm will have acquired some knowledge of the strategy. The disadvantage of pursuing a broad strategy could be that a competitor pursues a deep strategy and develops technology with superior performance, a lower cost, or both. The role of marketing in such a situation could be key in order to at least publicize those actions taken in order to buy time for the product groups to catch up.

Ford and Nissan's seat belts programs appear to be deep strategies and the advantage of pursing such a strategy in the technological substitution is that, if sufficient resources are put into place soon enough, the firm may have the potential to develop competitive advantage in the technology versus its rivals. The disadvantage is financial, as the return on investment for such a strategy is extremely difficult to estimate in advance and even with clear hindsight it is often difficult to calculate what the impact of not doing something would have been. It appears that the key aspect of pursuing such a strategy will be to have a clear political consensus or direction from the top to pursue such a strategy or to wait until the direction of change is clear, in which case there is a risk of starting out behind the competition.

- De-alignment, re-alignment

As shown in Sub-section 5.3.3, airbags appear to follow the *de-alignment, re-alignment* pathway and none of the four manufacturers studied followed a broad strategy. Such a strategy could be understood as pursuing different and even mutually exclusive technologies in parallel and the advantage would be to improve the chances of having a competitive solution when a new dominant design emerges. The disadvantage is that such a strategy can be expensive depending on the total amount spent on the different possibilities and also runs the risk of being far behind a competitor who has placed all their bets on one outcome and been either prescient or lucky or both. Critical to the success of such a strategy would be to cover all of the possibilities and then maintain the commitment to the technology and follow through on its deployment once the direction comes clear.

A deep strategy in the face of such a fluid situation ought to give a much higher return as long as the bet is placed on the right combination. The risk is, of course, to simply not cover the breadth of potential outcomes and end up with a solution which is of no use. At this point commitment can be a double-edged sword as a firm might in fact hold on too long to a solution which is headed for a dead end.

- Re-configuration

Sub-section 5.3.4 identifies hybrid vehicles as being on the *re-configuration* path and the thesis identifies Ford as pursuing a broad strategy with General Motors and Nissan pursuing a deep strategy. A broad program like Ford's appears to require making significant investments in multiple technologies and the advantage is that if true technological leadership can be achieved, the advantages can be very large. The disadvantage is that the financial return of such a strategy might be negative. Nissan and General Motors appear to both follow deep strategies but Nissan's is extremely limited and General Motors appears committed to catching up with Toyota, implying that a deep strategy could be useful for either objective. The risk in either pursuing a broad or a deep strategy in re-configuration is that the landscape pressure never reaches a critical point and "business as usual" can continue for a long periods of time rendering investments superfluous and perhaps leading to underinvestment in more immediate competitive issues.

The leader in hybrids, Toyota, appears to have pursued several different types of hybrids early on before focusing its attention on its *hybrid synergy drive* and this approach of starting out broad and then switching to a deep strategy might have validity for a larger sample of innovations on the *re-configuration* pathway. General Motors' deep strategy is based on the Chevy Volt which combines a small efficient internal combustion engine which acts as an electricity generator. While clearly a hybrid from a technical sense, GM takes great pains to describe the vehicle as a "range extended electric vehicle" as it hopes to jump past Toyota's hybrid technology. The advantage is that, if successful, the new technology can bring potentially superior performance at a more reasonable cost than making multiple commitments across a range of technologies.

- Transformation

Sub-section 5.3.5 identifies fuel cell vehicles as being on the *transformation* pathway and Section 6.2 classifies General Motors's fuel cell program as broad and Toyota's program as deep. Pursuing a broad program in the face of such a change involves spending very significant amounts of resources on multiple solutions and appears to justify the expenditure by having a clear idea that such a change will come about. The advantage of such a strategy is that it is the most likely to result in an incumbent influencing the transformation in such a way as to not only be able to survive but also to prosper in the new socio-technical regime from a strategic and technological basis. The disadvantage is that it requires tremendous financial resources and might not prove successful as such transformation depends on a variety of factors, many of which will always be beyond the control of even the most powerful corporations. General Motors fuel cell program is characterized as broad in Section 6.2 and has been thought of as making a serious effort on the technology, as discussed in Sub-section 2.2.3.

As not many firms have the financial resources to pursue such a broad strategy, a deep strategy represents another choice; Toyota's fuel cell strategy is an example. For a deep strategy to be successful a scenario is required for the outcome of the transformation, both in terms of technological architecture and timing, and for adequate resources to be put into place to realize that strategy. If the vision is correct and the execution is sound, then the firm has a real opportunity to enjoy superior performance and/or lower cost in the transformed socio-technical regime. If the technical solution or the timing is off by a large factor or if the program does not deliver, then the investment will be lost. One of the advantages of the strategy is that the financial cost could be contained such that the firm can continue to be competitive within the existing socio-technical regime. A very recent example of this strategy is Nissan's Battery Electric vehicle program which has been described by one of the interview panel as "a throw of the dice" and has reportedly taken up much of Nissan's advanced engineering budget over the last 18-24 months. Nissan is, as discussed in the thesis, behind in hybrids and will fall even further behind as the industry moves toward greater hybridization. If Nissan can, however, demonstrate the commercial viability of battery electric vehicles with lithium-ion batteries then there is a chance that they can limit the appeal of hybrids and be competitive in a very different game. Nissan has not, however, stopped investing in its traditional models during this time and would most likely survive whatever happens to the battery electric Nissan Leaf.

6.4 Discussion of theory

With regards to theory, Section 2.3 identifies a gap in the literature concerning how firms in general, and vehicle manufacturers in particular, manage technological development that is discontinuous and potentially disruptive. Section 2.3 reviews two threads in the literature which deal with such change and four approaches which are discussed but maintains that, in the implementation phase of technology development, using Tidd et al.'s (1997) framework, there is very little theory available. Section 5.1 applies Geels and Schot's (2007) technology pathways to the empirical data and Section 6.2 introduces the concepts of depth and breadth which can be used to inform decisions about what to do in the face of such technological change. Section 6.3 discusses the implications of applying these two concepts. The purpose of this section is to discuss the implications for theory and is focused on potential additions to Granstrand's (1998) theory of the technology-based firm which is reviewed in Sub-section 2.3.3. The thesis suggests that that the technological development mechanism that Granstrand's theory of the technology-based firm describes be expanded, that the theory be explicitly linked to the co-evolutionary literature and multi-level perspective as well as that dealing with dynamic capabilities, and that its definition be tightened.

- The origin of discontinuous innovation

Granstrand (1998) discusses a source of innovation in which the market will first encourage a firm to develop new technology which he calls "pull" (p.473). At some point the firm might use that technology in other applications or for additional segments creating technology "push" (p.473). Granstrand does not, however, mention the opposite case where a firm develops new technology and then, because of its introduction, creates demand. In the literature discussed in Sub-section 2.3.1, discontinuous technological innovation follows this second route and if the theory of technology-based firm is to be completed it appears that it must be expanded in this direction. For Tushman and Anderson (1986) the source of discontinuous innovation "are relatively rare and driven by individual genius" (p.440), while for Christensen and Bower (1996) it often comes from engineers who are not able to get adequate resources allocated to their ideas in one firm and go off to found new ones. In both cases, however, discontinuities do not normally come from market forces but from invention.

In the automotive industry many innovations are driven by regulation. As discussed in Sub-section 5.3.3, airbags are an example as it was government regulation which required vehicle manufacturers to develop passive safety technology. The general public eventually latched on to the idea that airbags made a car safer and demand increased. In the case of seat belt technology (Sub-section 5.3.2), the impetus appears to have shifted back and forth several times, much like the "pushmi-pullyu" creature in Lofting's 1920 book *The Story of Doctor Dolittle*. Public pressure and the example of Volvo and Saab pushing the technology led the U.S. government to legislate the incorporation of restraint systems on passenger cars. Manufacturers then chose to go beyond compliance (Reinhardt, 2005) and to offer more than was actually required. This was the case with GM's announcement on rear seat belts and later on Toyota's and Nissan's decisions to place pyrotechnic pretensioners on their entire fleet. The public now demands a certain level of safety equipment, going back to market pull.

Thus the first recommendation is to expand the mechanism for technology development and explicitly add the mechanism where technology push is followed by market pull to the theory of the technology-based firm.

- The theory of the technology-based firm and the co-evolutionary perspective

In his analysis, reviewed in Sub-section 2.3.3, Granstrand makes the case that other theories of the firm including neo-classical economics, agency theory, evolutionary theory or the resource-based view, do not address in a compelling way the co-evolutionary process between firms which develop technology and the environment in which those firms operate and compete. This is the primary reason he puts forward the theory of the technology-based firm. It appears, however, that neither Granstrand nor subsequent researchers who employed the theory of the technology-based firm or aspects of it made significant efforts to explicitly link the theory to the co-evolutionary perspective championed by Lewin and Volberda (1999). Of course, because of the timing of the different publications, Granstrand could not have cited Lewin and Volberda's 1999 prolegomena in his 1998 paper and it is also reasonable that they would not cite his paper as it had only just been published. The two literatures, however, have largely stayed separate over the last 10 years. While it is true that the co-evolutionary perspective deals more with strategy and Granstrand is better known to scholars interested in technology management, the explicit aim of both the theory of the technology-based firm and the co-evolutionary perspective was to transcend such functional boundaries and move toward more integrative research.

The thesis also draws on the multi-level perspective as this is yet another separate thread which can be woven together with co-evolution to make the fabric of the technology-based firm theory more robust. This thread was also first published in the late 1990's and shares many of the same principals of the co-evolutionary perspective and the theory of the technology-based firm. The multi-level perspective appears to fit into the co-evolutionary perspective as all five properties defined by Lewin and Volberda (1999) apply. By definition the perspective has *Multi-levelness* as it looks at the landscape, socio-technical regime, and niche level. *Multi-directional causalities* are clear in the perspective as there is pressure from both the landscape and niches on the regime and the regime itself affects the landscape and the process of niche formation and collapse. The pressures discussed above can have *non-linear* impacts, and the mechanism of explosive growth occurring in a specific niche is an example. *Positive feedback* is also clearly part of the model and is talked about in terms of technologies being potentially complementary or disruptive. Finally, *Path and history dependence* is also implicit in the model, and the discussion of different types of change patterns adapted from Suarez and Olivia's (2005) typology is evidence of this.

The thesis links these literatures by going through a rigorous application of Geels' seven aspects of a socio-technical regime to the automotive industry, placing cars and light trucks powered by internal combustion engines at the centre of the regime. It then uses Lewin and Volberda's (1999) five properties of a co-evolutionary system to show that the socio-technical regime described could be considered co-evolutionary. Finally, as stated above, the thesis uses Geels and Schot's (2007) technological pathways, which were derived for the multi-level perspective, to add depth to the theory of the technology-based firm.

- The theory of the technology-based firm and dynamic capabilities

Teece et al.'s (1997) dynamic capabilities framework sits clearly within the resource-based view and builds on the earlier work done in that area (Wernerfelt 1984, 1995; Barney 1991; Rumelt, 1991). Teece et al. consider that there have been three distinct threads in the strategy literature, and offer the dynamic capabilities framework as a fourth thread which they feel is particularly relevant to complex situations undergoing rapid change. In addition to the industrial organization and resource-based view threads, Teece et al. look at the strategic conflict thread, and while acknowledging the contribution of this approach, Teece et al. question its application to practice as the results of any given study depend largely on the game selected and the assumptions made in building the models. For Teece et al., one of the biggest differences between looking at things from the resource-based view as opposed to the industrial organization or competitive forces thread is the way one would approach high level strategic decisions such as market entry. From a competitive forces approach one would first pick an attractive industry, develop a competitive strategy to be successful in it, and then set out to secure the assets needed to compete through internal development, licensing, acquisition, etc. The resource-based view, on the other hand, suggests that a firm should first understand its unique assets, find markets in which those assets have value, and finally choose how to best capture the value that is available. Value might be captured by entering the business directly, becoming a supplier, or selling or licensing the capability.

One implication of the resource-based view is that developing new capabilities becomes a strategic issue. This is where the dynamic capabilities model comes in. Dynamic capabilities are defined as "as the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments" (Teece et al. 1987, p.516). Teece et al. thus provide a framework which adds to the resource view by allowing resources to evolve over time rather than being taken as a given. At the heart of the dynamic capabilities framework is the idea that a firm is much more than the sum of the items on its balance sheet and much of what is distinctive or strategic cannot, in fact, be purchased or acquired easily. For Teece et al. competences and capabilities are embedded in organisational processes and shaped by a firm's assets and historical paths and the terms processes, positions and paths are used to describe them.

Processes are considered for coordination and integration, learning, and reconfiguration and transformation of the business itself. Within the concept of coordination and integration, Teece et al. discuss the importance of a firm's processes having "a certain rationality or coherence" (p. 520) with each other as well as the criticality of a firm being able to combine and configure different capabilities in the face of environmental and technological change. Learning in the dynamic capabilities framework has to do with "common codes of communication and coordinated search procedures" (p. 520) and can be found in "patterns of activity" (p. 520) inside the firm. The final role of processes is to enable a firm to re-configure or transform in order to adapt to changes in its environment. Teece et al. discuss "organizational and managerial processes" (p. 518) which appear to be quite close to Granstrand's concept of management, and have three roles including coordination/integration, learning, and, reconfiguration.

In terms of positions, Teece et al. (1997) list eight categories of assets in which a firm might take positions and the first one is technology, with which Granstrand would concur, and the second one is complementary assets, echoing Teece (1993) in his seminal paper on profiting from innovation, in which he highlighted the importance of a firm having assets to complement its technology such as manufacturing capabilities or distribution networks. Teece et al. also include financial assets, reputation, structural assets, institutional assets, market assets and organisational boundaries in the model.

The third component of the dynamic capabilities model is to look at path dependencies or the history of a firm's investments and the sum total of its operational routines. For Teece et al., history matters and a firm's future development is constrained by its history (Barney, 1991). Related to this is the idea that a firm's technological opportunities at any given point in time is not completely exogenous, and that the actual state of a firm's processes, positions and paths will influence the set of opportunities that it can successfully explore.

Teece et al. also go into detail on how firms replicate capabilities and imitate their competitors. These two concepts are key to the dynamic capabilities framework, as it is the difficulty in acquiring or copying a full set of capabilities which is, in their view, the primary source of competitive advantage.

The only place that Granstrand and Teece et al. diverge sharply is that the dynamic capabilities model does not explicitly embrace the idea of co-evolution. Easterby-Smith et al. (2009) reflect on the ten years since the publication of the dynamic capabilities framework and conclude that the popularity of the concept has to do with its allowing researchers to use the resource-based view without considering the environment as static and allowing capabilities to evolve over time in response to those environmental changes. Several papers were also included in this review, which took a longitudinal view of the changing nature of capabilities, and Easterby-Smith et al. talk about the "growing interest in a co-evolutionary view which links the firm to the environment in which it is competing", but in fact the papers included all look at the mode in which the firm responds to its environment and not the other way around (McKelvie and Davidsson, 2009; Narayanan, et al., 2009; Bruni and Verona, 2009).

This gap is filled by Prencipe (2000) whose main focus was to add to the dynamic capabilities literature in his work on the different positions that different aircraft engine manufacturers enjoy with respect to engine control systems. Prencipe demonstrates the co-evolutionary process at work in his sample of manufacturers of aircraft engines which pass the three tests proposed above for technology-based firms. In the first place, there is a co-evolutionary process going on between manufacturers of airplanes and their key components, such as engines, and the rest of the aviation industry. The electronic control systems researched by Prencipe allowed engine manufacturers to improve fuel consumption giving aircraft greater range. This, in turn, changed route patterns for the airlines which then stimulated changes in engine specifications. Second, as there are only three major competitors in the industry, it is safe to say that each one has the ability to influence the industry as a whole. The third test was that one would put the artefact, in this case the aircraft engine, at the heart of the socio-technological regime under discussion and, again, it appears that this is the case, although a more in-depth analysis would be valuable. Prencipe also shows in his account of the shift from electromechanical control systems to digital control systems that the firms themselves made a huge impact on the rate and direction at which that shift happened. In other words, the companies themselves affected their environment in a co-evolutionary way and, as soon as the digital control systems were able to offer their customers superior performance such as enhanced fuel economy, then they became part of the new environment. For Prencipe, the important aspect was the way one of the firms in his study developed its competence in the new technology and he showed that it was a dynamic capability. He also, however, demonstrated that the dynamic capabilities framework is suitable for the analysis of technology-based firms.

The importance in linking these literatures lies in opening up an avenue to further develop the theory of the technology-based firm by incorporating into it findings derived in the co-evolutionary literature, the multi-level perspective, and dynamic capabilities. This idea has to do with breaking into what Granstrand calls the "dark box" (p.486) of management which is a key part of the theory of technology-based firm. There are dozens of threads in the literature discussing different aspect of management using these other perspectives, and by linking the perspectives it becomes possible to use this deep and growing body of knowledge to build on the theory of the technology-based firm.

- The definition of what is and what is not a technology-based firm

The theory of the technology-based firm has not been widely influential in terms of citations, and a reasonable question is why? One possible answer is that Granstrand took a very broad view of what a technology-based firm is and perhaps attempted to apply the theory too widely. In Granstrand's view, firms are made up of: dynamic and heterogeneous resources, an environment, an institutional setting, internal and external interactions, business ideas, goal structure and management. Firms require management and a business idea and the net management cost must be lower on average than the net transaction cost. For Granstrand "A technology-based firm is then a firm for which each of these firm-characterizing elements contains or is influenced by technology and technical artefacts in a vital way in some sense." (Granstrand, 1998, p. 487)

The problem with Granstrand's definition is that, in today's technologically advanced society, any firm has some of its characteristics "vitally" affected by technology. If, as suggested, literature from other perspectives can be used to complement the theory of the technology-based firm, a tighter definition could be useful in determining which studies are applicable and which are not. At the root of Granstrand's logic in putting forth a new theory of the firm was his belief that existing theories did not adequately capture the co-evolutionary nature of the technology development by the firms and the environment in which they participate, i.e., in those cases where the co-evolutionary dynamic mentioned above is more critical than other aspects of the firm. The three tests are thus derived from this idea and are:

1. That the firm must compete in a socio-technological regime which possesses the five properties of a co-evolutionary system (Lewin and Volberda, 1999). The thesis performs this analysis for the automotive industry in Section 4.2.

2. That the firm in question has the requisite level of influence to affect its environment at the niche, regime, or landscape level. Defining the idea of requisite level of influence opens up an interesting question as to what metrics to consider and if market share at the niche, regime, or landscape level is sufficient or if other factors such as brand recognition, reputation, technological assets or links to the public administration can play a critical role in allowing a firm to affect its environment in terms of technological adoption.

3. That the firm is primarily concerned with the development of technological artefacts or services, as opposed to marketing concepts, retail networks, etc. Prencipe (2000) affirms that the concept of *core competences* has been misapplied in many cases and that such competencies ought to deal only with what is at the heart of firm, and the thesis suggests that the theory of the technology-based firm should only be applied to firms for which engineering and technological development of a technological artefact or service lies at its core. Geels (2002) discusses socio-technological regimes in which an artefact such as a car or steamship is at the centre of the nexus and this idea could be the starting point for such a definition.

6.5 Alternative power train technology

Sub-section 2.3.2 reviewed the automotive literature dealing with the possible transition to alternatives to the dominant design in automotive power train technology based on the internal combustion engine and presents a typology for this literature which groups the research into six categories as follows:

1. History / Current Status
2. In Depth Modelling
3. Technical Performance
4. Supplier Involvement
5. Clearly Favourable
6. Clearly Sceptical

As discussed in Sub-section 2.3.2, apparently unbiased studies are quite rare and the literature does not only provide limited insight into the history of the technological developments to date but is not helpful in looking ahead as many studies seem to take it for granted that the transition will happen sooner or later while others are highly sceptical.

The theory of the technology-based firm together with Baron's (1995) non-market strategy concept and Reinhardt's (2005) framework concerning how "it pays to be green" can yield additional insight into the history of these technologies and, when combined with the concept of depth and breadth as applied to the technological trajectories in Section 6,3, some speculation as to the future of the technologies becomes possible.

- Non-market strategy and the automotive industry

Baron (1995) asserts that the role of non-market strategy becomes increasingly important in line with the government's role in regulating an industry, as well as the level and tone of consumer groups' and activists' responses to the industry's activities. The modern automotive industry has a very high exposure to both government regulations and other interests and thus is an industry where the importance of non-market strategy could be considered as very high. Section 5.3 reviews the history of the four technologies under consideration in the thesis and supports this idea. The automotive industry has been under increasing pressure to sharply reduce the emission of greenhouse gasses and other pollutants (Doyle, 2000; Nederveen et al., 2003). Doyle (2000) provides an account of interest in and legislation concerning automotive pollution since the 1970's and the industry's response over the years. Ealey and Mercer (2002) argue that the industry's response has centred on slowly improving the emissions performance and lobbying regulatory agencies to minimise or slow down the pace of legislation. Regardless of one's opinion about such findings, the landmark legislation leading to the Corporate Average Fuel Economy (CAFE) regulations in the United States in 1975 had a huge impact on the industry. Halberstam (1986) argues that interest in smaller, more fuel efficient cars during the 1970's arose due to the rise in gasoline prices, and Detroit's inability to produce such cars paved the way for the success of Nissan, Honda and Toyota in the U.S. market.

Baron discusses an industry's relationship with the larger environment and highlights four aspects of that relationship: issues, institutions, interests and information. All four parts of Baron's framework are important in automotive as follows:

1. *Issues* The automotive industry has had a major impact on society's development throughout the world. While the details might differ in different places, a partial list of pressing issues would include economic impact, fuel economy, pollution, safety, alternative energy, labour relations, health care, drunk driving and protectionism.

2. *Institutions* Public institutions are normally aligned around the issues mentioned above in the way that the NHTSA is responsible for enforcing automotive safety, and the Environmental Protection Agency (EPA) sets the pollution standards in the United States. There are also different levels of government distinguishing between rules in cities or towns, regions or states, countries and groups of countries such as the European Union or NAFTA.

3. *Interests* Besides the car companies and their suppliers and dealers, there are consumer groups involved in the industry such as drivers' clubs, consumer rights organisations and special interest groups such as Mothers Against Drunk Driving, Greenpeace and the Sierra Club. An additional interest in electric vehicles is the Electric Power Research Institute (EPRI) which is a consortium of the major U.S. electric companies. For EPRI, electric vehicles offer an opportunity as they would not only consume a huge amount of electricity but also, if charged at night, allow the electric companies to produce that power with no investment in new generation capacity.

4. *Information* Many of the policy debates concerning the automotive industry involve complex technical data which is often subject to detailed and even more complex statistical analysis. NHTSA, for example, produces its annual report on automotive safety in which accidents in the United States are tracked, categorised, and analysed determining things like the estimated number of lives saved by airbags, referred to in Sub-section 4.3.2 above. Firms in the industry undertake exhaustive testing procedures to demonstrate the safety and environmental performance of their vehicles, and magazines and web sites routinely publish the results of automotive crash tests and other technical data.

Another important part of the fuel cell story is the non-market aspects of the strategy of specific players such as General Motors. Hoed placed great emphasis on the fact that 9% of all industry patents were made in the alternative power train area, which he takes as proof that the programs were more than window dressing. Most of the patents were, however, filed by GM, Daimler, Toyota and, to a lesser extent, Ford, while most other manufacturers did very little. If one accepts interview subject number 6's account that an explicit agreement was made between regulators and GM and Ford on their committing to fuel cell technology in exchange for relief from further fuel economy standards, the scope of both companies programs comes into a different focus. GM had the most to lose from increased requirements and therefore led the way while Ford did invested $420 million in Ballard Power Systems in 1997.

- Beyond compliance in automotive

Reinhardt (2005) explores three reasons why a firm would go beyond compliance in terms of environmentally sustainable actions. As the thesis deals with technologies related to both safety and the environment, Reinhardt's ideas will be expanded to include automotive safety. At the microeconomic level, Reinhardt sees three reasons to move in the direction of environmental engagement; increasing willingness to pay through differentiation, reducing costs and managing risks. The following discussion will look at each of these areas in turn in the context of the automotive industry:

1. Differentiation

As discussed in Sub-section 4.3.1 and 4.3.2, Volvo has led the industry in safety related technologies, firmly associating their brand with safety and appears to have demonstrated the existence of a market segment that will pay more money for safer cars. Toyota's success with the Prius appears to indicate that there might also be a segment of environmentally conscious consumers who will pay more for environmentally benign cars. The problem with hybrid vehicles is that the addition of the electric motors and battery packs adds cost and weight to the vehicle and takes away space which could otherwise be used for trunk space, the passenger compartment or both. The resulting vehicles have a somewhat smaller package or interior space than a similarly equipped vehicle with a standard drive train and are more expensive. Table 6.13 shows three comparisons taken from Appendix D of vehicles currently on sale in the U.S. market, and one can see that the hybrids are at a disadvantage in terms of cost, interior space and weight.

Hybrid Model	**ICE Model**	**Price Difference**	**Weight Difference**	**Space Difference**
Ford Escape	Ford Escape Limited 2.5L 4WD	21% higher price ($7,080)	142 Kg more weight	8 litres less cargo space
Honda Civic Hybrid CVT 4dr	Honda Civic LX 4dr	19% higher price ($4,048)	86 Kg more weight	Smaller passenger compartment
Toyota Highlander Hybrid 4X4	Toyota Highlander 4x4 V6 4dr	15% higher price ($5,315)	150 Kg more weight	Less headroom and 2 fewer seats (back row)

Table 6.13 Selected Comparison of Hybrid and ICE vehicles
(from Jato Search engine, Automotive News Website, accessed 11.5.09)

Another argument for investing in safety and environmental technologies is to increase traffic in a brand's showrooms even if consumers will finally buy more inexpensive models without the new technology. This so-called "halo effect" is well known in the industry, although it is normally achieved with powerful cars such as the Dodge Viper rather than safer or more sustainable cars.

2. Cost reduction

Much of the debate cited by Reinhardt (2005) concerning cost reduction has to do with the efforts of industry to lower their costs at the same time as adopting environmentally friendly technologies such as increasing energy efficiency in factories and offices. The efforts of auto makers to lower their environmental footprint or increase worker safety are outside the scope of this thesis, although both are potentially a source of cost reduction. What is more central to understanding the evolution of hybrid cars is the cost benefit analysis discussed above, which is of course more compelling when gasoline prices are higher. U.S. gasoline prices reached $4.16 per gallon in the first two weeks of July, 2008 (U.S. Energy Information Agency) and, at this level, the total operational cost of hybrid vehicles becomes competitive with the internal combustion engine.

3. Risk management

Reinhardt's idea is that firms might engage in environmentally friendly technologies in order to be prepared for eventual changes in consumer behaviour or regulation which will require such changes. In this context there is always talk about increased environmental and safety standards by the different regulatory authorities, and an argument can be made defending the expense to stay ahead of legislation at least with some models and or options packages.

- Mimetic homogeneity and going beyond compliance

As discussed in Sub-section 2.3,2, Van den Hoed (2004) has documented how the automotive industry between 1996 and 2003 came to regard the fuel cell vehicle as the primary sustainable alternative to the internal combustion engine. Hoed chose Institutional Theory as his primary lens and argues that the rise of fuel cells is evidence of mimetic homogeneity. He uses the fact that so many of the industry players pursued the technology to prove his thesis. He also explores the role of legislation in the process as well as DaimlerChrysler's initial moves on the technology, granting it institutional legitimacy. What Hoed also acknowledges is the heterogeneity in the response that different companies have made. Using his own data, he showed that GM, Daimler, Toyota and, to a lesser extent, Honda dominated the fuel cell research agenda with 2-4 times as many demonstration vehicles any other manufacturer and being awarded 2-40 times as many patents. The data developed for the thesis gives similar findings with both GM and Toyota investing heavily and Ford and Nissan doing substantially less. In terms of the strategies of depth and breadth, the differences shown in the case studies in Chapter 5 give a deeper level of meaning to the data. Hoed links the heterogeneity in the manufacturers' responses to the relative importance of California to them as well as other factors. The problem is that one of the leading players, Daimler, does not have vital interests in California and, in order to explain its interest in the technology, Hoed looks at Daimler as an institutional entrepreneur and discuses its ownership of Dornier giving it access to fuel cell technology and its tendency to stay ahead of technological development in the industry.

Considering all the major automotive manufacturers as technology-based firms explains the heterogeneity in a more compelling way because it places technology and management at the centre, rather than at the periphery, of how the firm behaves. First, Daimler's behaviour is consistent when seen as a technology-based firm as one would expect its technological asset base and management preference to trump other factors. Second, by applying the tests of level of influence would also explain how GM and Toyota, the world's 1st and 3rd largest manufacturers, could believe that they can drive the agenda of the industry, and would also explain why Nissan would not even try given its position at that time of being relatively small and financially weak. Third, Ford's relatively modest program can be explained by the management problems occurring in Ford in the wake of the Firestone Tyre tragedy and the subsequent departure of Jacques Nasser, discussed in Sub-section 4.2.2. Finally, using Reinhardt's (2005) framework, Toyota's parallel commitment to hybrids and fuel cells can be understood by their conviction, later proved correct, that there was a market segment which would reward Toyota for being perceived as environmentally friendly.

Reinhardt's framework also explains the activities of smaller manufacturers who built a few demonstration vehicles and funded relatively modest programs during this time period, if one considers their activities as risk-mitigation strategies. As well documented by Doyle (2000) and Hoed (2004), it was not evident that CARB would relax its zero emissions mandate and there was, for a time, a real possibility that it would be extended to other states such as Massachusetts and New York, making investments on the order of tens of millions of dollars a small price to pay not to be left too far behind.

- Looking ahead

While it is not within the scope of the thesis, a degree of speculation as to the future of alternative power trains is possible with the theoretical frameworks applied and is therefore provided at a very conceptual level.

The clear advantage of hybrid vehicles is their compatibility with the current socio-technological regime which has been built around the internal combustion engine and it appears that hybrids, in different forms, will continue to be a feature of the automotive market for some time to come. At issue is which hybrid architecture or architectures will emerge as the dominant design if in fact any one solution does emerge. Toyota is now in the process of expanding its use of its hybrid synergy drive architecture in an effort to make it the industry standard, and it appears that both Ford and General Motors are determined to challenge Toyota albeit with very different technological solutions. As the hybrid idea appears to be gaining consumer acceptance, it appears that this competition will take place in fairly standard automotive terms with the bulk of the business going to the firm whose technology gives customers the best balance between fuel economy and total cost without sacrificing other performance attributes such as power, comfort, quality and, of course, safety. Toyota's safety problems in the winter of 2010 were clearly a public relations crisis but, at the time of this writing, it is too early to tell if the overall image of hybrid vehicles will be damaged to the extent that diesel powered cars were badly perceived by American consumers for a generation.

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With respect to fuel cell and battery electric vehicles, the main lesson from the empirical data in the thesis is that not even General Motors had the ability to initiate the transformation of the overall socio-technological regime in the late 1990's and, without a massive degree of increased environmental pressure or perhaps a sudden shock at the landscape level, such as a dramatic and lasting increase in the price of oil, it is difficult to see a major shift in the foreseeable future. What appears far more likely is the emergence of electric vehicles at the niche level and it appears that battery electric vehicles based on lithium-ion batteries are the first option that are currently being developed by companies such as Tesla Motors, Bright Automotive, and others for segments such as performance speedsters and delivery vans. The two question marks as to whether a more profound transformation might be possible are the Nissan/Renault electric vehicle program and developments in China. Nissan is, apparently, making a serious effort to develop a viable electric vehicle and the program would probably be sold under a Renault badge. At the same time, according to interview subject number 6, a number of Chinese vehicle manufacturers and component suppliers are investing in battery electric vehicle technology, and a scenario might emerge where regional sales of the vehicles take off in-line with local infrastructure development.

6.6 Chapter summary

This chapter has presented a definition of the ideas of depth and breadth at the level of technology deployment, grounded that definition in the literature, and explored to what extent the empirical data used in the thesis can be interpreted using these concepts. The discussion indicates that not only are the concepts applicable to the data but also a fairly robust correlation is found between the observation of depth and breadth in the representations of the patent data and the interpretation of the deployment data indicating a relationship between the two data sets. This relationship is then explored and a construct developed linking the two ideas. The implications of the concept have been explored around the issues of path dependence, medium-term deployment and technical performance, and the ideas of depth and breadth have been combined with Geels and Schot's (2007) technological pathways to develop a set of first ideas which might have use for practice in terms of which strategy might make the most sense in each of the four pathways explored. This chapter also discussed possible additions to Granstrand's theory of the technology-based firm derived in part from the thesis, reference was made to the literature on the possible evolution of automotive power train technology, and finally the theory of the technology-based firm was used together with Baron's (1995) non-market strategy concept and Reinhardt's (2005) framework concerning how "it pays to be green" to yield additional insights into the history of the technology and to even offer some limited ideas on its possible evolution.

CHAPTER 7. CONCLUSIONS

7.1 Introduction

Section 2.2 identifies a gap in the literature concerning how firms in general, and vehicle manufacturers in particular, manage the implementation phase of technology development, using Tidd et al.'s (1997) framework, for technology that is discontinuous and potentially disruptive. The thesis set out to make a contribution on this question and, after analyzing four companies and four technologies, the thesis found heterogeneity in their responses. Chapter 6 discusses the nature of that heterogeneity in terms of the ideas of depth and breadth and also the sources of this heterogeneity by considering both firm- and technology specific factors. Chapter 7 considers how these findings make a contribution to knowledge, discuss its limitations and consider several lines for additional research.

7.2 Contribution to knowledge

The thesis makes contributions to theory, practice, and method as follows:

- Contribution to theory

With regards to theory, the main contribution of the thesis is to add to Granstrand's (1998) theory of the technology-based firm. In his 1998 introduction Granstrand lays out the major elements of the theory and maintains that at issue is the management of scale, scope, time and space, and the thesis goes further on the issue of scope by introducing the concepts of depth and breadth as a contingent model of strategic choice. It also applies Geels and Schot's (2007) technological pathway levels at the technology to produce a much clearer picture of how new technology is deployed.

A second area of insight is to makes three suggestions to augment Granstrand's theory of the technology-based firm. One is to explicitly link the theory with the co-evolutionary perspective, a second is to tighten the definition of what is and what is not a technology-based firm, and the third is to link the theory to the dynamic capabilities literature.

A third idea is to suggest that institutional theory alone (Hoed, 2004) only goes so far in describing the evolution of fuel cell and electric vehicles, and that using the theory of the technology-based firm, as well as Baron's (1995) non-market strategy concept and Reinhardt's (2005) framework concerning how "it pays to be green", yields additional insight as discussed in Section 6.5.

- Contribution to method

The major conclusion with respect to method is in the area of what Trippe (2003) has called *patent informatics* and Gray (2007) referred to as the *fourth paradigm* of scientific endeavour. As discussed at length in Section 2.3, the last twenty years have seen researchers using patents at increasingly fine levels of granularity, and this trend will certainly continue.

The problem of the new tools is that they produce tremendous amounts of data which in turn require new ways to interpret and visualize that data; the use of *Themescape* maps in the thesis should be considered as a first step in the application of this type of tool. Prencipe (2000), Wang and Von Tunzelmann (2000) and Brusoni et al. (2005), reviewed in Section 2.5, were all interested in using patents as a way to better understand a firms' technological asset base, to use Granstrand's nomenclature, but such research is often limited to a patent's title and abstract and requires the researcher to classify patents using some classification scale. One problem that such research has to manage is the trade-off of increasing sample size to increase validity with increasing complexity to an unmanageable level.

The thesis provides one way of dealing with the trade-off by sidestepping the subjective process of classifying patents into technological sub-groups in a pioneering application of a probabilistic word-matching algorithm and mapping tool, described in Section 3.6, which allows for conceptual interpretation of the data. The tool, however, creates its own problems as described in detail in Section 3.6 and the use of the visual representation of patents for academic research should be considered very much in its infancy. The contribution of the thesis is to introduce the idea of using this approach into the academic tool kit although clearly much work remains to be done.

- Contribution to practice

By combining the ideas of depth and breadth with Geels and Schot's (2007) technological pathways, the thesis creates a framework shown in Sub-section 6.3.3 which might be of interest to practitioners in thinking through which strategies they might choose to consider when considering how to implement development in discontinuous and potentially disruptive technology.

7.3 Limitations and Ideas for future work

This section reviews the weaknesses in the thesis and explores areas for further research. Four specific weaknesses will be discussed which give rise to seven ideas.

The thesis reviews the limitations to using patents, deployment data and interviews in Sub-sections 3.5.2, 3.6.2, and 3.7.2 respectively. With respect to method, a first area of research would be to go deeper into the use of *Aureka* and other patent analysis and mapping tools in order to further develop the use of these tools to inform innovation theory. One direction for such research would be to apply the tools to data sets which have been studied using other methods and contrast results. The objective would be to fully explore the methodological issues involved in using such tools and derive constructs which would give more meaning to the different aspects of the topographical metaphor used in such maps, such as scale, height, types of land mass, etc. Part of that effort could be to build on Blanchard's (2007) work on the use of "stop words" in this type of software and develop guidelines on their use. The interview program for the thesis is limited and a second line of research would be to attempt to generalize the findings of the thesis by surveying a larger group of industry executives. Such a survey could be developed on the basis of the thesis and attempt to confirm the ideas related to depth and breadth.

In addition to these issues of method and data sources, the thesis suffers from three major limitations, each of which gives rise to ideas for further research. In the first place, the thesis is limited by its scope, which only looks at the automotive industry and a sample of four manufacturers and four technologies. Thus the generality of the thesis findings is limited. Within the automotive industry, the selection of different manufacturers and/or different technologies could yield potentially different results. Also, the applicability to other industries and the technology-based firms within them is not established. A third line of research would thus be to extend the investigation to additional automotive technologies and additional manufacturers in order to test the validity of the findings with more automotive data points. A fourth would be to look at other industries in which technological artefacts lie at the nexus of the socio-technical regime and investigate to what degree similar results are found. Whether significant homogeneity or heterogeneity across industries was revealed, this approach could yield interesting findings.

The second major limitation to the research is that it was based almost exclusively on publicly available data and expert opinion, without access to detailed data sets from the manufacturers themselves, and relies on the depth and breadth construct to infer what the strategies were based on available data. Such inference is always prone to error and, while the thesis relies on expert interviews to confirm the findings, there might be additional factors which drove the firm's decisions. Thus a fifth line of research would involve gaining access to a number of vehicle manufacturers and developing a methodology similar to that described in Sub-section 3.3.1, although the problems of data acquisition found in the Pilot site for that approach will need to be overcome.

The third major limitation to the thesis is that its objective was to add to the theory of the technology-based firm and not to develop a view as to what will happen in the unfolding story of electric vehicles, as it is always challenging to study a phenomenon while it is still going on. The thesis does, however, provide some ideas on the evolution of these technologies in Section 6.5, such that that a sixth line of research would be to apply Geels and Schot's pathways in a more rigorous way, in order to predict the outcome of the electric vehicle story. This idea could be broadened to include looking at a number of different technologies which all appeared to follow one or other of the pathways and looking for evidence to expand on the ideas shown in Figure 5.23 on the advantages of pursuing depth or breadth in the different pathways.

A seventh area of research which might be of interest is in working further with the concepts of co-evolution and the dynamics of socio-technological regimes in order to operationalize the three tests put forward for a technology-based firm. Such a study could focus on looking at different regimes and determining the degree to which the co-evolutionary process occurs, perhaps by developing a classification scale based on Lewin and Volberda's five properties. Also of interest would be to operationalize the idea of industry influence and determine to what extent it is, in fact, driven by market share, and to what extent other factors become important and in what cases. Finally the idea of limiting the theory to those firms where technology or a technological artefact is at the heart of the firm, could also be made more robust and could be part of this seventh idea for further research.

References

Abernathy, W. J. and Clark, K. B. (1985), “Innovation: Mapping the winds of creative destruction”, *Research Policy,* Vol. 14, No.1, p. 3-22.

Achilladelis, B., et al. (1990), “The dynamics of technological innovation: The case of the chemical industry”, *Research Policy,* Vol. 19, No. 1, p. 1-34.

Achilladelis, B., et al. (1987), “A study of innovation in the pesticide industry: Analysis of the innovation record of an industrial sector”, *Research Policy,* Vol. 16, No. 2-4, p. 175-212.

Acs, Z., et al. (2002), “Patents and innovation counts as measures of regional production of new knowledge”, *Research Policy,* Vol. 31, No. 7, p. 1069-1085.

Adler, P. 1989. Technology strategy: Guide to the literature. In R.S. Rosenbloom and R.A. Burgelman, eds., *Research on Technological Innovation, Management and Policy*. Greenwich, CT: JAI Press, p. 25-151.

Ahman, M. (2006),“Government Policy and the development of electric vehicles in Japan”, *Energy Policy*, Vol. 34, p.433-443.

Alexander, M. (2006), “Plug-in Hybrid Electric Vehicle Powertrain Requirements: Technical Update”, report number 1012459, Electric Power Research Institute, Palo Alto, Ca.

Archibugi, D. and Pianta, M. (1992), “Specialization and size of technological activities in industrial countries: The analysis of patent data”, *Research Policy,* Vol. 21, No. 1, p. 79-93.

Arora, A. (1997), “Patents, licensing, and market structure in the chemical industry”, *Research Policy,* Vol. 26, No. 4-5, p. 391-403.

Arundel, A. and Kabla, I. (1998), “What percentage of innovations are patented? Empirical estimates for European firms”, *Research Policy,* Vol. 27, No. 2, p. 127-141.

Avadikyan, A. and Llerena, P. (2010), “A real options reasoning approach to hybrid vehicle investments” *Technological Forecasting & Social Change*, Vol. 77 P. 649-661.

Avenel, E., et al. (2007), “Diversification and hybridization in firm knowledge bases in nanotechnologies”, *Research Policy,* Vol. 36, No. 6, p. 864-870.

Balconi, M., et al. (2004), “Networks of inventors and the role of academia: an exploration of Italian patent data”, *Research Policy,* Vol. 33, No. 1, p. 127-145.

Barkenbus J. (2009),”Our electric automotive future: CO2 savings through a disruptive technology”, *Policy and Society*, p. 399-410

Barney, J. (1991),"Firm resources and sustained competitive advantage", *Journal of Management*, Vol. 17, No. 1, p. 99-121.

Baron, D. P. (1995), "The non market strategy system", *Sloan Management Review*, Vol.37, No.1, p. 73-86.

Bas, C. L. and Sierra, C. (2002), "Location versus home country advantages' in R&D activities: some further results on multinationals' locational strategies", *Research Policy*, Vol. 31, No. 4, p. 589-609.

Basberg, B. L. (1987), "Patents and the measurement of technological change: A survey of the literature", *Research Policy*, Vol. 16, No. 2-4, p. 131-141.

Basberg, B. L. (1983), "Foreign patenting in the U.S. as a technology indicator: The case of Norway", *Research Policy*, Vol. 12, No. 4, p. 227-237.

Beaume R., et al. (2009), "Crossing innovation and product projects management: A comparative analysis in the automotive industry", *International Journal of project Management*, Vol. 27, p. 166-174

Bekkers, R., et al. (2002), "Intellectual property rights, strategic technology agreements and market structure: The case of GSM", *Research Policy*, Vol. 31, No. 7, p. 1141-1161.

Belderbos, R. (2001), "Overseas innovations by Japanese firms: an analysis of patent and subsidiary data", *Research Policy*, Vol. 30, No. 2, p. 313-332.

Ben Mahmoud-Jouini, S., et al.. (2007), "Multilevel integration of exploration units: Beyond the ambidextrous organization", *Academy of Management Best Paper Proceedings*

Ben Mahmoud- Jouini, S., et al. (2008), "Enhancing Discontinuous Innovation through Knowledge Combination: The Case of an Exploratory Unit within an Established Automotive Firm ", *Creativity and Innovation Management*, Vol. 17, No. 2, p. -134

Beneito, P. (2006), "The innovative performance of in-house and contracted R&D in terms of patents and utility models", *Research Policy*, Vol. 35, No. 4, p. 502-517.

Benner, M. and Tushman, M. (2003), "Exploitation, exploration, and process management: The productivity dilemma revisited", *Academy of Management Review*, Vol.28, No. 2, p. 238-256.

Benton, T. (1981), "Realism and Social Science: Some comments on Roy Bhaskar's *The Possibility of Naturalism*", *Radical Philosophy*, No. 27, p.13-21.

Bergek, A. and Berggren, C. (2004), "Technological internationalisation in the electro-technical industry: a cross-company comparison of patenting patterns 1986-2000", *Research Policy*, Vol. 33, No. 9, p. 1285-1306.

Berkhout, F., et al. (2004), “Socio-technical regimes and transition contexts” in Elzen, B., Gales. F.W., Green, K. (Eds.), *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy*, Edward Elgar, Cheltenham, p. 48-75.

Bessant, J. and Tsekouras, G. (2001), “Developing learning networks”, *A.I. and Society*, Vol. 15, No. 2, p. 82-98.

Bessant, J., et al. (2008), “Competing on knowledge”, *Business Strategy Review*, Special Report, Spring 2008, p. 75-89.

Bettencourt, L., et al. (2007), “Invention in the city: Increasing returns to patenting as a scaling function of metropolitan size”, *Research Policy,* Vol. 36, No. 1, p. 107-120.

Blind, K., et al. (2006), “Motives to patent: Empirical evidence from Germany”, *Research Policy,* Vol. 35, No. 5, p. 655-672.

Bhaskar, R. (1975) *A realist theory of science,* Verso, London.

Blaklie, N. (1993), *Approaches to Social Enquiry,* Blackwell, Cambridge, Mass.

Blanchard, A. (2007), “Understanding and customizing stopword lists for enhanced patent mapping”, *World Patent Information*, Vol. 29, p. 308-316.

Birkinshaw, J. and Gibson, C. (2004), “Building Ambidexterity Into an Organization”, *MIT Sloan Management Review*, Summer, 2004, p. 47-55.

Birkinshaw, J., et al. (2007) “Finding, Forming, and Performing: Creating Networks for Discontinuous Innovation”, *California Management Review*, Vol. 49, No, 3 p. 67-84.

Bosworth, D. L. (1984), “Foreign patent flows to and from the United Kingdom”, *Research Policy,* Vol. 13, No. 2, p. 115-124.

Bower, J. (1970) *Managing the resource allocation process* Irwin, Homewood, Il.

Bower, J. and Christensen, C. (1995) “Disruptive Technologies: Catching the Wave”, *Harvard Business Review*, Vol. 73, No.1, p. 43-53.

Breschi, S., et al. (2003), “Knowledge-relatedness in firm technological diversification”, *Research Policy,* Vol. 32, No. 1, p. 69-87.

Brouwer, E. and Kleinknecht, A. (1999), “Innovative output, and a firm's propensity to patent: An exploration of CIS micro data”, *Research Policy,* Vol. 28, No. 6, p. 615-624.

Bruni, D. S. and Verona, G. (2009), “Dynamic marketing capabilities in science-based firms: an exploratory investigation of the pharmaceutical industry”, *British Journal of Management*, Vol. 20, Sp. Iss., p. S101–S117.

Brusoni, S., et al. (2005), “The knowledge bases of the world’s largest pharmaceutical groups: What do patent citations to non-patent literature reveal?”, *Economics of Innovation & New Technology*, Vol. 14, No. 5, p. 395-415.

Burgelman, R. (1983), “A model of the interaction of strategic behavior, corporate context, and the concept of strategy”, *Academy of Management Review*, Vol. 3, No. 1, p. 61-69.

Burgleman, R. and Rosenbloom, R. (1989), “Technology strategy: An evolutionary perspective”, *Research on Technological Innovation Management and Policy*, Vol.4, p. 1-23.

Buss, D. (2001),”Green cars”, *American Demographics*, Vol. 23, No.1, p. 56-62.

Camuffo, A. (2000), “Rolling Out a "World Car": Globalization, Outsourcing and Modularity in the Auto Industry”, International Motor Vehicle Program, Cambridge, MA., available at http://www.imvpnet.org/publications.asp

Canzler, W. and Knie, A. (2009),“Mass motorization in China“, *International Journal of Social Economics*, Vol. 36, No. 9, p. 892-905.

Carle, G., et al. (2005), “Opportunities and Risks during the introduction of fuel cell cars”, *Transport review*, Vo. 25, No. 6, p. 739-760.

Cefis, E. and Orsenigo, L. (2001), “The persistence of innovative activities: A cross-countries and cross-sectors comparative analysis”, *Research Policy*, Vol. 30, No. 7, p. 1139-1158.

Chanaron, J. (1998), “Automobiles: A static technology, a wait-and-see industry?”, *International Journal of Technology Management*, Vol. 16, No. 7, p.595-631.

Christensen C. M. and Bower J.L. (1996), “Customer power, strategic investment, and the failure of leading firms”, *Strategic Management Journal*, Vol.17, No.3, p. 197-218.

Clark, K. (1989), “Project scope and project performance: The effect of parts strategy and supplier involvement on product development”, *Management Science*, Vol. 35, No. 10 P. 1247-1263.

Clark, K. and Fujimoto, T. (1991), *Product Development Performance: Strategy and Management in the World Auto Industry*, Harvard Business School Press, Boston MA

Clark, K. and Fujimoto, T. (1990), “The Power of Product Integrity”, *Harvard Business Review*, Vol. 68, No. 6, p. 107-118.

Coad, A. and Rao, R. (2008), “Innovation and firm growth in high-tech sectors: A quantile regression approach”, *Research Policy*, Vol. 37, No. 4, p. 633-648.

Collantes, G. and Sperling, D. (2008), “The origin of California’s zero emission vehicle mandate”, *Transportation Research part A*, Vol. 42, p. 1302-1313.

Cohen, W., et al. (2002), “R&D spillovers, patents and the incentives to innovate in Japan and the United States”, *Research Policy*, Vol. 31, No. 8-9, p. 1349-1367.

Connelly, M. (2003), “Bill Ford picks up pieces after Nasser's reign: The new plan: Return Ford Motor to its roots”, *Automotive News*, June 16th, 2003.

Coup, D. (1999), “Toyota’s Approach to Alternative Technology Vehicles: The Power of Diversification Strategies”, *Corporate Environmental Strategy*, Vol. 6, p. 258-269.

Cusumano, M. and Nobeoka, K. (1992), “Strategy, structure, and performance in product development: Observations from the auto industry”, *Research Policy*, Vol. 21, No. 3, p.265-293

Cusumano, M. and Nobeoka, K. (1997), Multiproject strategy and sales growth: The benefits of rapid design transfer in new product development”, *Strategic Management Journal*, Vol. 18, No. 3 p. 169-186.

Crabb, J. and Johnson, D. (2010), Fuelling Innovation: The Impact of Oil Prices and CAFÉ Standards on Energy-Efficient Automotive Technology”, *The Energy Journal*, Vol. 31, No. 1, p. 199-216.

Dahlin, K., et al. (2004), “Today's Edisons or weekend hobbyists: technical merit and success of inventions by independent inventors”, *Research Policy*, Vol. 33, No. 8, p. 1167-1183.

Daneels, E. (2004),”Disruptive Technology Reconsidered: A Critique and Research Agenda”, *The Journal of Product Innovation Management*, Vol. 21, No.4, p.246-258.

Davenport, S., et al. (2003), “The dynamics of technology strategy: an exploratory study”, *R&D Management*, Vol. 33, No. 5, p. 481-499

De Haven, H. (1952), “Accident survival ~Airplane and passenger car, report number 840393, Society of Automotive Engineers, Warrendale, PA

Diesel Technology Forum (2001), “Demand for Diesels: The European Experience Harnessing Diesel Innovation For Passenger Vehicle Fuel Efficiency and Emissions Objectives”, www.dieselforum.org accessed 5.16.09

Dietz, J. S. and Bozeman, B. (2005), “Academic careers, patents, and productivity: industry experience as scientific and technical human capital”, *Research Policy*, Vol. 34, No. 3, p. 349-367.

DiMaggio, P.J., Powell, W.W. (1983), “The iron cage revisited: institutional isomorphism and collective rationality in organizational fields”, *American Sociological Review* Vol. 48, p.147-160.

Dosi, G. (1982), “Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technological change”, *Research Policy*, Vol. 6, p. 147-162.

Doyle, J. (2000) *Taken for a ride; Detroit’s big three and the politics of pollution*. New York: Four Walls Eight Windows/Avalon

Drucker, P. (1946), *Concept of the Corporation*, John Day Co., New York, NY.

Dunn, S. (2002). “Hydrogen futures: Toward a sustainable energy system”, International *Journal of Hydrogen Energy*, Vol. 27, No. 3, p. 235-264.

Durkheim, E. (1964), *The Rules of Sociological Method*, Free Press, Glencoe, ILL

Duvall, M. (2004), “A Technology and Cost-Effectiveness Assessment for Battery Electric Vehicles, Power Assist Hybrid Electric Vehicles, and Plug-In Hybrid Electric Vehicles”, report number 1009299, Electric Power Research Institute, Palo Alto, Ca.

Duvall, M. and Alexander, M. (2005), “Performance, Durability, and Cost of Advanced Batteries for Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles”, report number 1010201, Electric Power Research Institute, Palo Alto, Ca.

Ealey, L. A. and Mercer, G. A. (2002) Tomorrow's cars, today's engines The McKinsey Quarterly: Iss. 3, pp. 40-54.

Easterby-Smith, M.,et al. (2009), “Dynamic Capabilities: Current Debates and Future Directions” *British Journal Of Management*, Vol. 20, Sp. Iss., p. S1-S8.

Easterby-Smith, M., et al. (2002) *Management Research: An Introduction*, Sage Publications, London.

Eisenhardt, K. (1989), “Building Theories from Case Study Research”, *Academy of Management Review*, Vol. 14, No. 4, P. 532-550.

Eisenhardt, K. (1991), “Better stories and better constructs: The case for rigor and comparative logic”, *Academy of Management Review*, Vol. 16, no. 3, p. 620-627.

Ebrahimi, M. and Holford,W.D. (2009), “Disruptive innovation within a dialectical firm”, *International Journal of Product Development*, Vol. 8, No. 4, p. 403

Ernst, H. (1998), “Industrial research as a source of important patents”, *Research Policy*, Vol. 27, No. 1, p. 1-15.

Ernst, H. (1998), “Patent portfolios for strategic R&D planning”, *Journal of Engineering and Technology Management*, Vol.15, p. 279-308.

Ernst, H. (2001), “Patent applications and subsequent changes of performance: evidence from time-series cross-section analyses on the firm level”, *Research Policy*, Vol. 30, No. 1, p. 143-157.

Fagerberg, J. (1987), “A technology gap approach to why growth rates differ”, *Research Policy*, Vol. 16, No. 2-4, p. 87-99.

Fine, C.H. and Raff, M.G. (2001), “Innovation Performance in the Automotive Industry Over the Long Twentieth Century”, in Nelson et al. (eds.), *Innovation and Economic Performance,* Princeton University Press, Princeton, NJ.

Flink, J.J. (1976), *The Car Culture*, MIT Press, Cambridge, Mass.

Flink, J.J. (1990), *The Automobile Age*, MIT Press, Cambridge, Mass.

Ford, D. (1988), “Develop Your Technology Strategy”, *Long Range Planning*, Vol. 21, No. 5, p. 85-95

Fornier, G. (2009), “How to cope with distance in the future? The impact of globalization and ecological requirements the destiny of the automotive industry and its suppliers”, *Economic and Business Review for Central and South-Eastern Europe*, Vol 11, No. 1 p. 75-100.

Foster, M.S. (2002) *A Nation on Wheels: The Automobile Culture in America Since 1945,* Wadsworth Publishing, Belmont, CA.

Frame, J. D. and Narin, F. (1990), “The United States, Japan and the changing technological balance”, *Research Policy*, Vol. 19, No. 5, p. 447-455.

Frenken, K, et al. (2004), “R&D portfolios in environmentally friendly automotive propulsion: Variety, competition and policy implications”, *Technological Forecasting and Social Change*, Vol. 71, p. 415-507.

Freyssenet, M. and Lung, Y. (1999), “Between Globalization And Regionalization: What Is The Future Of The Automobile Industry?”, International Motor Vehicle Program, Cambridge, MA., available at http://www.imvpnet.org/publications.asp

Frumau, C. C. F. (1992), “Choices in R&D and business portfolio in the electronics industry: What the bibliometric data show”, *Research Policy*, Vol. 21, No. 2, p. 97-124.

Furman, J. L., et al. (2002), “The determinants of national innovative capacity”, *Research Policy*, Vol. 31, No. 6, p. 899-933.

Furukawa, R. and Goto, A. (2006), “The role of corporate scientists in innovation”, *Research Policy,* Vol. 35, No. 1, p. 24-36.

Gambardella, A. (1992), “Competitive advantages from in-house scientific research: The US pharmaceutical industry in the 1980s”, *Research Policy,* Vol. 21, No. 5, p. 391-407.

Gambardella, A. and Torrisi, S. (1998), “Does technological convergence imply convergence in markets? Evidence from the electronics industry”, *Research Policy,* Vol. 27, No. 5, p. 445-463.

Garcia, R. and Calantone, R. (2002), “A critical look at technological innovation typology and innovativeness terminology: a literature review”, *The Journal of Product Innovation Management*, Vol. 19, No. 2, p.110-132.

Garcia-Vega, M. (2006), “Does technological diversification promote innovation?: An empirical analysis for European firms”, *Research Policy,* Vol. 35, No. 2, p. 230-246.

Geels, F.W. (2002), “Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study”, *Research Policy,* Vol. 31, No. 8-9, p.1257-1274.

Geels, F.W. (2005), “The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860-1930)”, *Technology Analysis & Strategic Management*, Vol. 17, No.4, p. 445-476.

Geels, F.W. and Schot, J. (2007), “Typology of sociotechnical transition pathways”, *Research Policy,* Vol. 36, No.3, p. 399-417.

Gergen, M. and Gergen, K. (2002), “Qualitative Inquiry: Tensions and Transformations“, in Denzin, N. and Lincoln, Y. (eds.), *Handbook of Qualitative Research*, 2nd Ed, Sage, Thousand Oaks, CA.

Geroski, P. A., Van Reenen, J. and Walters, C. F. (1997), “How persistently do firms innovate?”, *Research Policy,* Vol. 26, No. 1, p. 33-48.

Giliberti, C. (2008), “The Coming Boom in Hybrid Cars”, Strategy + Business, Booze & Company, available at www.strategy-business.com/sustainability

Giuri, P., et al. (2007), “Inventors and invention processes in Europe: Results from the PatVal-EU survey”, *Research Policy,* Vol. 36, No. 8, p. 1107-1127.

Glaser, B. and Straus, A. (1967), The Discovery of Grounded Theory, Wiedenfeld and Nicholson, London, UK

Granstrand, O. (1998), “Towards a theory of the technology-based firm”, *Research Policy*, Vol. 27, No. 5, p. 465.

Granstrand, O. and Sjölander, S. (1990),” Managing innovation in multi-technology corporations”, *Research Policy,* Vol. 19, No. 1, p. 35-60.

Granstrand, O. et al. (1997), "Multi-Technology Corporations: Why they have distributed rather than distinctive core competencies.", *California Management Review*, Vol. 39, p. 8–25.

Grey, J. (2007), "A Transformed Scientific Method" Edited Transcript of a talk given by Jim Gray to the NRC-CSTB1 in Mountain View, CA, on January 11, 2007 in *The Fourth Paradigm,* Microsoft Research, http://research.microsoft.com/en-us/collaboration/fourthparadigm

Griffa, A. (2008), "A paradigm shift for inspection: complementing traditional CMM with DSSP innovation, *Sensor Review*, Vol. 28, No. 4, p334 – 341.

Griliches, Z. (1990), "Patent Statistics as Economic Indicators: A Survey", *Journal of Economic Literature*, Vol. 28, No. 4; p. 1661 - 1707.

Gummesson, E. (2000) *Qualitative methods in management research,* Sage Publications, Thousand Oaks, CA.

Halberstam, D. (1986), *The reckoning*, Morrow, New York, NY.

Harborne, P. et al. (2007),"The Development and Diffusion of Radical Technological Innovation: The role of Bus Demonstration Projects in Commercializing Fuel Cell Technology", *Technology Analysis& Strategic Management*, Vol. 19, No.2, p. 167-187.

Hart, C. (1988), *Doing a Literature Review,* Sage, London

Hatfield, D., et al. (2001), "Facing the uncertain environment from technological discontinuities: Hedging as a technology strategy", *Journal of High Technology Management Research*, Vol. 12, P. 63-76.

He, Z. and Wong, P. (2004) "Exploration vs. Exploitation: An empirical test of the ambidexterity hypothesis", *Organization Science*, Vol. 15, No. 4, p. 481-494.

Hekkert, M. and; Hoed, R.v.d. (2004), "Competing Technologies and the Struggle towards a New Dominant Design: The mergence of the hybrid vehicle at the expense of the fuel cell vehicle", *Greener Management International,* Vol.47, p. 29-42.

Hicks, D., et al. (2001), "The changing composition of innovative activity in the US — a portrait based on patent analysis", *Research Policy,* Vol. 30, No. 4, p. 681-703.

Hicks, D. and Hegde, D. (2005), "Highly innovative small firms in the markets for technology", *Research Policy,* Vol. 34, No. 5, p. 703-716.

Hoed, R. v. d. (2004) *Driving fuel cell vehicles; how established industries react to radical technologies,* PhD thesis, Department of Design for Sustainability, School of Industrial Design. Delft, Netherlands, Delft University of Technology

Hoed, R.v.d.(2005), “Commitment to fuel cell technology? How to interpret carmakers’ efforts in this radical technology”, *Journal of Power Sources*, Vol. 141, p. 265-271.

Hoed, R.v.d.(2007), “Sources of radical technological innovation: the emergence of fuel cell technology in the automotive industry”, *Journal of Cleaner Production*, Vol. 5, p. 1014-1021.

Hoffman, P. (2001) *Tomorrow's Energy: Hydrogen, Fuel Cells, and the Prospects for a Cleaner Planet.* MIT Press, Cambridge, MA.

Howell, L. (2003), “Adapting GM Research to a New Corporate Strategy”, *Research technology Management*, Vol. 46, No. 3, p. 14-20.

Hu, M. and Mathews, J. A. (2005), “National innovative capacity in East Asia”, *Research Policy*, Vol. 34, No. 9, p. 1322-1349.

Iwasa, T. and Odagiri, H. (2004), “Overseas R&D, knowledge sourcing, and patenting: an empirical study of Japanese R&D investment in the US”, *Research Policy*, Vol. 33, No. 5, p. 807-828.

Jaffe, A. B. (1989), “Characterizing the “technological position” of firms, with application to quantifying technological opportunity and research spillovers”, *Research Policy*, Vol. 18, No. 2, p. 87-97.

Janesick, V.J.(2000), “The Choreography of Qualitative Research Design: Miuets, Improvisations, and Crystallization”, in Denzin, N.K. and Lincoln, Y.S. (Editors), *Handbook of Qualitative Research*, 2nd Ed., Sage Publications, Thousand Oaks, CA., p.379-399.

Jansen, J., et al. (2008), “Senior team attributes and organizational ambidexterity: The moderating role of transformational leadership” *Journal of Management Studies*, Vol. 45, No. 5 p. 982-1007.

Johannessen, G.H. (1984), *Historical Perspective on Seat Belt Restraint Systems*, report number 840393, Society of Automotive Engineers, Warrendale, PA

Johannessen, G.H. (1987), Historical *Review of Automatic Seat Belt Restraint Systems*, report number 870221, Society of Automotive Engineers, Warrendale, PA

Johnston, B., et al., (2005), “Hydrogen: The energy source for the 21st century, *Technovation*, Vol. 25, p. 569-585.

Kamath, R. and Liker, J. (1990), “Supplier dependence and innovation: A contingency model of suppliers’ innovative activities” *Journal of Engineering and Technology Management*, Vol. 7, p.111-127.

Karplus et al., (2009), *Prospects for Plug-in Hybrid Electric Vehicles in the United States and Japan: A General Equilibrium* Analysis, MIT Joint Program on the Science and Policy of Global Change, Report No. 172, Cambridge, MA.

Katila, R. and Mang, P. Y. (2003), "Exploiting technological opportunities: the timing of collaborations", *Research Policy*, Vol. 32, No. 2, p. 317-332.

Kemp, R., Schot, J, Hoogma, R. (1998),"Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management", *Technology Analysis & Strategic Management*, Vol. 10, No. 2, p. 175-195.

Kohn, K. (2006), "Managing the balance of perspectives in the early phase of NPD: A case study from the automotive industry", *European Journal of Innovation Management*, Vol. 9, No, 1, p.44-60.

Kondo, M. (1999), "R&D dynamics of creating patents in the Japanese industry", *Research Policy*, Vol. 25, p. l. 28, No. 6, p. 587-600.

Kosugi, T., et al. (2005), "Evaluating new CO2 reduction technologies in Japan up to 2030", *Technological forecasting and Social Change*, Vol. 72, p. 779-797.

Kratzke, S. R, (1995), *Regulatory History of Automatic Crash Protection in FMVSS 208*, report number 950865, Society of Automotive Engineers, Warrendale, PA

Kumar, N. (2001), "Determinants of location of overseas R&D activity of multinational enterprises: the case of US and Japanese corporations", *Research Policy*, Vol. 30, No. 1, p. 159-174.

Kumaresan, N. and Miyazaki, K. (1999), "An integrated network approach to systems of innovation—the case of robotics in Japan", *Research Policy*, Vol. 28, No. 6, p. 563-585.

Lamming, R., (1993), *Beyond Partnership: Strategies for innovation and Lean Supply*, Prentice-Hall, London

Lanjouw, J. O. and Mody, A. (1996), "Innovation and the international diffusion of environmentally responsive technology", *Research Policy*, Vol. 25, No. 4, p. 549-571.

Leifer, R., et al. (2000), *Radical Innovation*, Harvard Business School Press, Boston, MA

Leonard-Burton, D. (1995), Wellsprings of Knowledge, Harvard Business School Press, Boston MA.

Lenfle, S. (2008), "Exploration and project management", *International Journal of Project Management*, Vol. 26, p. 469-478.

Lettice, F., et al. (2010), “Buyer-supplier partnerships during product design and development in the global automotive sector: Who invests, in what and when?, *International Journal of Production Economics*, in-press.

Lewin, A.Y. and Volberda, H.W. (1999),” Prolegomena on Coevolution: A Framework for Research on Strategy and New Organizational Forms”, *Organization Science*, Vol. 10, No. 5, p. 519-534.

Lewis, D.L. and Goldstein, L. (1983), *The Automobile and American Culture*, University of Michigan Press, Ann Arbor, MI.

Lofting (1920), *The story of Doctor Dolittle, being the history of his peculiar life at home and astonishing adventures in foreign parts*, Frederick A. Stokes Company, New York, NY.

Lomborg, B. (2001), *The skeptical environmentalist*, Cambridge University Press, Cambridge, U.K

Maidique, M. and Patch, P. (1978), *Corporate strategy and technology policy*, Harvard Business School Case Services, Case # 9-679-033.

Malerba, F. and Orsenigo, L. (1999), “Technological entry, exit and survival: an empirical analysis of patent data”, *Research Policy,* Vol. 28, No. 6, p. 643-660.

Malerba, F. and Orsenigo, L. (1996), “Schumpeterian patterns of innovation are technology-specific”, *Research Policy,* Vol. 25, No. 3, p. 451-478.

Mann, R. J. and Sager, T. W. (2007), “Patents, venture capital, and software start-ups”, *Research Policy*, Vol. 36, No. 2, p. 193-208.

March, J. and Simon, H. (1958), *Organizations*, Wiley, New York

Mariani, M. (2004), “What determines technological hits?: Geography versus firm competencies”, *Research Policy,* Vol. 33, No. 10, p. 1565-1582.

Mascitelli, R. (2000), “From Experience: Harnessing Tacit Knowledge to Achieve Breakthrough Innovation”, *Journal of Product Innovation Management*, Vol. 17 p. 179-193.

McGrath, R. (1999), “Effects of Incumbency and R&D Affiliation on the Legitimation of Electric Vehicle Technologies”, *Technological Forecasting and Social Change*, Vol. 60, p. 247-262.

McKelvie, A. and Davidsson, P. (2009), “From resource base to dynamic capabilities: an investigation of new firms”, *British Journal of Management*, Vol. 20, Sp. Iss., p. S63–S80.

Meyers et al. (2004), “The scientometric world of Keith Pavitt: A tribute to his contributions to research policy and patent analysis, *Research Policy*, Vol. 33, p. 1405-1417.

Mikkola, J.(2001), “Portfolio management of R&D projects: implications for innovation management”, *Technovation*, Vol. 21, p. 423-435.

Miles, M.B. and Huberman, M. (1994) *Qualitative Data Analysis: An Expanded Sourcebook*, Page Press, London.

Mirow, C., et al. (2008), “The ambidextrous organization in practice: Barriers to innovation within research and development”, Academy of Management Meeting.

Mowery, D. et al. (1998), “Technological overlap and interfirm cooperation: implications for the resource-based view of the firm”, *Research Policy,* Vol. 27, No. 5, p. 507-523.

Mowery D. and Rosenberg, N. (1989), *Technology and the pursuit of economic growth*, Cambridge University Press., Cambridge, UK.

Murray, F. (2002), “Innovation as co-evolution of scientific and technological networks: exploring tissue engineering”, *Research Policy*, Vol. 31, No. 8-9, p. 1389-1403.

Nameroff, T. J., et al.. (2004), “Adoption of green chemistry: an analysis based on US patents”, *Research Policy,* Vol. 33, No. 6-7, p. 959-974.

Narin, F. and Breitzman, A. (1995), “Inventive productivity”, *Research Policy,* Vol. 24, No. 4, p. 507-519.

Nash, C.E.(2009), “Hugh DeHaven: Still Relevant for Rollovers”, Conference Paper, 2/5/2009, National Crash Analysis Center, The George Washington University, Washington D.C.

Narayanan, V. K., et al. (2009), “Building organizational platforms in the pharmaceutical industry: a process perspective on the development of dynamic capabilities”, *British Journal of Management*, Vol. 20, Sp. Iss., p. S25–S40.

Nederveen, A., et al. (2003), “Globalization, international transport, and the global environment: Technological innovation, policy making, and the reduction of transportation emissions”, *Transportation Planning and Technology*, Vol. 26, No. 1, p. 41-67.

Nelson R.R. and Winter S.G. (1977),”In search of useful theory of innovation”, *Research Policy* Vol. 6, p. 36 – 76.

Nobeoka, K. and Consumano M.A. (1997) “Multiproject strategy and sales growth: The benefits of rapid design”, *Strategic Management Journal*, Vol. 18, No. 3. p. 169-186.

Noke, H. (2006) *Creation of a new product development capability in UK manufacturing small and medium-sized firms*, PhD thesis, School of Management, Cranfield University.

Noyons, E, et al. (1994), “Exploring the science and technology interface: inventor-author relations in laser medicine research”, *Research Policy*, Vol. 23, No. 4, p. 443-457.

Noyons, E, et al. (1998), “Assessment of Flemish R&D in the field of information technology: A bibliometric evaluation based on publication and patent data, combined with OECD research input statistics”, *Research Policy,* Vol. 27, No. 3, p. 285-300.

Palda, K. S. and Pazderka, B. (1982), “International comparisons of R&D effort : The case of the Canadian pharmaceutical industry”, *Research Policy,* Vol. 11, No. 4, p. 247-259.

Patel, P. and Pavitt, K. (1987), “Is Western Europe losing the technological race?”, *Research Policy*, Vol. 16, No. 2-4, p. 59-85.

Patel, P. and Pavitt, K. (1994), “The continuing, widespread (and neglected) importance of improvements in mechanical technologies”, *Research Policy,* Vol. 23, No. 5, p. 533-545.

Patel, P. and Pavitt, K. (1997),”The technological competencies of the world' s largest firms" complex and path-dependent, but not much variety”, *Research Policy* 26, p.141-156

Pavitt, K. (1982), “R&D, patenting and innovative activities: A statistical exploration”, *Research Policy*, Vol. 11, No. 1, p. 33-51.

Pavitt, K. (1984), “Sectoral patterns of technical change: towards a taxonomy and a theory”, *Research Policy,* Vol. 13, No. 6, p. 343-373.

Pavitt, K. (1988), “Uses and abuses of patent statistics”, In: Raan, A.F.J.v. Ed. , *Handbook of Quantitative Studies of Science and Technology*. Amsterdam: Elsevier p. 509-536.

Penan, H. (1996), “R & D strategy in a techno-economic network: Alzheimer's disease therapeutic strategies”, *Research Policy,* Vol. 25, No. 3, p. 337-358.

Pfeffer, J. (1982), *Organizations and Organization Theory*, Pitmanm, Marshfield, MA.

Phillips, W., et al. (2006), “Beyond the steady state: Managing discontinuous product and process innovation”, *International Journal of Innovation Management*, Vol. 10, No. 2, p. 175-196.

Pilorusso, F. (1997), *Finding a place in the automotive supplier hierarchy in the year 200 and beyond*, International Motor Vehicle Program, Massachusetts Institute of Technology, Cambridge, MA.

Pisano, G. (2006), "Profiting from innovation and the intellectual property revolution", *Research Policy*, Vol. 35, No. 8, p. 1122-1130.

Popper, K.R. (1958), *The Logic of Scientific Discovery*, Hutchinson, London, UK

Porter, M. (1980) *Competitive strategy,* Free Press, New York, NY.

Prahalad, C. (2004), "The blinders of dominant logic", *Long Range Planning*, Vol. 37, No. 2, p. 171-179.

Prahalad, C. K. and Hamel, G. (1990), "The Core Competence of the Corporation.", *Harvard Business Review*, Vol. 68 No. 3, p. 79-91.

Prencipe, A. (1997), "Technological competencies and product's evolutionary dynamics a case study from the aero-engine industry", *Research Policy,* Vol. 25, No. 8, p. 1261-1276.

Prencipe, A. (2000) *Divide and Rule: Firm boundaries in the aircraft engine industry*, Science and Technology Policy Research Unit, University of Sussex, United Kingdom

Quintana-García, C. and Benavides-Velasco, C. A. (2008), "Innovative competence, exploration and exploitation: The influence of technological diversification", *Research Policy,* Vol. 37, No. 3, p. 492-507.

Reekie, W. D. (1973), "Patent data as a guide to industrial activity", *Research Policy*, Vol. 2, No. 3, p. 246-264.

Reinhardt, F. (2005), "Environmental Protection and the Social Responsibility of Firms: Perspectives from the Business Literature." In: Hay, et al., (Eds.), *Environmental Protection and the Social Responsibility of Firms*, Resources for the Future Press, Washington, D.C, p. 151-183.

Rip, A. and Kemp, R. (1998), "Technological change" In: Rayner, S., Malone, E.L. Eds., *Human Choice and Climate Change*. Battelle Press, Columbus, OH, p. 327–399.

Rodríguez-Duarte, A., et al. (2007), "The endogenous relationship between innovation and diversification, and the impact of technological resources on the form of diversification", *Research Policy,* Vol. 36, No. 5, p. 652-664.

Roland, N. (2009), "Obama Kills Development Of Hydrogen Fuel Cell Vehicles", *Automotive News*, May 8th, 2009.

Roper, S. and Hewitt-Dundas, N. (2008), “Innovation persistence: Survey and case-study evidence”, *Research Policy*, Vol. 37, No. 1, p. 149-162.

Rose, M.H. (1979), *Interstate: express highway politics, 1941-1956*, Regents Press of Kansas, Lawrence, KA.

Rothaermel, F. T. and Thursby, M. (2007), “The nanotech versus the biotech revolution: Sources of productivity in incumbent firm research”, *Research Policy*, Vol. 36, No. 6, p. 832-849.

Roussel et al. (1991), *Third Generation R & D: Managing the Link to Corporate Strategy*, Harvard Business Press, Cambridge, MA

Rumelt, R. P. (1991),”How much does industry matter”, *Strategic Management Journal*, Vol. 12, p. 167-185.

Ryan, N. (1996), “Technology strategy and corporate planning in Australian high-value-added manufacturing firms”, *Technovation*, Vol. 16, No.4, p. 195-201.

Sako, M. and Warburton, M. 1999, “Modularization and Outsourcing Project: Preliminary Report of the European Research Team”, International Motor Vehicle Program, Cambridge, MA. available at http://www.imvpnet.org/publications.asp

Santangelo, G. D. (2000), “Corporate strategic technological partnerships in the European information and communications technology industry”, *Research Policy*, Vol. 29, No. 9, p. 1015-1031.

Scherer, F. (1983), “The propensity to patent”, *International Journal of Industrial Organization*, Vol. 1 No. 1, p. 107-128.

Schiffel, D. and Kitti, C. (1978), “Rates of invention: international patent comparisons”, *Research Policy*, Vol. 7, No. 4, p. 324-340.

Schmookler, J.(1966), *Invention and Economic Growth*, Harvard University Press, Cambridge, MA..

Schot, J. (1998), “The usefulness of evolutionary models for explaining innovation. The case of the Netherlands in the nineteenth century”. *History of Technology*, Vol. 14, p. 173–200.

Schot, J. et al. (1994), “Strategies for shifting technological systems: The case of the automobile system”, *Futures*, Vol. 26, No. 10, p. 1060-1076.

Schumpeter, J. (1961), *History of economic analysis*, Oxford University Press, New York, NY.

Seidel, M., et al. (2005), “Quo Vadis, Automotive Industry? A Vision of Possible Industry Transformations”, *European Management Journal*, Vol. 22, No. 4, p. 439-449.

Shimokawa, K. (1999), “Reorganization of the Global Automotive Industry”, International Motor Vehicle Program, Cambridge, MA, available at http://www.imvpnet.org/publications.asp

Shwoon, M. (2006), “Simulating the adoption of fuel cell vehicles”, *Journal of Evolutionary Economics*, Vol. 16, p. 435-472.

Singh, J. (2008), “Distributed R&D, cross-regional knowledge integration and quality of innovative output”, *Research Policy,* Vol. 37, No. 1, p. 77-96.

Sirilli, G. (1987), “Patents and inventors: An empirical study”, *Research Policy,* Vol. 16, No. 2-4, p. 157-174.

Sirilli, G. (1984),“The innovative activities of researchers in Italian industry”, *Research Policy,* Vol. 13, No. 2, p. 63-83.

Smith, A., et al. (2005), “The governance of sustainable socio-technical transitions”, Research Policy, Vol. 34, p. 1491-1510.

Soete, L. (1987), “The impact of technological innovation on international trade patterns: The evidence reconsidered”, *Research Policy,* Vol. 16, No. 2-4, p. 101-130.

Soloman, J. (2001), *The Role of Technology Strategy in the Evolution of Competitive Advantage in Successful New Zealand Firms*, Masters of Management Studies Research Project, Victoria University of Wellington, New Zealand

Souitaris, V. (2002), “Technological trajectories as moderators of firm-level determinants of innovation”, Research Policy, Vol. 31, p. 877-898.

Sperling, D. and Gordon, D. (2009), *Two Billion Cars*, Oxford University Press, Oxford, U.K.

Spital, F. and Bickford, D. (1992), “Successful competitive and technology strategies in dynamic and stable product environments”, *Journal of Engineering and Technology Management*, Vol. 9, p. 29-60.

Steinemann, P. P. (1999) *R&D strategies for new automotive technologies: Insight from fuel cells*, Cambridge, Massachusetts: International Motor Vehicle Program, Massachusetts Institute of Technology

Stevens, G. and Swogger, K. (2009), “Creating a winning R&D culture”, research Policy, Vol. 52, No. 2, p. 22-29.

Story, V. et al. (2008), “The development of relationships and networks for successful radical innovation”, Journal of Customer Behaviour, Vol. 7, No. 3, p.187-200.

Strauss, A. and Corbin, J. (1998) *Basics of qualitative research: Techniques and procedures for developing grounded theory.* Thousand Oaks: Sage

Struble (1998), *Airbag Technology: What it is and How it Came to Be*, report number 840393, Society of Automotive Engineers, Warrendale, PA

Struben, J. and Sterman, J. (2008) “Transition challenges for alternative fuel vehicle and transportation systems.”, *Environment & Planning B: Planning & Design*, Vol. 35 No. 6, p. 1070-1097.

Suarez, F. and Oliva, R. (2005) “Environmental change and organizational transformation”, *Industrial and Corporate Change*, Vol. 14, No. 6, p. 1017-1041.

Sull, D. (1999) The dynamics of standing still: Firestone tire & rubber and the radial revolution. *Business History Review* Vol. 73, No. 3, p. 430-464.

Suurs, R., et al. (2010), “Understanding the formative stage of technological innovation system development: The case of natural gas as an automotive fuel”, *Energy Policy*, Vol. 38, p- 419-431.

Suzuki, J. and Kodama, F. (2004), “Technological diversity of persistent innovators in Japan: Two case studies of large Japanese firms”, *Research Policy*, Vol. 33, No. 3, p. 531-549.

Tan, K. and Perrons, R. (2009), “is globalization an enabler of radical innovation in Toyota?”, *International Journal of Entrepreneurship & Innovation Management*, Vol. 9, No. 3, p. 285-298.

Teece, D. (1993), “Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy”, *Research Policy*, Vol. 22, No. 2, p. 112-113.

Teece, D., et al. (1997), “Dynamic capabilities and strategic management”, *Strategic Management Journal* Vol. 18, No. 7, p. 509-533.

Tidd J., et al. (1997), *Managing Innovation: Integrating Technological, Market and Organizational Change*, John Wiley & Sons Ltd., Chichester, U.K.

Tijssen, R. (2002), “Science dependence of technologies: evidence from inventions and their inventors”, *Research Policy*, Vol. 31, No. 4, p. 509-526.

Tijssen, R. (2001), “Global and domestic utilization of industrial relevant science: patent citation analysis of science-technology interactions and knowledge flows”, *Research Policy*, Vol. 30, No. 1, p. 35-54.

Tijssen, R. and Korevaar, J. C. (1997), “Unraveling the cognitive and interorganisational structure of public/private R&D networks: A case study of catalysis research in the Netherlands”, *Research Policy*, Vol. 25, No. 8, p. 1277-1293.

Tong, X. and Frame, J. D. (1994), “Measuring national technological performance with patent claims data”, *Research Policy*, Vol. 23, No. 2, p. 133-141.

Trippe, A.J. (2003),”Patinformatics: Tasks to tools”, *World Patent Information*, Vol. 25, p. 211-221.

Trajtenberg, M. (2001), “Innovation in Israel 1968-1997: a comparative analysis using patent data”, *Research Policy*, Vol. 30, No. 3, p. 363-389.

Trajtenberg, M., et al. (1997), “University versus corporate patents: a window on the basicness of invention“, *Economics of Innovation and New Technology*, Vol 5, No.1 p.19-50

Tranfield, D., et al. (2003), “Towards a methodology for developing evidence-informed management knowledge by means of systematic review”, *British Journal of Management*, Vol. 14, No. 3, p. 207-222.

Tushman, M. and Anderson, P. (1986), “Technological discontinuities and organizational environments”, *Administrative Science Quarterly*, Vol. 31, No.3, p. 439-465.

Tushman, M. and O’Reilly, C. (1996), “Ambidextrous organizations: Managing evolutionary and revolutionary change”, *California Management Review*, Vol. 38, No. 4, p. 8-30.

Utterback, J. and Abernathy, W. (1975), “A dynamic model of process and product innovation”, *Omega*, Vol. 3, No.6, p. 639-656.

Varsakelis, N. C. (2001), “The impact of patent protection, economy openness and national culture on R&D investment: a cross-country empirical investigation”, *Research Policy*, Vol. 30, No. 7, p. 1059-1068.

Van Driel, H. and Schot, J. (2005), “Radical innovation as a multi-level process: introducing floating grain elevators in the port of Rotterdam” *Technology and Culture*, Vol.46, No.1, p. 51-76.

Vojak, B. and Chambers, F. (2004), “Roadmapping disruptive technical threats and opportunities in complex, technology-based subsystems: The SAILS methodology”, *Technology Forecasting and Social Change*, Vol. 71, No.1-2, p. 121-139.

Von Hippel, E. (1988), *The sources of Innovation*, MIT Press, Cambridge, MA

Von Wartburg, I., et al. (2005), “Inventive progress measured by multi-stage patent citation analysis”, *Research Policy*, Vol. 34, No. 10, p. 1591-1607.

Wang, Q. and von Tunzelmann, N. (2000), “Complexity and the functions of the firm: breadth and depth”, *Research Policy*, Vol. 29, No. 7-8, p. 805-818.

Weis, M., et al. (2003), “Comparative Assessment of Fuel Cell Cars”, MIT Laboratory for Energy and the Environment, Report No. LFEE 2003-001RP, Cambridge, MA.

Wernerfelt, B. (1984), “A resource-based view of the firm”, *Strategic Management Journal*, Vol. 5, p. 171-180.

Wernerfelt, B. (1995), “The resource-based view of the firm: Ten years after”, *Strategic Management Journal*, Vol. 16, p. 171-174.

Willander, M., (2006), “Fading eco-benign networks: The causes found at Volvo Car Corporation and Ford Motor Company”, *European Journal of Innovation Management*, Vol. 9, No. 1, p. 92-107.

Womack, J., et al. (1990), *The machine that changed the world : how Japan’s secret weapon in the global auto wars will revolutionize western industry*, Harper Perennial, New York, NY.

Yin, R.K. (1994), *Case Study Research Design and Methods*, Sage Publications, London.

Zapata, C. and Nieuwenhuis, P. (2010), “Exploring innovation in the automotive industry: new technologies for cleaner cars”, *Journal of Cleaner Production*, Vol. 18, p. 14-20.

Zahra, S. (1996), “Technology strategy and financial performance: Examining the moderating role of the firm’s competitive environment”, *Journal of Business Venturing*, Vol. 11, p. 189-219.

Zahra, S. and Bogner, W. (2000) “Technology strategy and software new venture’s performance: Examining the moderating role of the firm’s competitive environment”, *Journal of Business Venturing*, Vol. 15, p. 135-173.

Zitt, M., et al.. (1999),“Territorial concentration and evolution of science and technology activities in the European Union: a descriptive analysis”, *Research Policy*, Vol. 28, No. 5, p. 545-562.

Zucker, L., et al. (2007), “Minerva unbound: Knowledge stocks, knowledge flows and new knowledge production”, *Research Policy*, Vol. 36, No. 6, p. 850-863

Appendix A. Citations of papers using patents in *Research Policy*

Level Of Analysis	Author(s) and Year of Publication	# Citations (Science Direct)
Global	Schiffel, D. and Kitti, C. (1978)	13
	Macioti, M. (1980)	0
	Pavitt, K. (1982)	30
	Fagerberg, J. (1987)	25
	Patel, P. and Pavitt, K. (1987)	17
	Soete, L. (1987)	34
	Frame, J. D. and Narin, F. (1990)	6
	Archibugi, D. and Pianta, M. (1992)	11
	Daniels, P. (1993)	4
	Tong, X. and Frame, J. D. (1994)	11
	Malerba, F. and Orsenigo, L. (1996)	20
	Radosevic, S. and Auriol, L. (1999)	1
	Guellec, D. and van Pottelsberghe de la Potterie, B. (2001)	7
	Varsakelis, N. C. (2001)	5
	Cohen, W. M., et. al. (2002)	23
	Furman, J. L., et al. (2002)	31
	Mahmood, I. P. and Singh, J. (2003)	5
	Cantwell, J. and Vertova, G. (2004)	7
	Faber, J. and Hesen, A. B. (2004)	2
	Furman, J. L. and Hayes, R. (2004)	5
	Hu, M. and Mathews, J. A. (2005)	7
	Waguespack, D. et al. (2005)	0
	Baudry, M. and Dumont, B. (2006)	0
	Wang, E. C. and Huang, W. (2007)	0
	Quintana-García, C. and Benavides-Velasco, C. A. (2008)	0
Country	Blumenthal, T. (1978)	0
	Basberg, B. L. (1983)	13
	Horn, E. (1983)	1
	Bosworth, D. L. (1984)	7
	da Motta e Albuquerque, Eduardo (2000)	0
	Hicks, D., et. al. (2001)	15
	Trajtenberg, M. (2001)	6
	Álvarez, I. and Molero, J. (2005)	2

Level Of Analysis	Author(s) and Year of Publication	# Citations (Science Direct)
Regional	Noyons, E. et al. (1998)	2
	Zitt, M., et al. (1999)	3
	Acs, Z. J., et al. (2002)	13
	Acosta, M. and Coronado, D. (2003)	1
	Deyle, H. and Grupp, H. (2005)	1
	Ejermo, O. and Karlsson, C. (2006)	0
	Mainwaring, L. et al. (2007)	0
	Zucker, L. G., et. al. (2007)	1
	Mulas-Granados, C. and Sanz, I. (2008)	0
	Tappeiner, G., et al. (2008)	0
Industry	Reekie, W. D. (1973)	4
	Rothwell, R. (1981)	3
	Basberg, B. L. (1982)	3
	Palda, K. S. and Pazderka, B. (1982)	2
	Achilladelis, B. et al. (1987)	7
	Jaffe, A. B. (1989)	13
	Achilladelis, B.,et al. (1990)	9
	Arora, A. (1997)	10
	Arundel, A. and Kabla, I. (1998)	26
	Bergeron, S. et al. (1998)	4
	Kondo, M. (1999)	6
	Kumaresan, N. and Miyazaki, K. (1999)	5
	Malerba, F. and Orsenigo, L. (1999)	16
	Bekkers, R. et al. (2002)	10
	Giarratana, M. S. (2004)	1
	Greenhalgh, C. and Rogers, M. (2006)	3
	Corrocher, N. et al. (2007)	1

Level Of Analysis	Author(s) and Year of Publication	# Citations (Science Direct)
Firm	Narin, F. et al. (1987)	7
	Frumau, C. C. F. (1992)	1
	Gambardella, A. (1992)	20
	Geroski, P. A. et al. (1997)	7
	Ernst, H. (1998)	7
	Gambardella, A. And Torrisi, S. (1998)	14
	Mowery, D. C. et al. (1998)	42
	Brouwer, E. and Kleinknecht, A. (1999)	12
	Cantwell, J. and Janne, O. (1999)	25
	Santangelo, G. D. (2000)	0
	Belderbos, R. (2001)	14
	Cefis, E. and Orsenigo, L. (2001)	8
	Ernst, H. (2001)	9
	Kumar, N. (2001)	13
	Pitkethly, R. H. (2001)	5
	Bas, C. L. and Sierra, C. (2002)	3
	Breschi, S. et al. (2003)	10
	Katila, R. and Mang, P. Y. (2003)	4
	Bergek, A. and Berggren, C. (2004)	0
	Blind, K. and Thumm, N. (2004)	3
	Iwasa, T. and Odagiri, H. (2004)	7
	Mariani, M. (2004)	1
	Suzuki, J. and Kodama, F. (2004)	3
	Hicks, D. and Hegde, D. (2005)	2
	Beneito, P. (2006)	2
	Blind, K., et al. (2006)	2
	Colombo, et al. (2006)	3
	Garcia-Vega, M. (2006)	3
	He, Z., et al. (2006)	1
	Avenel, E., et. Al. (2007)	2
	Mann, R. J. and Sager, T. W. (2007)	0
	Rodríguez-Duarte, A., et. al. (2007)	0
	Rothaermel, F. T. and Thursby, M. (2007)	1
	Coad, A. and Rao, R. (2008)	0
	Quintana-García, C. and Benavides-Velasco, C. A. (2008)	0
	Roper, S. and Hewitt-Dundas, N. (2008)	0
	Singh, J. (2008)	0

Level Of Analysis	Author(s) and Year of Publication	# Citations (Science Direct)
Product	Penan, H. (1996)	5
	Príncipe, A. (1997)	8
	Wiseman, P. (1983)	2
	Patel, P. and Pavitt, K. (1994)	15
	Lanjouw, J. O. and Mody, A. (1996)	23
	Tijssen, R. J. W. and Korevaar, J. C. (1997)	6
	Murray, F. (2002)	14
	Nameroff, T. J. et al. (2004)	6
	Dahlin, K. B. and Behrens, D. M. (2005)	4
	von Wartburg, I. et al. (2005)	5
	Haupt, R. et al. (2007)	0
	Mina, A., et. al. (2007)	0
	Wagner, M. (2007)	0
	Liu, K., et al. (2008)	0
Inventor	Sirilli, G. (1984)	0
	Macdonald, S. (1986)	5
	Sirilli, G. (1987)	7
	Amesse, F., et. al. (1991)	3
	Noyons, E. C. M., et. al. (1994)	8
	Narin, F. and Breitzman, A. (1995)	8
	Fleming, L. and Sorenson, O. (2001)	16
	Tijssen, R. J. W. (2001)	12
	Stolpe, M. (2002)	4
	Tijssen, R. J. W. (2002)	10
	Balconi, M. et al. (2004)	14
	Dahlin, K., et al. (2004)	2
	Dietz, J. S. and Bozeman, B. (2005)	4
	Furukawa, R. and Goto, A. (2006)	2
	Meyer, M. (2006)	3
	Sorenson, O.,et al. (2006)	5
	Bettencourt, L. , et al. (2007)	3
	Bonaccorsi, A. and Thoma, G. (2007)	2
	Giuri, P, et. al. (2007)	1
	Hoisl, K. (2007)	1
	Mariani, M. and Romanelli, M. (2007)	1
	Weck, M. and Blomqvist, K. (2008)	0

Appendix B. Interview Programme

1. Interview guides

2. List of interviews

3. Interview notes
   - Andy Egglestone
   - Jan Olssen
   - Marc Wiseman
   - Steve Parker
   - Lou Bailoni
   - Cuneyt Oge
   - Glen Mercer
   - Donald Struble

Appendix B1. Interview Guides

Interview Guide
-Firm level

- Company situation and strategy
    - Today
    - Last 20 -25 years

- Technological assets and situation
    - Location and capabilities of major technological resources
    - Location and capabilities of specialized resources in safety and alternative power train areas

- Technology strategy
    - Areas where firm looks for competitive advantage
    - Areas were firm seeks to have differential level of technological capabilities

- Deployment Strategies
    - Pattern(s) of technological deployment across product line
    - Regularity of different patterns (existence of path)

- Review of data
    - Reaction to data generated
    - Reaction to hypothetical path (depth or breadth) as found in the data

- Thoughts on any link between the two deployment strategies to learning and performance
    - Learning
    - Technical superiority
    - Vehicle sales
    - Profits

Interview Guide
-Technology focus

- Understanding of the technology
    - Current situation in terms development
    - Future outlook
    - Historical perspective
- Firm-level competencies
    - Identification of leading firms
    - Discussion of specific capabilities of those leaders
    - Relative position of GM, Ford, Toyota, and Nissan with respect to leading firms
- Deployment Strategies
    - Pattern(s) of technological deployment across technology
    - Existences of specific technological advantages between different deployment strategies, i.e., scale economies.
    - Differences between firms
- Review of data
    - Reaction to data generated
    - Reaction to hypothetical path (depth or breadth) as found in the data
- Thoughts on any link between the two deployment strategies to learning and performance
    - Learning
    - Technical superiority
    - Vehicle sales
    - Profits

Appendix B2. List of Interviews

1.	Andy Egglestone	45 minutes, 13/8/09, Ford, Fuel Cells, Hybrids
2.	Jan Olssen	25 minutes, 17/8/09, Seat Belts, Airbags
3.	Marc Wiseman	40 minutes, 17/8/09, Fuel Cells, Hybrids
4.	Steve Parker	60 minutes, 17/8/09, Nissan
5.	Lou Bailoni	75 minutes, 25/8/09, Seat Belts, Fuel Cells, Hybrids
6.	Cuneyt Oge	90 minutes, 1/9/09, GM, Toyota, Electric Vehicles
7.	Glen Mercer	60 minutes, 1/9/09, Ford, Fuel Cells, Hybrids,
8.	Donald Struble	50 minutes, 1/9/09, Seat Belts, Airbags

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Appendix B3. Interview Notes

Interview:	**1**
Interviewee:	**Andy Eggleston**
Position:	**Independent Consultant,** **Formerly Marketing Director, Europe, Ford** **Program Leader for fuel cell electric motorcycle, Intelligent Energy**
Date:	**August 13, 2009, 45 minutes**
Type:	**Technology Focus – Hybrids and fuel cells** **Firm level – Ford**
Page:	**1 of 3**

Hybrids and fuel cells

- **Understanding of the technology**

Eggleston feels that Hydrogen is clearly the best hope for the future of mobility in a sustainable planet. He also believes, however, that there is a huge chasm between the current hydrocarbon economy and what has been called the hydrogen economy, and that hybrid technology appears to offer a bridge over that chasm. It might take 15-20 years to see hydrogen fuel cells with significant penetration in the market but they might in fact never become widespread. This depends mainly on battery development as the battery electric vehicle together with nuclear energy already offers a carbon-free personal transportation model with existing technology.

One thing which is clear for Eggleston is that the wind is shifting towards hybrids in the United States. He cites film stars and other opinion leaders as driving us toward an attitudinal change about who we are and how we impact the environment. Toyota's hybrid luxury SUV, for example, is striking a chord with people who want a vehicle that can give them great performance and also allows them to make a statement about themselves. The new US president, Barak Obama, will also push a more environmentally friendly agenda both for environmental reasons and also to foster the country's energy security, as the US cannot depend on unfriendly governments for its energy security. Hybrids could easily reach 20% penetration in markets like the US and Germany but probably not in China and India where the primary goal is economic development, and carbon limitations will perhaps not be in place for some time.

- **Firm-level competencies**

Toyota is clearly the leader in Hybrid technology. Ford, for instance, made the decision to acquire Toyota technology for its Escape Hybrid. Honda appears to be strong in advanced fuel cells but Eggleston is unsure of whether this will pay off.

He feels that Nissan's recent announcement to pursue battery electric is a bold move but that it might be a mistake; coming out "too soon" with a competitive, all-electric solution might put them in a situation with a vehicle in place but insufficient infrastructure. Paris and London, for example, would be great places to have electric cars but Eggleston wonders how one would charge vehicles of people who live in apartment buildings?

Interviewee: Andy Eggleston
Page: 2 of 3

- **Deployment Strategies**

Eggleston feels that reality is a "bit messier" than the simple choice highlighted by the depth and breadth framework. Central to his view is the sometimes tenuous link between R&D and marketing and he feels that many of the projects particularly on the fuel cell side are disconnected from any clear marketing goal.

There is an R&D budget that gets allocated to different projects and it is hard for Eggleston to credit the manufacturers with having a strategy, with respect to how they plan to deploy new technology, as clear as that illustrated by the depth and breadth construct.

- **Review of data**

When presented with the initial finding from the empirical data, however, Eggleston felt that "it made perfect sense" and that he recognized what he sees depth as the very American "big idea" or "silver bullet" that would somehow change the game and restore Detroit's competitiveness. He sees this in GM's autonomy concept car and also in the new Chevy Volt idea which he thinks has "a lot of merit".

He contrasts this approach with the "Toyota" way which is to think things through, make some bets, and delivers.

- **Thoughts on any link between the two deployment strategies to learning and performance**

Eggleston does not see any inherent advantage between the two implicit strategies of depth and breadth as he feels that what is really important is not what you set out to do but how well it actually gets done. For him, success is all about the quality of the execution and that learning, sales and profits will all flow from that. This, for him, is the lesson from Toyota's hybrid program.

Ford Motor Company

- **Company situation and strategy**

Eggleston was one of the new generation of Ford managers who was forced out after Jacques *Nasser left, but insists that, while he is not biased, he thinks the firm is doing "wonderfully". Eggleston feels that the new CEO is finally putting to rest Ford's North American myopia, lowering their reliance on SUVs and trucks and bringing successful European small cars to the US market. For Eggleston the question has always been that if Toyota, VW, Nissan, BMW, etc., can successfully design cars for the whole world, why can't Ford, GM, etc.*

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Interviewee: Andy Eggleston
Page: 3 of 3

With GM in government hands and sorting out their brands; and Chrysler going through its final "death throes"; Eggleston sees Ford as being positioned to be the leading US company with small cars, hybrids, and a solid fleet of trucks. He feels there will always be a segment of consumers who prefer to buy American made cars and that Ford will be able to take this market share.

- **Technological assets and situation**

Not covered to save time

- **Technology strategy**

When he was marketing Director for Ford of Europe, Eggleston brought about a change in the fundamental brand architecture of the company stressing three aspects: 1) dependable 2) contemporary 3) driving quality. He sees Ford's technology strategy over the last years as being driven from that change.

Part of dependability was safety and one of the major efforts done at the time was to reposition Ford's Mondeo vehicle as a "safe" vehicle because their consumer analysis showed that Mondeo buyers tended to have families and were increasingly concerned about automotive safety. The solution was to put airbags "all over the car" and to develop safety related ad campaigns such as the little girl who runs out to the car during a thunderstorm because she feels safe in it.

- **Deployment Strategies**

Eggleston was not able to characterize Ford using the breadth and depth framework but told the story of its launch of diesel engines in Europe which does appear to match the characteristics of a deep strategy.

In the rebranding exercise above it was detected that Ford had no diesel engines in its fleet and that Diesel was gaining in market share year by year. The solution was to buy an engine from VW and to put into the entire fleet over a few years. The engine was almost immediately put onto the Ford Galaxy minivan since it shared a platform with VW and much of the engineering work had already been done. This was followed sequentially with a version of the Mondeo and finally made available on the Focus. Eggleston feels that the hybrid program followed exactly the same pattern and was done for the same reasons.

- **Review of data**

Eggleston can confirm the idea that Ford tends more toward deep strategies than broad ones but sees Ford more in a reactive mode, doing what it has to as a reaction to years of complacency in Detroit.

- **Thoughts on any link between the two deployment strategies to learning and performance**

As above. Results depend on the quality of execution more than the strategy,

Interview: 2
Interviewee: Jan Olssen
Position: Director, Research & Development, Autoliv
Date: August 17, 2009, 25 minutes
Type: Technology Focus
Page: 1 of 2

Seat Belts and Airbags

- **Understanding of the technology**

According to Olssen, the advent of new sensing devices such as radar and machine vision will enable more pre-crash sensing which gives the opportunity to greatly improve the performance of seat belts and, to a lesser extent, airbags. The next major innovation will be a device on an electric motor which he calls a pre-pretensioner, which will tighten the seatbelts in case there is a possibility of a crash and, of course, loosen them again if the crash is avoided.

In terms of penetration, both front and back seat belts are pretty much standard everywhere but load limiters and pretensioners still have some way to go.

In airbags, Olssen feels that the front airbag systems are fairly ubiquitous in the west and that the major challenge will be to take the cost down sufficiently for their deployment in less-developed countries such as China and India where some local models are still not equipped with the devices. He expects this to occur sooner rather than later.

For Olssen and Autoliv, the biggest challenge for airbags is to increase the penetration of side airbags and the inflatable curtain which are still far below their potential.

- **Firm-level competencies**

Mercedes and Volvo are the leaders in safety systems and Autoliv has a long relationship with Volvo which has proved mutually beneficial over the years.

Olssen believes that Ford was very quick to install front airbags and sees the Japanese as having decided to push safety in order to develop competitive advantage in the US market.

In terms of research, Olssen has great respect for both Ford and GM's R&D people but is not sure to what degree they are connected to the platform engineering teams.

The US manufacturers, for example, define the safety system and select its components quite early in their product development process, thus locking in their capabilities years before product launch. The Japanese, on the other hand, leave space for the system components and then choose them as late as possible in order to have the best technology on the vehicle.

Interviewee: **Jan Olssen**
Page: **2 of 2**

- **Deployment Strategies**

Olssen did not recognize the patterns of depth and breadth in his customers and preferred to think of technology leaders who would do expensive original research and strive to be first on the market and others who would be happy to be fast followers and would implement proven technology across the vehicle fleet in a broad way once someone else had developed it. Although Olssen was careful not to name any manufacturer, it appeared that he would put Mercedes and Volvo into the first category and Nissan and Toyota in the second. When asked if there was a third category of slow followers and if GM and Ford could be characterized as such, Mr. Olssen demurred although it appeared that he agreed.

In terms of deployment rates, however, Olssen felt that the safety rating done by NHTSA and others in the US and equivalent organizations in Europe play a huge role in the choices the manufacturers make. In the case of the inflatable curtain, for example, he understands that the European and Japanese testing protocols make it more important for vehicles to have them than their American counterparts and that this is the primary reason for low penetration.

For Olssen the technical specifications of a seat belt or an airbag are not as important as how these components behave in the entire safety system. *In fact the overall safety of a vehicle depends on the seat belts and airbags interacting with each other and the rest of the system which includes sensors, seats, instrument panel, other key components and the structure of the car itself.*

- **Review of data**

When some of the high level conclusions of the deployment data were shared with Mr. Olssen he found them to be correct, confirming the behaviour of the four companies.

- **Thoughts on any link between the two deployment strategies to learning and performance**

Olssen feels the issue is to lead or to follow and did not dwell on depth and breadth although one could argue that, by his definition, a technological leader would have to follow a deep strategy while a follower might follow a broad one in terms of deployment, and that a leader would engage in a large volume of R&D work while a follower would do much less.

Interview: 3
Interviewee: Mark Wiseman
Position: Director, Alternative Powertrain, Ricardo
Date: August 17, 2009, 45 minutes
Type: Technology Focus
Page: 1 of 2

Hybrids and Fuel Cells

- **Understanding of the technology**

Wiseman gives a US perspective to the situation of hybrids and feels that it is a challenging area. His firm, Ricardo, is an engineering company that actually developed some of the first hybrid vehicles under contract to the OEMs and had argued for a gradual, cost-driven process which would start with mild hybrids and then slowly improve in fuel economy and the degree of hybridization. In fact, many companies are pursuing much stronger hybrid technologies led, of course, by Toyota.

One aspect of the hybrid situation that Wiseman focused on was the debate about whether the technology was better for light trucks or passenger cars, and he maintains that GM led the discussion on the side of trucks and that Toyota argued that all of the arguments for trucks can also be made for cars. In his view both GM and Ford used hybrid versions of their trucks and SUVs to make the case to the public that these vehicles were not so bad for the environment and that the programs needed to be seen in marketing light.

Another aspect that is important for Wiseman is the current political situation in the United States. The Obama administration has publicly challenged the auto industry to reach fleet average of 35.5 miles per gallon and is ready to write that figure into the next round of CAFE legislation driven by the dual goals of energy independence and CO2 emissions. Clearly hybrids and electric vehicles will play a role in achieving those targets with people predicting 1 million new plug-in hybrid cars per year.

Comment [A9]: please check this correction

In his view, GM's fuel cell program was due to the conviction of Larry Burns, former head of R&D, as well as the Bush administration which spent $1 billion to promote the technology. Wiseman understood that Detroit had made a deal with Washington to spend significantly on fuel cells in exchange for no increase in the federal CAFE fuel economy legislation. GM and Ford were reportedly spending $300 million and $150 million respectively on fuel cells every year but that this was nothing compared to the cost of increasing average fuel economy which might have been on the order of $500 per car.

What happened in Wiseman's view is that the "bubble" burst and that the realities of fuel cells never came close to the political hype. On a well-to-wheel basis, the fuel cell becomes uncompetitive against hybrids and even if one could make hydrogen from renewable electricity, then it seems more logical to go straight to electric vehicles.

Wiseman does not really buy the "who killed the electric car" story and sees it coming from a very narrow viewpoint. In his view, there are different paths to sustainable transportation and when the electric vehicle was launched in the 1990s, there were serious problems with battery technology and infrastructure which were simply not well worked out.

He knew people personally involved with GMs Impact program and he insists that they were trying to make it successful but that GM's PR group bungled the recall which eventually killed the program.

At one time politics and technology put fuel cells out in front and today it's all about hybrids and plug-in hybrids. Wiseman sees the plug-in hybrid offering the cleanliness of an electric car without the problem of range or infrastructure and sees this as the most likely path although he does not rule out a fuel cell comeback or the ability of someone like Nissan to leapfrog the technology with an all-electric solution.

- **Firm-level competencies**

Toyota is clearly the leader but Wiseman's view is that one needs to go a bit deeper in looking at each OEM.

In his view, Toyota actually pursued a broad strategy and developed several hybrid technologies in parallel with the Prius program, including a 42-volt vehicle and a panel truck in Japan, and that they only focused their efforts on the synergy drive system when the Prius started to take off.

Wiseman also feels that GM's fleet coverage is overstated and that, to get a better idea of relative commitment, the fleet coverage should be calculated on the basis of sales volumes, not models.

Wiseman's view of Ford is that it was well advanced with a dedicated electric car group, a fuel cell group and the investment in TH!NK and mentioned its groundbreaking joint venture with Bollard and Daimler as an example of its position.

What happened is that Ford came under financial constraints and was not able to justify the business case for these investments and scaled back their efforts to a much more limited and practical program but that they are still pursuing their own technology.

Nissan also had started down its own path and Wiseman places some importance of the Tino hybrid program which went on the market in Japan before being wound down in favour of licensing technology from Toyota.

Interviewee: **Mark Wiseman**
Page: **3 of 3**

- **Deployment Strategies**

Wiseman felt that the depth and breadth construct had some merit and felt that what would be most interesting would be to calculate the relative cost of pursuing one strategy or another; the engineering expense, for example, of putting a tested hybrid drive onto a new model would cost from $25-50 million and after that there would be much larger costs of tooling and manufacturing for both the OEM and its suppliers.

- **Review of data**

As stated above, Wiseman thought that Toyota had clearly pursued a broad program on hybrids.

He also urged caution in looking at the patent data as he believes that much of the patenting done in automotive is defensive in nature and that the OEMs strive to protect themselves from legal challenges by first patenting what they can and second making cross licensing agreements with each other.

He did accept the data on the number of patents and felt that their relative number did broadly reflect the OEMs priorities.

- **Thoughts on any link between the two deployment strategies to learning and performance**

Wiseman feels that the manufacturers are simply not interested in learning and that their primary focus was in the cost benefit of different options.

Interview: 4
Interviewee: Stephan Parker
Position: Independent Consultant,
Formerly Managing Director, Ricardo Strategic Consulting and advisor to Nissan
Date: August 18, 2009, 60 minutes
Type: Firm level – Nissan
Page: 1 of 3

- **Company situation and strategy**

Ever since Carlos Ghosn took Nissan through its recovery plan, Nissan has been in turnaround mode. The recovery plan, of course, put Nissan into a very profitable position and Nissan has managed to continue to do fairly well until the current downturn.

According to Parker, who is a close advisor to one of the members of Nissan's management board, the company has followed a three-part strategy over the last few years which has gotten mixed results. The first part of the strategy was a massive product offensive which has generally been well received by the public due to attractive styling and competitive pricing.

The second element has been internationalization which also seems to be proceeding well.

The third element has been continuous cost reduction which has reduced some costs both in the supply base and in Nissan's internal operation. What Nissan has not managed to do, however, is to realize economies of scale across the different markets and model range or be able to charge premium prices and this is, according to Parker, the strategic priority at the moment.

In Parker's view the key to success in automotive is to be able to monetize technology investments and he sees that Volkswagen. Mercedes and BMW do a much better job at that than most others, including Nissan.

- **Technological assets and situation**

Parker could not think of an area where Nissan has technological advantage although he does have hope for its major bet on battery electric vehicles which was made 18 – 24 months ago.

- **Technology strategy**

The electric vehicle program is reportedly thought of inside Nissan as "one big roll of the dice" and Parker understands that they have put virtually all of their development money into the program at the exclusion of everything else.

Parker supports the view that Nissan was so far behind Toyota and the US firms in hybrids that it had to bet on a game-changing play or would certainly lose if the market really does turn "green".

He is a bit sceptical about how the hybrid and electric vehicle story will play out as he accepts the view given by Neville Jackson, the chief scientist at his old firm, that the economics and environmental science still puts diesel technology as the best bet for sustainable transportation. Parker contrasts Nissan's strategy with Volkswagen's which he feels is much broader and touches on different power train technologies based on different fuel types and is all being marketed under the "Blue Motion" campaign.

BMW has a similar program called "Efficient Dynamics" and Parker feels that this kind of clear technological leadership program coupled with savvy marketing is the key to success and sees Nissan failing at both.

- **Deployment Strategies**

Parker felt that the depth and breadth concepts were useful characterizations of the way the different OEMs behaved and saw Nissan as pursuing deep strategies again and again. The electric vehicle program mentioned above is a perfect example of depth and Nissan has just announced building two European plants to manufacture the cars.

He sees VW as pursuing a broad strategy and made an interesting point that Ford, as recently as 2002, was pursuing 600 different research initiatives in Europe alone while VW was only looking at 5-6 major research areas. While these areas might be further broken down into 50-60 projects, one gets the sense that if VW's strategy is broad then Ford's was simply a mess. That said, Parker felt that Ford tended to broader, rather than deeper deployment strategies.

With respect to Toyota, Parker did not feel he had enough of a sense of their path but was aware that Toyota was engaged in a major re-think of the way they do business and that Toyota had come to the conclusion that they were a "boring" company and would need to become more interesting both as individuals and as a firm to succeed in the future.

In his view, GM is such a mess that there is no benefit to looking for any pattern in the GM data.

- **Thoughts on any link between the two deployment strategies to learning and performance**

Parker sees deep strategies as what an OEM should use in a turnaround situation and cites two examples where this worked well.

One was Audi's "Quattro"4X4 power train which it developed over several years, perfected and then launched across the product line. He sees the "Quattro" as being fundamental in re-positioning the brand.

Another example is VW's 10 year program to develop exciting and efficient diesel engines which he sees has been one of the key reasons for their market success over the last 3-4 years.

Broad strategies are what is called for to leverage a strong brand and, as stated above, Parker sees this behaviour in Volkswagen and BMW.

Interview: **5**
Interviewee: **Lou Bailoni**
Position: **Vice President, Bright Automotive**
Former Management Consultant and Industry Analyst
Date: **August 25, 2009, 75 minutes**
Type: **Technology Level – Alternative Power train**
Page: **1 of 3**

- **Company situation and strategy**

Speaking about the automotive industry in general, Bailoni feels we are in a time of uncertainty and change. GM, for example is "all over the map" and has recently expressed an interest in keeping its Opel subsidiary which has been for sale for the last few months.

Another surprising announcement by GM was to bring some aspects of airbag technology back in house after years of relying on companies such as Autoliv. Bailoni feels that this is part of a trend in the supplier strategies of the OEMs. In recent years the major OEMs have increasingly given their suppliers more responsibilities and at the same time decreased their in-house capabilities closing down engineering departments, spinning off internal suppliers, etc.

What Bailoni sees is that the increases in advanced safety systems and electric cars has brought a number of new technologies and new suppliers into the automotive industry and left the OEMs without the same level of knowledge as they had with more "traditional" automotive technologies. He expects we will see them bringing more of these exotic technologies in house at least to some degree in order to build their own competence in these areas.

- **Technological assets and situation**

Car companies are still focused on the same thing and this does not change. It's all about developing and delivering products which live up to the brand promise. This will delight customers and make them loyal, creating the possibility of earning money.

- **Technology strategy**

Bailoni spoke at length about electric vehicle technology and the limits he sees for electric cars. One of the reasons for speaking to Bailoni was that in 2005 he conducted a survey of the leading power train managers at all of the major OEMS as well as their key suppliers in order to understand their view of the future of electric vehicles.

According to him, the key issue in the possible switch from internal combustion engines to some other technology is consumer economics. The consensus view of the power train managers was that consumers would change their behaviour only if gasoline prices reached $4-5 per gallon AND it was perceived that this situation would last for a significant time.

Bailoni cites the hybrid sales during the summer of 1998 which peaked when gasoline reached $4 per gallon but then dropped back down as soon as it fell below $3 a few months later.

Bailoni admits that there is a segment of the population who has the extra money to purchase more expensive environmentally friendly vehicles but they are a minority and he does not expect electric vehicles to reach more than 2-3 % market penetration in five years and perhaps 10% in ten.

- **Understanding of the technology**

With his focus on consumer cost drivers, it is difficult for Bailoni to see how electric vehicles will ever be competitive.

He understands that the Chevy Volt will have a list price on the order of $40,000, which is about double the cost of a similar size hybrid like the Prius and perhaps 3 or even 4 times the price of a similarly equipped traditional vehicle. The high price is driven by having all of the costs associated with a 1.1 litre engine as well as the entire electric vehicle system, including a battery pack which might cost up to $15,000. To this one has to amortize high development and tooling costs and divide them by relatively low expected sales volumes. A final cost which is an interesting area for study is the prevision for warranty costs that must be included as there is very little data to use in calculating this.

According to Bailoni, Nissan seems to understand this and has committed itself to holding the purchase price of the Nissan Leaf to a level comparable to its traditional competitors. The plan appears to be to lease the battery separately and have the battery and all of its associated warranty and replacement issues as the responsibility of Nissan or a third party. This way the consumer economics will be to buy a car (or lease one) and then pay a battery charge which will be equivalent conceptually to the cost of filling the gas tank.

One point to make about advanced batteries is that the current Lithium Ion battery concepts are in fact thousands of individual cells literally wired together and there are a lot of things that can go wrong with these devices.

Another critical issue for Bailoni is that electric vehicle technology does not stand alone but needs to be constantly evaluated against the alternatives and he feels there is at least an additional 20% of improvement potential for gasoline powered internal combustion engines using technology which has already been developed and tested. Internal combustion engines have been around for a long time and are very reliable. In Bailoni's view, if the world were serious about reducing CO2 and decreasing reliance on oil then compressed natural gas offers the best alternative as it again uses proven technology with a 20-25% cost disadvantage. The problem with CNG of course is building the requisite infrastructure.

Interviewee: Lou Bailoni
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- **Deployment Strategies**

Bailoni felt that the basic concepts of depth and breadth made sense but that the key to technological introduction was cost and perceived value.

Taking a traditional automotive view on new technology, what one sees is that new features are first seen on very high-end cars such as Porsche and Mercedes Benz and only trickle down to the mass market as the cost comes down or because regulations change requiring the new devices. Bailoni gives the example of tyre pressure sensors which in 2000 were only available on selected models of the most expensive cars. In the aftermath of Ford's Firestone tyre tragedy, it was found that underinflated tyres were a direct cause of the deadly rollovers and this resulted in new laws requiring the devices. In 5 years virtually every new car sold in the US was equipped with the pressure sensor and Bailoni feels that a normal roll out would have taken 15 to 20 years.

- **Review of data**

On the pretensioner data set which shows Nissan and Toyota moving quickly and GM moving very slowly, Bailoni felt strongly that the data can be misleading. At issue is not incorporating pretensioners but achieving 5-star safety ratings from the government testing agency, NHTSA. Dynamic crash protection depends on a myriad of factors including seat belts but also including the design of interior components and most of all the structural integrity of the cars. In Bailoni's view the most likely explanation for GM's slow deployment of pretensioners was that they simply did not need them to get the 5-star rating due to having a heavier steel structure.

In some technologies the general public might come to demand a particular device or feature but in those cases where the public is unaware of the details one would need to look at the whole system.

- **Thoughts on any link between the two deployment strategies to learning and performance**

Bailoni felt that the specific technology would drive these issues more than the generic strategy and each case might be different.

Interview: 6
Interviewee: Cuneyt Oge
Position: Director, PRTM
Date: September 1, 2009, 90 minutes (face to face)
Type: Technology Focus –Electric vehicles
Firm level – GM
Page: 1 of 4

Electric Vehicles

- **Understanding of the technology**

Oge feels it is important to distinguish between fundamental system changes such as fuel cells and hybrids and more component level changes such as seat belts and airbags.
Oge is of the firm conviction that the electric vehicle is the future of automotive and in fact projects that 30% of vehicles will have some kind of electric drive train by 2030.
Oge is currently working with both Nissan and Toyota on a project related to this area and believes that sufficient momentum is already in place to bring about the change, at least for some applications.

He is also convinced that China's decision to push electric technology will have a tremendous impact. In his view China might in fact place as many as 30 million vehicles on the road in the next three years and that such a huge amount of component production will allow costs to drop on critical components such as electric motors, batteries and power electronics. For Oge, what is key is not the quality of the cars that Chinese OEMs produce, as such cars will probably not meet western safety standards or be exported, but the volume of components which will certainly be exported to the West.

One aspect of technological development in automotive that is very important for Oge is that over the last 30 years virtually all technological advancement has been driven by emissions and safety regulation rather than market demands and technological push. The only exception to this is perhaps some comfort features and telematics or infotainment.

He cites Ted Levitt and Kim Clark as writing about the last true automotive innovation which he feels was the V8 engine. He also recommends the biography of Kettering, an automotive pioneer who invented many of the key systems in the modern vehicle in the last century.

Interviewee: Cuneyt Oge
Page: 2 of 4

- **Firm-level competencies**

Oge feels that Toyota has a big problem. In his view they have overcommitted to hybrid technology and that, while some aspects of their technology might be applicable to electric vehicles, he sees them falling behind Nissan and GM. To compound the problem further, he sees Toyota's consensus based management style unable to cope with the present global downturn in the industry and that senior management is not ready to start making tough decisions.

Oge also thinks it is important to recognize the role of the Japanese government's research arm, MITI, in encouraging Toyota to invest in hybrid technology and giving it $1.5 billion for the purpose.

Oge applauds Nissan's crash electric program which he sees as leapfrogging Toyota's lead in hybrids. Nissan has assembled a multicultural team which is "pragmatic and determined to succeed". He sees the Nissan guys as having "the guts" to make this work and while he acknowledges that it might be a kind of "Hail Mary" strategy, he is convinced it will pay off. He does not see the same level of courage to make decisions in the Toyota camp.

Oge did not comment on Ford as much of the conversation centred on General Motors.

On electric vehicles Oge discussed the Chevy Volt and points out that the design of its battery configuration is the same as GM's EV1 vehicle from the 1990s. In Oge's view, GM was years ahead of the rest of the industry but allowed that lead to evaporate due to a political battles inside GM.

Oge dismisses hybrid technology as not being truly revolutionary because the internal combustion engine still drives the wheels and that the electric motor just adds limited torque. Oge also concurred with the characterization of many twomode hybrids as being simply motorized automatic gearboxes.

- **Deployment Strategies**

Oge felt that the characterization of depth and breadth "made sense" but felt strongly that the choice of which path to follow was driven more by the specific technology than the idea of path dependencies by company.

- **General Motors**

With respect to General Motors and its repeated failure to capitalize on its broad technological leadership, Oge cites four areas which he sees as fundamental.

The first has to do with the internal accounting rules of the OEMs. In GM and Ford, for example, if a specific model or platform is the first to be equipped with a new component or system then that program needs to pay for its development cost as well as its industrialization both at the OEM and its suppliers. Thus, if the first application of airbags goes onto a Cadillac, then the Cadillac division must bear all of the development costs. This is the reason that expensive technology is often seen on the most expensive models first as they are the only ones with enough profitability to absorb these costs.

Oge understands that Toyota and Honda, for instance, do not do this and instead spread the costs for new technology or classify it in a different way, since once the decision is made to develop something then they see no reason to penalize a specific platform or product group.

He feels that these companies have done a much better job of systematically managing their technology portfolio than the American firms. What is key for such a process, in Oge's view, is to have the discipline to stick to your ideas.

The second critical factor is the "make or buy" decision process and here Oge seems to think that, in new technology, it might be better to develop things in-house, and he cites the clean diesel programs at major heavy duty engine manufacturers as an example. For clean diesels it seems the fuel injection and turbo chargers need to be very different and according to Oge these two technologies are each dominated by two companies - Bosch/Siemens in fuel injection and Honeywell/Borg Warner in fuel injection. It seems that Navistar relied upon its suppliers and was not able to meet Ford's cost targets and quality requirements while Cummins chose to build these key components in-house and has been able to do much better.

The third factor is how the technology development portfolio fits into the product development process and vehicle cycle plan.

In the product development process, for example, Honda and Toyota will only use proven technology at the component and systems level in order to avoid major launch problems. In terms of cycle planning, Toyota does not replace major power train systems when it launches a new model but instead does so at a model's 2-year re-styling.

According to Oge this policy reduces the risks involved in launching a new model considerably and is in contrast to GM's normal practice of changing everything at model change; a practice which just makes it more likely that something will go wrong either at the component, system or systems integration level.

The final and most damaging problem that General Motors has had is internal politics, as discussed above.

In Oge's view, there are always intense politics in any organization but it is the absence of sound and disciplined processes, such as Toyota's technological portfolio, which allows such politics to drive the technology strategy.

- **Company situation and strategy (GM)**

Oge does believe that President Obama's task force "has some smart people" on it and thinks they will try to push the company in the right direction.

- **Technology strategy (GM)**

In terms of fuel cells, Oge supports the idea that there was an implicit or explicit arrangement with the Bush administration on fuel cells in exchange for a limit to increased CAFE legislation and estimates that they spent no more than $300 million per year on the program. While that is a large dollar amount, Oge insists that such money is a relatively small price to pay for relief from CAFE legislation.

As mentioned above, the new bet at GM is on electric vehicles and Oge agrees with GM that the Chevy Volt is unlike the hybrid vehicles on the market as the internal combustion engine can only drive the wheels via the electric motors.

- **Deployment Strategies & Review of data (GM)**

Interview: 7
Interviewee: Glen Mercer
Position: Director, International Motor Vehicle Program
Formerly, Senior Partner, McKinsey & Co.
Member, Automotive Industry Council, Gerson Lehman Group
Date: September 1, 2009, 60 minutes
Type: Firm level – Ford
Page: 1 of 3

- **Industry overview**

Mercer began by giving an overview of where he sees the four companies in the sample. In 1985, Mercer determined that three best OEMs in the world was BMW for brand management, Toyota for its production system, and Honda for its engine technology, and he sees no reason to change his mind today.

According to Mercer, Toyota's problems with its Tundra pick up and closing its famed joint venture with General Motors, NUMI, are only "chinks in the armour" and that its manufacturing prowess still sets it ahead of the other OEMs. Toyota is its own worst enemy but that they have correctly developed technology for whatever power train scenarios develop. Whether this strategy, which dates from the early 1990s, was exceptionally smart or just turned out to be right, is difficult to say but in any case Mercer feels Toyota is on the right track.

Mercer feels that Nissan is trying to figure out what it is and will be. He sees several distinct phases in Nissan's development over the last years. Nissan had originally been very close to the Japanese government. Then it went through a "copy Toyota" phase which led to its profound crisis in the 1990s. After the alliance with Renault was formed, Nissan began its recovery plan under Carlos Ghosn and has been in "turnaround" mode ever since. For Mercer, Nissan still has not developed a clear view of where it is going and has been "thrashing around" looking for something new.

Mercer confirms that the latest idea, to be the electric vehicle company, is a "hail Mary" play.

Mercer's view is that perhaps GM emerged from bankruptcy too quickly and there is a feeling in the company that they are "done" and can now move on. On the positive side he feels that GM has shed a lot of costs but he is not sure if the board was too quick to confirm Fritz Henderson as CEO as it is unclear to him how 'lifetime' GM people can save the company.

GM's strategy today is to launch a "model onslaught" and what surprises Mercer is that the US government obliged GM to reduce its brands from 6 to 4. The company is now simply putting out more models under the remaining brands but has not really changed its way of thinking.

For Mercer, General Motors has always believed in its tremendous scale as the answer to all of its problems. If you believe in economies of scale and are the biggest player, then it is logical to assume you will always have the ability to do anything. In the case of fuel cells he believes you can see this pattern of behaviour and the only problem was that "the laws of physics" did not agree.

Mercer feels that General Motors was incredibly consistent pouring money into fuel cells but did not show the same level of consistency in the EV-1.

According to Mercer, it was Bob Lutz, a legendary industry executive, who returned from retirement to GM on the condition that the Chevy Volt project be fully funded, as his conviction is also that the electric vehicle with different potential sources for electricity, i.e., batteries, generators, fuel cells, etc,. is clearly the future.

Mercer says that the culture at GM would "polish the hairs off a doorknob" meaning that the engineers would do whatever it takes to get the best solution and that this was partly driven by a degree of "technological arrogance" and partly by being "deeply risk-averse" and afraid of the costly implications of recalls.

- **Company situation and strategy (Ford)**

According to Mercer, who has recently written a book chapter on Ford, the company "lurches" back and forth per the thinking of the current CEO and understands that the current CEO of Ford, Alan Mulally, is a "good guy".

Ford went from Alex Trottman's global vision to Nasser's downstream idea to environmentalism and then a return to basics under Bill Ford. Mulally has now focused Ford on profit and consistency and saved the company by taking steps to correct its direction before the current crisis hit.

- **Technology strategy**

In Mercer's view, Ford has finally worked out how to bring its European designs, technology and thinking to the US and feels this is the best way to get affordable small cars on the market. GM's approach, in contrast, is to "de-content" its larger vehicles and import small substandard cars from its Daewoo subsidiary.

In terms of power train technology Mercer quotes a presentation recently given at the University of Michigan which places accelerated incremental improvement of the internal combustion engine at the heart of Ford's strategy.

Mercer says that Ford is also "pedalling very quickly" to get its own non-Toyota hybrid system up to speed. Toyota's system, according to Mercer, is over-engineered and Ford has an opportunity and also runs a risk by designing its system "closer to the ragged edge".

- **Deployment Strategies**

Mercer thought that the characterization of depth and breadth was correct but saw it play out in cultural terms. He felt that the German manufacturers, i.e., Mercedes, BMW and Volkswagen, typically pursued deep strategies and that the Japanese would pursue broad strategies. This applies to Honda and Toyota and to Nissan prior to Carlos Ghosn's leadership. In his view, US companies go back and forth between the two.

He also feels there is much variance between technologies as one of the critical issues is the size of the technological bet and the sensitivity of the system or component. A recall of a million hybrid vehicles with a $5,000 cost per vehicle could sink a company while fixing a few hundred thousand DVD players would be manageable, and he felt this issue is at the heart of many such discussions.

- **Understanding of the technology (Alternative Power Train)**

Mercer takes exception to what he calls "the grand equation" which, in his view, is deeply embedded in the minds of industry executives.

The idea is that there is a rational calculation one could make between the additional cost of a hybrid or a battery electric vehicle and the net present value of the savings on gasoline or diesel fuel which will result.

Mercer cites a University of California study which found that only 3% of Toyota Prius buyers actually "did the math" and that most people buy such cars for an emotional reason or as a political statement.

In his view anyone who chooses to buy a new car is by definition not being rational as the most cost effective transportation option is a five-year-old Honda.

The current trend to hybrids is like the emergence of safety as an issue back in the 1990s. Mercer clearly remembers when seat belts were considered superfluous and how the car-buying public changed their perceptions very quickly. Whether we are coming close to the "inflection point" is difficult for him to say.

In terms of the future he shares the view often called "horses for courses" in which different technologies will be most popular in certain applications and with certain types of consumers. The biggest barrier to higher penetration of all types of alternative power train vehicles in his view is the current state of "sectarian violence" existing between proponents of different systems.

All electric proponents, for example, argue that hybrids lose money, clean diesel people talk about the toxic nature of a used lithium ion battery, etc., fuel cells are always 10 years away and clean gasoline is catching up. Mercer feels that the average consumer is simply confused by the virulent tone of debate.

Interview: **8**
Interviewee: **Donald E. Struble**
Position: **President, Struble Walsh Engineering and author of "Airbag Technology" SAE paper 980648, February 1998**
Date: **September 1, 2009, 50 minutes**
Type: **Technology Focus**
Page: **1 of 2**

Seat Belts and Airbags

- **Understanding of the technology**

Don Struble was a member of the design team of the minicars RSV, one of the first prototypes of a modern airbag system in 1979 and authored the definitive history of airbag development SAE paper 980648. His company investigates crash dynamics for OEMs including Toyota and Nissan and has followed the development of airbags and seatbelts throughout his career.

Struble believes we are reaching a level of airbag deployment where the incremental cost might not be really justified by an increase in safety and used the phrase "diminishing returns" to describe the current situation. Side airbags, for example, came out in the late 1980s before there were any clear test protocols, metrics or dummy telemetry and he finds the cost benefit data is not compelling. In his view most of the latest developments have been market led.

- **Firm-level competencies**

Struble credits General Motors with the development of the modern airbag and feels that the company has always enjoyed vast amounts of talent and capability. He recalls GM's Dave Potter who ran its Environmental Activities lab in the 1970s as saying "there is not a problem we can't solve. The only question is which problems to solve".

With respect to Ford, Struble believes the legacy of Robert McNamara and the "whiz kids" has permanently left its imprint on the organisation and would sum up Ford's attitude as "there is nothing that can't be analysed". According to Struble, Ford developed a very complex model to estimate the costs and benefits of safety technology early on and still prefers analysis to testing. He does see the recruitment of Boeing's Mullaly as a "brilliant move" and believes Ford has a bright future.

Struble underscores the fact the safety technology in general and airbags in particular required a completely new set of technologies for the OEMs and cites this fact as the reason that the technology has been led by suppliers since the early days.

Cars had virtually no electronics in them before the 1970s and thus the suppliers ended up doing much of the basic research and providing complete systems when they were available. Sensor technology and the microprocessors needed for actuation were particularly new for the industry, to say nothing of the pyrotechnic fuel.

According to Struble, it was Chrysler, not GM, who really brought airbags into the mainstream in the United States. He recalls that Chrysler's flamboyant CEO, Lee Iacocca, told President Richard Nixon that the cost of developing airbag technology would bankrupt Detroit. What happened later was that when he saw how expensive and problematic the automatic 3-point seat belts would be he changed his mind and began to lobby for airbags. By that time Chrysler had "hollowed itself out", laying off most of its engineers and thus had to completely rely on suppliers to develop the systems. GM did play a leading role in recognizing the tragic issue of children and front seat airbags and in taking steps to protect them.

Looking ahead Struble sees more computers, more advanced sensors, fewer mechanical components and more complexity in airbag systems but maintains that we have reached or are reaching the limit of the technology in terms of saving lives at a reasonable cost.

- **Deployment Strategies**

With respect to the deployment data observed for both airbags and seat belts Struble is not surprised that the Japanese companies appear to be faster than Ford and GM. The reaction of the Japanese to changing US regulation has been, in his view, to accept the changes and figure out what they have to do. US firms, on the other hand, would send their lawyers and lobbyists to Washington and try to "lower the bar".

With respect to airbags, it made sense to proceed incrementally rather than all at once due to the nature of the technology. One reason is the fact, stated above, that airbags were "foreign technology".

Another is that supply chain reliability was a major factor and, in the early days, a fire at a Morton Thikol plant actually stopped the Lincoln Continental production line. It simply was not evident that the manufacturers of sensors and actuators could ramp up production to the volumes required by the automotive industry and meet its quality and price requirements.

A third reason to go slowly in the case of GM is its basic nature to be cautious. Part of GM's history is to do things in "fits and start" and this reflects the competing political agendas of different people and groups within the company. On the specific issue of pretensioners, Struble suspects that it is likely that GM felt that the devices were simply not needed and only became convinced over time. An interesting question for the future is whether the "new GM" will do anything differently.

In contrast with GM, Toyota takes the long view and when they do get "in motion" everyone in the company from "top to bottom" is "on board". Toyota also has its product cycles "all figured out" and thus is able to plan its technology deployment very well.

Appendix C. Hybrid and electric vehicles in the U.S. market

1. Full list of models offered

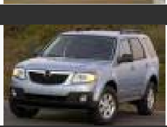
2. Selected comparisons of hybrids and conventional vehicles
   Ford Escape Comparison
   Honda Civic Comparison
   Toyota Highlander Comparison
   Saturn Aura Comparison
   Lexus RS400Comparison

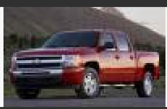
3. Model range analysis

Appendix C1. Full list of models offered
(Jato Search engine, Automotive News Website, accessed 5/11/09)

	Honda Insight LX PZEV 5dr hatchback '10	$ 19,800
	Honda Insight LX 5dr hatchback '10	$ 19,800
	Toyota Prius I 4dr hatchback '10	$ 21,000
	Honda Insight EX PZEV 5dr hatchback '10	$ 21,300
	Honda Insight EX 5dr hatchback '10	$ 21,300
	Toyota Prius II 4dr hatchback '10	$ 22,000
	Toyota Prius III 4dr hatchback '10	$ 23,000
	Honda Insight EX with Navigation PZEV 5dr hatchback '10	$ 23,100
	Honda Insight EX with Navigation 5dr hatchback '10	$ 23,100

	Honda Civic Hybrid CVT 4dr sedan '09	$ 23,650
	Honda Civic Hybrid CVT W/Leather 4dr sedan '09	$ 24,850
	Chevrolet Malibu Hybrid 1HY 4dr sedan '09	$ 25,555
	Honda Civic Hybrid CVT w/Navi 4dr sedan '09	$ 25,650
	Toyota Prius IV 4dr hatchback '10	$ 25,800
	Toyota Camry 2.4 Auto Hybrid 4dr sedan '10	$ 26,150
	Saturn Aura 2.4 Hybrid 4dr sedan '09	$ 26,325
	Nissan Altima 2.5 HEV Auto 4dr sedan '09	$ 26,650
	Honda Civic Hybrid CVT Leather w/Navi 4dr sedan '09	$ 26,850
	Toyota Prius V 4dr hatchback '10	$ 27,270
	Ford Fusion Hybrid 4dr sedan '10	$ 27,270

	Mercury Milan I4 Hybrid 4dr sedan '10	$ 27,500
	Saturn VUE Hybrid FWD 4dr sport utility vehicle '09	$ 28,160
	Mazda Tribute 2.5 Auto Touring HEV 4dr sport utility vehicle '09	$ 28,175
	Ford Escape Hybrid 2.5L 4dr sport utility vehicle '09	$ 29,645
	Mazda Tribute 2.5 Auto Touring 4wd HEV 4dr sport utility vehicle '09	$ 29,925
	Mercury Mariner Hybrid FWD 4dr sport utility vehicle '09	$ 30,090
	Mazda Tribute 2.5 Auto Grand Touring HEV 4dr sport utility vehicle '09	$ 30,695
	Ford Escape Hybrid 2.5L 4WD 4dr sport utility vehicle '09	$ 31,395
	Mercury Mariner Hybrid 4WD 4dr sport utility vehicle '09	$ 31,840
	Ford Escape Hybrid Limited 2.5L 4dr sport utility vehicle '09	$ 31,975
	Mazda Tribute 2.5 Auto Grand Touring 4wd HEV 4dr sport utility vehicle '09	$ 32,445

	Ford Escape Hybrid Limited 2.5L 4WD 4dr sport utility vehicle '09	$ 33,725
	Toyota Highlander Hybrid 4x4 4dr sport utility vehicle '09	$ 34,700
	Chevrolet Silverado 1500 1HY Hybrid Crew Cab 4dr pickup '09	$ 38,020
	GMC Sierra 1500 2WD Hybrid Crew Cab 3HA 4dr pickup '09	$ 38,390
	Toyota Highlander Limited Hybrid w/3rd Row Seat 4x4 4dr sport utility vehicle '09	$ 41,020
	Chevrolet Silverado 1500 1HY 4X4 Hybrid Crew Cab 4dr pickup '09	$ 41,170
	GMC Sierra 1500 4WD Hybrid Crew Cab 3HA 4dr pickup '09	$ 41,540
	Lexus RX 400h Hybrid 4dr sport utility vehicle '08	$ 42,080
	Lexus RX 400h Hybrid AWD 4dr sport utility vehicle '08	$ 43,480
	Chevrolet Silverado 1500 2HY Hybrid Crew Cab 4dr pickup '09	$ 44,155
	GMC Sierra 1500 2WD Hybrid Crew Cab 3HB 4dr pickup '09	$ 44,525

	Dodge Durango Limited HEV 4X4 4dr sport utility vehicle '09	$ 45,040
	Chrysler Aspen Limited HEV 4x4 4dr sport utility vehicle '09	$ 45,270
	Chevrolet Silverado 1500 2HY 4X4 Hybrid Crew Cab 4dr pickup '09	$ 47,305
	GMC Sierra 1500 4WD Hybrid Crew Cab 3HB 4dr pickup '09	$ 47,675
	Chevrolet Tahoe 2WD Hybrid 4dr sport utility vehicle '09	$ 50,455
	GMC Yukon 2WD Hybrid 4dr sport utility vehicle '09	$ 50,920
	Chevrolet Tahoe 4WD Hybrid 4dr sport utility vehicle '09	$ 53,260
	GMC Yukon 4WD Hybrid 4dr sport utility vehicle '09	$ 53,730
	Lexus GS 450h Hybrid 4dr sedan '09	$ 56,550
	Cadillac Escalade 2WD Hybrid 4dr sport utility vehicle '09	$ 73,135

	Cadillac Escalade AWD Hybrid 4dr sport utility vehicle '09	$ 75,685
	Cadillac Escalade 2WD Platinum Hybrid 4dr sport utility vehicle '09	$ 84,935
	Cadillac Escalade 4WD Platinum Hybrid 4dr sport utility vehicle '09	$ 87,435
	Lexus LS 5.0 AUTO 600h L 4dr sedan '09	$ 106,035
	Tesla Roadster 2dr roadster '09	$ 109,000
	Tesla Roadster Sport 2dr roadster '09	$ 128,500

Appendix C2. Selected comparisons of hybrids and conventional vehicles
(Jato Search engine, Automotive News Website, accessed 5/11/09)

Ford Escape Comparison

Ford Escape Hybrid Limited 2.5L 4WD 4dr sport utility vehicle '09
$ 33,725 MSRP

Ford Escape Limited 2.5L 4WD 4dr sport utility vehicle '09
$ 26,670 MSRP

The Ford Escape Hybrid Limited 2.5L 4WD 4dr sport utility vehicle '09 has the following advantages over the Ford Escape Limited 2.5L 4WD 4dr sport utility vehicle '09:
Comfort
✓ Climate control [Ford]
✓ Electric Sunroof [Ford]
✓ Audio system includes single CD [Ford]
✓ Heated driver's seat [Ford]
✓ Heated passenger seat [Ford]
Safety
✓ Parking distance sensors [Ford]
Engine / Suspension
✓ 5 more horsepower
✓ 4 more kW
✓ Number of speeds: variable
Dimensions
✓ 2 mm lower
✓ 0.1 in lower

The Ford Escape Limited 2.5L 4WD 4dr sport utility vehicle '09 has the following advantages over the Ford Escape Hybrid Limited 2.5L 4WD 4dr sport utility vehicle '09:
Key Differences
✓ $ 7,055 lower price
Comfort
✓ Audio system Disc Autochanger [Ford]
✓ Disc autochanger capacity
Exterior
✓ Wheel opening moldings
Engine / Suspension
✓ 35 lb ft more torque
✓ 48 Nm more torque
✓ 5 l larger fuel tank
✓ 1.4 gal larger fuel tank
Dimensions
✓ 142kg lower curb weight
✓ 16kg greater payload allowance
✓ 314 lb lower curb weight (lbs)
✓ 680kg higher braked gross trailer weight
✓ 1,500 lb higher braked gross trailer weight
✓ 8 l greater load area, seats down, to roof
✓ 0.3 cu ft greater load area, seats down, to roof
✓ 160 mm longer cargo area
✓ 213 mm wider cargo area
✓ 99 mm taller cargo area

Honda Civic Comparison

Honda Civic Hybrid CVT 4dr sedan '09
$ 23,650 MSRP

Honda Civic LX 4dr sedan '09
$ 19,062 ($ 1,607 of Options included)MSRP

Added as Option	
Deck Lid Spoiler (Dealer)	$ 387
16" Alloy Wheels (Dealer)	$ 1,220

The Honda Civic Hybrid CVT 4dr sedan '09 has the following advantages over the Honda Civic LX 4dr sedan '09:
Comfort
✔ Climate control
✔ Steering wheel mounted Remote audio controls
✔ 6 Speakers
✔ External temperature
✔ Automatic drive indicator on dashboard
✔ Computer
Safety
✔ Electronic traction control
✔ Brake assist system
✔ Stability control
✔ 4 Disc brakes
✔ Power locks includes trunk/hatch
✔ Variable intermittent wipe Windshield wipers
Engine / Suspension
✔ Number of speeds: variable
Dimensions
✔ 5 mm lower
✔ 0.2 in lower
✔ 183 mm smaller curb to curb turning circle
✔ 0.6 in smaller curb to curb turning circle (ft)

The Honda Civic LX 4dr sedan '09 has the following advantages over the Honda Civic Hybrid CVT 4dr sedan '09:
Key Differences
✔ $ 4,588 lower price
Exterior
✔ 16 in Wheels
✔ 10 mm wider Tires
✔ 10% lower profile Tires
✔ H tyre rating Tires
✔ 0.5 in wider wheel rims
Engine / Suspension
✔ 0.5 l larger engine
✔ 4 valves per cylinder
✔ 30 more horsepower
✔ 22 more kW
✔ 5 lb ft more torque
✔ 7 Nm more torque
✔ 3 l larger fuel tank
✔ 0.9 gal larger fuel tank
Dimensions
✔ 3 mm more shoulder room in front
✔ 0.1 in more shoulder room in front
✔ 3 mm more shoulder room in rear
✔ 0.1 in more shoulder room in rear
✔ 86kg lower curb weight
✔ 190 lb lower curb weight (lbs)

Toyota Highlander Comparison

Toyota Highlander Hybrid 4x4 4dr sport utility vehicle '09

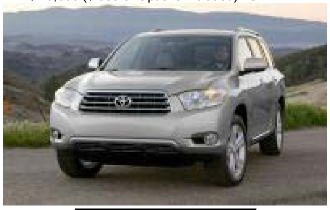
$ 34,920 ($ 220 of Options included)MSRP

Added as Option

Special Color $ 220

Toyota Highlander w/3rd Row Seat 4x4 V6 4dr sport utility vehicle '09

$ 29,605 ($ 555 of Options included)MSRP



Added as Option

Tow Package	$ 220
Molded Dash Applique (PIO)	$ 275
Immobilizer	$ 60

The Toyota Highlander Hybrid 4x4 4dr sport utility vehicle '09 has the following advantages over the Toyota Highlander w/3rd Row Seat 4x4 V6 4dr sport utility vehicle '09:
Comfort
Heated Door mirrors
External temperature
Computer
Wood/woodgrain Luxury trim on doors
Safety
Front and rear Roof airbag
Card key Power locks
Engine / Suspension
Number of speeds: variable
Comfort (Options)
Climate control
Electric trunk/hatch pull down
Rear Reading lights

The Toyota Highlander w/3rd Row Seat 4x4 V6 4dr sport utility vehicle '09 has the following advantages over the Toyota Highlander Hybrid 4x4 4dr sport utility vehicle '09:
Key Differences
$ 5,315 lower price
7 seating capacity
Comfort
Tachometer
Engine / Suspension
0.2 l larger engine
8 l larger fuel tank
2.0 gal larger fuel tank
Automatic transmission with multiple modes
Manual mode (auto only) Transmission
Full-time four wheel drive type
Dimensions
91 mm smaller curb to curb turning circle
0.3 in smaller curb to curb turning circle (ft)
8 mm greater headroom in rear
0.3 in greater headroom in rear
5 mm more hip room in rear
0.2 in more hip room in rear
5 mm more shoulder room in rear
0.2 in more shoulder room in rear
150kg lower curb weight
179kg greater payload allowance
330 lb lower curb weight (lbs)
680kg higher braked gross trailer weight
1,500 lb higher braked gross trailer weight
36 l greater load area, seats down, to roof
1.3 cu ft greater load area, seats down, to roof
Comfort (Options)
Rear air conditioner [Toyota]
Electric Sunroof
Audio system Disc Autochanger [Toyota]
Driver's seat with adjustable lumbar support [Toyota]
Electrically adjustable driver's seat [Toyota]
Exterior (Options)
Roof rails [Toyota]

Saturn Aura Comparison

Saturn Aura 2.4 Hybrid 4dr sedan '09
$ 26,325 MSRP

Saturn Aura 2.4 XE 4dr sedan '09
$ 22,655 MSRP

The Saturn Aura 2.4 Hybrid 4dr sedan '09 has the following advantages over the Saturn Aura 2.4 XE 4dr sedan '09:
Comfort
Climate control
Exterior
Alloy Wheels
Dimensions
427 mm smaller curb to curb turning circle
1.4 in smaller curb to curb turning circle (ft)
Comfort (Options)
Leather Seat upholstery

The Saturn Aura 2.4 XE 4dr sedan '09 has the following advantages over the Saturn Aura 2.4 Hybrid 4dr sedan '09:
Key Differences
$ 3,670 lower price
Exterior
Spacesaver Spare wheel
Engine / Suspension
5 more horsepower
4 more kW
1 lb ft more torque
1 Nm more torque
Number of speeds: 6
Manual mode (auto only) Transmission
Dimensions
39kg lower curb weight
87 lb lower curb weight (lbs)
Comfort (Options)
Heated driver's seat [Saturn]
Heated passenger seat [Saturn]

Lexus RS400Comparison

Lexus RX 400h Hybrid AWD 4dr sport utility vehicle '08
$ 43,480 MSRP

Lexus RX 350 AWD 4dr sport utility vehicle '10
$ 38,200 MSRP

The Lexus RX 400h Hybrid AWD 4dr sport utility vehicle '08 has the following advantages over the Lexus RX 350 AWD 4dr sport utility vehicle '10:
Exterior
Projector beam Headlights [Lexus]
Engine / Suspension
Number of speeds: variable
Dimensions
795 mm smaller curb to curb turning circle
2.6 in smaller curb to curb turning circle (ft)
8 mm greater headroom in front
0.3 in greater headroom in front
66kg lower curb weight
7kg greater payload allowance
145 lb lower curb weight (lbs)
681kg higher braked gross trailer weight
1,500 lb higher braked gross trailer weight
124 l greater load area, seats down, to roof
4.4 cu ft greater load area, seats down, to roof
Comfort (Options)
Leather Seat upholstery [Lexus]
DVD/VCD [Lexus]
Door mirror position Memorized adjustment [Lexus]
Steering wheel position Memorized adjustment [Lexus]
Wood/woodgrain Luxury trim on instrument panel
Safety (Options)
Rain sensor Windshield wipers [Lexus]

The Lexus RX 350 AWD 4dr sport utility vehicle '10 has the following advantages over the Lexus RX 400h Hybrid AWD 4dr sport utility vehicle '08:
Key Differences
$ 5,280 lower price
Comfort
Telescopic adjustment Steering wheel [Lexus]
9 Speakers
Rear Reading lights
Tachometer
Wood/woodgrain Luxury trim on doors
Electric adjustment Steering wheel [Lexus]
Safety
Card key Power locks
Exterior
18 in Wheels [Lexus]
10 mm wider Tires
5% lower profile Tires [Lexus]
1.0 in wider wheel rims
Engine / Suspension
0.2 l larger engine
7 more horsepower
5 more kW
8 l larger fuel tank
2.0 gal larger fuel tank
Automatic transmission with multiple modes
Dimensions
15 mm longer
0.6 in longer
41 mm wider
1.6 in wider
3 mm lower
0.1 in lower
26 mm longer wheelbase
1.0 in longer wheelbase
5 mm greater headroom in rear
0.2 in greater headroom in rear
18 mm more hip room in front
0.7 in more hip room in front
15 mm greater leg room in front
0.6 in greater leg room in front
10 mm greater leg room in rear
0.4 in greater leg room in rear
2 mm more shoulder room in front
0.1 in more shoulder room in front
13 mm more shoulder room in rear
0.5 in more shoulder room in rear
Comfort (Options)
Heated driver's seat [Lexus]
Heated passenger seat [Lexus]
Navigational systems [Lexus]
Exterior (Options)
Roof rails [Lexus]

Appendix C3. Model range analysis

To compare the hybrid coverage of the fleet of each manufacturer, the manufacturer's web sites were consulted (17/8/09) and then the data had to be processed to be sure of comparing like with like. First, only principal vehicles were included and these were taken from the web sites requesting "all vehicles". This step, for example, merges the front wheel and four wheel drive models of Ford's Escape into one model. Next, multiple body styles such as 4-and 5-door versions, coupes and convertibles were collapsed into one model as such modifications do not affect the power train. This step, for example, collapsed 4 versions of the Chevrolet Corvette into one model. Finally, the largest vehicles in GM's line-up, which includes vehicles such as two 15 passenger buses, were taken out as these vehicles go beyond the common definition of cars and light trucks used in the industry. The table below shows the models considered for each manufacturer with the actual number of hybrid and total models and the resulting percentage.

Manufacturer	2009/10 Conventional models	2009/10 Hybrid Models
GM 8/34 23.5 %	**Chevrolet** Aveo, Camaro, Cobalt, Colorado, Corvette, Equinox, HHR, Impala, Malibu, Silverado, Surburban, Tahoe, Traverse, Avalanche **Buick** Enclave, Lucerne, LaCrosse **Cadillac** CTS, STS, DTS, Escalade, Escalade EXT, SRX, XLR **Saturn** Aura, Sky, Astra, Vue, Outlook **GMC** Acadia, Sierra, Canyon, Envoy, Yukon	Malibu, Silverado 1500, Tahoe, Escalade, Saturn Vue, Saturn Aura, GMC Sierra, GMC Yukon
Ford 4/25 16.0%	**Ford** Focus, Fusion, Mustang, Taurus, Edge, Flex, Escape, Sport Trac, Explorer, Expedition, Ranger, F-150. Super Duty, E-Series **Lincoln** MKS, MKZ, MKX, MKT, Navigator, Town car **Mercury** Milan, Mariner, Sable, Mountaineer, Grand Marquis	Fusion, Escape, Mercury Milan, Mercury Mariner
Toyota 7/23 30.4%	**Toyota** Yaris, Corolla, Matrix, Camry, Pirus, Venza, Avalon, Tacoma, Tundra, Rav 4, FJ Cruiser, Highlander, 4Runner, Sequoia, Land Cruiser, Sienna **Lexus**, LS, IS, ES, GS GX, RX, LX	Prius, Camry, Highlander. Lexus LS, Lexus GS, Lexus HS, Lexus RX
Nissan 1/18 5.6 %	**Nissan** Cube, Versa, Sentra, Altima, Maxima, Z, GT-R, Quest, Rouge, Murano, Xterra, pathfinder, Armada, Frontier, Titan **Infiniti** G, M, FX, QX	Altima

Appendix D Seat Belt Data

1. Time line for major innovation and US regulations in Seat Belts
2. NHTSA Data set for rear seat belts
3. NHTSA Data set for pretensioners

Appendix D1 Time line for major innovation and US regulations in Seat Belts
(from http://www.andoauto.com accessed 6.6.09)

Seat belts were invented by George Cayley in the 1800s.
Seat belts were introduced in aircraft in 1913 by Adolphe Pegoud, the first man to fly a plane upside-down.
Edward J. Claghorn was granted U.S. Patent 312,085 on February 10, 1885 for a safety belt providing protection for a person ascending or descending a ladder or pole.
Edward J. Hock invented the safety belt first used by the Ford Motor Company as standard equipment. In 1955 his idea was accepted by the naval authorities. He was awarded $20.50 for his invention. He never received anything other than the $20.50, a letter of recognition and a newspaper article to his credit.

1930's
Several U.S. physicians equip their own cars with lap seat belts.

1954
Sports Car Club of America requires that competing drivers to wear lap seat belts.

1955
Society of Automotive Engineers (SAE) appoints Motor Vehicle Seat Belt Committee.

1956
Ford and Chrysler offer lap seat belts in front as an option on some models.

1958
Nils Bohlin, a design engineer with Volvo in Sweden, patents the "Basics of Proper Restraint Systems for Car Occupants," better known as a three-point safety belt. U.S. patent 3,043,625.

Volvo provides anchors for two-point diagonal belts in rear.

1959
Volvo offers three-point seat belts as a standard.
New York considers and rejects a bill to require seat belts in new cars sold in the State.

1961
SAE issues standard for U.S. seat belts.
New York and Wisconsin require seat belt anchors at front outboard seat positions.

1962
U.S. manufacturers provide seat belt anchors in front outboard positions as standard.

1963
Volvo introduces 3-point belt in front as standard in the USA.
Some U.S. manufacturers provide lap seat belts in front outboard positions.

1964
About half the U.S. States require seat belt anchorages at front outboard.

Most U.S. manufactures provide lap belts at front outboard seat positions.

1965
U.S. Commerce Department issues first seat belt standard.

All U.S. manufacturers providing lap belts in front outboard positions by this time.

Some U.S. manufacturers provide automatic locking retractors (ALRs) in front seat belts.

1966
U.S. Congress passes P.L. 89-593, establishing National Highway Safety Bureau, NHTSA.
The Sports Car Club of America requires competing drivers to wear a shoulder harness as well as a lap belt.

1967
U.S. manufacturers provide lap seat belts at rear outboard positions.

NHSB issues initial Federal Motor Vehicle Safety Standards 208, 209 setting standards for lap and shoulder seat belts in front outboard positions and lap seat belts in all other positions.

1971
NHTSA amends FMVSS 208 to require passive restraints in the front.

1972
NHTSA requires anchorages for detachable shoulder straps for rear outboard (FMVSS 210).

1974
NHTSA requires 3-point belt non-detachable shoulder straps in front outboard positions.
U.S. cars provide "vehicle-sensitive" ELRs in front outboard shoulder belts. The lap belt portion has ALR.

1985
New York makes belt use mandatory in front and rear (rear for persons 10 years or older).

1986
General Motors started installing lap seat belts with shoulder harness straps for rear outer seats *(this data contradicts NHTSA data and the GM web site which says that GM only announced its plans in 1986).*

1987
New York becomes the first state to require seat belts on large school buses.

1996
Seat belts required on minibuses and coaches carrying groups of children on organized trips.

2001
The state of California extends implementation of AB 15 that required lap/shoulder belts on all new school buses purchased after January 1, 2002. Retrofitting would not be permitted.

Appendix D2. NHTSA Data set for rear seat belts (1999)

Data taken from appendix A of DOT HS 808 945, NHTSA Technical Report Effectiveness of Lap/Shoulder Belts, dated June 1999

Data key:

- bkls MY first Model Year (MY) with standard back seat outboard lap/shoulder belts first MY first MY that this car or light truck existed
- last MY last MY that this car or light truck existed
- ABS MY first MY that Antilock Brake Systems (ABS) was standard or was sold on over 50 percent of cars
- airbag MY first MY that airbags were present on 50 percent or more of this make/model
- remod MY1 first major remodeling
- remod MY2 second major remodeling
- TY Transition Year (TY) to back seat lap/shoulder belts (usually same as bkls MY)
- YT± number of matching model years available before and after TY
- EXPLANATION OF CODES
- a always had back seat outboard lap/shoulder belts, ABS, or airbags depending on which
- column
- x in bkls MY column - never had back seat outboard lap/shoulder belts.
- x in TY, YT± column - excluded from “matching make/models”
- N/A excluded from analysis

make-model		bkls MY	first MY	last MY	ABS MY	airbag MY	remod MY1	remod MY2	TY	YT±
GENERAL MOTORS										
Buick	Regal	89	<85	>95	93	94	88		89	3
Buick	LeSabre	88	<85	>95	94	92	86		88	3
Buick	Estate Wagon	89	<85	91	91	91			89	2
Buick	Electra	89	<85	>95	91	91			89	2
Buick	Roadmaster	a	92	>95	a	a			x	x
Buick	Riviera	88	<85	>95	91	90	86	95	88	3
Buick	Skylark	x	<85	85					x	x
Buick	Skyhawk	89	<85	89					89	1
Buick	Century	89	<85	>95	94	93			89	3
Buick	Somerset/Skylark	89	85	>95	92	94			89	3
Buick	Reatta	N/A	88	91	a	90			x	x
Cadillac	DeVille	89	<85	>95	91	90	90	94	89	2
Fleetwood	D'Elegance	89	<85	>95	89	90	90	94	x(ABS.)	x
Fleetwood	Brougham	88	<85	>95	90/91?	93			88	2
Cadillac	Eldorado	88	<85	>95	91	90	86		88	3
Cadillac	Allante	N/A	87	93	a	90			x	x
Cadillac	Seville	88	<85	>95	91	90	86	92	88	3
Cadillac	Cimarron	x	<85	88					x	x
Chevrolet	Caprice	89	<85	95	91	91			89	2
Chevrolet	Corvette	N/A	<85	>95	86	90			x	x
Chevrolet	Camaro	89	<85	>95	93	90			89	3
Chevrolet	Monte Carlo	x	<85	88	88				x	x
Chevrolet	Chevette	x	<85	87					x	x
Chevrolet	Citation	x	<85	85					x	x
Chevrolet	Cavalier	89	<85	>95	92	95	95		89	3
Chevrolet	Celebrity	89	<85	90					89	2
Beretta/Corsica		88	87	>95	92	91			88	1
Chevrolet	Lumina	a	90	92	95				x	x
Chevrolet	Spectrum	89	85	89					89	1
Nova/Prizm		88	85	>95		93	89	93	88	3
Sprint/Metro		89	<85	>95		95	89		89	3
Geo	Storm	a	90	93		a			x	x
Chevrolet	Monte Carlo	a	95	>95	a	a			x	x
Cutlass	Supreme	89	<85	>95	93	94	88		89	3
Olds	Delta 88	88	<85	>95	94	92	86		88	3
Olds	Custom Cruiser	89	<85	91	91	91			89	2
Olds	98	89	<85	>95	91	91			89	2
Oldsmobile	Toronado	88	<85	92	91	90	86		88	3
Olds	Firenza	x	<85	88					x	x
Olds	Ciera	89	<85	>95	94	93			89	3
Olds	Calais	89	85	91					89	3
Olds	Achieva	a	92	95	a	94			x	x
Oldsmobile	Aurora	a	95	>95	a	a			x	x
Pontiac	Bonneville	88	85	>95	92	92	87		88	3
Parisienne/Safari		89	<85	89					89	1
Pontiac	Fiero	N/A	<85	88					x	x
Pontiac	Firebird	89	<85	>95	93	90			89	3
Pontiac	Grand Prix	89	<85	>95	93	94	88		89	3
Pontiac	T1000	x	<85	87					x	x
Pontiac	Sunbird/Sunfire	89	<85	>95	92	95	95		89	3
Pontiac	6000	89	<85	91					89	3
Pontiac	Grand Am	89	85	>95	92	94			89	3
Pontiac	LeMans	a	88	93					x	x
Saturn	SL sedan	a	91	>95	93				x	x
Saturn	SC coupe	a	91	>95	93				x	x
Saturn	SW wagon	a	93	>95	a				x	X

make-model		bkls MY	first MY	last MY	ABS MY	airbag MY	remod MY1	remod MY2	TY	YT±
FORD MOTOR COMPANY										
Ford	Mustang	90	<85	>95		90	94		90	3
Ford	Thunderbird	89	<85	>95		94	89		89	3
Ford	LTD	x	<85	86					x	x
Ford	Escort	91	<85	>95		94	90		91	3
Ford	EXP	x	<85	88					x	x
Ford	Tempo	90	<85	94					90	3
Ford	Crown Victoria	90	<85	>95		90			90	3
Ford	Taurus	88	86	>95		90			88	2
Ford	Probe	90	89	>95		93	93		90	1
Ford	Festiva	90	88	93					90	2
Ford	Contour	a	95	>95		a			x	x
Ford	Aspire	a	94	95		a			x	x
Lincoln	Town car	90	<85	>95	90	90			x(ABS.)	x
Lincoln	Mark7/8	90	<85	>95	86	90	93		90	3
Lincoln	Continental	88	<85	>95	86	89	88		88	2
Mercury	Capri	x	<85	86					x	x
Mercury	Cougar	89	<85	>95	94	89	89	3		
Mercury	Marquis	x	<85	86					x	x
Mercury	Lynx	x	<85	87					x	x
Mercury	Topaz	90	<85	94					90	3
Mercury	Grand Marquis	90	<85	>95		90			90	3
Mercury	Sable	88	86	>95		90			88	2
Mercury	Capri XR2	a	89	94		91			x	x
Mercury	Tracer	90	88	>95		94	91		90	3
Mercury	Mystique	a	95	>95		a			x	x
NISSAN										
Nissan	200-240SX	89	<85	>95		95	89	95	89	3
Nissan	300ZX	90	<85	>95	90	91	90		x(ABS.)	x
Nissan	Maxima	87	<85	>95		92	89	95	87	2
Nissan	Stanza	89	<85	92			86-87		89	3
Nissan	Sentra	90	<85	>95		93	87		90	3
Nissan	Pulsar/NX	90	<85	93		90	87	91	90	3
Nissan	Altima	a	93	>95		a			x	x
Nissan	Axxess	a	90	91					x	x
TOYOTA										
Toyota	Corolla	89	<85	>95		93	93		89	3
Toyota	Celica	89	<85	>95	90	87	94		89	3
Toyota	Supra	89	<85	>95	?	90	86	93	x(ABS.)	x
Toyota	Cressida	88	<85	92	?		86		88?	3?
Toyota	Tercel	89	<85	>95		94	87		89	3
Toyota	Camry	88	<85	>95		92	92		88	3
Toyota	MR-2	N/A	<85	>95		91	91		x	x
Toyota	Paseo	a	92	>95		94			x	x
Toyota	Avalon	a	95	>95		a			x	x
Lexus	ES-250/300	a	90	>95	a	a	92		x	x
Lexus	LS-400	a	90	>95	a	a	95		x	x
Lexus	SC-300/400	a	92	>95	a	a			x	x
Lexus	GS-300	a	93	>95	a	a			x	x

Appendix D2. NHTSA Data set for rear seat belts (2001-2010)

2001

Make	2001 Model	Pre.	Make	2001 Model	Pre.	Make	2001 Model	Pre.
01 Buick	Regal		Ford	F-150	S	Nissan	Maxima	S
Buick	Park Avenue		Ford	Club Wagon	S	Nissan	Quest	S
Buick	LeSabre		Ford	Crown Victoria	S	Nissan	Sentra	S
Buick	Century		Ford	Mustang		Nissan	Pathfinder	S
Cadillac	Deville		Ford	EV Ranger	S	Nissan	Pathfinder	S
Chevrolet	Monte Carlo		Ford	Econoline	S	Nissan	Frontier	S
Chevrolet	Cavalier		Ford	Windstar	S	Nissan	Xterra	S
Chevrolet	Impala		Ford	Explorer		Nissan	Altima	S
Chevrolet	Tahoe		Ford	Expedition	S	Nissan	Frontier	S
Chevrolet	S-10		Ford	Ranger	S	Nissan	Maxima	S
Chevrolet	Prizm	S	Ford	Focus	S	Infiniti	I30	S
Chevrolet	Suburban		Ford	Taurus	S	Infiniti	QX4	S
Chevrolet	Cavalier		Ford	Escape	S			
Chevrolet	Prizm	S	Ford	Escort				
Chevrolet	Tracker		Ford	Taurus	S	Toyota	Tacoma	S
Chevrolet	Silverado		Ford	Ranger	S	Toyota	Avalon	S
Chevrolet	Venture	S	Lincoln	LS	S	Toyota	Solara	S
Chevrolet	Malibu		Lincoln	Town Car	S	Toyota	Camry	S
Chevrolet	Blazer		Lincoln	Navigator	S	Toyota	4Runner	S
Chevrolet	Impala		Mercury	Sable	S	Toyota	Echo	S
Chevrolet	Astro		Mercury	Mountaineer		Toyota	Sienna	S
Chevrolet	Camaro		Mercury	Grand Marquis	S	Toyota	Corolla	S
Chevrolet	Lumina		Mercury	Mountaineer		Toyota	Prius	S
GMC	Safari		Mercury	Sable	S	Toyota	Corolla	S
GMC	Sonoma		Mercury	Cougar		Toyota	Tundra	S
GMC	Jimmy		Mercury	Villager	S	Toyota	RAV4	S
GMC	Yukon					Toyota	Celica	S
GMC	Sonoma					Lexus	RX300	S
GMC	Sierra					Lexus	IS300	S
Oldsmobile	Bravada					Lexus	ES300	S
Oldsmobile	Silhouette	S						
Oldsmobile	Alero							
Oldsmobile	Intrigue							
Oldsmobile	Aurora							
Plymouth	Neon							
Pontiac	Grand Prix							
Pontiac	Montana	S						
Pontiac	Grand Am							
Pontiac	Firebird							
Pontiac	Bonneville							
Pontiac	Sunfire							
Pontiac	Grand Am							
Pontiac	Aztek	S						
Pontiac	Sunfire							
Saturn	L							
Saturn	SL							

2002

Make	2002 Model	Pre.	Make	2002 Model	Pre.	Make	2002 Model	Pre.
Buick	Regal		Ford	Explorer	S	Nissan	Frontier	S
Buick	Century		Ford	Mustang		Nissan	Quest	S
Buick	LeSabre		Ford	EV Ranger	S	Nissan	Maxima	S
Buick	Century		Ford	Explorer Sport		Nissan	Pathfinder	S
Buick	Rendezvous		Ford	Thunderbird	S	Nissan	Xterra	S
Buick	Park Avenue		Ford	Expedition	S	Nissan	Pathfinder	S
Cadillac	Deville		Ford	F-150	S	Nissan	Sentra	S
Cadillac	Eldorado		Ford	F-150	S	Nissan	Altima	S
Cadillac	Seville		Ford	Focus	S	Nissan	Altra EV	
Cadillac	Escalade		Ford	Econoline	S	Infiniti	QX4	S
Chevrolet	Avalanche		Ford	Escort		Infiniti	Q45	S
Chevrolet	Cavalier		Ford	F-150	S	Infiniti	I35	S
Chevrolet	Express		Ford	Taurus	S	Infiniti	G20	S
Chevrolet	S-10		Ford	Escape	S			
Chevrolet	Blazer		Ford	Ranger	S	Toyota	Corolla	S
Chevrolet	Tahoe		Ford	ZX2		Toyota	RAV4	S
Chevrolet	Suburban		Ford	Crown Victoria	S	Toyota	Prius	S
Chevrolet	Prizm	S	Ford	Focus	S	Toyota	Celica	S
Chevrolet	Cavalier		Ford	Windstar	S	Toyota	RAV4 EV	S
Chevrolet	Monte Carlo		Ford	Taurus	S	Toyota	Sequoia	S
Chevrolet	Trailblazer		Ford	Ranger	S	Toyota	Tundra	S
Chevrolet	Blazer		Ford	Focus	S	Toyota	Echo	S
Chevrolet	Malibu		Ford	Windstar	S	Toyota	Solara	S
Chevrolet	Impala		Ford	Excursion	S	Toyota	MR2	S
Chevrolet	S-10		Ford	Continental		Toyota	Highlander	S
Chevrolet	Astro		Ford	LS	S	Toyota	Sienna	S
Chevrolet	Venture	S	Ford	Town Car	S	Toyota	Tacoma	S
Chevrolet	Tracker		Lincoln	Blackwood	S	Toyota	Avalon	S
Chevrolet	Camaro		Lincoln	Navigator	S	Toyota	Tundra	S
Chevrolet	Tracker		Lincoln	Cougar	S	Toyota	Camry	S
Chevrolet	Corvette		Lincoln	Sable	S	Toyota	4Runner	S
Chevrolet	Prizm	S	Lincoln	Mountaineer	S	Toyota	Solara	S
Chevrolet	Impala		Mercury	Sable	S	Toyota	Landcruiser	S
Chevrolet	Silverado		Mercury	Villager	S	Lexus	IS300	S
GMC	Yukon		Mercury	Grand Marquis	S	Lexus	GS300	S
GMC	Sierra		Mercury			Lexus	SC430	S
GMC	Safari		Mercury			Lexus	IS300	S
GMC	Savana		Mercury			Lexus	ES300	S
GMC	Envoy		Mercury			Lexus	LS430	S
GMC	Sonoma					Lexus	LX470	S
Oldsmobile	Bravada		Saturn	VUE		Lexus	RX300	S
Oldsmobile	Intrigue		Saturn	L-Series				
Oldsmobile	Alero		Saturn	SL				
Oldsmobile	Silhouette	S						
Oldsmobile	Aurora							
Pontiac	Bonneville							
Pontiac	Firebird							
Pontiac	Aztek							
Pontiac	Grand Am							
Pontiac	Sunfire							
Pontiac	Grand Prix							
Pontiac	Montana	S						

2003

Make	2003 Model	Pre.	Make	2003 Model	Pre.	Make	2003 Model	Pre.
Buick	LeSabre		Ford	Explorer	S	Nissan	Maxima	S
Buick	Regal		Ford	Taurus	S	Nissan	Altima	S
Buick	Century		Ford	Econoline	S	Nissan	Maxima	S
Buick	Regal		Ford	Ranger	S	Nissan	Pathfinder	S
Buick	Century		Ford	Windstar	S	Nissan	Murano	S
Buick	Park Avenue		Ford	Focus	S	Nissan	Frontier	S
Buick	Rendezvous		Ford	Explorer Sport	S	Nissan	Xterra	S
Cadillac	Seville	S	Ford	Focus	S	Nissan	Frontier	S
Cadillac	Escalade		Ford	Mustang		Nissan	350Z	S
Cadillac	Deville		Ford	Crown Victoria	S	Nissan	Pathfinder	S
Cadillac	CTS	S	Ford	Excursion	S	Nissan	Sentra	S
Chevrolet	Tracker	S	Ford	Mustang		Infiniti	QX4	S
Chevrolet	Venture	S	Ford	Ranger	S	Infiniti	FX45	S
Chevrolet	Corvette		Ford	Taurus	S	Infiniti	G35	S
Chevrolet	SSR		Ford	F-150	S	Infiniti	Q45	S
Chevrolet	Impala		Ford	Expedition	S	Infiniti	M45	S
Chevrolet	Blazer		Ford	ZX2		Infiniti	I35	S
Chevrolet	Silverado		Ford	Thunderbird	S			
Chevrolet	Tahoe		Ford	Escape	S	Toyota	4Runner	S
Chevrolet	Express		Ford	Taurus	S	Toyota	Matrix	S
Chevrolet	Impala		Lincoln	Navigator	S	Toyota	Corolla	S
Chevrolet	Cavalier		Lincoln	Blackwood	S	Toyota	Avalon	S
Chevrolet	Trailblazer		Lincoln	Aviator	S	Toyota	Sienna	S
Chevrolet	Astro		Lincoln	LS	S	Toyota	Echo	S
Chevrolet	Tracker	S	Lincoln	Town Car	S	Toyota	Echo	S
Chevrolet	Malibu		Mercury	Sable	S	Toyota	Tundra	S
Chevrolet	Avalanche		Mercury	Mountaineer	S	Toyota	Matrix	S
Chevrolet	S-10		Mercury	Grand Marquis	S	Toyota	Prius	S
Chevrolet	Suburban		Mercury	Marauder		Toyota	MR2	S
GMC	Yukon					Toyota	Landcruiser	S
GMC	Savana		Pontiac	Vibe	S	Toyota	Highlander	S
GMC	Sierra		Pontiac	Sunfire		Toyota	RAV4	S
GMC	Sonoma		Pontiac	Grand Prix		Toyota	Solara	S
GMC	Safari		Pontiac	Montana	S	Toyota	Solara	S
GMC	Envoy		Pontiac	Aztek		Toyota	Camry	S
GMC	Sonoma		Pontiac	Grand Am		Toyota	Celica	S
Oldsmobile	Alero		Pontiac	Bonneville		Lexus	LS430	S
Oldsmobile	Silhouette	S				Lexus	SC430	S
Oldsmobile	Aurora					Lexus	LX470	S
Oldsmobile	Bravada		Toyota	Tacoma	S	Lexus	ES300	S
Saturn	L-Series		Toyota	Tundra	S	Lexus	GX470	S
Saturn	VUE		Toyota	RAV4 EV	S	Lexus	IS300	S
Saturn	Ion	S	Toyota	Sequoia	S	Lexus	GS300	S
			Toyota	Tacoma	S	Lexus	RX300	S

2004

Make	2004 Model	Pre.	Make	2004 Model	Pre.	Make	2004 Model	Pre.
04 Buick	Regal		Ford	F-150	S	Nissan	Altima	S
Buick	Rendezvous	S	Ford	Crown Victoria	S	Nissan	Quest	S
Buick	Rainier		Ford	Explorer	S	Nissan	Sentra	S
Buick	Century		Ford	Mustang		Nissan	Xterra	S
Buick	Park Avenue		Ford	Focus	S	Nissan	Frontier	S
Buick	LeSabre		Ford	Freestar	S	Nissan	Murano	S
Cadillac	CTS	S	Ford	Explorer Sport Trac	S	Nissan	Titan	S
Cadillac	Escalade		Ford	Ranger	S	Nissan	Pathfinder	S
Cadillac	Deville		Ford	Taurus	S	Nissan	Maxima	S
Cadillac	XLR	S	Ford	Expedition	S	Nissan	350Z	S
Cadillac	Seville		Ford	Escape	S	Nissan	Frontier	S
Cadillac	SRX	S	Ford	Econoline	S	Nissan	Titan	S
Chevrolet	Silverado		Ford	Crown Victoria	S	Nissan	Armada	S
Chevrolet	Monte Carlo		Ford	Thunderbird	S	Infiniti	FX35/45	S
Chevrolet	Blazer		Lincoln	Aviator	S	Infiniti	Q45	S
Chevrolet	Cavalier		Lincoln	Town Car	S	Infiniti	M45	S
Chevrolet	SSR	S	Lincoln	Navigator	S	Infiniti	I35	S
Chevrolet	Suburban	SF	Lincoln	LS	S	Infiniti	G35	S
Chevrolet	Tracker		Mercury	Grand Marquis	S			
Chevrolet	Colorado	S	Mercury	Mountaineer	S	Toyota	4Runner	S
Chevrolet	Classic		Mercury	Sable	S	Toyota	Tundra	S
Chevrolet	Impala		Mercury	Monterey	S	Toyota	Tacoma	S
Chevrolet	Malibu	S	Mercury	Grand Marquis	S	Toyota	RAV4	S
Chevrolet	Tahoe		Mercury	Marauder	S	Toyota	Prius	S
Chevrolet	Astro					Toyota	Sequoia	S
Chevrolet	Avalanche		Pontiac	Bonneville		Toyota	Scion xA	S
Chevrolet	Express		Pontiac	Sunfire		Toyota	Sienna	S
Chevrolet	Trailblazer EXT		Pontiac	Aztek		Toyota	Landcruiser	S
Chevrolet	Corvette		Pontiac	Grand Am		Toyota	Corolla	S
Chevrolet	Impala		Pontiac	Vibe	S	Toyota	Celica	S
Chevrolet	Trailblazer		Pontiac	Grand Prix	S	Toyota	Solara	S
Chevrolet	Venture	S	Pontiac	GTO	S	Toyota	Camry	S
Chevrolet	Aveo	S	Pontiac	Montana	S	Toyota	Tacoma	S
GMC	Sierra					Toyota	Tacoma	S
GMC	Envoy					Toyota	Solara	S
GMC	Canyon	S				Toyota	Scion xB	S
GMC	Sonoma					Lexus	IS300	S
GMC	Yukon		Toyota	Tundra	S	Lexus	IS300 Sportcross	S
GMC	Safari		Toyota	Avalon	S	Lexus	RX330	S
GMC	Savana		Toyota	Highlander	S	Lexus	GX470	S
Oldsmobile	Bravada		Toyota	Echo	S	Lexus	GS300	S
Oldsmobile	Silhouette	S	Toyota	Echo	S	Lexus	LX470	S
Oldsmobile	Bravada		Toyota	MR2	S	Lexus	LS430	S
Oldsmobile	Alero		Toyota	Matrix	S	Lexus	ES330	S
Saturn	VUE	S	Toyota	Tundra	S	Lexus	SC430	S
Saturn	L-Series							
Saturn	Ion	S						

2005

Make	2005 Model	Pre.	Make	2005 Model	Pre.	Make	2005 Model	Pre.
Buick	Terraza	SF	Ford	Explorer	SF	Nissan	350Z	SF
Buick	Century		Ford	F-150	SF	Nissan	Altima	SF
Buick	Rainier	SF	Ford	Escape Hybrid	SF	Nissan	Armada	SF
Buick	Park Avenue		Ford	Mustang	SF	Nissan	Maxima	SF
Buick	Rendezvous	SF	Ford	Thunderbird	SF	Nissan	Frontier	S
Buick	LeSabre		Ford	Taurus	SF	Nissan	Titan	S
Buick	LaCrosse	SF	Ford	Crown Victoria	SF	Nissan	Pathfinder	SF
Buick	Terraza	SF	Ford	Focus	SF	Nissan	Murano	SF
Cadillac	SRX	SF	Ford	Escape		Nissan	Quest	S
Cadillac	STS	SF	Ford	Crown Victoria	SF	Nissan	Sentra	SF
Cadillac	Deville		Ford	Taurus	SF	Nissan	Xterra	SF
Cadillac	XLR	SF	Ford	Focus	SF	Infiniti	G35 Coupe	SF
Cadillac	Escalade		Ford	Mustang	SF	Infiniti	G35 Sedan	SF
Cadillac	CTS	SF	Ford	Expedition	SF	Infiniti	Q45	SF
Chevrolet	Tahoe		Ford	Ranger	SF	Infiniti	QX56	SF
Chevrolet	Cobalt		Ford	Freestar	SF	Infiniti	FX35/45	SF
Chevrolet	Trailblazer	SF	Ford	GT	SF			
Chevrolet	Tahoe		Ford	Excursion		Toyota	Highlander	SF
Chevrolet	Malibu	SF	Ford	Five Hundred	SF	Toyota	Tacoma	SF
Chevrolet	Uplander	SF	Ford	Freestyle		Toyota	Scion tC	SF
Chevrolet	Classic		Ford	LS	SF	Toyota	Scion xA	SF
Chevrolet	Cavalier		Ford	Town Car	SF	Toyota	4Runner	SF
Chevrolet	Silverado		Ford	Navigator	SF	Toyota	Scion xB	SF
Chevrolet	Avalanche		Ford	Aviator	SF	Toyota	Sequoia	SF
Chevrolet	Uplander	SF	Ford	Mountaineer	SF	Toyota	Celica	SF
Chevrolet	Colorado	SF	Lincoln	Montego		Toyota	Landcruiser	SF
Chevrolet	Silverado		Lincoln	Grand Marquis	SF	Toyota	Corolla	SF
Chevrolet	SSR		Lincoln	Sable	SF	Toyota	Echo	SF
Chevrolet	Corvette	SF	Lincoln	Monterey	SF	Toyota	Tundra	SF
Chevrolet	Express		Mercury	Mariner		Toyota	Avalon	SF
Chevrolet	Impala		Mercury	Sable	SF	Toyota	Tundra	SF
Chevrolet	Aveo	SF	Mercury			Toyota	Matrix	SF
Chevrolet	Cobalt		Mercury			Toyota	MR2	SF
Chevrolet	Astro		Mercury			Toyota	Solara	SF
Chevrolet	Equinox	SF	Mercury			Toyota	Prius	SF
Chevrolet	Impala		Mercury			Toyota	RAV4	SF
Chevrolet	Monte Carlo		Mercury			Toyota	Sienna	SF
Chevrolet	Express 3500 15 Passenger					Toyota	Tacoma	SF
Chevrolet	Suburban		Pontiac	Grand Prix	SF	Toyota	Camry	SF
Chevrolet	Venture	SF	Pontiac	Montana	SF	Toyota	Tundra	SF
Chevrolet	Blazer		Pontiac	Sunfire		Lexus	GS300/430	SF
GMC	Yukon		Pontiac	G6	SF	Lexus	GX470	SF
GMC	Safari		Pontiac	Aztek		Lexus	RX400h	SF
GMC	Envoy	SF	Pontiac	Bonneville		Lexus	RX330	SF
GMC	Sierra		Pontiac	Grand Am		Lexus	LX470	SF
GMC	Canyon	SF	Pontiac	Vibe	SF	Lexus	LS430	SF
GMC	Savana		Pontiac	Montana SV6	SF	Lexus	ES330	SF
Saturn	Relay	SF	Pontiac	GTO	SF	Lexus	IS300 Sportcross	SF
Saturn	VUE	SF	Pontiac	G6	SF	Lexus	SC430	SF
Saturn	L-Series		Pontiac	Montana SV6	SF	Lexus	IS300	SF
Saturn	Ion	SF						

2006

Make	2006 Model	Pre.	Make	2006 Model	Pre.	Make	2006 Model	Pre.
Buick	LaCrosse	SF	Ford	Fusion	SF	Nissan	Murano	SF
Buick	Terraza	SF	Ford	F-150	SF	Nissan	Titan	SF
Buick	Lucerne	SF	Ford	Five Hundred	SF	Nissan	Frontier	SF
Buick	Rendezvous	SF	Ford	Crown Victoria	SF	Nissan	Armada	SF
Buick	Rainier	SF	Ford	Crown Victoria	SF	Nissan	350Z	SF
Cadillac	DTS	SF	Ford	Ranger	SF	Nissan	Titan	SF
Cadillac	XLR	SF	Ford	Mustang	SF	Nissan	Maxima	SF
Cadillac	CTS	SF	Ford	Five Hundred	SF	Nissan	Frontier	SF
Cadillac	Escalade		Ford	Ranger	SF	Nissan	Pathfinder	SF
Cadillac	STS	SF	Ford	Taurus	SF	Nissan	Altima	SF
Cadillac	SRX	SF	Ford	E-350 15 Passenger	SF	Nissan	Quest	SF
Chevrolet	Colorado	SF	Ford	Focus	SF	Nissan	Xterra	SF
Chevrolet	Uplander	SF	Ford	Focus	SF	Nissan	Sentra	SF
Chevrolet	Express 3500 15 Passenger	SF	Ford	Taurus	SF	Infiniti	QX56	SF
Chevrolet	Aveo	SF	Ford	Freestyle	SF	Infiniti	FX35/45	SF
Chevrolet	Tahoe		Ford	Escape Hybrid	SF	Infiniti	M35/45	SF
Chevrolet	Trailblazer	SF	Ford	F-150	SF	Infiniti	G35 Coupe	SF
Chevrolet	Malibu	SF	Ford	Freestar	SF	Infiniti	Q45	SF
Chevrolet	Express	SF	Ford	E-150	SF	Infiniti	G35 Sedan	SF
Chevrolet	Silverado		Ford	F-150	SF	Toyota	Tacoma	SF
Chevrolet	Suburban		Ford	Explorer	SF	Toyota	Solara	SF
Chevrolet	HHR	SF	Ford	Freestyle	SF	Toyota	Tundra	SF
Chevrolet	Equinox	SF	Ford	Escape	SF	Toyota	RAV4	SF
Chevrolet	SSR	SF	Ford	Expedition	SF	Toyota	Scion xB	SF
Chevrolet	Corvette	SF	Ford	GT	SF	Toyota	Sequoia	SF
Chevrolet	Monte Carlo	SF	Lincoln	LX470	SF	Toyota	Tacoma	SF
Chevrolet	Cobalt	SF	Lincoln	Mark LT	SF	Toyota	4Runner	SF
Chevrolet	Monte Carlo	SF	Lincoln	LS	SF	Toyota	Landcruiser	SF
Chevrolet	Impala	SF	Lincoln	Navigator	SF	Toyota	Scion tC	SF
Chevrolet	Colorado	SF	Lincoln	Zephyr	SF	Toyota	Scion xA	SF
Chevrolet	Avalanche		Mercury	Grand Marquis	SF	Toyota	Sienna	SF
GMC	Fusion	SF	Mercury	Grand Marquis	SF	Toyota	Tacoma	SF
GMC	Savana	SF	Mercury	Mariner Hybrid	SF	Toyota	Tundra	SF
GMC	Canyon	SF	Mercury	Mountaineer	SF	Toyota	Matrix	SF
GMC	Sierra		Mercury	Milan	SF	Toyota	Prerunner	SF
GMC	Yukon		Mercury	Mariner	SF	Toyota	Prius	SF
GMC	Envoy XL	SF	Mercury	Montego	SF	Toyota	Tundra	SF
Pontiac	G6	SF	Mercury	Montego	SF	Toyota	RAV4	SF
Pontiac	Grand Prix	SF	Mercury	Milan	SF	Toyota	Avalon	SF
Pontiac	Solstice	SF	Mercury	Monterey	SF	Toyota	Camry	SF
Pontiac	G6	SF				Toyota	Corolla	SF
Pontiac	GTO	SF				Toyota	Highlander	SF
Pontiac	Torrent	SF				Toyota	Prerunner	SF
Pontiac	Montana SV6	SF				Toyota	Highlander Hybrid	SF
Pontiac	Vibe	SF				Lexus	Envoy	SF
Saturn	VUE	SF				Lexus	IS250/350	SF/SR
Saturn	Ion	SF				Lexus	RX400h	SF
Saturn	Relay	SF				Lexus	GS300/430	SF/SR
Saturn	Ion	SF				Lexus	GX470	SF
						Lexus	RX330	SF
						Lexus	LS430	SF/SR
						Lexus	ES330	SF/SR
						Lexus	SC430	SF

2007

Make	2007 Model	Pre.	Make	2007 Model	Pre.	Make	2007 Model	Pre.
Buick	Lucerne	SF	Ford	F-150	SF	Nissan	Sentra	SF
Buick	Terraza	SF	Ford	Freestar	SF	Nissan	Pathfinder	SF
Buick	Rendezvous	SF	Ford	Focus	SF	Nissan	Frontier	SF
Buick	Rainier	SF	Ford	E-150	SF	Nissan	Maxima	SF
Buick	LaCrosse	SF	Ford	Focus	SF	Nissan	Titan	SF
Cadillac	Escalade	SF	Ford	Ranger	SF	Nissan	Frontier	SF
Cadillac	STS	SF	Ford	Taurus	SF	Nissan	Versa	SF
Cadillac	CTS	SF	Ford	Freestyle	SF	Nissan	Altima	SF
Cadillac	DTS	SF	Ford	Edge	SF	Nissan	Quest	SF
Cadillac	XLR	SF	Ford	Five Hundred	SF	Nissan	350Z Roadster	SF
Cadillac	STS	SF	Ford	Fusion	SF	Nissan	Versa	SF
Cadillac	SRX	SF	Ford	Freestyle	SF	Nissan	Murano	SF
Chevrolet	Trailblazer	SF	Ford	Crown Victoria	SF	Nissan	Xterra	SF
Chevrolet	Equinox	SF	Ford	E-350 15 Passenger	SF	Nissan	Titan	SF
Chevrolet	Monte Carlo	SF	Ford	Escape	SF	Nissan	Armada	SF
Chevrolet	Cobalt	SF	Ford	Mustang	SF	Nissan	350Z	SF
Chevrolet	Tahoe	SF	Ford	Explorer	SF	Infiniti	M35/45	SF
Chevrolet	Avalanche	SF	Ford	Ranger	SF	Infiniti	G35 Coupe	SF
Chevrolet	Malibu	SF	Ford	Expedition	SF	Infiniti	QX56	SF
Chevrolet	Cobalt	SF	Ford	Escape Hybrid	SF	Infiniti	FX35/45	SF
Chevrolet	Express 3500 15 Passenger		Ford	Crown Victoria	SF	Infiniti	G35 Sedan	SF
Chevrolet	Corvette	SF	Ford	Taurus	SF			
Chevrolet	Suburban	SF	Lincoln	MKX	SF			
Chevrolet	Silverado	SF	Lincoln	Mark LT	SF			
Chevrolet	Monte Carlo	SF	Lincoln	Town Car	SF			
Chevrolet	Aveo	SF	Lincoln	MKZ	SF			
Chevrolet	Impala	SF	Lincoln	Navigator	SF			
Chevrolet	Malibu Maxx	SF	Mercury	Mariner Hybrid	SF	Toyota	Tacoma	SF
Chevrolet	HHR	SF	Mercury	Grand Marquis	SF	Toyota	4Runner	SF
Chevrolet	Silverado	SF	Mercury	Milan	SF	Toyota	Scion tC	SF
Chevrolet	Express	SF	Mercury	Monterey	SF	Toyota	Solara	SF
Chevrolet	Uplander	SF	Mercury	Montego	SF	Toyota	Yaris	SF
Chevrolet	Colorado	SF	Mercury	Mountaineer	SF	Toyota	Sienna	SF
GMC	Envoy	SF	Mercury	Mariner	SF	Toyota	Camry	SF
GMC	Savana	SF	Mercury	Grand Marquis	SF	Toyota	RAV4	SF
GMC	Sierra	SF				Toyota	Corolla	SF
GMC	Canyon	SF	Saturn	Outlook	SF	Toyota	Highlander	SF
GMC	Yukon	SF	Saturn	Relay	SF	Toyota	FJ Cruiser	SF
GMC	Sierra	SF	Saturn	Aura	SF	Toyota	Matrix	SF
GMC	Acadia	SF	Saturn	Ion	SF	Toyota	Matrix	SF
GMC	Savana 3500 15 Passenger		Saturn	Sky	SF	Toyota	Tundra	SF
Pontiac	G5	SF	Saturn	VUE	SF	Lexus	GS350/430	SF
Pontiac	G6	SF				Lexus	RX400h	SF
Pontiac	Vibe	SF	Toyota	Prius	SF	Lexus	SC430	SF
Pontiac	Grand Prix	SF	Toyota	Tundra	SF	Lexus	LX470	SF
Pontiac	G5	SF	Toyota	Avalon	SF	Lexus	IS250/350	SF/SR
Pontiac	Torrent	SF	Toyota	Camry Hybrid	SF	Lexus	RX350	SF
Pontiac	Vibe	SF	Toyota	Landcruiser	SF	Lexus	GX470	SF
Pontiac	Solstice	SF	Toyota	Sequoia	SF	Lexus	GS450h	SF
Pontiac	G6	SF	Toyota	Highlander Hybrid	SF	Lexus	LS460/460L	SF
			Toyota	Tacoma	SF	Lexus	ES350	SF

2008

Make	2008 Model	Pre.	Make	2008 Model	Pre.	Make	2008 Model	Pre.
Buick	Lucerne	SF	Ford	Expedition	SF	Nissan	Rogue	SF
Buick	Enclave	SF	Ford	Escape	SF	Nissan	Versa Hatchback	SF
Buick	LaCrosse	SF	Ford	F-150	SF	Nissan	Altima Hybrid	SF
Cadillac	CTS	SF	Ford	Crown Victoria	SF	Nissan	Altima	SF
Cadillac	XLR	SF	Ford	E-350 12 Passenger	SF	Nissan	350Z Roadster	SF
Cadillac	SRX	SF	Ford	Ranger	SF	Nissan	Sentra	SF
Cadillac	DTS	SF	Ford	Escape Hybrid	SF	Nissan	350Z	SF
Cadillac	Escalade	SF	Ford	Taurus X	SF	Nissan	Altima	SF
Cadillac	STS	SF	Ford	Edge	SF	Nissan	Quest	SF
Chevrolet	Colorado	SF	Ford	F-350	SF	Nissan	Titan	SF
Chevrolet	Tahoe Hybrid	SF	Ford	Taurus	SF	Nissan	Maxima	SF
Chevrolet	Tahoe	SF	Ford	Focus	SF	Nissan	Frontier	SF
Chevrolet	Silverado	SF	Ford	F-250	SF	Nissan	Versa	SF
Chevrolet	Malibu Hybrid	SF	Ford	Explorer	SF	Nissan	Armada	SF
Chevrolet	Malibu	SF	Ford	Mustang	SF	Nissan	Frontier	SF
Chevrolet	Trailblazer	SF	Ford	Fusion	SF	Nissan	Xterra	SF
Chevrolet	Uplander	SF	Ford	F-250	SF	Nissan	Titan	SF
Chevrolet	Express Cargo		Ford	Crown Victoria	SF	Nissan	Pathfinder	SF
Chevrolet	Express 1500 Cargo	SF	Ford	F-350	SF	Infiniti	G35	SF
Chevrolet	Avalanche	SF	Lincoln	MKX	SF	Infiniti	FX35/45	SF
Chevrolet	HHR	SF	Lincoln	MKZ	SF	Infiniti	M35/45	SF
Chevrolet	Impala	SF	Lincoln	Navigator	SF	Infiniti	QX56	SF
Chevrolet	Suburban	SF	Lincoln	MKZ	SF	Infiniti	G37	SF
Chevrolet	Express 3500 15 Passenger	SF	Lincoln	Mark LT	SF	Infiniti	EX35	SF
Chevrolet	Aveo	SF	Lincoln	Town Car	SF			
Chevrolet	Cobalt	SF	Lincoln	Navigator	SF	Toyota	Camry	SF
Chevrolet	Equinox	SF	Mercury	Mariner Hybrid	SF	Toyota	Tacoma	SF
Chevrolet	Corvette	SF	Mercury	Sable	SF	Toyota	Sienna	SF
GMC	Sierra	SF	Mercury	Mountaineer	SF	Toyota	RAV4	SF
GMC	Yukon Hybrid	SF	Mercury	Milan	SF	Toyota	Prius	SF
GMC	Yukon	SF	Mercury	Mariner	SF	Toyota	Matrix	SF
GMC	Savana Cargo 3500		Mercury	Grand Marquis	SF	Toyota	Scion xB	SF
GMC	Savana Passenger 1500	SF	Mercury	Mariner Hybrid	SF	Toyota	Matrix	SF
GMC	Savana Cargo 2500					Toyota	Scion xD	SF
GMC	Savana Cargo 1500	SF	Saturn	VUE	SF	Toyota	Corolla	SF
GMC	Acadia	SF	Saturn	Aura	SF	Toyota	Scion tC	SF
GMC	Canyon	SF	Saturn	Outlook	SF	Toyota	Landcruiser	SF/SR
GMC	Sierra	SF	Saturn	Sky	SF	Toyota	Sequoia	SF
GMC	Envoy	SF	Saturn	Astra	SF	Toyota	Yaris Liftback	SF
Pontiac	Vibe	SF	Saturn	VUE Hybrid	SF	Toyota	Highlander Hybrid	SF
Pontiac	G6	SF	Saturn	Aura Hybrid	SF	Toyota	Solara	SF
Pontiac	G5	SF				Lexus	IS250/350	SF/SR
Pontiac	G6	SF				Lexus	LS460/460L	SF/SR
Pontiac	G8	SF	Toyota	Tacoma	SF	Lexus	LS600hL	SF/SR
Pontiac	Torrent	SF	Toyota	Tundra	SF	Lexus	ES350	SF/SR
Pontiac	Solstice	SF	Toyota	Avalon	SF	Lexus	IS F	SF/SR
Pontiac	Vibe	SF	Toyota	Highlander	SF	Lexus	SC430	SF
Pontiac	Grand Prix	SF	Toyota	Yaris	SF	Lexus	GS450h	SF/SR
			Toyota	Camry Hybrid	SF	Lexus	GX470	SF
			Toyota	FJ Cruiser	SF	Lexus	RX400h	SF
			Toyota	Tundra	SF	Lexus	RX350	SF
			Toyota	4Runner	SF	Lexus	GS350/460	SF/SR
			Toyota	Tundra	SF	Lexus	LX570	SF/SR

2009

Make	2009 Model	Pre.	Make	2009 Model	Pre.	Make	2009 Model	Pre.
09 Buick	Lucerne	SF	Ford	Fusion	SF	Nissan	Sentra	SF
Buick	LaCrosse	SF	Ford	Crown Victoria	SF	Nissan	Titan	SF
Buick	Enclave	SF	Ford	Mustang	SF	Nissan	Versa	SF
Cadillac	CTS	SF	Ford	Escape Hybrid	SF	Nissan	Murano	SF
Cadillac	STS	SF	Ford	Expedition	SF	Nissan	Pathfinder	SF
Cadillac	CTS - V	SF	Ford	E-150	SF	Nissan	Armada	SF
Cadillac	DTS	SF	Ford	E-350 15 Passenger	SF	Nissan	Rogue	SF
Cadillac	Escalade	SF	Ford	F-250		Nissan	350Z Roadster	SF
Cadillac	XLR	SF	Ford	Edge	SF	Nissan	Xterra	SF
Cadillac	SRX	SF	Ford	Escape	SF	Nissan	Altima	SF
Chevrolet	Malibu	SF	Ford	Focus	SF	Nissan	GT-R	SF
Chevrolet	Aveo	SF	Ford	Taurus	SF	Nissan	Altima	SF
Chevrolet	Cobalt	SF	Ford	Taurus X	SF	Nissan	Altima Hybrid	SF
Chevrolet	Traverse	SF	Ford	Ranger	SF	Nissan	Maxima	SF
Chevrolet	Silverado	SF	Ford	Explorer	SF	Nissan	Cube	SF
Chevrolet	Express 1500 Cargo	SF	Ford	Explorer Sport Trac	SF	Nissan	Frontier	SF
Chevrolet	Malibu Hybrid	SF	Ford	E-350 12 Passenger	SF	Nissan	370Z	SF
Chevrolet	Trailblazer	SF	Ford	Expedition	SF	Nissan	Quest	SF
Chevrolet	Corvette	SF	Ford	F-350		Infiniti	FX35/50	SF
Chevrolet	Express 3500 12 Passenger		Ford	Flex	SF	Infiniti	EX35	SF
Chevrolet	Express 2500 12 Passenger		Lincoln	MKX	SF	Infiniti	QX56	SF
Chevrolet	Silverado	SF	Lincoln	Navigator	SF	Infiniti	G37	SF
Chevrolet	Suburban	SF	Lincoln	MKS	SF	Infiniti	M35/45	SF
Chevrolet	Avalanche	SF	Lincoln	Town Car	SF			
Chevrolet	Silverado Hybrid	SF	Lincoln	Navigator	SF			
Chevrolet	Colorado	SF	Lincoln	MKS	SF			
Chevrolet	Equinox	SF	Lincoln	MKZ	SF			
Chevrolet	Express 1500 Passenger	SF	Mercury	Mountaineer	SF			
Chevrolet	Tahoe	SF	Mercury	Milan	SF			
Chevrolet	Tahoe Hybrid	SF	Mercury	Sable	SF			
Chevrolet	HHR	SF	Mercury	Mariner	SF	Toyota	Tacoma	SF
Chevrolet	Impala	SF	Mercury	Mariner Hybrid	SF	Toyota	Camry	SF
GMC	Envoy	SF	Mercury	Grand Marquis	SF	Toyota	Sienna	SF
GMC	Sierra Hybrid	SF				Toyota	Sequoia	SF
GMC	Sierra	SF	Saturn	Astra	SF	Toyota	Scion xD	SF
GMC	Acadia	SF	Saturn	VUE Hybrid	SF	Toyota	RAV4	SF
GMC	Savana Cargo 1500	SF	Saturn	Aura	SF	Toyota	Prius	SF
GMC	Savana 3500 15 Passenger		Saturn	Sky	SF	Toyota	Landcruiser	SF/SR
GMC	Savana Passenger 1500	SF	Saturn	VUE	SF	Toyota	Highlander	SF
GMC	Yukon	SF	Saturn	Outlook	SF	Toyota	Camry Hybrid	SF
GMC	Sierra Hybrid	SF	Saturn	Aura Hybrid	SF	Toyota	Tacoma	SF
GMC	Canyon	SF				Lexus	SC430	SF
GMC	Yukon Hybrid	SF	Toyota	Avalon	SF	Lexus	IS F	SF/SR
GMC	Savana 2500 12 Passenger		Toyota	Highlander Hybrid	SF	Lexus	IS250/350	SF/SR
Pontiac	Vibe	SF	Toyota	4Runner	SF	Lexus	GS350/460	SF/SR
Pontiac	Torrent	SF	Toyota	Tacoma	SF	Lexus	LS460/460L	SF/SR
Pontiac	G8	SF	Toyota	Corolla	SF	Lexus	LS600hL Hybrid	SF/SR
Pontiac	G5	SF	Toyota	Matrix	SF	Lexus	LX570	SF/SR
Pontiac	Solstice	SF	Toyota	Venza	SF	Lexus	RX350	SF
Pontiac	G6	SF	Toyota	Yaris	SF	Lexus	ES350	SF/SR
Pontiac	G3	SF	Toyota	Tundra	SF	Lexus	GS450h Hybrid	SF/SR
			Toyota	FJ Cruiser	SF	Lexus	GX470	SF

2010

Make	2010 Model	Pre.	Make	2010 Model	Pre.	Make	2010 Model	Pre.
2010Buick	LaCrosse	SF	Ford	Escape	SF	Nissan	Pathfinder	SF
Buick	Lucerne	SF	Ford	Mustang	SF	Nissan	Xterra	SF
Buick	Enclave	SF	Ford	Fusion Hybrid	SF	Nissan	Titan	SF
Cadillac	DTS	SF	Ford	F-150	SF	Nissan	Rogue	SF
Cadillac	SRX	SF	Ford	Ranger	SF	Nissan	Sentra	SF
Cadillac	CTS	SF	Ford	E-350 12 Passenger	SF	Nissan	Versa Hatchback	SF
Cadillac	Escalade	SF	Ford	F-350		Nissan	Titan	SF
Cadillac	Escalade Hybrid	SF	Ford	Edge	SF	Nissan	Murano	SF
Cadillac	STS	SF	Ford	Taurus	SF	Nissan	Armada	SF
Chevrolet	Express 2500 12 Passenger		Ford	Mustang	SF	Nissan	Versa	SF
Chevrolet	Express 1500 Passenger	SF	Ford	Escape Hybrid	SF	Nissan	Altima Hybrid	SF
Chevrolet	Corvette	SF	Ford	Expedition	SF	Nissan	Altima	SF
Chevrolet	Equinox	SF	Ford	Focus	SF	Nissan	370Z Roadster	SF
Chevrolet	Express 1500 Cargo	O	Ford	Flex	SF	Nissan	Altima	SF
Chevrolet	Silverado	SF	Ford	Ranger	SF	Nissan	370Z	SF
Chevrolet	Camaro	SF	Ford	F-250		Nissan	Frontier Crew	SF
Chevrolet	Traverse	SF	Ford	Fusion	SF	Nissan	Frontier King	SF
Chevrolet	Tahoe Hybrid	SF	Ford	F-150	SF	Nissan	GT-R	SF
Chevrolet	Tahoe	SF	Ford	Transit Connect	SF	Nissan	Maxima	SF
Chevrolet	Suburban	SF	Ford	Crown Victoria	SF	Infiniti	QX56	SF
Chevrolet	Express 3500 12 Passenger		Ford	Explorer	SF	Infiniti	M35/45	SF
Chevrolet	Malibu	SF	Lincoln	MKS	SF	Infiniti	G37	SF
Chevrolet	Impala	SF	Lincoln	MKZ	SF	Infiniti	FX35/50	SF
Chevrolet	HHR	SF	Lincoln	Town Car	SF	Infiniti	EX35	SF
Chevrolet	Express 3500 15 Passenger		Lincoln	Navigator	SF			
Chevrolet	Silverado 1500	SF	Lincoln	MKX	SF	Toyota	Venza	SF
Chevrolet	Avalanche	SF	Lincoln	MKT	SF	Toyota	Scion tC	SF
Chevrolet	Colorado	SF	Lincoln	Navigator	SF	Toyota	RAV4	SF
Chevrolet	Cobalt	SF	Mercury	Milan	SF	Toyota	Prius	SF
Chevrolet	Aveo	SF	Mercury	Mariner	SF	Toyota	Avalon	SF
GMC	Sierra	SF	Mercury	Mariner Hybrid	SF	Toyota	Yaris	SF
GMC	Savana Passenger		Mercury	Milan Hybrid	SF	Toyota	Tundra	SF
GMC	Yukon	SF	Mercury	Mariner	SF	Toyota	Corolla	SF
GMC	Yukon Hybrid	SF	Mercury	Grand Marquis	SF	Toyota	Scion xB	SF
GMC	Terrain	SF	Mercury	Mountaineer	SF	Toyota	Tacoma	SF
GMC	Savana 1500 Cargo	O				Toyota	Matrix	SF
GMC	Acadia	SF				Lexus	GS350/460	SF/SR
GMC	Canyon	SF				Lexus	LS460/460L	SF/SR
Pontiac	G6	SF	Toyota	Sequoia	SF	Lexus	RX350	SF/SR
Pontiac	Vibe	SF	Toyota	Tacoma	SF	Lexus	GX460	SF
Saturn	VUE	SF	Toyota	Camry	SF	Lexus	IS250/350	SF/SR
Saturn	Outlook	SF	Toyota	Camry Hybrid	SF	Lexus	LS600hL Hybrid	SF/SR
Saturn	Aura	SF	Toyota	4Runner	SF	Lexus	LX570	SF/SR
			Toyota	Scion xD	SF	Lexus	SC430	SF
			Toyota	Highlander Hybrid	SF	Lexus	IS250C/350C	SF
			Toyota	FJ Cruiser	SF	Lexus	RX450h Hybrid	SF/SR
			Toyota	Landcruiser	SF/SR	Lexus	HS250h Hybrid	SF/SR
			Toyota	Highlander	SF	Lexus	ES350	SF/SR
			Toyota	Tacoma	SF	Lexus	IS F	SF/SR
			Toyota	Sienna	SF	Lexus	GS450h Hybrid	SF/SR

Appendix E Airbag Data

The following table gives airbag characteristics by model type and year for models for sales in the United States (1995-2006)

TOYOTA			
Model	Year	Notes	Number and type of airbags
Camry	2005	• Driver front airbag intelligent, passenger front airbag with occupant sensors intelligent	2, advanced
4 Runner	1996 -1998	• Driver and passenger front airbag	2, 2nd generation
4 Runner	1999-2004	• Driver and passenger front airbag intelligent	2, 2nd generation, smart
4 Runner	2005	• Driver front airbag intelligent, passenger front airbag with occupant sensors intelligent.	2, advanced
Avalon	1995-1997	• Driver and passenger front airbag	2, 1nd generation
Avalon	1998-2003	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
Avalon	2005	• Driver front airbag intelligent, passenger front airbag with occupant sensors intelligent. • Front and rear roof airbag • Front side airbag	5, advanced
Camry Solara	1999-2003	• Driver and passenger front airbag intelligent	2, 2nd generation, smart
Camry Solara	2004- 2005	• Driver front airbag intelligent, passenger front airbag with occupant sensors intelligent • Front side airbag	3, advanced
Celica	1995-2004	• Driver and passenger front airbag	2, 2nd generation
Corolla	1995-1998	• Driver and passenger front airbag	2, 2nd generation
Corolla	1999-2004	• Driver and passenger front airbag intelligent	2, 2nd generation,
Corolla	2005	• Driver front airbag intelligent, passenger front airbag with occupant sensors intelligent	2, advanced
ECHO	2000-2005	• Driver and passenger front airbag	2, 2nd generation,
Highlander	2001-2003	• Driver and passenger front airbag	2, 2nd generation,

TOYOTA (continued)			
Model	Year	Notes	Number and type of airbags
Highlander	2004-2005	• Driver front airbag intelligent, passenger front airbag with occupant sensors intelligent	2, advanced
Landcruiser	1995	• Driver and passenger front airbag	2, 2nd generation
Landcruiser	2004-2005	• Driver and passenger front airbag intelligent	2, 2nd generation, smart
Toyota Matrix	2003	• Driver and passenger front airbag	2, 2nd generation
Matrix	2004	• Driver and passenger front airbag intelligent	2, 2nd generation, smart
MR2	1995	• Driver and passenger front airbag	2, 2nd generation
MR2 Spyder	2000-2005	• Driver front airbag, passenger front airbag with occupant switch off	2, 2nd generation
Prius	2001-2003	• Driver and passenger front airbag	2, 2nd generation
Prius	2004-2005	• Driver and passenger front airbag intelligent	2, 2nd generation, smart
RAV4	1996-2003	• Driver and passenger front airbag	2, 2nd generation
RAV4	2004-2005	• Driver front airbag intelligent, passenger front airbag with occupant sensors intelligent	2, advanced
Sequoia	2001-2004	• Driver and passenger front airbag	2, 2nd generation
Sequoia	2005	• Driver and passenger front airbag with occupant sensors intelligent	2, 2nd generation, smart
T-100	1995-1998	• Driver front airbag	1, 1st generation
Tacoma	1995-1997	• Driver front airbag	1, 1st generation
Tacoma	1998	• Driver and passenger front airbag	2, 2nd generation
Tacoma	2004	• Driver front airbag , passenger front airbag with occupant switch off	2, 2nd generation
Tacoma	2005	• Driver front airbag intelligent , passenger front airbag with occupant switch off intelligent	2, advanced
Supra	1995-1998	• Driver and passenger front airbag	2, 2nd gen.

FORD			
Model	Year	Notes	Number and type of airbag
Aerostar	1996-1997	• Driver front airbag	1, 1st generation
Aspire	1995-1997	• Driver and passenger front airbag	2, 2nd generation
Bronco	1995-1996	• Driver front airbag	1, 1st generation
Contour	1995-2000	• Driver and passenger front airbag	2, 2nd generation
Crown Victoria	1995-2003	• Driver and passenger front airbag	2, 2nd generation
Crown Victoria	2004-2005	• Driver and passenger front airbag intelligent	2, 2nd generation, smart
Ford E-150	2002-2005	• Driver and passenger front airbag	2, 2nd generation
E-150 Econoline	1997-2001	• Driver and passenger front airbag	2, 2nd generation
E-250	2002-2004	• Driver and passenger front airbag	2, 2nd generation
E-250 Econoline	1997-1999, 2001	• Driver and passenger front airbag	2, 2nd generation
E-250 Econoline	2000	• Driver front airbag	1, 1st generation
E-350 Econoline	1997-1998	• Driver and passenger front airbag	2, 1st generation
E-350 Econoline	1999-2000	• Driver front airbag	1, 2nd generation
E-350 Econoline	2001	• Driver and passenger front airbag	2, 2nd generation
Escape	2001-2003	• Driver and passenger front airbag	2, 2nd generation
Escape	2004	• Driver and passenger front airbag	2, 2nd generation
Escape	2005	• Driver front airbag with occupant switch off intelligent , passenger front airbag with occupant sensors intelligent	2, advanced
Excursion	2000-2005	• Driver and passenger front airbag	2, 2nd generation
Explorer	1995-2003	• Driver and passenger front airbag	2, 2nd generation
Explorer	2004-2005	• Driver and passenger front airbag with occupant sensors intelligent	2, advanced
F-150	1995-1996	• Driver front airbag	1, 1st generation
F-150	1997-2000	• Driver and passenger front airbag	2, 2nd gen
F-150	2007	• Driver front airbag with occupant sensors and multi-stage deployment , passenger front airbag with occupant sensors, occupant switch off and multi-stage deployment	3rd generation or multistage airbag
F-150	2001	• Driver front airbag , passenger front airbag with occupant switch off	2, 2nd generation,
F-150	2004-2005	• Driver front airbag with occupant sensors intelligent , passenger front airbag with occupant sensors and occupant switch off intelligent	2, advanced
F-250	1995-1997	• Driver front airbag	1, 1st generation
F-250	1998-2000	• Driver and passenger front airbag	2, 2nd generation
F-250	2001-2005	• Driver front airbag , passenger front airbag with occupant switch off	2, 2nd generation,
F-350	1995-1998	• Driver front airbag	1, 1st generation
F-350	1999-2000	• Driver and passenger front airbag	2, 2nd generation
F-350	2001-2005	• Driver front airbag , passenger front airbag with occupant switch off	2, 2nd generation

FORD (Continued)			
Model	Year	Notes	Number and type of airbag
Ford ZX2	2002-2003	• Driver and passenger front airbag	2, 2nd generation
Ford GT	2005	• Driver front airbag , passenger front airbag with occupant switch off	2, 2nd generation,
Taurus	1995-1997	• Driver and passenger front airbag	2, 2nd generation
Taurus	2002-2003	• Driver and passenger front airbag with occupant sensors	2, 2nd generation,
Taurus	2004-2005	• Driver and passenger front airbag with occupant sensors intelligent	2, advanced
Probe	1995-1997	• Driver and passenger front airbag with occupant sensors	2, 2nd generation,

Nissan			
Model	Year	Notes	Number and type of airbag
1995-1998	200SX	• Driver and passenger front airbag	2, 1st generation
1995-1998	240SX	• Driver and passenger front airbag	2, 1st generation
1995-1996	300ZX	• Driver and passenger front airbag	2, 1st generation
2003	350Z	• Driver front airbag with occupant sensors , passenger front airbag with occupant sensors and occupant switch off	2, 2nd generation
2004-2006	350Z	• Driver and passenger front airbag with occupant sensors	2, 2nd generation
Altima	1995-1999	• Driver and passenger front airbag	2, 2nd generation
Altima	2000-2001	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
Altima	2002	• Driver and passenger front airbag	2, 2nd generation
Altima	2003, 2005, 2006	• Driver and passenger front airbag with occupant sensors	2, 2nd generation
Altima	2004	• Driver and passenger front airbag with occupant sensors intelligent	2, 2nd generation, smart
Armada	2004-2006	• Driver and passenger front airbag with occupant sensors	2, 2nd generation
Frontier	1998-2000, 2006	• Driver and passenger front airbag	2, 2nd generation
Frontier	2001-2002, 2004	• Driver front airbag , passenger front airbag with occupant switch off	2, 2nd generation
Frontier	2003	• Driver front airbag , passenger front airbag with occupant switch off intelligent	2, 2nd generation, smart
Frontier	2005	• Driver and passenger front airbag intelligent	2, 2nd generation, smart
Maxima	1995-1997, 2000-2002	• Driver and passenger front airbag	2, 2nd generation,
Maxima	1999, 2003	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
Maxima	2004-2006	• Driver and passenger front airbag with occupant sensors • Front and rear roof airbag • Front side airbag	5, advanced
Murano	2003-2006	• Driver and passenger front airbag with occupant sensors • Front and rear roof airbag • Front side airbag	5, advanced
Xterra	2000-2002	• Driver and passenger front airbag	2, 2nd generation
Xterra	2003	• Driver and passenger front airbag with occupant sensors	2, 2nd generation
Xterra	2005	• Driver and passenger front airbag with occupant sensors intelligent	2, 2nd generation, smart
Xterra	2006	• Driver and passenger front airbag with occupant sensors and multi-stage deployment	2, advanced, multistage airbag
Sentro	1995-2001, 2003-2006	• Driver and passenger front airbag	2, 2nd generation

GENERAL MOTORS (GM)			
Model	Year	Notes	Number and type of airbag
GMC C1500	1995-1996	• Driver front airbag	1, 1st generation
GMC C1500	1997-1998	• Driver and passenger front airbag	2
GMC C2500	1998-2000	• Driver and passenger front airbag	2, 2nd generation
GMC C3500	1995-1997	• No	
GMC C3500	1998-2000	• Driver and passenger front airbag	2, 2nd generation
GMC Envoy	1998-2001	• Driver and passenger front airbag	2, 2nd generation
GMC Envoy	2002-2003	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
GMC Envoy	2004	• Driver and passenger front airbag intelligent	2, smart
GMC Envoy	2005-2006	• Driver front airbag intelligent , passenger front airbag with occupant sensors intelligent	2, smart
GMC ENVOY XL	2002	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
GMC ENVOY XL	2003	• Driver and passenger front airbag	2, 2nd generation
GMC ENVOY XL	2004	• Driver and passenger front airbag intelligent	2, smart
GMC ENVOY XL	2005	• Driver front airbag intelligent , passenger front airbag with occupant sensors intelligent	2, smart
GMC ENVOY XUV	2004	• Driver and passenger front airbag intelligent	2, smart
GMC ENVOY XUV	2005	• Driver front airbag intelligent , passenger front airbag with occupant sensors intelligent	2, smart
GMC G1500	1996	• Driver front airbag	1, 1st generation
GMC G1500	1997-1998	• Driver and passenger front airbag	2
GMC K2500	1995-1997	• No	
GMC K2500	1998-2000	• Driver and passenger front airbag	2, 2nd generation
GMC Yukon XL	2000-2002	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
GMC Yukon XL	2003, 2005-2006	• Driver front airbag , passenger front airbag with occupant sensors	2, 2nd generation
GMC Yukon XL	2004	• Driver front airbag intelligent , passenger front airbag with occupant sensors intelligent	2, smart
GMC Yukon	1995-1996	• Driver front airbag	1, 1st generation
GMC Yukon	1997-2001	• Driver and passenger front airbag	2
GMC Yukon	2002	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
GMC Yukon	2003	• Driver front airbag , passenger front airbag with occupant sensors	2, 2nd generation
GMC Yukon	2004-2006	• Driver front airbag intelligent , passenger front airbag with occupant sensors intelligent	2, smart

BUICK			
Buick Century	1995-1996	• Driver front airbag	1, 1st generation
Buick Century	1997-2004	• Driver and passenger front airbag	2
Buick Century	2005	• Driver and passenger front airbag intelligent	2, smart
Buick LaCrosse	2005	• Driver front airbag intelligent , passenger front airbag with occupant sensors intelligent	2, smart
Buick LaCrosse	2006	• Driver front airbag intelligent , passenger front airbag with occupant sensors • Front and rear roof airbag	4, smart
Buick Lesabre	1995-1999	• Driver and passenger front airbag	2
Buick Lesabre	2000-2002	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
Buick Lesabre	2003	• Driver and passenger front airbag	2, 2nd generation
Buick Lesabre	2004-2005	• Driver and passenger front airbag intelligent	2, smart
Buick Lucerne	2006	• Driver and passenger front airbag with occupant sensors intelligent • Front and rear roof airbag • Front side airbag	5, smart
Buick Park Av.	1995-1999	• Driver and passenger front airbag	2, 2nd generation
Buick Park Av.	2000-2004	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
Buick Park Av.	2005	• Driver and passenger front airbag intelligent • Front side airbag	2, smart
CADILLAC			
Cadilac Catera	1997, 2000-2001	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
Cadilac Catera	1998-1999	• Driver and passenger front airbag	2, 2nd generation
Cadilac CTS	2003	• Driver and passenger front airbag with occupant sensors • Front roof airbag • Front side airbag	4, 2nd generation
Cadilac CTS	2004	• Driver and passenger front airbag with occupant sensors intelligent • Front roof airbag • Front side airbag	4, smart
Cadilac CTS	2005	• Driver front airbag intelligent , passenger front airbag with occupant sensors intelligent • Front and rear roof airbag • Front side airbag	5, smart
Cadillac Deville	1995-1996	• Driver and passenger front airbag	2, 1st generation
Cadillac Deville	1997-2002	• Driver and passenger front airbag • Front side airbag	3, 2nd generation
Cadillac Deville	2003-2004	• Driver and passenger front airbag with occupant sensors • Front side airbag	3, 2nd generation
Cadillac Deville	2005	• Driver and passenger front airbag with occupant sensors intelligent • Front side airbag	3, smart

Appendix F Search strings for 1st systematic review

Long Term Strategy

- Scenario Planning
- Resource Allocation
- Strategic Planning Process
- Dealing with Uncertainty
- Corporate governance
- National Culture
- Non-market strategy
- Comparative advantage of nations
- Long view
- Resource based view
- Futuring
- Charismatic leaders

Disruptive Technologies

- Disruptive technology
- Disruptive innovation
- Discontinuous technology
- Discontinuous Innovation
- Innovator's dilemma
- 3rd generation R & D
- Resource allocation
- Agile business model
- Technological innovation
- Emerging technologies

Energy Availability & Climate Change

- Global warming
- Climate change
- Hydrogen economy
- Oil reserves
- Middle East stability
- Natural gas reserves
- Alternative Energy
- Fuel cells
- Hybrid vehicles

Appendix G Examiners comments and corrections made to thesis

Task	Concept	Examiners Comments	Action Taken
1	Abstract	Should not have references in it – will need to be rewritten to reflect changes in the rest of the thesis	Abstract rewritten to reflect new approach and references removed.
2	Opening paragraphs	The opening paragraph (pg 1) starts with disruptive innovation – but this theme is not picked up later in the thesis and does not appear to be central to the research. It would be better to open the document with something that is central to the thesis – like technology management strategy, the automotive sector or patents.	Opening paragraphs rewritten and thesis adapted to focus on disruptive innovation which was original theme of research.
3	Compelling reason	The first section should provide a more compelling reason or justification for the research – why this work is important and worthy of PhD study – both theoretically and practically	Compelling reason clearly stated around the idea of building theory which would better inform practice about what to do in the face of potentially disruptive change.
4	Origin of Research Question	Page 2 – need to explain where the research question (RQ) comes from – show how it is derived from the literature and is therefore theoretically relevant to be studied.	Research Question now fully embedded in literature Gap in the area of informing practice about what to do.
5	Research Question	The RQ needs to be reformulated – it is currently narrow and closed. It is currently not clear how the RQ relates to Granstrand, Geels, Lewin and Volberda etc – link back to clarifying the contribution to knowledge and make sure that the two are coherent.	New Research question formulated in more open way i.e. "What strategies do automotive companies follow with respect to the investigation and deployment of discontinuous technologies?" and linked to gap identified in the literature.
6	Literature review Re-focus	The literature review feels disjointed and covers many different topics – it is hard to work out what is central to the thesis. A deeper review of less topics would help to clarify the focus of the thesis. Link to research question(s) as the literature review should help to justify your RQ.	Literature review re-written in more focused way with strategy literature being removed and automotive literature dealing with alternative vehicles, a potentially disruptive technology being added. Focus is on identifying gaps and linking literature to the Research Question.

Task	Concept	Examiners Comments	Action Taken
7	Critical tone of review	The literature review is not particularly critical – it is more of a summary of key papers. For example, pg 7 – could cite Souitaris (2002) Research Policy paper that critiques Pavitt's trajectories for not considering managerial and organisational factors and for being essentially a firm level analysis. Or pg 14 – critique of Geels and Schot – depends on perspective of the analyst and/or actors and point in time of the analysis because radical system change is the result of multiple incremental changes. You need to clearly highlight the key debates in your field.	Additional nuance has been introduced in looking at the key concepts where a gap has been identified introducing criticisms of the threads in the literature discussed.
8	Automotive literature	There has been quite a bit of research on the automotive sector (technology management, product development, supplier management etc) – some of this research must be included in the lit review and can be used to show gaps.	Automotive literature has been reviewed and that dealing with potentially disruptive technology added to the literature review.
9	Automotive discussion in Literature Review	Page 8 – the discussion of the automotive sector, though good, does not belong in the literature review chapter	Discussion moved to Chapter 4 together with review of Pavitt's 5 trajectories.
10	Definition of Depth and Breadth	The depth and breadth concept is central to this research – but the words are generic and used in many different ways. As this is central to your research, the definitions used by others need to be discussed and compared and critiqued. This will help to justify your definitions and why and how they are different.	New chapter created to discuss Depth and Breadth (Chapter 6) in line with examiners recommendation. Definitions provided in this chapter as well as contrast with other researcher's uses of the terms in related contexts.
11	Gaps in literature	Page 27 – Need to clearly summarise the key gaps and/or debates and inconsistencies in the literature to help to show how your work will address these	Literature review re-written and focused clearly on gaps.
12	Conclusion to patent review	Page 43 – Need to summarize the conclusions having reviewed the patent literature. Use this to lead to the justification for your approach to patent analysis.	Conclusion added and shown in Sub-section 2.3.6.

Task	Concept	Examiners Comments	Action Taken
13	Methodology chapter	Throughout this chapter it is essential to argue for your choice in a transparent and balanced manner. This means presenting alternative options available to you, discussing the strengths and weaknesses of each alternative and explaining why you chose the one alternative and how you plan to deal with any weaknesses.	Chapter rewritten and discussion of research choices and blind alleys added including strengths and weaknesses of current approach.
14	Philosophy/ epistemology	Page 44 – Philosophy/epistemology sections – these need developing further. Explain the positivist-realist debate and the different research philosophies (strengths and weaknesses) to clearly justify your approach and why it is the most relevant for your RQ and why you did not take other approaches.	Philosophy section expanded to discuss major threads in the philosophy of science, and resons for choosing critical realist ontology and inductive epistemology given and tied back to Research Question.
15	Thesis purpose in chapter 3	Page 45 – The purpose of the thesis is presented as adding to Granstrand's theory – if so, this needs to be an explicit part of the RQ in Ch 1 or it needs to be clearer how answering the RQ will help to add to Granstrand's theory.	Purpose of the thesis has been modified along the lines of the new Research Question and text edited to reflect new focus and can be found in Sub-section 3.2.2.
16	Case study references	No description of case studies method is given, but these is central to your approach (Fig 3.1) – should look at and draw on e.g Yin and Eisenhardt and other authors that have applied a case study approach to their research.	Eisenhardt (1989) and Yin(1994) are referenced to explain choice of using cases and Eisenhardt's roadmap explicitly used to discuss thesis content.
17	Selection of cases	Page 46 – selection of cases needs to be more thoroughly described at all levels – automotive sector, companies, technologies. Clearly explain the criteria for selection/exclusion at each level. This justification of cases needs to explicitly link back to the RQ.	Site selection discussion has been expanded and criteria clearly explained in light of the new Research Question.

Task	Concept	Examiners Comments	Action Taken
18	Themescape maps method	The process for patent analysis needs to be more thoroughly and explicitly described. As the algorithm for producing the maps is not available, you need to find a way to check that the maps do show what you say they show. This data is central to the thesis and so needs to be robust. In particular height, land mass, scale and the meaning of distance are all critical to the utility of the map metaphor and need to be fully discussed.	The themescape validity has been checked with Thompson Scientific as well as checked by manually coding two sets of patents as discussed in Sub-section 3.5.3. Section 5.2 is clearer on how the maps are analyzed and Chapter 6 uses a much more rigorous definition of depth and breadth and guidelines for the analysis to draw conclusions from the maps.
19	Interview method	The interview analysis needs more explanation – how were questions designed, how was the data analysed. Need to reference key qualitative data analysis texts e.g Miles and Huberman, Strauss and Corbin, Silverman etc	The interview methodology outlined in section 3.7 has been expanded based on ideas in Miles and Huberman (1994) and Easterby-Smith et al. (2002) and choices made in terms of recording and coding explained.
20	Chapter 4	Need to explain the purpose of this chapter – clarify whether it is to give a description of the cases or to test/apply key theories. It could be written as either a case description using frameworks from literature to give it more structure or a test of the theories by applying them in this context. If the latter, then you would need to critique the theories having applied them and make this an explicit purpose of the research and reflect it in the RQ. Chapter moves between firm level and technology level, which is confusing.	Purpose of Chapter 4 defined as rigorously defining context in order to better understand boundary between context and phenomena (Yin, 1994), demonstrate examples of co-evolution in automotive, and make explicit prior knowledge in order to control for bias. Chapter 4 re-focused at industry level with detailed technology discussion moved to aument technology case studies in Chapter 5.
21	Chapter 5 - general	Needs to be much more precise in how you are using the maps/patent analysis, deployment data and interview data to conclude that strategies are deep or broad	Chapter 5 focused on presenting the case studies with discussion of depth and breadth moved to Chapter 6 in line with examiners recommendation. That chapter uses clear definitions and a construct to make distinction between depth and breadth.
22	Table 5.31	Page 137 – Table 5.31 – this needs much more description/analysis – it is central to what you have found and should be further explored and explained.	Summary of depth and breadth observations, formerly Table 5.31 is now shown in Table 6.6 and fully discussed in sections 6.4, and 6.5.

Task	Concept	Examiners Comments	Action Taken
23	Competitive Advantage ?	Page 139 –mixing competitive advantage (firm level – hard to attribute to a single technology in a complex product such as a car) with technical performance of the technology. This also applies to other parts of thesis where competitive advantage used.	References to competitive advantage removed and discussion focused on technical performance in for example Table 6.9 and the discussion of implications for practice in Sub-section 6.3.3.
24	Fig 5.23	Page 141 – Fig 5.23 mixes lots of concepts which are not fully described.	Figure 5.23 removed and replaced with Figures 6.3 and Figure 6.4 each of which is explained in detail and then enriched with the discussion in Sub-section 6.3.3.
25	Conclusion Chapter 5	Chapter 5 needs a clear conclusions section at the end	Conclusions given in Chapter summary found in Section 5.4.
26	New Discussion Chapter (6)	Need to insert a new chapter between the current Chapters 5 and 6 – Discussion - which synthesises and discusses findings from data. Plus how the findings relate to the literature and exploring different explanations and some of the key literature around these different explanations. This will involve moving conclusions part from Chapter 5 and section 6.2 into this new chapter.	New discussion chapter created in whch the idea of depth and breadth is connected to the literature, defined, and applied. This chapter also includes new sections on the implications for practice, what the thesis says about alternative power trains and includes the discussion of theory.
27	Chapter 7	The new Chapter 7 Conclusions would then briefly summarize the thesis, clearly state the substantive contribution to knowledge, limitations and further research.	New Chapter 7 created.
28	Dark Box ?	Page 143 – need to be more explicit about how this research has added to our understanding of the “dark box”. Refer back to findings to illustrate this.	Addition to idea of "dark box" moved to discussion in Chapter and more fully described in sections 6.3 and 6.4
29	Push/Pull	Fig 6.1 - 3 of your cases are from push/pull – discuss how this might have affected your findings and how it is different to the cases used by Granstrand.	The idea that the theory of the technology-based firm be expanded to include technology push followed by market pull is made explicit.
30	Comment on two threads	Page 144 – need to explain how your findings could add to 2 threads (Christensen and Bower/Tushman and Anderson) or remove this comment	Discussion of theory given in Section 6.4 centered on additions to Granstrand’s theory of the technology-abased firm and comment removed.
31	Themescape maps	Patent diagrams need to be larger in the main text so they can be more easily read (and can then be removed from the appendix)	Diagrams enlarged and moved to company case studies in Chapter 5 and removed form appendix.

Task	Concept	Examiners Comments	Action Taken
32	Referencing	Inconsistent referencing in main text – sometimes three authors named, sometimes et al – should be consistent throughout the document	Referencing made consistent citing up to two authors and then applying et al.
33	Typos	Marked typos throughout the thesis documents and additional specific comments to consider	Typos corrected and thesis reviewed by two external editors.
34	Quotes	All direct quotes should have page numbers (p17, 18, 22, 29, 30, 34, 45, 60, 145, 146)	Page numbers added to all direct quotes.