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Uncovering the True Potential of Hybrid Electric Vehicles

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Abstract

"Our house is burning down and we're blind to it. Nature, mutilated and overexploited, can no longer regenerate and we refuse to admit it. Humanity is suffering. It is suffering from poor development, in both the North and the South, and we stand indifferent. The earth and humankind are in danger and we are all responsible."

(Chirac, 2002)

Over the last decade, 'Sustainable Development' became the priority of international regulatory bodies. In order to protect the environment, significant cuts in terms of toxic emissions have to be made. Moreover, as the world's feedstock of fossil resources gradually diminishes, prompt actions must be taken in order to develop the use of renewable sources of energy.

The automotive industry, a major contributor to Green House effect, is well aware of the necessity to develop a new technology that would enable an environmental-friendly transportation sector. Several pathways are currently being explored, however, the technology that will be used to propel tomorrow's car has not yet been selected.

Indeed, there is no consensus among the stakeholders of the industry as to which technology will prove to be the dominant design for the future. As a result, the industry is currently in a period of upheaval in which all emerging technologies are competing for power, support, and momentum. Among all the potential alternatives a technology which increasingly has gained importance is the Hybrid technology.

This thesis will attempt to clarify to what extent the emerging alternatives comply with the environmental requirements. As such, the true potential of Hybrid Electric Vehicles to become a sustainable alternative will be presented. A direct comparison with rival technologies enabled to demonstrate that Hybrid technology offers the possibility to eliminate toxic emissions as well as the use of fossil resources, while providing a high level of functionality at low cost.

Key words: Hybrid Electric Vehicle, emerging technologies, technological trajectories, dominant design

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List of Abbreviations

B100	100 percent Biodiesel
B20	20 percent Biodiesel mixed with 80 percent petroleum diesel
BEC	Business Environmental Conditions
CGH_2	Compressed Gas Hydrogen
CH_2	Compressed Hydrogen
CO	Carbon Monoxide
CO_2	Carbon Dioxide
E10	10 percent Ethanol with 90 percent gasoline
E28	28 percent Ethanol with 72 percent gasoline
E85	85 percent Ethanol with 15 percent gasoline
E95	95 percent Ethanol with 5 percent gasoline
E100	100 percent Ethanol
EU	European Union
EV	Electric Vehicles
FCV	Fuel Cell Vehicles
FV	Flexible Vehicles
FVB	Flexible Vehicles Biodiesel
FVE	Flexible Vehicles Ethanol
GDP	Gross Domestic Product
GHG	Green House Gases
GM	General Motors
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
LH_2	Liquid Hydrogen
LPG	Liquefied Petroleum Gas
NOx	Nitrogen Oxides
OECD	Organisations for Economic Co-operation and Development
R & D	Research and Development
SO_2	Sulphur Dioxide
UN	United Nations
US	United States
VW	Volkswagen
LCA	Life Cycle Analysis

1 Introduction

"Has the time finally arrived? Is the automotive industry on the brink of a change the likes of which they haven't seen since the days of the Stanley Steamer?…Has the industry awakened to the need to move toward a sustainable model."

(Smith, 2001)

In the beginning of the 21st century, the environmental dimensions of sustainable development became a key element of policy-making at international, regional and national levels. Indeed, the fear that current needs will compromise the ability of future generations to meet their requirements is omnipresent. The planet's natural resources are currently overexploited, and the constant increase of toxic emissions could result in an ecological disaster if no actions on the global scale are taken.

The necessity to develop a production as well as a consumption model that spare natural resources while reducing toxic emissions is evident. However, it requires a tremendous degree of commitment from all parties involved whether it is government bodies, business firms or consumers.

The automotive industry, generally perceived as one of the main contributor to global warming, is well aware of such a responsibility. For many years now, car manufacturers have invested a colossal amount of money, time and human resources into Research and Development (R&D) in order to reconcile 'mobility' and 'sustainability'. This is generally referred as the 'sustainable mobility paradox'.

1.1 Problem Background

There are two main reasons behind the need to develop a 'clean' automotive industry, namely a growing concern regarding toxic emissions generated by transportation, as well as the dramatic reduction of our feedstock of non-renewable resources over the last few years. An extensive description of these two concerns and their impacts, in addition to the progress achieved by international authorities to tackle these issues, will thus be discussed and assessed.

- Air contamination and Global Warming

Global warming is commonly viewed as one of the most serious threats to our world. The main reason causing climate change originates from the man made emissions of several toxic elements regrouped under the generic term 'greenhouse gases'. The primary substance affecting Earth's climate is undeniably Carbon Dioxide (CO_2). The burning of fossil resources such as coal, oil or gas, emit large quantities of CO_2 that blankets the Earth, traps in heat, and causes global warming (David Suzuki Foundation, 2004a).

Numerous studies have been published, which highlight the dramatic impact climate change has on ecosystems, economies and local weather. Noticeably is the report from the Intergovernmental Panel on Climate Change (IPCC, 2004) as well as a study published by the US National Research Council (NRC, 2004). The increase in temperature resulting from the greenhouse effect will differ greatly from one place to another. While some regions will experience more extreme heat, others will significantly cool down. The energy stored in a warming atmosphere will also generate violent storms, and extreme weather events, while several parts of the world will suffer flooding, drought and intense summer heat (David Suzuki Foundation, 2004a).

Climate change also has considerable effects on human health. Tropical conditions will arise in higher latitudes, along with tropical diseases such as the West Nile virus and other water-borne and heat diseases to which the old, the young and the ill are particularly sensitive (David Suzuki Foundation, 2004a). Air pollution is also responsible for heart disease and respiratory malfunctions such as asthma. Increased toxic emissions will therefore amplify public health concerns.

Global warming will additionally have impacts on the economic environment. Indeed, several major industries are highly dependent on climate. Agriculture, fisheries and tourism are closely linked to weather conditions. As a result, climate change could have serious effects on the GDP performance of economies relying heavily on these industries. In fact, one could consider that every industry is affected in some way or another by global warming and that its effects could be devastating. A good example is the insurance industry. As the David Suzuki Foundation highlights:

"Before 1988, the global insurance industry never had claims for more than US $1 billion in any single natural disaster. Yet between 1988 and 1996, 15 such events occurred, and a number of insurance companies closed down in the wake of these disasters."

(David Suzuki Foundation, 2004b)

The automotive industry is well aware of its contribution to air pollution. In fact, its estimated that road transportation in the EU accounts for nearly a fifth of the EU's total man made CO_2 emissions (Eurostat, 2004; European Commission, 2003). In the US, transportation accounts for one third of greenhouse gases (Cheon, 2003).

- Dependence on non-renewable resources

Today's economies rely heavily on non-renewable resources. Currently, our everyday life is entirely dependent on fossil fuels. The vast majority of our electricity production requires the use of fossil resources (World Bank, 2001). Additionally, fossil fuels are used extensively in the transportation and manufacturing industries. The inherent problem of non-renewable resources is that we have a limited amount of reserves, and the only way to prolong supply is to discover new fuel deposits.

In light of the recent economic development, it seems that our ability to sustain our needs on non-renewable resources is compromised. Indeed, the oil industry, one of the most crucial sources of energy, is suffering from a lack of synergy between supply and demand. Today, we are consuming a superior amount of oil than the actual supply capacity (Longwell, 2002).

Oil demand has been constantly growing since World War II at a steady level, and a majority of industry experts admit that this trend will continue for at least another 15 years (Longwell, 2002). However, it is far from sure that the oil industry will be able to discover new deposits of petroleum in order to satisfy the market demand. Uncertainties in terms of supply in a growing demand context have enormous effects on the price of a commodity. This has never been truer than over the few last years. While in August 2002, the price of a barrel was below 30US$, prices of oil have broken through 40US$ in the middle of 2004 and are still increasing. One can assume that geopolitical instabilities in the Middle East are reinforcing such a trend, and that it is unlikely that oil will become drastically cheaper in the very short term.

The high level and instability of oil price is generally considered to have negative impacts on the economy of Organisations for Economic Co-operation and Development (OECD) countries, which are highly dependent on imported oil. As a result the trade balance between exports and imports tend to deteriorate and could result in significant loss in terms of economic growth. Similarly, high oil price will generate inflation, especially on fuel used for transportation.

In order to eliminate the uncertainties in terms of supply availability and market sensitivity, government bodies do not have other choice but to eliminate the dependence on non-renewable resources, and more specifically on oil. There is a clear need for securing new sources of energy. However, replacing oil by another non-renewable product does not consist in a relevant alternative, as it will displace the problem from one commodity to another.

The automotive industry cannot remain passive towards these developments. Both the fuel and car manufacturing industries are dependent on oil, as it is a compulsory complementary product. Major corporations must strive towards reducing the transportation sector's dependence on oil by implementing alternative solutions.

- Government Policy and actions towards sustainable mobility

Strong international co-operation towards a sustainable development originated in 1992 when nearly 200 nations ratified the UN Framework Convention on Climate Change. The primary objective was to stabilise greenhouse gases concentrations in the atmosphere in order to prevent the impact of humanity on climate (European Union, 2001).

The UN framework was primarily based on voluntary targets that were soon enough to be assessed as inadequate in regards to the enormous task. As a result, the international community agreed in 1995 to develop a legal framework in which developed countries would further commit to reduce toxic emissions. The result of this process is the well-known and hotly debated Kyoto Protocol.

The Kyoto Protocol is a stepping-stone in the process to achieve deep, significant cuts in terms of toxic emissions. Most of the countries around the world are involved in a common objective, even if, in its first phase, the Protocol do not foresee participation of developing countries in the binding quantified emission reduction system (European Union, 2001). November 18th 2004 will be remembered as an historic date, as the Russian Federation ratified the protocol. After several years of uncertainty, the Kyoto Protocol will finally come into force on February 16th, 2005.

"This is a historic step forward in the world's efforts to combat a truly global threat. Most important, it ends a long period of uncertainty. Those countries that have ratified the Protocol, and which have been trying to reduce emissions of greenhouse gases even before its entry into force, now have a legally binding obligation to do so. Businesses that have been exploring the realm of green technology now have a strong signal about the market viability of their products and services."

(Annan, 2004)

Such a statement is of critical importance, especially for the automotive industry, as it highlights the tremendous degree of commitment from the international community. However, one can cheapen the importance of this statement by highlighting the fact that the US, now fairly isolated, is still refusing to ratify the Kyoto Protocol. Being the largest market for car manufacturers, it can be assumed that the non-ratification of US is a considerable shortcoming of the Kyoto Protocol. Nevertheless, apart from the US it must be noted that all major markets have ratified the Protocol, including Japan.

Indeed, sustainable mobility is a core objective set by international authorities. The Agenda 21, a program initiated by the UN in 1992, provides a clear plan of actions related to transportation, to be implemented from a global to local scale (Agenda 21, 1992). More precisely, Chapter 9 and 7 emphasise the need of action in the transportation sector, as it will be the major driving industry behind a growing world demand of energy, and as its current development patterns are not sustainable (UN Department of Economic and Social Affairs, 2004).

- The New Business Environment Conditions (BEC)

Global warming, uncertainties about the capability to supply oil on the long term, and a tremendous International commitment of policy makers to tackle these concerns constitute a major new set of rules for the automotive industry. Car manufacturers can no longer manage their business in the same conditions as they did in the 20th century.

The authors believe that these New Business Environment Conditions could be summarised as follows

- The necessity to reduce the dependence on non-renewable resources.
- The necessity to reduce toxic emissions.

This thesis will therefore focus on how the automotive industry could tackle these issues. In that respect, the authors will aim at providing an overview of the progress that has been achieved so far, and then evaluate to what extent it matches the new BEC.

1.2 Problem discussion

"Overall, the progress towards sustainable mobility by all of the participating technologies and energy sources is very impressive…'There is no single choice, no one path alone to achieving our ultimate goal of environmentally-positive road transportation that is enjoyable to drive and safe for drivers and passengers. Each year, the variety of technologies and creative innovations displayed offer proof that sustainable mobility is within our grasp "

(Oliva, 2003)

Indeed, car manufacturers have already investigated numerous alternatives in order to satisfy the new BEC. From the promotion of renewable fuels to the development of radical technological innovations in order to produce high efficiency vehicles, it is sometimes difficult for anyone to clearly identify how tomorrow's cars will be propelled. Divergence of opinion amongst experts in the car manufacturing industry is a direct consequence of this dilemma. While some brands are investing massively on Flexible Vehicles, others consider that Hydrogen Fuel Cell propelled cars are the only relevant solution towards sustainable mobility. Consequently, while a tremendous amount of money has already been invested, there is still no clear consensus regarding what will be the technology used in tomorrow's cars. This constitutes a critical issue in regards of the colossal amount of money at stake.

Despite a clear commitment on the international level, this dilemma has had consequences on policies adopted by national authorities. While Brazil has developed a regulatory framework focusing on promoting and supporting the use of Ethanol, a renewable fuel made from sugar cane, Germany has decided to support a rather different alternative, Biodiesel, a renewable fuel made from vegetable oil. On the other hand, the US government is now strongly committed to develop a Hydrogen economy, which would be used massively in the transportation sector in the years to come. The problem is that each of these solutions require car manufacturers to develop a specific powertrain, and therefore to invest colossal amount of money in R&D. However, the apparent lack of synchronisation amongst governments has dramatic impacts on the market introduction of a relevant alternative on a global scale. Why would car manufacturers invest millions of Euro on a specific technology when the outcome is more than uncertain?

- Powertrain vs. Alternative Fuels

On one hand, the industry could adopt a design relying on Biofuels (ecological fuels made from biomass) that would replace the traditional gasoline. Potentially, the technology is available, sources of supply are unlimited, renewable, and enable to eliminate toxic emissions. It can be used in any conventional engine with minor modifications for equivalent performances (Flexible Vehicles). The car manufacturing industry, for minimal incremental costs, would therefore be able to provide an ideal alternative matching the new BEC. However, the problem is much more complex. Biofuels would require a complete modification of the value chain in terms of fuel supply: the plants from which is made Biofuel have to be grown, production facilities and refineries have to be built, the existing pipeline has to be redesigned. One could estimate that the costs involved would have to be measured in billions of Euro. Even if, in an ideal scenario, costs are not an issue, the time required for developing such infrastructures highlights the hurdles towards a near to medium term implementation of Biofuels, and time is a critical issue. Who can predict that in the few next years to come, there won't be a more feasible, cheaper alternative?

On the other hand, car manufacturers could adopt a design relying on electricity, an abundant and relatively clean fuel, already available whenever and wherever around the world in vast quantity. It is commonly assumed that car manufacturers already master the technology that electric cars could and should be made available to the consumer as soon as possible. Unfortunately, this is far from the truth. Even if few Electric Vehicles are already on the road, numerous technical problems have to be solved by manufacturers: cost, range and performance of Electric Vehicles are still major issues. Without massive investments in terms of R&D, electric cars will never be able to compete with conventional engines.

A third solution would consist in combining advances made by both the fuel and the car manufacturing industry. This is commonly referred as the Hydrogen alternative, which is currently the most vividly debated topic within the automotive industry. Hydrogen is the simplest and most abundant element in the universe. The only by-product of cars running on pure Hydrogen would be water, and therefore many industry experts believe that Hydrogen is the ultimate solution towards a fully clean and environmental friendly transportation industry. However, this is probably the most uncertain and costly alternative ever investigated by car manufacturers.

Firstly, as for Biofuels, the entire fuel supply chain has to be rebuilt from scratch. Whether it is production plants or refuelling stations, the current infrastructures are not compatible with a Hydrogen economy. Moreover, even if it is an abundant element, Hydrogen is not available in its pure form. It has to be manufactured, and the negative impacts of this production process on the environment are commonly underestimated. Secondly, the powertrain technology required to enable cars to run on Hydrogen is far from being ready. Indeed, if various prototypes have been uncovered by major brands, numerous technological hurdles remain. As for Electric Vehicles, range, performance and costs are critical issues that car manufacturers have to overcome before Hydrogen Vehicles are released in the market.

- Hybrid Electric Vehicles (HEV) – a unique approach

As of today, there seems to be one eco-friendly alternative that shows potential to match the new BEC while avoiding the fuel supply and technological hurdles, and that is the Hybrid Electric Vehicles. HEV is a combination of the traditional Internal Combustion Engine (ICE) and the major breakthroughs achieved by the Electric Vehicle technology.

Japanese corporations have been the first stakeholders to realise the potential of HEV technology and to capitalise upon it. Noticeably, the Toyota Prius, first launched in 1997, and followed by the 'new Prius' in 2003, have gained increasing importance. Indeed, Toyota has sold over a quarter of million of Hybrid vehicles (Toyota, 2004a). For the year 2004 only, sales volume is expected to reach 130,000 vehicles including 49,000 units for the North American market alone (Toyota, 2004b). These figures are expected to grow over the next few years and Toyota Motor Sales USA, Inc., recently announced that the allocation of Prius' vehicles dedicated to US market will be doubled up to 100,000 units in 2005.

"With this significant increase in allocation for 2005, Prius will become one of our top-selling passenger cars as it continues to solidify its position as a mainstream vehicle"

(Toyota, 2004c)

This decision is primarily aimed at satisfying the growing demand from consumers. In fact, one of the major concerns of Toyota lies in its under-capacity, in terms of production, which is currently resulting in long delivery delays. One could interpret the excellent sales results of the Prius as the sign that HEV will become a major segment of the market. However, these results have to be taken with caution.

The problem with HEV is two-fold. First of all, in essence, HEV do not enable the automotive industry to eliminate neither the dependence on non-renewable resources, nor toxic emissions. The economies that can be achieved regarding these two issues are tremendous, but some industry experts estimate that it is a major shortcoming of the HEV technology. Secondly, the potential for HEV to constitute a sustainable market is still questionable. Over time, other technology such as Fuel Cell vehicles could make HEV obsolete. As a result, numerous analysts consider that HEV would never gain the potential to become a sustainable eco-friendly alternative.

"As it stands today, there is no solid answer to the question of how long hybrids will be around. Increasingly, the industry is viewing hybrids as longer-term, but not necessarily long-term, technology".

(Malesh, 2002)

"No one's really sure where this market is going. Some analysts believe that hybrids are just a stepping-stone to fuel cell cars, or hydrogen fuel...and at one percent of the car market, no one's rushing to pour ad dollars into the segment, so agencies will need stealth campaigns to catch the wave"

(Swanson, ?2004)

At the end, from a business firm's perspective, it all comes down to cost. Let's not forget that the main preoccupations of a company are survival, growth and profit. However, protecting the environment has a cost and one cannot expect corporations to invest tremendous amount of money while the outcome is more than uncertain. Before committing themselves into implementing a relevant alternative, the stakeholders must be convinced that the technology chosen will be sustainable over time, as it could facilitate return on investments. As of today, it appears that the potential of HEV to achieve market sustainability is clouded by a high degree of uncertainty.

The reasons behind this tremendous divergence of opinions within the automotive industry is primarily a result of a lack of studies or reports that clearly compare and assess the true potential of all green alternatives at once. The vast majority of the literature only consists in the promotion and “glorification” of a specific eco-friendly solution. Indeed, lobby groups always have a tendency to steer the automotive industry into the direction that best suits their interests.

As such, one can assume that there is an apparent need to clarify, not only what is the true potential for each technology to meet the new BEC, but also the real potential for HEV to become a relevant and sustainable alternative for the automotive industry.

1.3 Problem formulation

In lights of the problem background and problem discussion, the authors have decided to explore the potential of HEV to become a sustainable alternative. The research problem is thus formulated as follows:

“***In regards of the business environment conditions, to what extent is Hybrid technology a sustainable alternative for a car manufacturer?”***

In order to provide a valid answer to the research problem it appears that a clear description of all emerging technologies will be required. Only by comparing Hybrid technology with competing alternatives will it be possible to determine its true potential to become sustainable.

1.4 Purpose

The purpose of this thesis is to provide valid information and insights regarding the true potential of Hybrid technology to become a sustainable alternative, while reducing the dependence on non-renewable resources and reducing toxic emissions.

2 Research Framework and Methodology

2.1 Constructing the research Framework

Since the development of the proposal, we have been very well aware of the large scope of our thesis project. Not only the research problem touches upon abstract concepts such as sustainability and technology, but it also refers to one of the largest and most complex industries. Moreover, the process of writing a thesis is a task that we have relatively little acquaintance with. It differs greatly from traditional scholar work projects, which are often limited in time and labour required. In our opinion, writing an extensive multi-chapter thesis can therefore easily become an overwhelming task. However, such a challenge is in many ways an exciting opportunity. Not only does it enable us to put in practice all different theories that we might have come across along our studies, but it could also permit us to test our ability to be creative, to share some of our opinions, views and thinking process with the research community.

At an initial stage, it was our understanding that our research problem would require a thorough investigation of a particular phenomenon that requires extensive documentation from an empirical perspective. Indeed, at the beginning, we only had little knowledge of the major achievements of the automotive industry in the field of eco-friendly alternatives. Shortly after we started to gather information, we realised the diversity of alternatives, and the extent to which they differ greatly from one to another not only in terms of characteristics but also in terms of performances. As a result, the necessity of processing with an extensive review and description of all eco-friendly alternatives became evident.

It was also our belief that students undertaking a thesis would have to make use of their analytical skills in order to contribute to the ongoing debate in the field of theoretical research. In that respect, our research problem seemed to constitute an appropriate playground. Indeed, this thesis touches upon what we believed to be a fairly opened topic for discussion: how do emerging technologies compete? What does it take for an emerging technology to penetrate a market and to become sustainable? After a preliminary investigation, which enabled us to put our hands on very interesting articles and studies in that field, we noticed that there is a relatively important diversity of opinions amongst researchers. We believed that this situation would not only provide us with relevant theoretical tools to answer our research problem, but that it would also give us an opportunity to contribute to the debate by sharing our opinions and conclusions regarding what has already been written.

One of our initial tasks has been to assess what would be the most suitable approach to tackle our research problem. We believe that this is always a difficult yet critical step in writing a thesis. At an initial stage, it is practically impossible to evaluate and clearly identify all the major hurdles, concerns and problems that might arise throughout a research project. Our past experience has taught us that as knowledge is constantly gained throughout a writing process, researchers always discover new theories, new evidence that might influence or require an adjustment of the research problem. As a result, one can assume that researchers must find a way to structure their thinking in order to ensure a smooth sequence of operations required for writing a thesis. The authors believe that this structuring process requires the construction of a clear design, a display, in which the research problem would be broken into smaller 'pieces' or 'areas' that could be researched relatively independently from one another. We believe that such an approach would enable us to conduct several distinct tasks upfront, while avoiding a possible drawback.

Indeed, even if a major unanticipated breakthrough or finding is made in a specific 'piece' of research, the impact on the other area would be limited and would not require an entire revision of the work already done. On the contrary, such an approach would allow us great freedom in deeply exploring every area of the research problem.

As a result, our first task has been to construct a display in which our research problem could be split into smaller pieces or areas of investigation. Indeed we assume that a graphic representation of the research problem enable us to clearly determine, for each area, what are the necessary data to be collected, a specific set of objectives to be achieved and what should be the overall methodological approach. Miles and Huberman (1994) seem to support such an approach. They suggest that using displays is a way of ensuring that each step in the data collection, methodology and analysis of a research project fits together to create a logical and cohesive whole. Moreover, they state that

"at the proposal stage and in the early planning and start-up stages, many design decisions are being made--some explicitly and precisely, some implicitly, some unknowingly, and still others by default"

(Miles & Huberman, 1994 pp 16)

2.2 Elaborating the Research Design Display

We believe that our research problem touches upon a topic where little is know about the forthcoming future. As a matter of fact, the automotive industry has not been confronted with such a radical technological change since its birth. In fact, oil used in the conventional combustion engine has been the one and only way to propel cars for about a hundred years. As a consequence, the potential of a new technology to efficiently replace the current design has never been explored by the industry. Thus, a qualitative approach seems to be the best approach to tackle our research problem. Indeed, a qualitative approach would better enable us to study in-depth and in detail the potential of Hybrid technology to become a sustainable alternative. This assumption seems to be supported by Patton (1990), who suggests that a qualitative approach permits an evaluator to study selected issues in depth and in detail. Bill Gillham (2000) also supports the idea that a qualitative approach would best suit our research problem as:

“Qualitative methods focus primarily on the kind of evidence…that will enable [us] to understand the meaning of what is going on”

(Gillham, 2000, pp.10)

Based upon this, we believe that extreme attention has to be paid to avoid the common traps into which qualitative researches fall. This is especially true at the initial design stage. In that respect, Ronald J. Chenail (1997) highlights that:

“as qualitative research projects are conceptualized and conducted, they can grow out of alignment as researchers make choices as to their Area of Curiosity, Mission Question, Data Collected, and Data Analysis”

(Chenail, 1997)

This is especially applicable to our case as we decided to break down our research into smaller areas with different sets of objectives. Therefore, we had to make sure that each area of investigation would serve the interests of the whole project and that they would not deviate from the overall research problem. In order to avoid such a pitfall, Chenail suggests to use a ‘Plumbing Line’ that would ensure a perfect alignment between the area of curiosity, mission objective, data collected and data analysis.

We decided to apply this plumbing line into the development of our research design, and for each ‘piece’ of our design, we would make sure that:

- Each Area of Investigation or ‘small piece’ serves the overall objective of the research problem
- The objectives to be achieved, or questions to be answered by each area would perfectly match the overall research problem.

We also assumed that the plumbing line would further help us to determine what kind of information we would have to collect and how we would analyse them. By combining the display design approach and the Plumbing Line approach, we elaborated the research design illustrated in figure 1 below.

"In regards to the new business environment conditions, to what extent is Hybrid technology a sustainable alternative for a car manufacturer?"

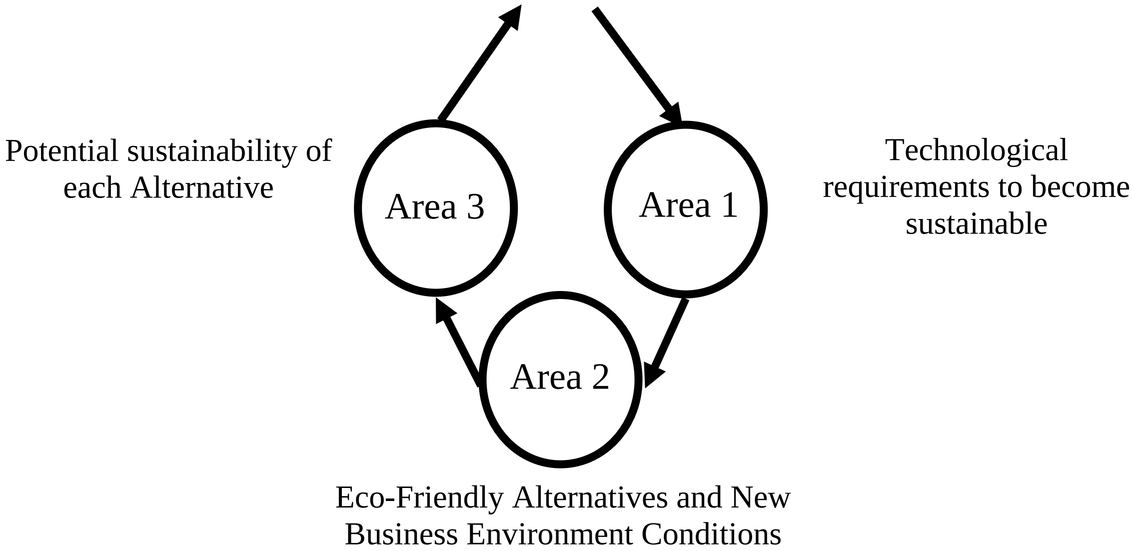

Figure: 1 – Research Design Display

The first area of investigation is devoted to clarify what the requirements are for a technology to become sustainable. Indeed, we are very well aware of the ambiguity of the term 'sustainable', especially in terms of technology. It could be assumed that in the real world nothing is sustainable. In fact, a better technology could always enter the market and replace an obsolete design, process or product. We therefore assume that this area of investigation should provide us with relevant information regarding the way emerging technologies compete. Indeed, it can be assumed that to remain sustainable, a technology needs to be able to efficiently compete with other alternatives. By focusing on solely analysing the competitive nature of 'emerging' technologies, we believe that the purpose of this investigation will not deviate from the overall research problem. In that respect, as described in the problem background and discussion, our main focus is to analyse the potential of Hybrid technology to become sustainable amongst the other emerging eco-friendly alternatives.

In light of the complexity of the research problem, we also believe that we will need a solid theoretical model in order to facilitate answering the research problem. By exploring the competitive nature of technologies, we will gain a first theoretical tool to better assess the true potential of Hybrid technology. However, we assume that this will probably not be sufficient. In an ideal situation, the most powerful tool would be to clearly know what are the criteria enabling a given technology to become sustainable. After a brief investigation in that matter, we noticed that there is an apparent lack of material within this field. Despite several pervious attempts to tackle this issue, a simple generic model that could be applied within an industry has not yet been developed. We anticipated that such a situation would result in a major hurdle in answering our research problem. However, in light of the various studies published, we believe that we can and should attempt to fill this theoretical gap.

As a result we established a clear set of objectives to be fulfilled by the first area of investigation. These objectives are clearly in line with the overall research problem and can be listed as follows:

Objective 1: to determine the evolution and competitive nature of emerging technologies

Objective 2: to determine the criteria required for a given technology to become sustainable

Objective 3: to develop a valid theoretical model in order to assess the potential for each technology to become sustainable

The second area is dedicated to providing a clear description of all the emerging technologies currently competing. As highlighted in the problem background and discussion, there are currently several major eco-friendly alternatives, each one having advantages and demerits. In that respect, the majority of reports assessing the true potential of these alternatives to match the new BEC is often one sided and do not attempt to compare one alternative to another. We clearly mentioned in our problem formulation that the ability to match the new BEC is a key issue in our research. In other words, the true potential for Hybrid technology to become a sustainable alternative can only be assessed if its potential to match the new BEC is apparent. Moreover it was our initial understanding that, in order to become sustainable, Hybrid technology must prove to have the potential to efficiently compete with other alternatives. As a result, we strongly believe that a thorough description of the characteristics of each eco-friendly alternative will have to be conducted. As a result a number of objectives were established to fulfil the second area of investigation.

Objective 1: To provide a clear description of the emerging technologies

Objective 2: To highlight the major hurdles towards physical implementation of these emerging technologies

Objective 3: To determine the degree of compliance between the emerging technologies and the New Business Environment Conditions

We believe that if all the objectives from the first and second area of investigation were to be fulfilled, we would have a considerable amount of both theoretical and empirical evidence. This would facilitate answering the research problem. However, before we are able to raise valid conclusions, we consider a final step to be necessary. The third and final area will require us to process with a thorough analysis of our findings by combining a theoretical model with the characteristics of each green alternative. Once again, in order to avoid the shortcomings of previous studies, we did not want to exclude any green alternative from this analysis. This will enable us to clearly assess the potential of Hybrid technology compared to other eco-friendly solutions. Therefore we have decided that the third area of investigation will be dedicated to analysing the potential sustainability of each alternative, and several objectives to be achieved are set as follows:

Objective 1: To compare the overall potential of emerging technologies to become sustainable

Objective 2: To assess the true potential for Hybrid technology to become sustainable

We believe that this final area of investigation will enable us to formulate clear and relevant conclusions that will permit us to answer the research problem.

2.3 Conducting the research

We believed that the construction of the research design was a major achievement as it enabled us to clearly identify what will be the primary fields of research. However, we then had to face a second major issue: how to collect the most relevant information we need in an efficient way? Indeed, we believe that any research is subject to shortcomings in terms of objectivity and one can assume that such a problem is impossible to overcome. As Bill Gillham (2000, pp. 27-28) states:

"Human Intelligence is by its nature selective…When you read research papers you can often see that people have found what they wanted to find"

Having this in mind, we decided that we had to adopt a fix set of rules, a "philosophy" when it comes to collecting evidence. In itself, these rules would not guarantee a complete objectivity. However, we wanted to ensure that we would not fall into the trap of "uncritical subjectivity". These rules could be summarised as follows:

- Always keep an open and critical mind
- Always look out for contradictory data

- When evidence is extracted from a specific source, always make sure that it is confirmed by numerous studies
- When investigating a specific issue, always use the most reliable and objective sources

From the very beginning of our research it also appeared apparent that the nature of data that would have to be collected would be rather different for each area of investigation. We therefore paid extra attention to explore which would be the most suitable methodology to adopt in each area of investigation.

It seemed to us that 'Area 1' would require an inductive approach. Indeed, in order to fulfil the objectives, we assumed that an extensive literature review of numerous theories would be required. This would enable us to derive relevant generalisations from the works already published by experts. However, we could not limit ourselves to a simple review, as we also had to formulate a relevant theory based on this empirical evidence. As Merriam (1998) suggests, an inductive approach is characterised by empirical data collected and subsequent theory formulation, based on these findings. Merriam also suggests that by using an inductive approach, the researcher generates new theories aiming to explain phenomena, due to a lack of existing theories. It therefore became apparent that the only way to tackle the objectives of 'Area 1' would be to adopt an inductive approach and to process with an extensive theoretical review.

By its nature, we believed that 'Area 2' would require a descriptive approach. This area of investigation mainly focuses on making sense of the accumulated knowledge in terms of the potential of eco-friendly alternatives to match the new BEC. In that respect we believed that the empirical evidence are given facts that cannot be discussed. For instance, the CO_2 emission generated by a gasoline-propelled vehicle is an existing data that cannot be contested (given the fact that it is obtained from a valid source). However, we also adopted a literature review method in order to eliminate possible discrepancies or contradictions.

Finally, we assumed that 'Area 3' would require an abductive approach. As a matter of fact, this area of investigation must be understood as an analysis in which we combine empirical findings with a theoretical framework. Merriam (1998) supports our choice. He suggests that an abductive approach is suitable when the starting point is the empirical findings, which, together with existing theories, form the basis for discovering certain hypothetical patterns.

2.4 Limitations

The reader must understand that this thesis will attempt to provide a holistic view of the technological battle currently taking place within the automotive industry. As such, the approach taken to tackle the research problem will consist in studying the potential of Hybrid technology from an industry perspective. Therefore, a consideration will not be taken into firms' specific strength or characteristic requirements when competing for technological superiority.

The primary reason for this was the difficulty to gather primary sources of information. More precisely, the authors did not have the opportunity to conduct this research for a specific case company. As a result, an easy access to primary sources, which might have helped the gathering of relevant industry and firm specific information, was not feasible. However, the authors believe that, due to the tremendous amount of secondary sources available, such a shortcoming was easily overcome. In addition, in the technological field, the validity of primary sources can be argued. As a matter of fact, experts working in a specific company or industry tend to excessively promote their point of view without considering contradictory evidence. The extensive use of secondary sources would therefore enable the authors to easily verify the validity of evidence, as well as facilitate the search for contradictory information.

In these lines, it must be understood that this thesis does not consist of a business plan aiming at clearly defining the most suitable way for firms to introduce a specific technology into the market. The authors believe that such a step could only be done after the true potential of a technology to become sustainable has been thoroughly assessed.

Furthermore, a decision was made not to include any review or description of the automotive industry. Mainly, since the degree of complexity of the automotive industry is such that a clear description of it could in itself constitute an entire thesis topic. Moreover, this thesis focuses on providing information to industry experts and investors who already have considerable knowledge about the industry. Therefore, as a limitation, the authors consider that the reader already has extensive knowledge regarding the structure and business environment of the automotive industry.

No benchmarking with other industries will be conducted within this thesis. Primarily, since the authors believe that the automotive industry cannot efficiently be compared with another industry, due to the complexities and current state of the industry.

Similarly, the authors will not process with an in-depth analysis of the influence of consumers, or consumer's behaviour, upon the possible outcome of a technology battle. More precisely, the authors will only consider price and minimum requirements issues that might influence consumers when it comes to purchasing an eco-friendly vehicle. Ideally, an analysis of consumer adoption processes and the new trends regarding 'Green Marketing' would provide relevant and interesting insights. However, the authors believe that regulatory bodies and other institutional forces already represent the best interests and needs of consumers. In that respect, by including institutional constraints within this research, the authors believe that no additional data related to consumer will be required.

In addition, an in-depth analysis of the automotive manufacturers' supplier base and their current supply capacity will not be conducted. However, the extent to which each technology and related know-how is mastered by the industry will be explored and assessed. Nonetheless, as this research is taken from an industry perspective, the authors believe that the automotive industry will circumvent eventual supply difficulties. In that respect, it is assumed that if a technology shows potential to become sustainable, the automotive industry will naturally process with all required investments to guarantee a sufficient supply of parts.

Last, but not least, when it comes to the eco-friendly alternatives that will be analysed throughout the thesis, the authors had to limit themselves to the current progress achieved in the automotive industry. This limitation is easily understandable since the authors cannot anticipate if a major breakthrough will happen in the industry. As such, a preliminary scanning enabled the identification of the Hybrid Electric Vehicles (HEV), Flexible Vehicles (FV), Electric Vehicles (EV) and Fuel Cell Vehicles (FVC) technologies, which are the predominant designs currently considered by the automotive industry. The Natural Gas Vehicles and Liquefied Petroleum Gas alternatives have been excluded from the thesis as they entirely rely on non-renewable fossilised resources.

2.5 Thesis Disposal

In order to clarify all the choices we have made regarding the design of the research framework as well as the methodology, we feel that we should construct another display that would enable a clearer picture of how our research will be conduct. Therefore, we combined all our methodological decisions into a tentative thesis disposal display that can be found below:

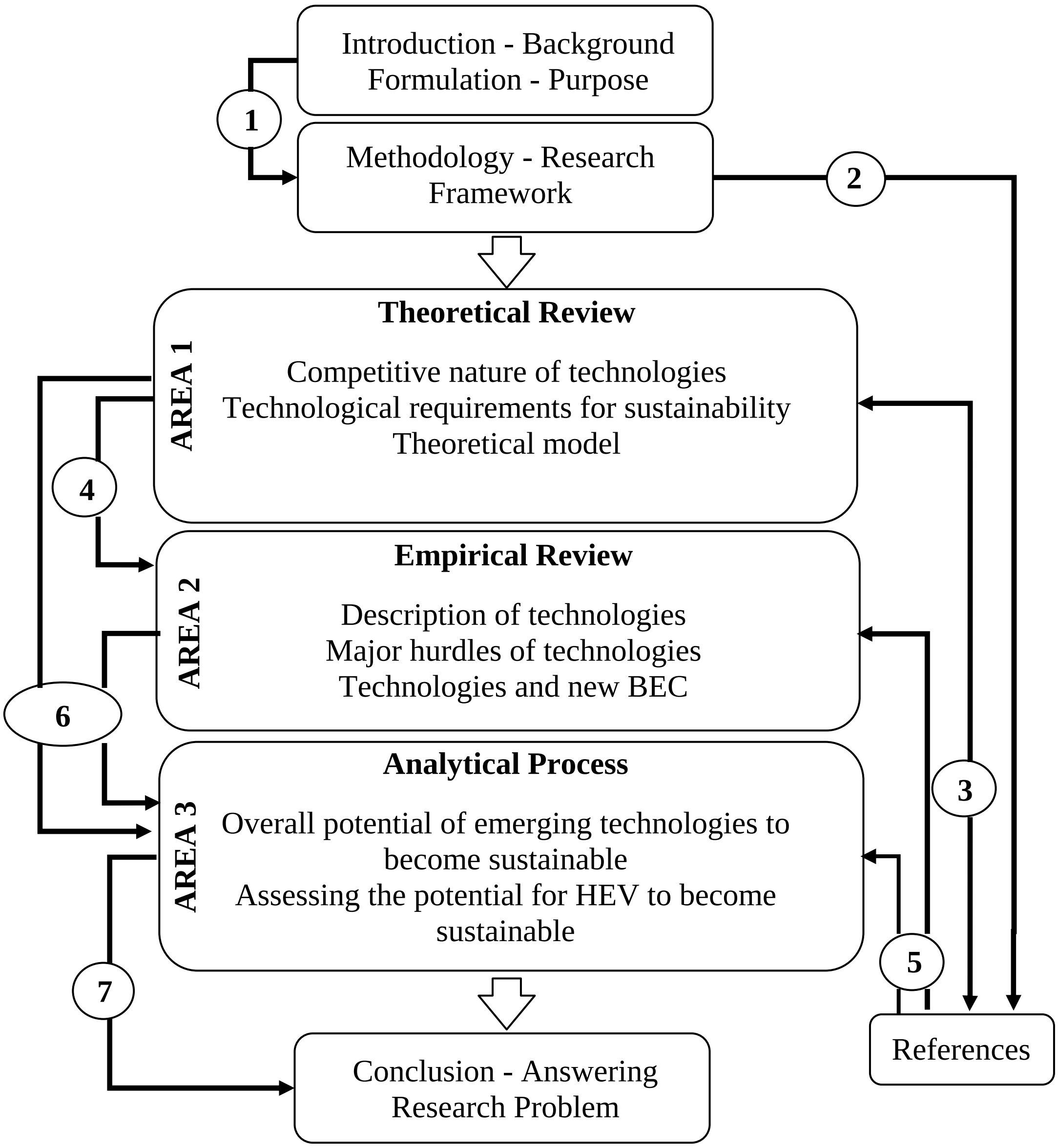

Figure: 2 – Thesis Disposal

We also believe that it will be a great help for us if we can try to establish a clear sequence of the operations required for writing our thesis. In that respect, the reader must understand that each arrow in which can be found a number correspond to the different stages that we will have to follow in order to ensure completion of our project.

3 Theoretical Review

This chapter examines the causes and effects of technology change and competition. It further analyses the constraints technologies needs to surmount in order to become sustainable. A generic theoretical framework is then proposed for understanding the processes by which technologies overcome these constraints and achieve sustainability. As such, the theoretical review focuses on building a model from an industry perspective.

3.1 What is a Technological Shift?

There is a considerable amount of literature on technological evolution and competition. However, understanding the dynamics of technology evolution has always been a highly complex task. As a result, researchers have developed numerous suggestions and solutions in order to tackle the topic, leading to disputes and somewhat unclear conclusions.

In fact, some suggest that technological change is inherently a chance or a spontaneous event driven by technological genius (Schumpeter, 1961). Dosi (1982) argues that the internal activities and capabilities within individual firms primarily drive evolution. Others suggest that technological change is a function of historical necessity (Gilfillan, 1935) whereas some further argue that it is a function of economic demand and growth (Schmooker, 1966).

These theoretical evolutionary suggestions could, nonetheless, be divided into two dominant approaches, namely the externally or internally driven motives for change. Although, both approaches emphasise key aspects of technological change, technology could evolve in response to the interplay of both approaches (Mowery and Rosenberg, 1979). Anderson and Tushman (1986) further advocate this point of view by suggesting that none of these perspectives alone encapsulates the complexity of technological change.

Despite the differing opinions regarding the origins of technological shifts, there is a general consensus that technological change is a bit-by-bit cumulative process, which ultimately is punctuated by a major advance (Abernathy and Clark, 1985; Andersson and Tushman, 1990; Dosi, 1982; and Rosenkopf and Nerkar, 1999). Indeed, Tushman et al (1985) state that business firms experience long periods of convergence of incremental changes, which later become punctuated by periods of upheavals. Tushman et al define these upheavals as “concurrent and discontinuous changes, which reshape the entire organization”. Anderson and Tushman (1986) further identify that these technological upheavals, either affect underlying processes or the products themselves. Consequently, these discontinuities are triggered by either process or product discontinuities. Product discontinuities arise in the emergence of new product classes or fundamental product improvements that command a vital cost, performance, or quality advantages over prior product forms. Process discontinuities originate from either process substitution, or process innovations, which result in radical improvements in the industry.

For the purpose of this thesis, the authors strongly believe that theories involving product discontinuities are the most suitable. Indeed, the new BEC forces the automotive industry to introduce new products that will require major advancements in terms of performance and quality advantages over current products.

3.2 Technological Evolution

3.2.1 Period of ferment and trajectories

The periods of technological upheavals, or discontinuities, initiate an era of intense technological variation. As new product classes emerge, the rate of product variation is considerable, as alternative products compete for dominance (Utterback and Abernathy, 1975). Dosi (1982) define the different emerging technologies as technological trajectories. Trajectories describe the path of a moving object across space and time. Technical trajectories can thus be described as the series of paths each emerging technology will follow before it penetrates the market.

Anderson and Tushman (1986) refer to these periods, where competition among the differing technological trajectories is fierce, as periods of ferment. This situation results in heavy industry fragmentation, symbolised by the existence of numerous differing technological trajectories. Indeed, the number of trajectories tend to increase because the emerging technology in itself is not completely understood. Moreover, since pioneering firms have an incentive to differentiate from competitors, each business firm will find great interest in developing its own alternative trajectory (or product).

Additionally, during the introduction of a revolutionary technology, it is crude and experimental, implying that an era of experimentation follows as organisations struggle to absorb or destroy the innovative technology (Anderson and Tushman, 1990). In other words, companies struggle to understand both the new technology and competitive environment. At the intra-firm level, these discontinuities often result in organisational inertia. In that respect, business firms are reluctant to process with the sharp shift in strategy, power, structure, and control that is required when adopting a new technology (Tushman et al, 1986). This organisational inertia further amplifies the actual existence and quantity of emerging rival solutions. Porter (1996) touches upon this issue, when highlighting the dilemma managers face within these periods of strong technological variation, when stating that:

"…in a newly emerging industry or in a business undergoing revolutionary technological changes…managers face a high level of uncertainty about the needs of customers, the products and services that will prove to be most desirable, and the best configuration of activities and technologies to deliver them. Because of this uncertainty, imitation and hedging are rampant: unable to risk being wrong or left behind, companies match all features, offer all new services, and explore all technologies."

Dosi (1982), moreover, identifies in the aftermath of a discontinuity, that each trajectory has three core attributes, namely their power, momentum and degree of uncertainty. Power and momentum refer respectively to the degree of influence and trust behind a trajectory. Building upon this, Rosenkopf and Nerkar (1999) argue that technologies might gain or lose influence and momentum from other technologies, implying that trajectories may either be complementary or competitive. Hence, complementary trajectories increase the power and momentum, whereas competing trajectories reduce them. Levithal (1998) even identifies that a high degree of complementarity may lead to convergence, where one progress is directly fused with another. Competing technologies, on the other hand, tend to derive power and momentum from one another, since development in one tend to come at the expense of development of others.

3.2.2 When does a period of ferment end?

However, another critical issue resides in determining the actual length of a period of ferment. The duration of a period of upheaval corresponds to the degree of inherited differentiation a breakthrough technology has in comparison with existing technology. When a specific trajectory builds upon revolutionary technology, rather than upon existing technological know-how, it often takes longer for business firms and other market forces to commit to, and realise the benefits of such an alternative.

Anderson and Tushman (1990) further support this position by arguing that firms, which are confronted with the choice of abandoning existing know-how, will defend older technologies more stubbornly. Furthermore, the aggregation of the internal and external uncertainties (technology-, organisational- and industry-factors) together with the lack of a common understanding among technical experts about the economic performance of differing technologies, result in industry inertia (Anderson and Tushman, 1990). Hence, radical technological developments will result in prolonging the period of ferment.

Nonetheless, a period of ferment, irrespective of technologic diversity, ends in the selection of a single dominant configuration of the new technology (Anderson and Tushman, 1986) as an amalgamation of a number of proven concepts (Utterback and Abernathy, 1975). A dominant configuration or design reflects the emergence of product class standards and ends the period of technological ferment (Abernathy and Clark, 1985). Alternative trajectories are mostly crowded out, when a dominant design emerges, and development focuses on elaborating a widely accepted product (Abernathy and Clark, 1985). This process where one technology eventually becomes dominant, and the losing technologies gradually disappear is characterized as the process of creative destruction (Shumpeter, 1950).

There appears to be a great deal of uncertainty regarding the evolution of technological alternatives during the period of ferment. Determining which trajectory could win a technological battle, and when the period of ferment ends is a complex task, as many factors influence the outcome of a battle. Nonetheless, there resides a consensus amongst researchers regarding the evolution of industries. Indeed, a product discontinuity leads to the emergence of diverse technological trajectories that either complements or competes for power, momentum and reduction in uncertainty. This will eventually result in the emergence of a dominant product design, which gradually crowd out alternative variations. Consequently, the process of achieving dominant design needs to be extensively reviewed and analyzed, as it appears to be the key in eliminating competition amongst technological alternatives.

3.3 The Dominant Design Paradigm

3.3.1 What is the Dominant Design Paradigm?

First introduced by Utterback and Abernathy (1975), the concept of “Dominant Design” can be defined as follows:

“A dominant design in a product class is, by definition, the one that wins the allegiance of the marketplace, the one that competitors and innovators must adhere to if they hope to command significant market following.”

(Utterback, 1994, pp.24)

The notion of one technological trajectory eventually prevailing is widely debated. Utterback and Abernathy (1975) argue that dominant design gradually emerge and reflect a consolidation of industry trajectories, and as such, crowd out alternative designs and become a beacon for further product as well as process improvements. Anderson and Tushman (1990) together with Suarez (2003) support this argument by arguing that ultimately one technological trajectory will prevail. Supported with their extensive longitude research, Anderson and Tushman (1986) discovered that there is no case where two standards coexisted or where the position of dominance rotated among competing trajectories. The differing opinion is illustrated through Nairand and Ahlstrom's (2003) research, which argue that the nature of an industry and institutional factors (i.e. regulatory bodies) could allow coexistence of competing technologies. The authors of this thesis believe that there is truth in both opinions, however more so on the former suggestion. Indeed, competitive forces will naturally push towards dominant design, as both supply- (i.e. to achieve economies of scale and learning) and demand forces (i.e. customers) strive for it.

The dominant design concept is well explained by Abernathy and Utterback's (1975) model. This model highlights the correlation between product and process innovations over time with the emergence of dominant design, illustrated in figure 3 below.

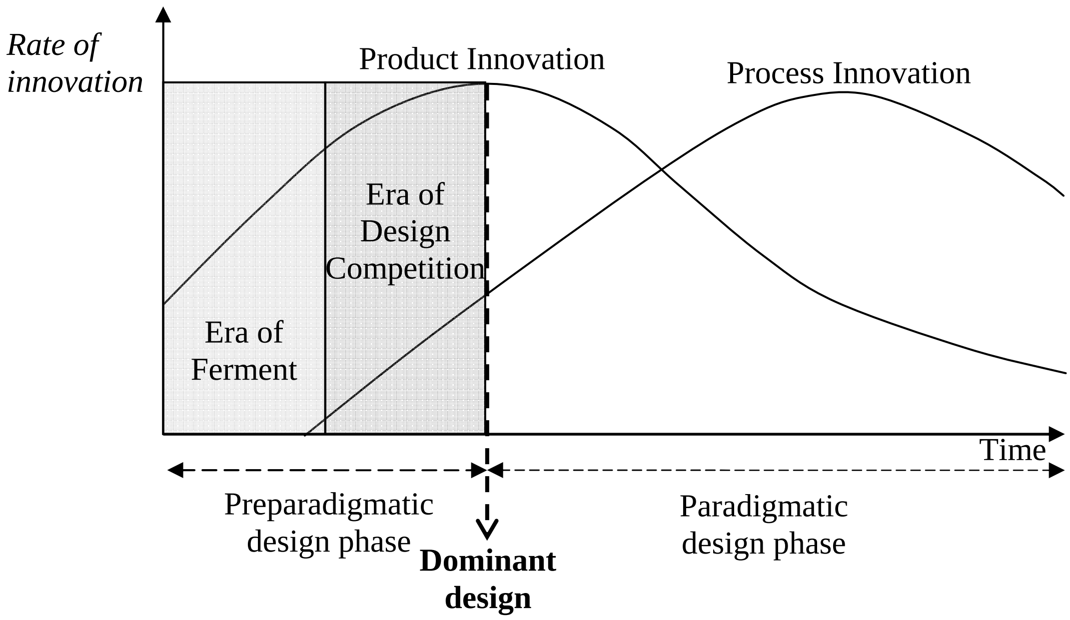

Figure 3 – Dominant Design Paradigm
Source: Adopted from Teece, 1987 and Anderson & Tushman, 1991

A discontinuity initiates a fluid stage (Utterback and Abernathy, 1975) or era of ferment (Anderson & Tushman, 1991), where product innovation is the main source of occupation due to the inherited uncertainty with emerging technologies, as figure 3 indicates. This fluid stage gives way to a transitional stage where the rate of product innovation slows down and the rate of process innovation speeds up. At this stage product variety gives way to standard designs that have proven themselves in the marketplace. In other words, these standard designs emerge since they either satisfy user needs or suit designs that have been dictated by accepted standards, through legal or regulatory bodies (Utterback and Abernathy, 1975).

Teece's (1987) allegory, where he compares the similarities between evolutionary stages of a science with that of technology evolution, sheds further light on the dilemma. There exist two stages of scientific evolution; the preparadigmatic stage, where no generally accepted conceptual treatment of the phenomena exists; and the paradigmatic stage, which begins when a body of theory appears to have passed the canons of scientific acceptability. The emergence of a dominant paradigm signals scientific maturity and the acceptance of agreed standards, implying a signal that 'normal' scientific research can be processed again (Teece, 1987). Porter (1983, pp 22) summaries the dominant explanation for this preparadigmatic phase:

"Initially…product design is fluid, and substantial product variety is present. Product innovation is the dominant mode of innovation and aims primarily at improving product performance. Successful product innovations ultimately yield a 'dominant design' where the optimal product configuration is searched. Process innovation is initially minor in significance, and early production processes are characterized by small scale, flexibility, and high labor skill levels. As product design stabilizes, increasingly automated production methods are employed and process innovation to lower costs takes over as the dominant innovation mode."

Adner and Levinthal (2001) and Keppler (1996) further develop this view, by arguing that process innovation gradually evolves as firms' appropriate returns from their investments. This is supported with the fact that increased volume production would facilitate firms with the means for process innovation. Indeed, increased volume production creates scale economies due to learning by doing, and further reduces demand uncertainty. In fact, an increasing user base provides the manufacturer with better understanding of maintenance and product requirements. As such, when a technology gains a foothold within the market it will gradually develop its product as well as process innovations. Consequently, once a design approaches dominance other existing trajectories would gradually disappear. This is in line with Suraez (2003) who argued that once a technology gains momentum it may be difficult to stop its advances. He elegantly expressed this as follows:

"The presence of a clear forerunner…[in the dominance battle]…has a chance of winning the battle, as its larger installed base tends to create some 'excess-inertia' – a bias towards the technology with the largest market share. The final outcome will depend on how fast the competitors improve on their own designs and how fast the market grows"

Suarez (2003) further states that an early forerunner could achieve more than 50 percent market share for a few years, even though it might be an inferior technology compared to rival ones. The fact that an inferior technology inhibits the same opportunities, from a purely technological point of view, to achieve dominance seems to be the general opinion among researchers. In fact, Anderson and Tushman (1991) argue that, more often than not does dominant designs lag behind the state-of-the-art technology. Nonetheless, once a dominant design is achieved it may only temporarily maintain its position as it might be overrun by a rival technology, or dominance may even pass back and forth among rival designs. As Anderson and Tushman (1990) expressed it:

"One technology might achieve temporary ascendance only to be supplanted by a competing design, which it might again overtake. Second, several rival designs might achieve stable and roughly equal market shares. Though one might account for a higher percentage, neither could be said to be dominant."

Emerging technologies do, however, sooner or later replace the substituted technology, which gradually disappear from an industry. Dominant design could therefore be seen as the second milestone within the technological evolution process, since it shifts the competitive nature from ferment into its 'natural' state of convergence, which will prevail until the next period of upheaval. The technology life cycle could therefore be seen as a continuum, with altering periods of convergence and upheaval as Tushman et al (1985) suggested.

3.3.2 Dominant design – the key to sustainability

After reviewing the gathered data, it became clear to the authors that achieving dominant design is a key factor to win a technological battle. This is in line with Anderson and Tushman (1986, 1990), Utterback and Abernathy (1975) who state that eventually only one technology can eventually prevail. In fact, our findings suggest that the technology that achieves dominant design first would gain the greatest ability to sustain itself, as stated by Suarez (2003). It has, furthermore, been demonstrated that a dominant technology would have the potential to inhibit the chances of competing technologies to penetrate the market. This competitive pattern is summarised and illustrated in figure 4 below.

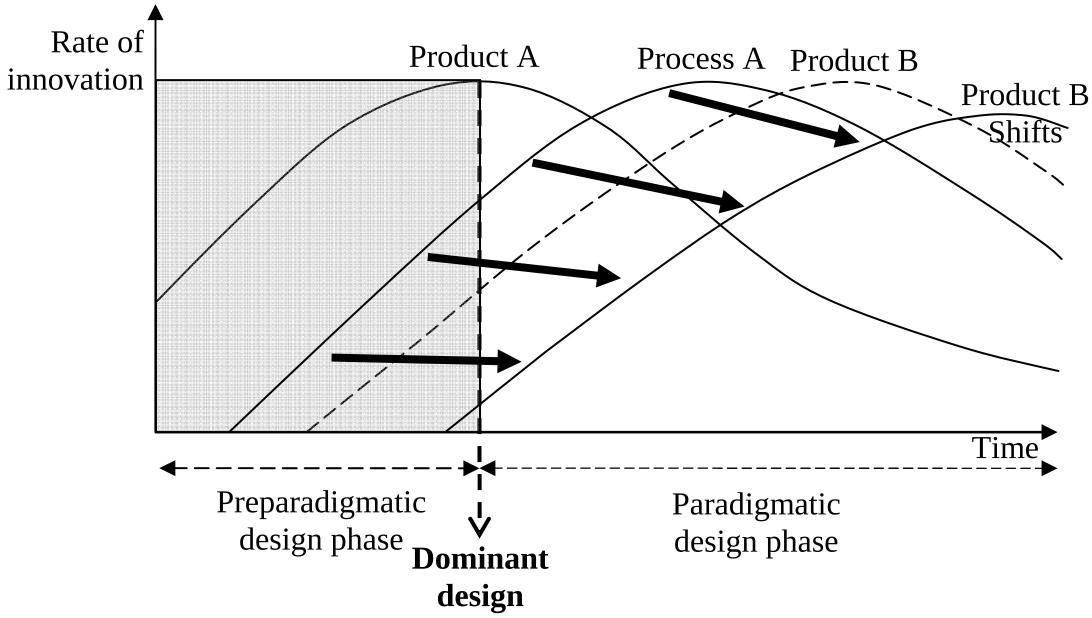

Figure 4 – Dominant Design Shift

Figure 4 represents what would happen if two technologies (A and B) were to compete in a given industry. As illustrated, during the preparadigmatic design phase, it appears that technology A wins the battle by achieving a dominant position first. As a result, the potential of technology B to enter the market is either destroyed or pushed further away in time. When Technology A shift its competitive focus from product to process innovation it will achieve economies of scale and scope, whereas technology B struggles to achieve a suitable product-market fit. Therefore, one can assume that technology A will constantly increase its competitive advantages towards technology B.

As a result, technology A will have better chances to become sustainable than technology B. One could therefore conclude that the criteria required for a technology to become sustainable are closely linked with the criteria required to become dominant. The dominant design paradigm seems relevant in the case of the automotive industry. Indeed, the car industry could be considered as a mass market with fairly homogeneous consumer tastes. These characteristics emphasise the importance to rapidly achieve economies of scale and scope, by emphasising the importance of a swift switch from product to process innovation. Consequently, in order to determine the criteria that are required for a given technology to become sustainable, an assessment of the criteria to become dominant is required.

3.4 Current Models for Achieving Dominant Design

While assessing if a model currently exists in order to establish what the criteria for reaching dominance are, the authors have had little success. An extensive literature review yielded little result as researchers primarily focuses on specific niches and investigates isolated events. In fact, the technology dominance phenomenon (Utterback and Abernathy, 1975), in conjunction with the development of technological trajectories (Sahal, 1982; Dosi, 1982), has led to a rich flora of studies which further developed the theory of dominant design (i.e. Anderson and Tushman, 1990; Suarez and Utterback, 1995; Christens et al, 1998; Tegarden et al, 1999; Cusumano et al; 1992; Willard and Cooper, 1985; Tripas, 1997; Khazam and Mowery, 1994 etc.). These have been followed by the 'new' concepts of 'network economics' (David and Greenstein, 1990; Katz and Shapiro, 1986), 'institutional perspective' (Garud et al, 2002; Scott, 1994; Tushman and Rosenkopf, 1992) and 'platforms' (Meyers and Lehnerd, 1997; Cusumano and Gawer, 2002).

However, none of these authors take a holistic perspective on how dominant design emerges. Consequently, there is an apparent lack of researches that aggregate the findings from all these studies and create an integrative model that would enable a valid and holistic assessment of dominant design. However, two apparent research studies were identified to merge and draw upon these fragmented conclusions, recommendations, theories and models. These were the studies of Shapiro and Varian's, (1999) and Suarez's (2003).

Shapiro and Varian's (1999) research focus on the development of standards, within what they refer to as 'standards wars', by considering the factors firms need to overcome when fighting a standards war. Suarez (2003) model tries to develop an integrative framework for understanding the process by which a technology achieves dominance when competing with other technologies within different stages of evolution.

Considering the research question, which is to determine the sustainability of Hybrid-technology, there exists a necessity to determine whether or not it can become dominant. As such, an analytical framework needs to be created that determines both Hybrid and other alternative technologies potential of becoming dominant. Currently, only Suarez (2003) model considers the culmination of dominant design from a holistic perspective; however, this is from a firm- and not an industry perspective. His model is therefore, not applicable when answering the research problem, as this would require an industry and not a firm perspective. This necessity for an industry perspective becomes transparent when considering that it is the technologies themselves that are to be assessed and not firms' development and introduction of new technologies. The importance of such a model and the apparent lack of a holistic model determining dominant design highlight the need to develop one. This apparent lack of dominant design models is further stressed by Suarez (2003) when he state:

"…no framework had linked the ideas and conclusions coming form the different studies and streams of literature dealing with the topic in a way that it is helpful both to researches and to practitioners"

Therefore an apparent need exists for the authors to develop a theoretical framework that determines the constraints of achieving dominant design from an industry perspective.

3.5 Constraints Inhibiting Dominant Design

The dominance process fundamentally consists of different technological trajectories or designs that are sponsored by different actors. These compete for dominance through a process where economic, technological, and socio-political factors are intertwined (Tushman and Rosenkopf, 1992). As, Dosi (1982) advocates, new technologies are selected through a complex interaction between fundamental economic factors (the search for increased profits, market shares, efficiency etc.), together with powerful institutional factors (the interest and commitment of existing firms, involvement of governments, etc.). Anderson and Tushman (1990) even argue that the closing of an industry standard is an inherently political and organisational phenomenon constrained by technical possibilities.

Institutional forces (i.e. organisations, industry associations, regulatory agencies etc.) affect the emergence of dominant designs. In other words, the establishment of a particular technical regime might have national repercussions, which may lead to direct involvement of sovereign states in the process of technological evolution (Anderson and Tushman, 1990).

The actions of business firms alone and in conjunction with strategic alliances also attempt to establish dominance. The underlying reason for alliances is predominantly the inherited risks involved, which create an array of organisations and collective forces that facilitates the emergence of a new design (Anderson and Tushman, 1990). LeCraw (1987) even stated that the market power of a dominant producer might put enough weight behind a particular design to make it dominant or that a powerful user may mandate a standard.

Another factor that influences the creation of dominant designs, in addition to the institutional ones, is the demand factor. Anderson and Tushman (1990) clarify the additional importance of consumers and its correlation between the other factors when they suggest:

"De facto standards emerge when users prefer on design over another, which suggests that dominant design emerges from market demand, which is affected by the combination of technological possibilities and individual, organizational and governmental factors."

In fact, Adner and Levinthal (2001) establish a correlation between the demand environment and the evolution of technology and thus add another dimension into the establishment of a dominant technology: the consumer impact. Nonetheless, dominant designs could therefore be said to emerge as manufacturers, regulatory agencies and customers, inhibited by technological constraints, compete to decrease the uncertainty associated with product variations during the era of ferment.

Suarez's (2003) aggregation of the factors that affect the emergence of dominant design, are divided between firm- and environmental-level factors. The separation between these is most likely done to emphasise the differences between controllable and uncontrollable elements constraining corporations. Nonetheless, Suarez developed a model, while fully aware of the difficulties in assessing the myriad of relevant theory encompassed within these subjects. Nonetheless, he managed to develop a generic model that distinguishes four broad firm-level factors and four environmental factors, which corporations need to consider when striving for dominant design. These factors are illustrated in figure 5 below.

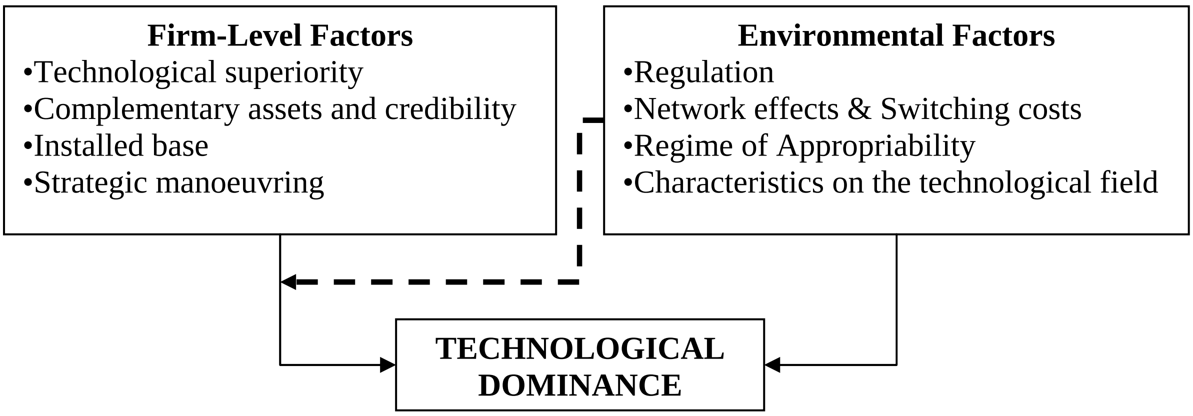

Figure 5 – Firm- and Environmental Factors Influencing Outcome of Technology Battles
Source: Adapted from Suarez (2003)

Despite Suarez's (2003) extensive research, the separation between firm and environmental forces constraining organisations is to some extent not adaptable to the research problem. The aim of this thesis is to assess the potential sustainability of Hybrid technology in itself. As such, there is a need to make an industry assessment of competing technologies. Furthermore, Firm-Level factors might not prevent a technology, from an industry perspective, to achieve dominance. Consequently, a reassessment and development of the forces presented by Suarez's model is necessary. Indeed, the authors believe that the creation of a new theoretical model for determining dominant design, from an industry perspective will facilitate the necessary validity and reliability to gain an objective answer for the research problem.

3.6 Industry Constraints Inhibiting Dominant Design

There is a consistent view that dominant design emerges from the interplay of a number of differing factors that either sustain or constrain its development. Nonetheless, there is a consensus that dominant design emerges from the interrelationship between the technology itself (i.e. Anderson and Tushman, 1990; Tushman and Rosenkopf 1992; and Suarez, 2003), institutional factors (i.e. Anderson and Tushman, 1990; Dosi 1982; LeCraw, 1987; and Das and Van de Ven, 2000), demand factors (i.e Adner and Levinthal, 2001; and Anderson and Tushman, 1990) and network factors (i.e. Abrahamson and Rosenkopf, 1993; Schilling, 2002; and Suarez, 2003).

The established institutions within an industry (i.e. competing firms, industry organisations and regulatory bodies), wherein an emerging technology enters to substitute an 'old' technology either support or hamper the development of dominant design. Consumers will similarly support or hamper technologies by choosing to adopt a new technology or not depending upon certain sets of consumer criteria. Network factors arise from a combination of the above-mentioned factors. In other words, when a technology gains institutional, or consumer support, other stakeholders within the industry will tend to constantly increase their degree of commitment to this technology. As a result, it must be admitted that the industry forces constraining the emergence of dominant design stem from either technological, institutional, demand or network variables.

Even though the differing constraints in achieving dominance within an industry context have been identified, there is a difficulty, identical with Suarez's (2003), in reviewing all involved theoretical aspects and factors within each of these generic constraints. Although the wide variety of models available means it is not feasible to incorporate a complete review of the literature within the scope of this thesis, key generic aspects and factors of the model will be highlighted. Each factor might later be further developed with the use of other existing theories and models.

3.6.1 Technology Constraints

Anderson and Tushman (1986) identify that emerging technological discontinuities are not alike. These technological shifts are either competence-destroying or competence-enhancing. Competence-destroying discontinuities are so significantly different that the skills and knowledge base, which are required to operate the current core technology, shift. Hence, the hallmark of a competence-destroying technology is that the mastery of the new technology alters the set of relevant competencies within a product class. As such, they require new skills, abilities, and knowledge in the development and production of the new technology. Competence-enhancing discontinuities build on existing know-how within a product class and are order-of-magnitude improvements in price and/or performance. These technologies thus substitute older technologies. However, they do not render obsolete the skills required to master 'old' technologies. They also considerably alter previous attainable price/performance relationships within a product class.

Das and Van de Ven (2000) agreed with this separation, when they distinguished emerging discontinuities between evolved and novel technologies. An evolved technology has new performances while being based upon existing knowledge, whereas a novel technology, also with new performances, is represented by a completely new way of meeting a functional need.

Hence, amongst researchers, there is a consensus regarding the emergence of competence-enhancing (evolved) and competence-destroying (novel). These differing discontinuities could emerge simultaneously as an industry develops varying solutions in response of an upheaval. In that respect, the authors believe that the implications and physical hurdles before the implementation of a 'novel' technology are far greater than in the case of an 'evolved' technology. The former implies developing new skills, knowledge and functional infrastructures that require time, money and synchronisation amongst the stakeholders of an industry.

Moreover, regardless of competence, new technologies need to be evaluated when they emerge to replace older technologies. According to Das and Van de Ven (2000) the main evaluation criteria technologies are judged upon, within an industry, is the direct comparison between old and new technology. Consequently, technological constraints also refer to the technology performance in itself; namely how well it performs in comparison with competing alternatives. From a purely technological point of view, it may be argued that the better a technology performs with respect to other competing ones; the higher is its probability of becoming dominant. However, Cusumano et al (1992) state that technological superiority does not always play a significant role in dominance battles. Nonetheless, the imperative factor is to determine the nature of a technology in question, in essence whether it is a competence-enhancing or -destroying technology.

3.6.2 Market Constraints

There are tremendous difficulties in assessing market demand for emerging technologies, in fact market demand in general. Adner and Levinthal (2001) stress this problem together with the apparent lack of investigations researching the impact demand has on technology evolution. They thus develop a demand-based view of technology evolution, which focuses on the interaction between technology developments and demand environment in which the technology ultimately is evaluated. Adner and Levinthal (2001) based their framework on the fact that in demand heterogeneous markets (different trajectories) initial technological development is motivated by the drive to meet market requirements. Well aware of the inherited diversity that underlines the notion of 'market' demand and the widely differing needs and requirements of consumers Adner and Levinthal (2001) characterize consumers by two attributes. These are the minimum performance requirements that a technology must satisfy in order for the consumers to be prepared to purchase it, and the consumer's willingness to pay for technology performance.

The critical element affecting consumers' preference is the minimum performance threshold (independent of price) that a product must reach before it is to be valued by a given customer. Deriving from this, there is a need to determine the trade-offs resulting from the introduction of a new technology in terms of costs. These criteria are referred to as 'functional threshold' and 'net utility' threshold respectively. Although the concept of thresholds is well established in a variety of literature, the application of it and the common view is that adoption, and purchase of a good, is a discrete decision that is prompted by some threshold of 'attractiveness' being surpassed.

A functional threshold specifies the performance level below which a customer will not accept a product, regardless of its price. If a product falls under this threshold, consumers will perceive it as rubbish and would not accept it at any price. The functionality thresholds are determined to some extent, by inherited task requirements and by context (purpose). Alternatively, the functionality requirements could be externally imposed, by the downstream customers or by externally imposed regulation (i.e. governments).

Net utility threshold encompasses the interaction of technology performance and price. This reflects the highest price a consumer is willing to pay for a product that just meets their requirements. In that respect, customers often have similar functionality requirements; however, they might have different net utility thresholds. This stems from the fact that customers may differ in the value they derive for the product for a number of reasons.

Market constraints thus refer to how well competing technologies perform in comparison with one another and the established functional and net utility thresholds. In other words, it is a benchmarking of the inherited potential competing technological variations has in comparison with the existing thresholds from a technical point of view. The vital factors to assess within this sphere are thus whether or not a technology fulfills the functionality thresholds currently established within an industry and how well the competing technologies correlate with the net utility threshold of the ‘old’ technology.

3.6.3 Institutional Constraints

The differing institutional forces within an industry encompass existing firms, governments and industry organizations. Technological regimes are highly dependent upon the actions and reactions of these differing institutions, as they either support or reject an emerging technology.

As industries are faced with a degree of inertia, due to a lack of understanding of new technological regimes, they tend to disagree upon which technological trajectory encompass the best future potential. Competition and cooperation thus emerge between these different institutional stakeholders as they support competing trajectories. Further, this implies that the ‘best’ emerging technology, the one with superior long run potential, might subdue within a technology battle. This industry inertia suggests that there is room for intervention (Suarez, 2003) since competition between technologies does not ensure that the ‘best’ technology will prevail. A central authority with full information on future returns, and who knows which technology has the superior long run potential, may attempt to tilt the market balance in favour of this technology. Albeit regulatory intervention occurs, it may in many cases not be clear that the chosen technology offers the greatest potential.

Regulatory intervention has in fact the power to enforce a dominant design (standard). Often governments are forced or motivated to intervene directly and mandate the use of a particular technology when the technological regime may have national repercussions (Anderson and Tushman, 1990). Yet, the role of government is not merely restricted to regulation as it may distorts competition through public procurement (Suarez and Utterback, 1995) or economic incentives of a technology in the early states of its development. This may further tilt the balance in favour of that particular technology.

Industry organisations also try to tackle the problems of inertia and lack of knowledge in an era of ferment, by attempting to establish a common industry technology. This is generally achieved though alliances amongst corporations who will speak with a common voice and thus strive to mandate a dominant design.

Corporations also affect the outcome of technological battles, predominantly through their installed base of users. Research has pointed out that an installed base in itself can have an effect on customer's demand (Suarez, 2003). There exists a correlation between a firm's installed base and higher rates of adoption for a specific technology. A large installed base could thus provide a technology with an extra push towards dominance (LeCraw, 1987). Hence, a familiar brand may reduce the uncertainty associated with new technologies and ease adoption. A firm's strategic manoeuvring, additionally, affects the outcome of dominance. As such, customers' perception regarding a new technology might be influenced by the type of licensing agreements pursued by the firm, as well as the form and intensity of marketing and public relations activities (Suarez, 2003). The correlation and importance of a firm's licensing policy has been established, as it is a key driver of industry adoption of a technology (Cusumano et al, 1992). Mainly, as a lenient licensing policy could introduce more firms to support a specific technological regime and thus increase adoption.

This goes in line with Teece's (1986) theory regarding regime of appropriability. Teece (1986) argue that the profitability for a firm to introduce a new technology is dependent on the regime of appropriability. In other words, what degree of possibilities a firm has to protect its innovation from potential imitators through regulatory protection, and possibilities of preventing firms from invention 'around' its technology. From an industry perspective the weaker the technological appropriability is, the more rapidly it will be adopted by the industry, and most likely become dominant. In that respect, the authors would like to stress the fact that a lenient licensing strategy could consist in protecting a product from rival technologies, while allowing competitors to use the license in order to introduce products based on the same standard. Such a strategy will therefore result in facilitating a specific technology to achieve dominance.

Das and Van de Ven (2000) stress marketing's importance by arguing that a market may not exists for a new technology which implies that the consumers need to be educated. Even if a market exists, firms need to inform customers regarding the benefits derived from new technologies, and thereby also stress its advantages over other trajectories.

To summarise, all these institutional aspects need to be aggregated, in order to illustrate the overall industry trends and technological support. This is done to determine the varying technological trajectories overall installed base and possible strategic support. Firm support of differing technologies need to be compared to the differing government support incentives and regulations in an aggregated manner. A technology's overall amount of industry support could thus illuminate the amount of power and momentum a technological trajectory receives among the institutional factors. Chakravorti (2004) supports this when suggesting that the success of a technology depends upon its ability to gain enough participants to back it up.

Institutional constraints thus refer to the amount of aggregated support a technology can gain within an industry context. Therefore, there is a need to assess the degree of support differing technological trajectories receive from firms, governments and industry organizations.

3.6.4 Network Constraints

Network effects usually arise within an industry environment when a consumer's benefit from using a technology increases with the number of users employing the same technology. As such, the number of customers adopting a technology, its installed base, will thus have a spiralling positive effect upon technology adoption (Katz & Shapiro, 1986). The classic examples are markets involving physical networks, such as railroads or telecommunication. However, network effects could also occur in markets that do not have physical networks, where, for example, a user's benefit may increase with the number of users of the same good when compatibility is important (Schilling, 2002). The correlation and effects an installed base has on technology adoption have been empirically supported during the past decade within several studies (i.e., Cottrell, 1998 and Wade, 1995).

There are basically two kinds of networks, which are direct network effects and indirect or complementary networks (Srinivasan, 2004). Direct network effects arise when a customer's utility from a product increases as the number of customers who use identical products increase (Katz and Shapiro 1986). In other words, when the utility of a product to each user in a network depends on the quantity of other users, the product exhibits direct network effects.

Indirect or complementary network effects happen as a result of increasing demand for complementary products or services (Katz and Saipiro, 1985). Indeed, Schilling (2002) point out that many technologies are dependent on the availability of complementary goods, since many technologies are not desirable to customers without an associated set of complementary goods. When a technology requires complementary goods, their availability will play a crucial role in consumers' choice between competing technologies (Choi, 1994; Farrell & Saloner, 1985; Katz & Shapiro, 1986). A technology with low availability of complementary goods would be much less likely to be adopted. In fact, Cusumano et al (1992) found a correlation between availability of complementary products and ability to achieve dominant design, with their case about the triumph of VHS over Beta.

Schilling (2002), nonetheless, point out that these forces live in a sense of symbiosis, since the size of the installed base reinforces the availability of complementary goods and vice versa. This becomes evident when considering that products with a large installed base are likely to attract more developers of complementary goods, which in turn influence consumers' subsequent choice among competing technologies. The size of the installed base and the availability of complementary goods are therefore likely to be highly correlated.

As the majority of potential adopters will await the emergence of an industry standard before purchasing a new product design (Anderson and Tushman, 1990), the emergence of a potential dominant design will trigger the accumulation of adopters. This is especially apparent when networks and complementary products are important, as products that embody dominant design will increase in value as more adopters choose it (Abrahamson and Rosenkopf, 1993). The emergence of a dominant design in product categories with network effects will ensure potential adopters that the dominant design's network will be largest, resulting in further adoption of it. Such behavior could further be explained with the fact that every network generates economies of scale.

Chakravorti (2004) argues that there usually exist two types of economies within a product network. First, products within large networks are often cheaper than the ones with smaller networks. Secondly, a product's value to each user increase as size of the network grows. These factors motivate customers to switch to the 'right' technology for fear of losing out, as the support for a declining design may backfire. Albeit, this kind of behaviour is not merely a demand-oriented issue, as the sheer number of organisations adopting a technology can cause a bandwagon pressure (Abrahamson and Rosenkopf, 1993), prompting customers to adopt this technology.

Bandwagons are diffusion processes whereby organisations adopt a technology, not through their individual assessment of the technologies efficiency or returns, but because of an institutional pressure. In other words, the fear of losing out on a potential future dominant design can cause organisations to adopt innovations they assess as technically inefficient (Abrahamson and Rosenkopf, 1993). This implies that when a technology gains power and momentum, more and more organisation will adopt this technology, which results in an increased installed and complementary base at the expense of other technological trajectories.

However, another aspect of network effects suggests an opposing process. Customers may adopt a “wait-and-see” attitude, postponing adoption resulting in “excess inertia” (Farrell and Saloner 1986; Goldenberg et al, 2002). This concerns the dilemma customer face when selecting among technological trajectories. Indeed, the absence of a dominant design has its associated risks. If customers adopt the wrong technology they must either incur switching costs or forgo the benefits of adopting a dominant standard (i.e. scale economies, access to infrastructure designed around the standard etc.). Such excess inertia not only exists in direct network markets but also within indirect network markets, where the lack of complementary goods causes a ‘chicken-and-egg’ co-ordination problem.

These findings highlight the importance of timing in terms of market entry. In fact, the sooner an emerging technology enters a market, the better is its chances of early adoption, since an early entry helps to build a larger installed base, creates reputation and learning effects, which often results in product improvements (Suarez, 2003; Cusumano et al; 1992). On the contrary, if a technology is underdeveloped, if its abilities to meet customer needs are unknown or if there is a lack of necessary complementary goods and services, it might fail to attract customers (Schilling, 2002). Nonetheless, if a technology gets ahead by good fortune, it gains a considerable advantage despite technological performance: it can then attract further adopters who might otherwise have gone along with rival technologies resulting in early adoption and domination of a specific trajectory.

Network constraint thus concerns to which degree a technological trajectory requires network effects and complimentary goods in order to establish itself as a dominant design. In that respect, there is a need for assessing the degree of dependence a technology has upon the establishment of network effects to establish whether or not the speed of entry is a vital factor. Additionally, it is necessary to assess the dependency and availability of existing complementary goods. The dependency on complementary goods could be assessed using Teece’s (1986) framework, where he divid complementary assets into three degrees of dependency; generic, specialised and cospecialised. Generic assets are general-purpose assets that do not need to be tailored to the technology in question. Specialised assets are those with unilateral dependence between the technology and the complementary assets, whereas cospecialised are those with bilateral dependence.

3.7 A Suggested Model for Assessing Dominant Design

As a period of technological upheaval commences, it initiates an era of intense technological variation. This fragmentation and arise of various technological trajectories stem from a lack of technological understanding and because differentiation is the main source of competitive advantage. These emerging technological trajectories initially face stiff competition, not only between each other, but also from the entrenched technology. Fierce competition thus exists among all these technologies to enhance their respective amount of power and momentum, while at the same time reducing the degree of uncertainty surrounding each technology. As certain technologies gain more power and momentum than others, these will gradually crowd out alternative designs as it facilitates the possibility of increased product and process improvements. This behaviour initiates a sequence of events, by sending signals to the industry that this particular technology might achieve a dominance status. Industry stakeholders that previously supported other technological alternatives will most likely support or switch to this ‘winning’ technology, from fear of losing out. This fear is founded upon the fact that these technological battles often determine not only the fate of the winning or losing technology but also the fate of their sponsoring firms. Nonetheless, the escalation of industry support continues until a specific technological trajectory has gained enough power and momentum to achieve dominance, and thus eliminates competing technologies.

The emerging technological trajectories power and momentum stems from the complex interplay of a number of differing sources, which either sustain or constrain their development. From an industry perspective these sources of development are considered to be technological-, institutional-, demand- and network factors. These factors compete and collaborate with each other to decrease the uncertainty associated with the varying trajectories during the era of ferment. These forces are by no means independent, but rather coexist in a state of symbiosis, where factors affecting one force often result in repercussions within another, as illustrated in figure 6 below. Indeed, the nature of a technology in itself will affect all other forces, as it influences the degree of uncertainty inherited within a technology. Hence, the industry finds it hard to judge technologies, which degree depends on whether the technology is competence-enhancing or -destroying. Additionally, demand and institutional factors are bound to each other, with the fact that suppliers must satisfy consumers’ functional requirements, while customers might have to fold for governmental pressure or supplier unity. These mentioned factors are all intertwined with the network force, as it might initiate a bandwagon effect that may result in the emergence of a dominant design. In these lines, the authors agree with Suarez (2003) that no factor of dominance is strong enough to tilt the balance in favour of a particular technology. Hence, the final outcome is the result of the relationships between all of these industry constraints.

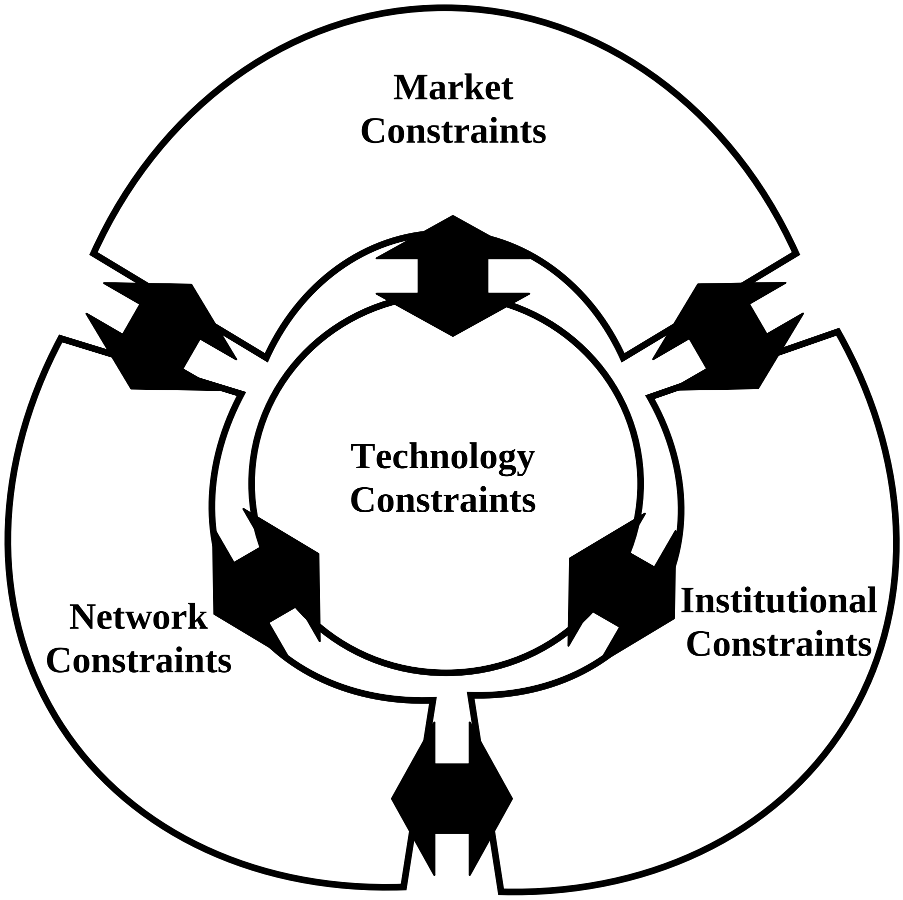

Figure 6 –Constraints for Achieving Dominant Design

After reviewing the factors that influence the emergence of a dominant design, the authors could develop a generic model that assesses varying technological trajectories potential of achieving dominance. A comparison between the different constraints would yield sufficient guidelines for determining which technological trajectory has the best competitive position to achieve dominance. However, first an analysis within these separate constraints needs to be conducted, to determine the competitive support differing trajectories obtain within these separate constraints. In a later stage, an aggregated assessment of these constraints needs to be conducted. From these aggregated results, it will be possible to determine which trajectory possesses most industry support and thus has the ‘best’ chances of achieving dominant design. In that respect, a generic model is derived from this approach that will enable such an analysis amongst the eco-friendly alternatives. This model is illustrated in figure 7 below.

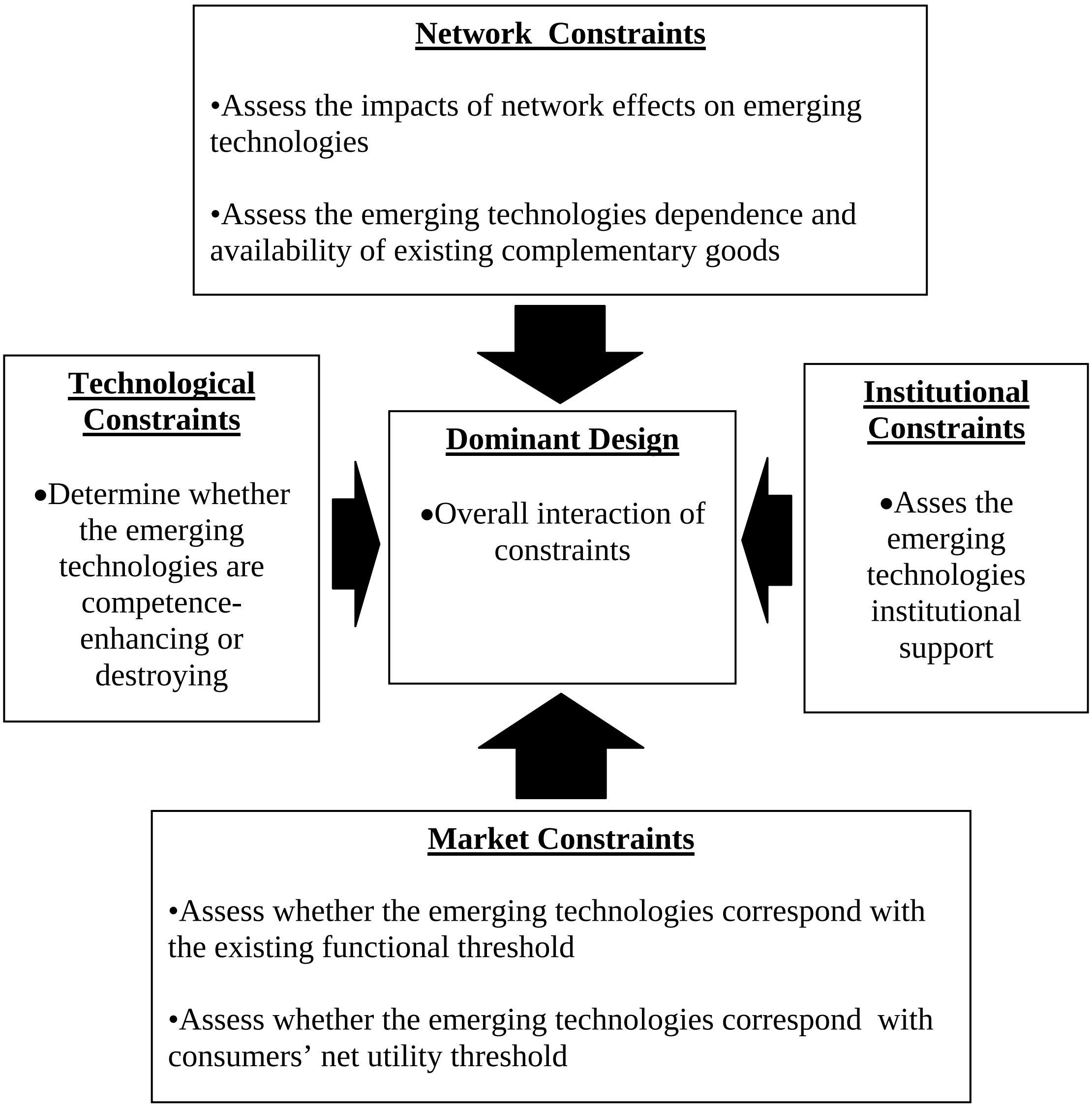

Figure 7 – Determining Dominant Design

4 Empirical Review

The automotive industry has to face two major challenges: eliminating toxic emissions while reducing the dependence on non-renewable resources.

Several concepts and technologies are currently under development in order to answer these problems. In that respect, one must consider that two approaches are currently explored by the automotive industry. Firstly, achieving a better efficiency in terms of fuel consumption could reduce toxic emissions. It must be admitted that a car that needs less fuel to achieve a greater distance will produce fewer toxic emissions. Therefore, a relevant alternative would consist in improving the technology used to propel the car. This requires the development of new powertrains enabling the production of high efficiency vehicles. Secondly, car manufacturers are considering the possibility to replace the current fuel used by Internal Combustion Engines (ICE) and to introduce cleaner, renewable fuels that would produce lower emissions.

In theory, these two approaches are closely linked. Indeed, one can imagine that a new source of fuel could be used in a new technology, enabling greater performances while providing a clean alternative to Conventional Vehicles.

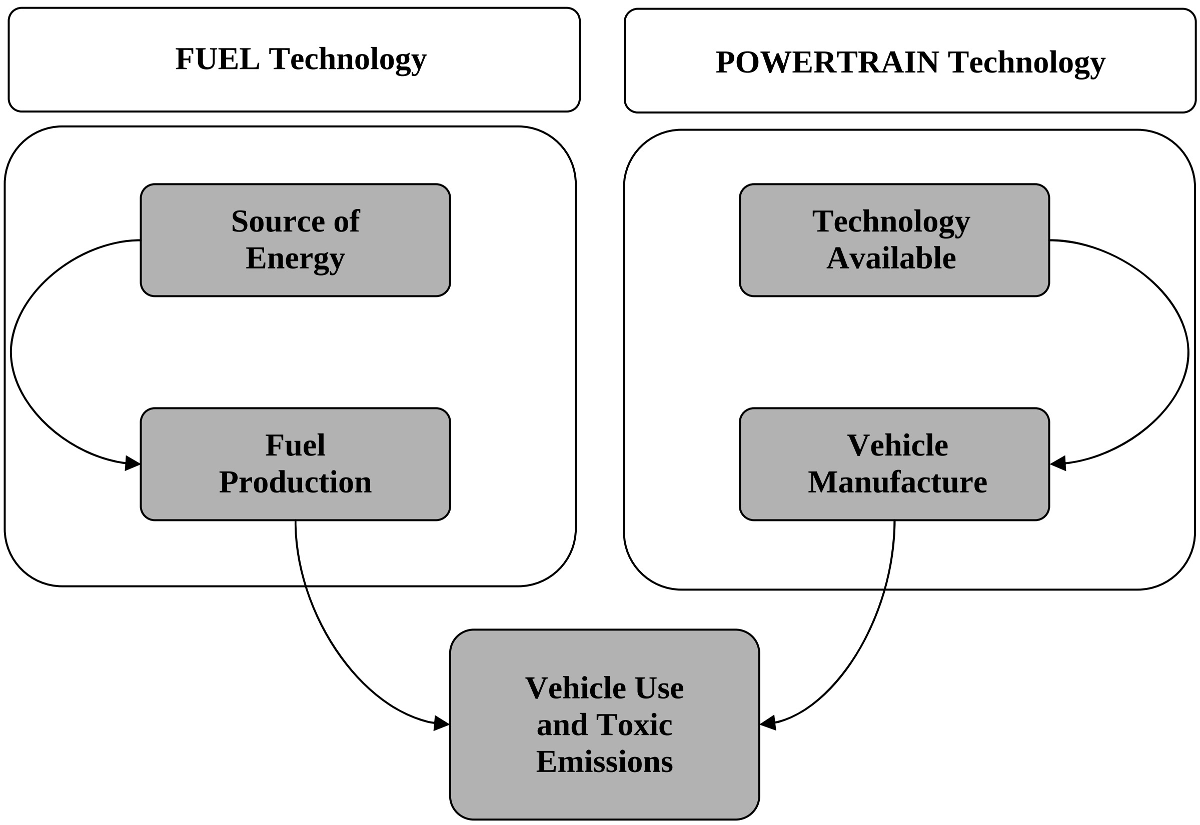

Figure 8 – Interrelationships between Fuel and Powertrain Technologies

When looking at which "green alternatives" currently exist, the authors must therefore explore not only the progress that has been made in terms of technology, but also investigate what the fuel alternatives enabling fewer toxic emissions are.

In the first part of this section, the authors will examine the alternative green fuels that could be used in the automotive industry. In that respect, an assessment of Biofuels, Electricity and Hydrogen fuels will be done.

In the second part of this section, the authors will proceed with the assessment of technologies dedicated to these alternative fuels, which are Flexible Fuel Vehicles (FV), Electric Vehicles (EV), Hybrid Electric Vehicles (HEV) and Fuel Cell Vehicles (FCV).

4.1 Alternative "green" fuels

4.1.1 Biofuels

Biofuels are produced from organic matter, such as plants. These fuels are therefore defined as renewable, which means it is possible to develop a continuous supply of them. Although Biofuels do not completely eliminate toxic emissions, recent applications in the automotive industry have demonstrated their ability to reduce CO and other pollutant emissions from the tailpipe. Moreover, the plants that are grown to produce Biofuel would remove CO_2 from the atmosphere. As a consequence, industry experts estimate that Biofuels' net emission of carbon dioxide will be close to zero (NREL, 2001). Regulatory bodies are very well aware of the positive impacts of Biofuels on the environment. Indeed, both the EU and the US strongly support the development of Biofuels. As President Bush stated:

"These fuels are gentle on the environment. They are fuels that can be renewed year after year, and fuels that can expand our farm economy. These fuels are made right here in America, so they can't be threatened by any foreign power… Ethanol and biofuels are fuels of the future for this country. Since the beginning of my administration, I have strongly supported ethanol and biofuels. And the energy plan I sent to Congress back in the spring supports biofuels."

(Bush, 2001)

- Biodiesel overview

Biofuels can be divided in two categories: Biodiesel and Ethanol. Biodiesel is an "ester" product, similar to vinegar. It is produced by chemically re-acting an alcohol (such as methanol) with vegetable-based oils, animal fats or waste cooking oils. The result is a very clean burning and non-toxic fuel (NREL, 2001). Currently, Biodiesel is already used to propel engines, either using pure

Biodiesel (B100, in which case the engine will have to suffer slight technical modifications) or by using it as a blend in combination with petroleum diesel. As of today, the most popular use form of Biodiesel is called the B20 (20 percent Biodiesel – 80 percent petroleum diesel) which can be used in any conventional diesel engine with essentially no vehicle modifications required. In terms of performances, Biodiesel is generally viewed as more efficient than diesel. Experiments have revealed that Biodiesel has the same fuel consumption, horsepower, torque, range and payload capacity as conventional diesel fuel (Canada Clean Fuels, 2004).

Biodiesel is well developed in EU, where diesel engines represent an important part of the total market. Indeed, it was first produced in Germany in 1991. The EU Biodiesel market is supported by a 2003 EU Directive, which requires 2 percent (by energy) of the fuel supply to be Biofuels by 2005, and 5.75 percent by 2010 (UK Department Of Transport, ?2004). Moreover, tax incentives on Biodiesel are applied by some member states.

- Environmental performances of Biodiesel

In terms of performance, some recent studies have shown the great potential of Biodiesel to consist in a relevant "green" alternative.

Life Cycle toxic emissions of Biodiesel compared to conventional diesel		
Emission	**B20**	**B100**
Unburned Hydrocarbons (smog/ozone)	-11%	-56,30%
Particulate matter (respiratory disease)	-18%	-55,40%
CO_2 *(greenhouse effect)*	-16%	-78%
Nox (smog)	1%	6%
CO (smog)	-13%	-43%
Cancer risk	-27%	-94%
Ozone formation	-10%	-50%

Table 1 - Life Cycle toxic emissions of Biodiesel compared to conventional diesel
Source: National Biodiesel Board, 2003; Jia et al., 2003; Camobreco et al., 1998

Despite the increase of Nitrogen Oxide emissions (NOx) which is an element contributing to the creation of Smog, the benefits of B100 on the environment are enormous. Moreover, research is currently being carried out in order to reduce NOx emissions associated with the use of Biodiesel (Camobreco et al., 1998). In addition, looking at the whole life cycle of Biodiesel (from production to combustion), industry experts estimate that B100 has the ability to reduce total CO_2 emissions by 78.5% compared to traditional diesel fuel (Camobreco et al., 1998). Another key benefit of Biodiesel lies in its simple and environmentally friendly production inputs and outputs. The production process does not require any unusual toxic substances, and there are no dangerous by-products resulting from the production.

Even if Biodiesel is defined as a renewable source of energy, the production process still requires energy consumption. In order to truly assess the benefits of using Biodiesel, industry experts have to evaluate the energetic ratio of Biodiesel production. This energetic ratio compares the amount of energy produced with the fossil energy used all along the production process. When this ratio is above 1, the energy produced is superior to the energy consumed. In the case of traditional diesel or gasoline, the energetic ratios are inferior to 1, however, some research has demonstrated that the ratio for Biodiesel is 2.5 in average (Jossart, 2003). These results can be interpreted in the following manner: for a production of 100 ‘units’ of energy, 40 fossil energy units will have been used for producing Biodiesel, while 111 units will have been used for producing conventional diesel. This demonstrates the ability of Biodiesel to drastically reduce the dependence on non-renewable sources of energy (Jossart, 2003).

- Biodiesel applications in the automotive industry

Biodiesel is still in the early stage of implementation into the car industry. Even if government bodies and institutions tend to promote the use of Biodiesel, B100 is not available to consumers on a global scale. Moreover, even if B20 can be used in any conventional engine, B100 requires car manufacturers to develop specific parts and to make few ‘minor’ modifications to the engine.

A relatively good example of physical implementation can be seen in Germany, which is currently advanced in terms of using Biodiesel. In 2002, more than 2.5 million cars were approved to run on Biodiesel, which could be purchased at more than 1,400 out of the 17,000 gas stations throughout Germany (Lieberz, 2002). The price of Biodiesel varied from 69.9 up to 79 Eurocents per litre while the price for fossil diesel ranged from 76.9 to 85 Eurocents per litre (Lieberz, 2002). However such a competitive price was only reachable thanks to an enormous tax support from the government. Indeed, at a comparable taxation system, the price of Biodiesel would have increased by 44 Eurocents (Lieberz, 2002). This is due to the fact that production costs of Biodiesel are dramatically higher than the costs of production of traditional diesel. In average, Biodiesel is 50% more expensive to produce than diesel (Lieberz, 2002).

Production costs clearly appear to be a major hurdle towards the implementation of Biodiesel as a large-scale alternative. However, one could consider that such a barrier could be overcome by increasing the total volume of production and achieving economies of scale. However, there resides a second major concern. In order to produce a large supply of Biodiesel, the area needed to grow plants for producing oil would be enormous. As of today, production facilities, current distribution infrastructures as well as potential developments of the activities might not even suffice to meet the EU Biofuel goals set for 2010 (5.75% of all fuel supply must be Biofuel) (UK Department Of Transport, ?2004). Therefore, it is practically impossible to assume that Biodiesel could represent a large scale alternative to conventional fuels on the near to mid term.

In terms of transportation, storage and distribution to end-users, recent studies have shown that most of the existing infrastructures used for traditional diesel are compatible with pure Biodiesel. However, few minor modifications are required as B100 will degrade soften, or seep through some hoses, gaskets, seals, elastomers, glues and plastics with prolonged exposure (Tyson, 2001). As a consequence, dedicated dispenser and the modification of minor dispensing equipment will have to be done all along the distribution chain.

To summarise, it must be admitted that Biodiesel is a great alternative in regards of the changing new Business Environment conditions. The benefits on environment and the ability to produce a continuous supply of energy while reducing the dependence on non-renewable sources of supply are great achievements. However, the development of the Biodiesel market relies nearly exclusively on government supports. In the automotive industry, Biodiesel might find practical applications in narrow markets such as public procurement or public transportation.

- Ethanol overview

Ethanol is very similar to Biodiesel. In fact, Ethanol is to gasoline what Biodiesel is to diesel fuel. Ethanol is an alcohol typically made from corn, or corn by-products, using a process which is similar to brewing beer (NREL, 2001). Currently the most common form of use of Ethanol comes in a blend mixture between Ethanol and gasoline: E10 (10 percent Ethanol), E85 and E95. Ethanol is a very clean burning fuel as it contains a high proportion of oxygen. E10 blend is generally assumed by car manufacturers to be safe for use in any vehicles. However, there is a concern regarding higher blends. Indeed, higher concentrations of Ethanol have been reported as accelerating wear on engine components and fuel lines, and reducing fuel economy (Consumer Affairs Victoria, 2003). As a result, for higher blends of Ethanol, modifications have to be made in several parts of the car, primarily the carburator, fuel lines and injection system. The estimations regarding the incremental costs of such modifications vary from one source to another, but some experts estimate that the cost to purchase an Ethanol compatible vehicle is usually not more that an additional $600 compared to regular vehicles (University of Houston, ?2004). For car manufacturers, an analysis based on the report “A Better Way of

Getting From Here to There: A commentary on the Hydrogen economy and a proposal for an alternative strategy” (Morris, 2003) estimates that the incremental costs for producing Ethanol cars is about $150 (ILSR, ?2004).

- Environmental performances of Ethanol

Life Cycle analysis of the potential environmental performances are somewhat various and contradictory. Indeed, the emissions related to the use of Ethanol vary depending on the source or technology used to produce Ethanol. However, the average emissions could be summarized as below:

Life Cycle emissions of Ethanol compared to conventional gasoline		
Emission	**Low-level Blends (E10)**	**High-level Blends (E85)**
CO (smog)	-25% to –30%	-25% to -30%
CO_2 (greenhouse effect)	-10%	Up to –100%
Nox (smog)	-5% to +5%	-20%
Volatile Organic Carbons (VOC's)	-7%	-30%
Particulate matter (respiratory disease)	Decrease	Significant decrease (-20%)
Aldehydes (health concern)	+30 to +50% increase (but negligible due to catalytic converter)	Insufficient data
Aromatics (Cancer risk)	Decrease	-50%
Greenhouse effect	-3,9%	-37,1%

Table 2 - Life Cycle emissions of Ethanol compared to conventional gasoline
Source: Canadian Renewable Fuels Association, ?2004; Tulsa Clean Cities, ?2004.

In terms of energy ratio, according to Jossart (2003), Ethanol scored 2.0 in average, slightly lower than Biodiesel. This result demonstrates the strong potential of Ethanol in reducing the dependence on non-renewable resources. Just as Biodiesel, another key benefit of Ethanol is the fact that the production process does not require any unusually toxic substances, and there are no dangerous by-products resulting from the production.

- Ethanol applications in the automotive industry

Ethanol has already found many applications in the automotive industry and is available to end-users in a large scale. E10 and E85 blends have been highly promoted by several governments, especially in the US and Brazil. As of today, Ethanol has remained competitive compared to gasoline thanks to enormous government supports and tax incentives. Indeed, the costs of production are currently very high.

In average, and depending on which primary resource is used in the production process (i.e. corn, wood or agricultural waste, etc), the cost of production of a gallon of Ethanol varies between US$ 1.10 to 1.43; in contrast, the wholesale price of gasoline is 90US cents per gallon (Oregon Department of Energy, ?2004). In addition, one must consider the fact that Ethanol contains less energy than conventional gasoline. Therefore, the production cost of Ethanol has to be multiplied by 1.5 to make an energy-cost comparison with gasoline (Oregon Department of Energy, ?2004). This means that the actual price per gallon of Ethanol to equal the energy of gasoline is $1.65. Ethanol is therefore 83% more expensive than gasoline. To overcome this major hurdle and in order to support the development of the Ethanol industry and the infrastructures required, the US governments currently applies a 54 cents tax on Ethanol, enabling it to remain competitive, yet more expensive than gasoline.

One could assume that Ethanol also has to face a major hurdle in terms of distribution. However, most of the technology currently used for storing and dispensing gasoline can be applied to E85 and below blends. Indeed, E85 can be stored in most storage devices except fibreglass or plated metal tanks. The only dedicated infrastructures that are required by E85 are a specific dispenser and other general dispensing equipment (hoses, nozzles and fitting connectors) that have to be installed at the gas stations (US Department of Energy, ?2004).

All empirical evidence seem to highlight the strong potential and benefits that can be gained by using Ethanol as a fuel in tomorrow’s car. If the industry manages to overcome the difficulties lying in the expensive cost of production, and if car manufacturers are willing to promote dedicated vehicles, Ethanol could be a relevant answer to the new business environment conditions.

However, as for Biodiesel, one of the major concerns regarding the Ethanol alternative is its ability to become a major source of supply in the years to come. Supplying a sufficient amount of Ethanol for a vast fleet of Ethanol vehicles would require the development of numerous production facilities and infrastructures related. Moreover, huge agricultural areas will have to be dedicated to the production of primary resources whereas it is corn or other. It is not likely that the creation of such an industry can be made on the short to mid term, and even though constant technological process will enable a more efficient production process, securing a sufficient volume of production will be a major barrier in establishing market dominance.

4.1.2 Electricity

- Electricity overview

When used to propel a car, electricity is qualified as an alternative fuel. Indeed, it is commonly considered to be the ultimate solution to air pollution and toxic emissions as it doesn't emit any pollutants. Contrary to Biofuels, electricity requires car manufacturers to develop fully dedicated vehicles, with a completely different and rather immature technology.

- Environmental performances of Electricity

Even if using electricity result in no air pollution, its production process results in substantial toxic emissions. According to industry experts, the total Life Cycle (excluding car manufacturing) for the 2003 fully Electric Toyota Rav4 can be summarized as below:

Life Cycle Emissions Produced by driving 100 km with Electric Toyota Rav4					
Generation option	CO_2 in gram	SO_2 in milligram	NO_x in milligram	NMVOC in milligram	Particulate matter in milligram
Hydropower	500	650	450	0	100
Coal – modern plant	19720	330200	59720	470	6930
Nuclear	610	530	1020	0	40
Natural gas (combined cycle)	9000	150040	5130	2360	110
Biomass forestry waste combustion	1160	1520	26510	0	5370
Wind	1310	1080	640	0	400
Solar photovoltaic	7440	5140	3560	1400	2020

Table 3 - Life Cycle Emissions Produced by driving 100 km with Electric Toyota Rav4
Source: Adapted from Nuclear Energy Institute, ?2004; and US Department of Energy, 2004.

Despite the poor results of generation of electricity through coal and natural gas, one can say that NOx and SO_2 emissions are dramatically low. When it comes to CO_2 emissions, the performance of electricity is better than gasoline, especially in the case of Hydropower, Nuclear and Wind electricity generation. For example, industry experts estimate that conventional gasoline would produce more than 15,000 grams of CO_2 for 100 km on a Life Cycle basis (adapted from Schindler, 2003), which is 30 times higher than for the electric Toyota Rav4, if the electricity was to be produced through Hydropower.

As a matter of fact, these results have to be taken with caution: only a minor part of the electricity produced is done through Wind or Hydropower generation. In that respect, if EV were to be propelled by Coal-electricity only, the CO_2 resulting from transportation would increase by approximately 30% (based on Table 3 data).

According to the World Bank data (World Bank 2001), the total world production of electricity by source of energy could be summarised as follows:

Global Sources of electricity generation 2001	
Natural Gas	18,3%
Oil	7,4%
Coal	38,8%
Nuclear	17,2%
Hydropower	16,6%

Table 4 – Global Sources of electricity generation 2001
Source: World Bank, 2001

Based on these data, and assuming the fact that Oil-electricity generates as much CO_2 as Coal-electricity, it appears that the Toyota Rav4 would emit 10945 grams of CO_2 for 100 kilometres. This would represent a reduction of CO_2 emissions of 26% on a life cycle basis (based on table 3 data).

- Applications in the automotive industry

So far, the availability of Electric Vehicles (EV) to the mass market has been very disappointing. Indeed, even if there is no apparent hurdle to fuel supply or availability to end-users (electricity is cheap and easily available worldwide), the technological barriers to significant market penetration are enormous. Indeed, Toyota who introduced the RAV4 EV in early 2002, decided to discontinue the product in 2003. The reasons were mainly cost and technology related:

"…technical issues tied to electric vehicles remain a major hurdle. The California Air Resources Board published a guidance statement regarding EV battery life. The guideline stated that when the battery capacity decreases to less than 80% of the original capacity, the battery needs to be replaced. A battery's capacity is the amount of charge that it holds, and is commonly measured by the range of the vehicle. It is cost-prohibitive to replace an EV battery. The cost to replace the battery is more than the value of the vehicle."

(Toyota, ?2003)

Other concerns regarding Electric vehicles lie in the very low mileage, which rarely exceeds 100 miles when fully charged. Moreover, life expectancy of batteries is still limited.

To summarise, even if electricity appears to be the ultimate environmental friendly fuel, some major improvements in terms of technology have to be made in order to enable significant penetration into the mass market.

4.1.3 Hydrogen

- Hydrogen overview

Hydrogen as an alternative fuel is currently a very hotly debated topic. It is a simple, abundant element found in organic matter, notably in the hydrocarbons that make up many of our fuels, such as gasoline, natural gas, methanol or propane. Moreover, when used to propel a car, the only by-product of Hydrogen is water. Therefore, one could assume that there cannot be any better alternative as a fuel.

However, there is no supply of pure Hydrogen and as a result, it has to be manufactured. It is commonly produced by using heat to separate Hydrogen from water or hydrocarbons, but its main advantage is to have a wide and flexible source of supply and production processes. Today, most of the Hydrogen is made from natural gas. Below is a table summarising the multiple sources of supply that could be used to produce Hydrogen.

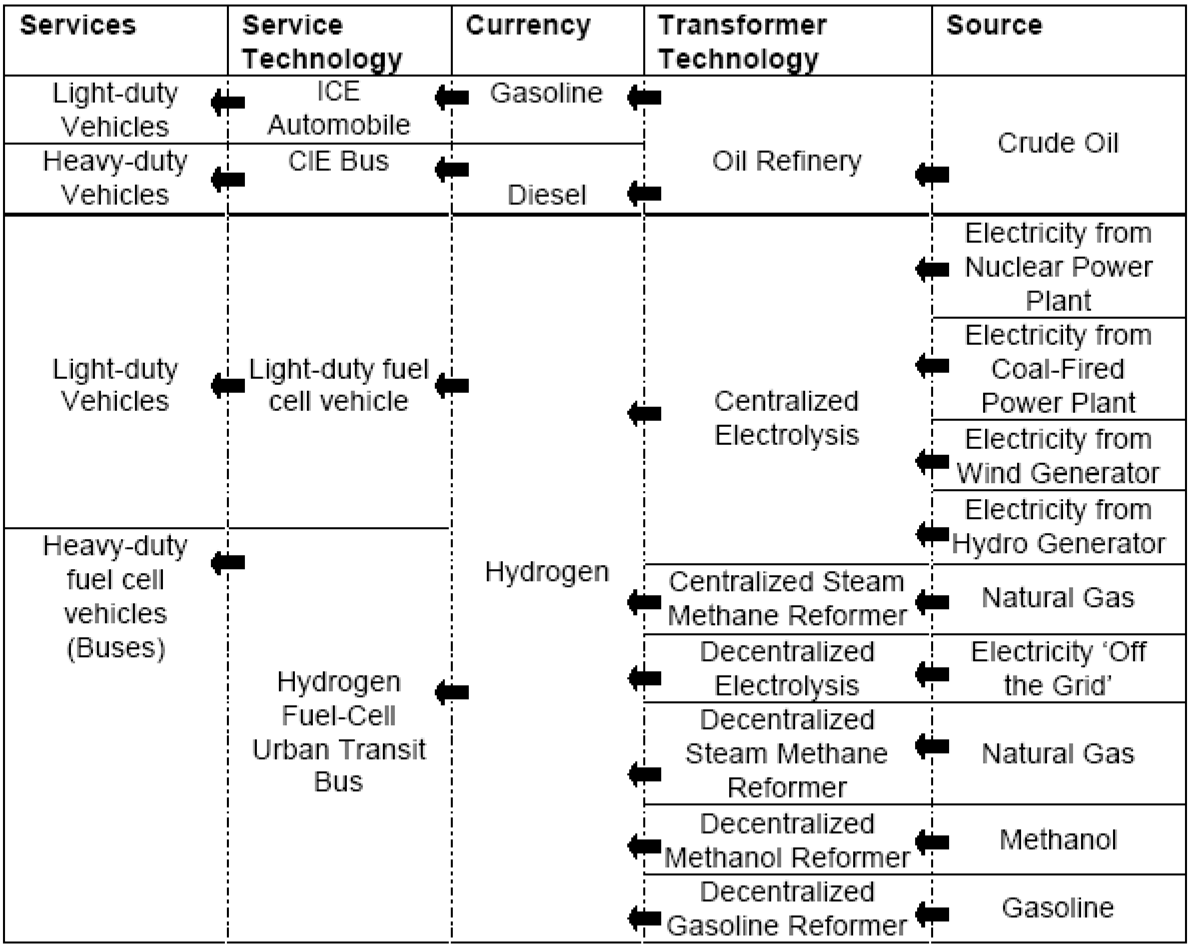

Figure 9 – Hydrogen Production Pathways
Source: Ernst & Young, 2003

Hydrogen can be used in combination with gasoline or Ethanol in order to reduce NOx. It is also already the fuel of choice for propelling space shuttles. Some investigations have also been made to use Hydrogen in ICE, however the primary interest of using Hydrogen is to supply 'fuel cell stacks' that would power Fuel Cell Vehicles.

Both the US government and the EU commission are joining forces into promoting the development of an Hydrogen economy. Indeed, during the EU-US summit in June 2003, both parties agreed to collaborate on the acceleration of the development of the Hydrogen economy. Former EU Commission President Romano Prodi announced that Hydrogen looks like the best candidate to address sustainable development (Prodi, 2003). Moreover, President's Bush Hydrogen Fuel Initiative, announced on January 28 2003, has the objective to transform the American transportation fleet from a total reliance on petroleum to an increasing use of clean-burning Hydrogen (Bush, 2003).

As a result, over the period 2003 – 2007, the US government will invest $1.7 billion to develop Hydrogen-powered cars and Hydrogen infrastructure under the projects “The Hydrogen Fuel Initiative” and “the FreedomCAR (Cooperative Automotive Research) initiative” (Bush, 2003).

- Hydrogen Environmental performances

The sources to produce Hydrogen are numerous, but, like electricity, if Hydrogen is a clean burning fuel, the production process still results in toxic emissions and the use of non-renewable resources. Hydrogen is mostly made from natural gas, but can also be produced using electricity, coal, Biomass (Ethanol) or crude oil. As a result, not all manufacturing processes have the same environmental impacts which make it difficult to evaluate the environmental benefits of using Hydrogen as a fuel. Moreover, Hydrogen as an end product could be used into two different ways: Liquid Hydrogen (LH_2) or Compressed Hydrogen (CH_2) who do not produce the same toxic emissions on a Life Cycle basis.

In terms of dependence on non-renewable resources, it is relatively easy to clarify the situation. According to the US National Hydrogen Association, the current sources for Hydrogen could be summarised as follows:

Worldwide Sources of Commercial Hydrogen 2002	
Natural Gas	48%
Oil	30%
Coal	18%
Water Electrolysis	4%

Table 5 – Worldwide Sources of Commercial Hydrogen 2002
Source: US National Hydrogen Association, 2002

It appears clear that, currently, Hydrogen is highly dependent on non-renewable resources as 96% of the total commercial Hydrogen is produced using fossil resources.

- Environmental performance of Electrolysis

Determining the total CO_2 emission of producing Hydrogen is an extremely difficult task, not only because of the wide availability of primary sources, but also because there are several radically different production processes. Each production process will have specific performances in terms of toxic emissions. It is therefore important to clarify the situation regarding electrolysis, which is perceived by the majority of industry experts to be the ultimate solution towards a clean automotive industry.

Electrolysis is an electrochemical reaction in which an electric current travels through water. This process results in a clean chemical reaction in which water is split into two elements: oxygen and Hydrogen. By itself, this reaction does not emit any single toxic gas or product. Consequently, industry experts believe that electrolysis would be the key towards the mass production of a clean fuel. However, the fact that electrolysis requires electricity generation is often eluded. Indeed, in order to provide a clear assessment of CO_2 emissions on a Life Cycle Basis, the CO_2 emitted by electricity generation must be taken into account. One can argue that it is possible to produce electricity through renewable sources such as wind, hydro or solar power. However, renewable sources of electricity, is less than 20% of the electricity produced worldwide (Worldbank, 2004).

It can't be denied that Hydrogen produced through windpower/electrolysis appears to be an ideal solution. Indeed, some experts estimate that, on a life cycle basis (excluding emissions generated from building a wind powerplant), almost no emission is generated through Hydrogen production process (Mann et al, 2004). It also admitted that Hydrogen generation through other 'clean processes' such as Biomass or Hydropower show the same benefits than windpower in terms of toxic emissions (Buch et al., 2002).

- Environmental performances of Hydrogen produced through Non-Renewable resources

Most of the Hydrogen produced is made from Natural Gas, Coal and Oil, which do not permit to eliminate Green House Gases (GHG) emissions. When it comes to Natural Gas Hydrogen generation compared to windpower electrolysis, the below results could be found:

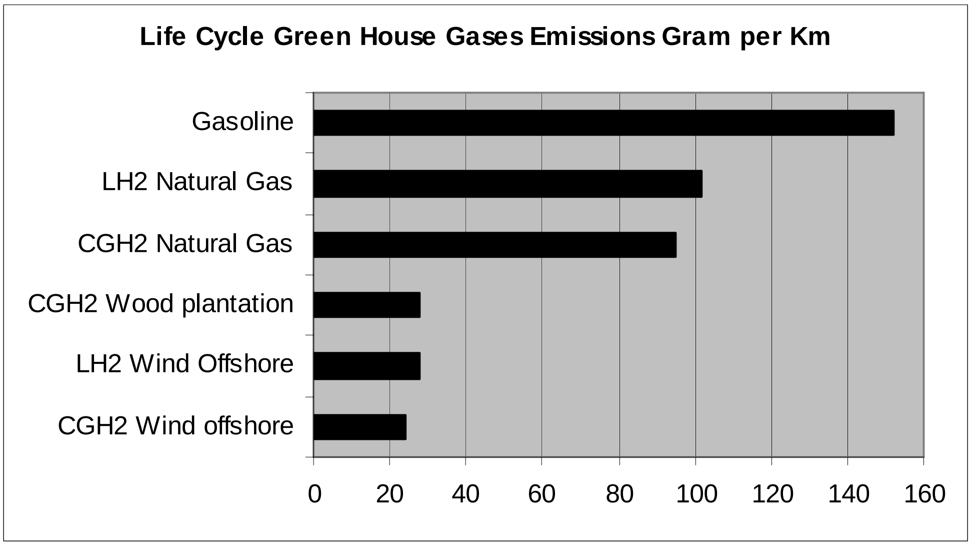

Figure 10 – Life Cycle Green House Gases Emissions Gram per Km
Source: Heywood et al., 2003 and Schindler, 2003.

The positive impacts of Hydrogen produced through Natural gas are somewhat disappointing. Even if GHG could be reduced by approximately 40% while using Compressed Gas Hydrogen (CGH_2) from natural gas, it remains some way inferior to the reductions that could be obtained when using Biofuels.

The poor result of the Natural Gas pathway is mainly related to its production process: the so called ‘steam reforming’ process. Indeed, it is considered that the vast majority of CO_2 emissions are inherent to a ‘steam reforming powerplant’ (Mann et al. 2001). It is interesting to note that all hydrocarbons used to produce Hydrogen are currently using this process (including; oil, coal and other hydrocarbon), (Buch et al., 1999). The steam reforming process can be summarised as follows:

“[Steam Reforming] basically involve heating the raw materials and/or heating steam that is mixed with the raw material. The ensuing reaction splits both water molecules and the raw material, thereby creating hydrogen, CO and CO_2. In other words, the hydrogen that is left comes both from the steam and the hydrocarbons”

(Buch et al., 1999)

As a result, one can wonder how relevant the steam reforming alternative actually is. As a matter of fact it completely relies on non-renewable resources, while emitting a considerable amount of green house gases. Nevertheless, the outmost advantage is that it is possible to capture and store the toxic emissions generated by steam reforming. Thus, no toxic emissions will be released in the atmosphere (Buch et al., 1999).

CO_2 capture and sequestration is a relatively new concept within the power generation industry, although it is already used in the oil and gas industry. It is estimated, if CO_2 capture was to be widely applied in the power industry, it will generate significant incremental costs as well as less efficiency in terms of electricity generation.

“If capture is used to minimise CO_2 emissions from power plant it would add at least 1.5 US cents/kWh to the cost of electricity generation. In addition, the generating efficiency would be reduced by 10 to 15 percentage points”

(IEA, 2004)

Applying the CO_2 sequestration is an approach seriously considered by experts when it comes to producing Hydrogen from non-renewable resources. Even though it would significantly increase the cost of production of Hydrogen, it will enable to avoid toxic emission discharges into the atmosphere. However, in order to do so, some specific infrastructures have to be developed within the ‘Hydrogen powerplants’. The CO_2 captured and stored would then have to be injected deep underground in depleted gas and oil reservoirs, unminable coal beds or deep saline aquifier (IEA, 2004). CO_2 could also be stored in oceans, where it could eventually be absorbed (IEA, 2004). However, a major concern arises: the CO_2 would have to be stored for thousands of years in order to avoid it from affecting the atmosphere. One could question the safety and relevance of such a process (IEA, 2004).

- Cost, performance and other concerns related to Hydrogen

When it comes to fuel efficiency, Hydrogen is considered to be a good alternative in regards to its high-energy content compared to its weight. Moreover, recent studies have shown that when used to propel a Light Duty Vehicle, Hydrogen requires 85% less energy than a conventional Gasoline propelled vehicle (Ernst & Young, 2003). Many experts have used such an argument in favour of the benefits that can be gained from using Hydrogen. However, a counterpart to such an advantage is a fundamental problem to the development of an Hydrogen economy: the density of Hydrogen is much lower than regular gasoline, which means that the volume needed to produce an equivalent amount of energy is far greater than for gasoline (Table 6, below).

Summary of weight and volume of different tank types		
Vehicles with equal driving distances per fill-up	Mass (kg)	Volume (litre)
Gasoline/combustion engine	50	70
Compressed Hydrogen (350 bar) / fuel cells	90	320
Compressed Hydrogen (700 bar) / fuel cells	~ 100	180
Liquid Hydrogen / fuel cells	45	190

Table 6 - Summary of weight and volume of different tank types
Source: Buch et al., 2002

In the best scenario case (LH_2), the tank of a car using Hydrogen would have to be 2.5 times bigger than they currently are. Moreover, this problem has effects on all the stages of the value chain: distribution, storage at production facilities as well as refuelling stations, transportation devices, etc. Handling and storing of Hydrogen is actually a critical issue, since Hydrogen is a highly flammable element. It can ignite in low concentrations, which means that leaks in transport or storage infrastructures could present serious public safety hazards.

In order to avoid the difficulties of storing Hydrogen in the car, the automotive industry is exploring two different pathways, the first one being research and development of new materials that would enable better efficiency in terms of storage. The second pathway is to supply a car with methanol or Ethanol, and to produce Hydrogen directly on board of the car. These approaches are radically different but it seems unlikely that on-board reforming will be a relevant and cost efficient alternative (Northeast Advanced Consortium, 2003).

The supply of Hydrogen as a fuel would also require massive investments in terms of infrastructures. A completely new distribution process would have to make available Hydrogen at refuelling stations. This requires the development of completely new gas stations able to store and supply Hydrogen.

When it comes to the cost efficiency of Hydrogen, industry experts have estimated the price of Hydrogen produced either from Electrolysis or Steam Reforming with Gasoline.

Production Cost of Gasoline and Hydrogen through Electrolysis and Steam Reforming per km for a light duty vehicle - in Canadian dollars			
Production Process	Electrolysis	Steam methane reformer	Gasoline
Primary Energy Input costs	0,0124	0,0057	0,0097
Other Energy Costs	0,0005	0,0011	0,0009
Maintenance, Overhead and Labour Costs	0,0011	0,0009	0,001
Production Equipment Costs	0,0010	0,0011	0,0008
Supply Costs	0,0028	0,0028	0,0003
Fuelling Station Costs	0,0007	0,0007	0,0001
Interest Expenses	0,0025	0,0025	0,0006
Total cost of fuel Before Income Tax	**0,0209**	**0,0148**	**0,0134**

Table 7 - Production Cost of Gasoline and Hydrogen through Electrolysis and Steam Reforming per km for a light duty vehicle - in Canadian dollars
Source: Adapted from Ernst & Young, 2003

More important than the total cost (which could vary from one country to another), it is essential to note that producing Hydrogen per km driven is roughly 10% more expensive than gasoline in the case of steam reforming, and 56% in the case of electrolysis. This could give an explanation as to why Hydrogen is mostly produced through steam reforming using non-renewable resources, and not through electrolysis of water (cleaner process that does not rely on non renewable resources).

- Hydrogen applications in the automotive industry

Due to tremendous effort from government bodies in promoting a Hydrogen economy, car manufacturers are encouraged to develop vehicles using Hydrogen as a fuel. The answer of the industry has been to develop the so-called Fuel Cell cars, which basically convert Hydrogen into Electric power in order to propel the car. Numerous prototypes and fleet sales vehicles have been introduced in the market; however, car manufacturers are reluctant to introduce such a technology into the mass market for numerous reasons. In 2002 while introducing its newest fuel cell model, American Honda Executive Vice President announced he had no plans to introduce fuel cell to the mass market:

"Certification allows Honda to place fuel cell vehicles in commercial operation … We'll have an opportunity to evaluate fuel cell vehicles in real world applications and to study the development of a refuelling infrastructure to support fuel cell vehicles. However, it is important to remember that significant cost, technology and infrastructure issues remain prior to the mass marketing of fuel cell vehicles"

(Elliott, 2002)

Indeed, introduction of Hydrogen as a fuel would require heavy synchronisation between governments, fuel suppliers and car manufacturers. As of today, it has not yet been agreed which type of fuel or refuelling infrastructures are needed for Hydrogen powered vehicles. Whether it will be CH_2 or LH_2 to be used directly in the car; or Ethanol, methanol and gasoline using an on board reformer is a key issue, and the infrastructures related are rather different and costly. Moreover, all complementary infrastructures related to Hydrogen production and CO_2 sequestration would require tremendous investments (Morris, 2003).

4.2 Alternative Powertrains

All alternative fuels assessed previously do have the potential to deal with the new Business Environment Conditions. In fact, they all have the potential to reduce toxic emissions and decrease the dependence on non-renewable resources. Nonetheless, it has been highlighted that all these fuels require car manufacturers to develop specific equipment and powertrains in order to bring the technology to the market. Whether it is Biofuels, Electricity or Hydrogen, the automotive industry will have to manufacture dedicated vehicles that require minor to major changes.

Moreover, car manufacturers have recently introduced a new technology that does not rely on the alternative fuels analysed above, the so-called Hybrid Electric Vehicles (HEV). As a result, the following section will study and analyse the achievements of the car industry in terms of new powertrains. The four technologies analysed will be Flexible Vehicles (FV), Electric Vehicles (EV), Fuel Cell Vehicles (FCV) and HEV. The below figure attempts to describe on which fuel technology each of these powertrains rely on:

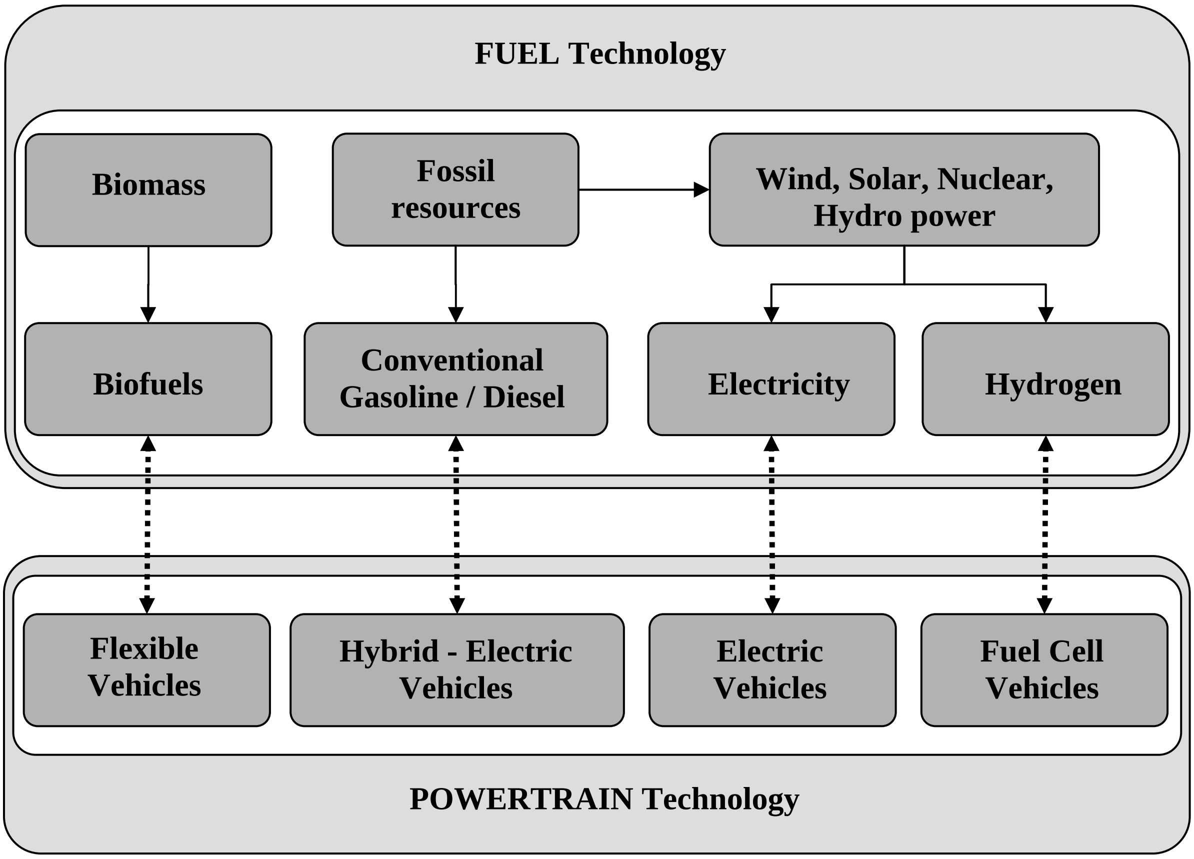

Figure 11- Fuel Technologies and Related Powertrain Technologies

4.2.1 Flexible Vehicles (FV)

These vehicles refer to cars manufactured in order to be able to run on Biofuels. Technically speaking, the modifications to be made to a conventional engine are considered to be minor. All major brands in the industry have developed FV that are available to customers. The vast majority of these vehicles are built for E85, though Biodiesel engines require fewer modifications.

- Biodiesel FV

In theory, any conventional diesel engine can run on diesel, any blend of Biodiesel, and on pure Biodiesel. However, car manufacturers are still reluctant to ensure full warranty when vehicles are using B100. The only major corporation to have a wide offer of B100 approved vehicles is the VAG Group (Volkswagen – Audi).

"All current Volkswagen (and other VW Group) diesel engines, including the new Pumpe-Duse (PD) units, are able to run on pure biodiesel, and have been biodiesel-compatible for around four years now. Warranties are unaffected."

(Channel4, ?2004)

Indeed, VAG group has decided to fully support the German initiative to promote the use of B100. This reflects that no technical barriers seem to affect the design of Biodiesel-compatible vehicles. Regarding the incremental costs involved, one could assume that they are insignificant, if applied on a whole range of vehicles. Indeed, the only parts that would require modifications are some hoses, gaskets, seals, elastomers, glues and plastics with prolonged exposure (EERE, 2004). Very few elements of this sort are to be found on a diesel engine and fuel injection system.

In that respect, the decision from VAG to modify all diesel engines to be B100 compatible appears to be wise as economies of scale might enable car manufacturers to practically eliminate incremental costs.

The question is why so few manufacturers do not ensure compatibility of diesel engines with B100? Indeed, brands tend to promote the use of Biodiesel as blends (B5, B20) but do not support B100. Maria Alovert of the Berkeley Ecology Centre has formulated part of the answer:

"If you're a commercial producer or industry person there's a set of responsibilities about telling people the most conservative thing you can. One of those responsibilities is the liability -- you could get sued if you don't give a customer all the warnings… In reality there are not a lot of problems with seals and hoses on most 1980s vehicles available in the US… The NBB (US National Biodiesel Board) takes the attitude that biodiesel is a fuel extender. They pay lip service to B100 but they're primarily interested in B20, and they stress such blends as much as they can… They advise against biodiesel -- it's their job. It doesn't mean that we don't prove them wrong every day"

(Alovert, ?2004)

- Ethanol FV

Ethanol dedicated vehicles are more widely developed than B100 FV. Indeed, the vast majority of car manufacturers operating in a large scale on the American market have developed vehicles available to end-users for many years. One could assume that one of the main reason lie in the fact that gasoline is widely used in the US whereas Diesel is far less developed than in Europe. It is therefore understandable that car manufacturers focus R&D efforts primarily on Ethanol.

Technically speaking, Ethanol FVs are more complex and require more modifications to be made to the engine. However, as a result of intensive research, car manufacturers have easily overcome the technological barriers since 1993.

"Changes to ethanol flexible-fuel vehicles relative to gasoline vehicles consist mostly of a sensor which will detect the type of fuel being pumped to the engine, and sets of engine maps

to ensure that the vehicle operates on ethanol in a manner consistent with its operation on gasoline. Additionally, since higher flow-rate fuel injectors are used to accommodate the lower energy density of ethanol relative to gasoline, software changes relative to injector control (injector duration, etc.) may be necessary to ensure proper operation of the fuel injection system."

(Report to Congress, 2002)

These modifications result in a relatively low incremental cost per unit. Research has shown that industry experts estimate incremental production costs will reach US$ 284 (Report to Congress, 2002) for a production of 100,000 units a year.

In terms of mileage performance, whereas Biodiesel FV can achieve the same results as Diesel engine, Ethanol FV are in average between 25 to 40% less efficient than conventional vehicles, when using E85 (US Department of Energy, 2004a). It is important to note that between models produced in 2000 and the ones planned to be introduced in 2005, no significant improvement in terms of mileage has been reached (US Department of Energy, 2004b). This simply confirms that total mileage that can be achieved with E85 is far less than conventional gasoline.

To summarise, it seems that FV do not encounter any technical hurdles, as many vehicles are currently adapted to Biofuels. In that respect, FV appear to be a satisfying alternative to conventional vehicles. Moreover, FV do present the advantage to be able to run either on pure gasoline/diesel, up to any blend of Biodiesel or Ethanol. Furthermore, from a manufacturer perspective, incremental costs of production are rather small, especially in the case of Biodiesel. Nevertheless, it is important to note that, in terms of mileage performance, Biodiesel FV are far more efficient than Ethanol FV.

4.2.2 Electric Vehicles (EV)

In comparison with conventional gasoline vehicles, EV require a completely different technology. The main components involved are motor controllers, inverters, batteries as well as battery management system. Indeed, EV require radical transformations in terms of design.

So far EV have been almost inexistent in the market. Very few physical implementations have taken place apart from minor fleet and prototype vehicles sold to government bodies or associations. The reasons are mainly related to energy storage devices: batteries. As of today,

"A battery for an EV must meet certain performance goals. These goals include: quick discharge and recharge capability; long cycle life (the number of discharges before becoming unserviceable); low cost; recyclability; high specific energy (amount of usable

energy, measured in watt-hours per pound [lb] or kilogram [kg]); high energy density (amount of energy stored per unit volume); specific power (determines the potential for acceleration); and the ability to work in extreme heat or cold. No battery currently available meets all these criteria."

(US Department of Energy, 2004c)

Incremental costs of production for EV are extremely difficult data to obtain for the main reason that so few models have been introduced into the mass-market. However, some researches estimate that the costs of batteries alone would average US$ 4125 (Cuenca et al., 1999). It is also estimated that in the best scenario case, EV would affect manufacturer suggested retail price with an increase of US$ 4745 (Cuenca et al., 1999). Suppliers are actively increasing R&D efforts, however, little progress has been made so far despite the fact that numerous pathways have been explored.

As a result, the car manufacturing industry has considerably stepped back from the EV alternative. Even Toyota, who has always been on the edge in terms of eco-friendly solutions, decided to cancel the production of its RAV4 EV vehicle. Indeed, the costs related to EV technology, as well as technical hurdles, do not encourage the promotion of EVs as a relevant alternative.

From an end-user perspective, such a decision could seem disappointing. In reality, the net financial gain that can be obtained while using EV is considerable. If the Toyota RAV4 EV is compared to its gasoline counterpart, the consumer would pay only US$ 362of electric fuel on a yearly basis whereas the price of gasoline for the same amount of kilometres would be US$ 1127 (US Department of Energy, 2004d).

4.2.3 Hybrid Electric Vehicles (HEV)

- HEV overview

One of the most successful eco-friendly alternative that has been developed by car manufacturers is the so called HEV. Recent market introduction of models such as the Toyota Prius and Honda Civic, 2004 model year have received praise by industry experts and analysts. Indeed, the newest Toyota Prius has received more than ten different awards, including the 2004 North American best car of the year. In November 2004, the Prius also received the European award for best car of the year 2005 (Brafman , 2004).

In the purpose of this research, HEV must be understood as a specific concept; a combination of two different sources of energy, electricity and fuel, into one single car. More precisely, an HEV combines a conventional Internal Combustion Engine with the battery and electric propulsion motor of an

Electric Vehicle. It can seem a paradox for Hybrid to use the EV technology that, according to industry experts, is currently underachieving. However, the combination of it with conventional ICE enables to overcome the major hurdles faced by EVs in terms of discharge – recharge capability; specific energy and range. Thanks to a Regenerative Braking and Power Assist system,

"The electric motor applies resistance to the drivetrain causing the wheels to slow down. In return, the energy from the wheels turns the motor, which functions as a generator, converting energy normally wasted during coasting and braking into electricity, which is stored in a battery until needed by the electric motor…The electric motor provides additional power to assist the engine in accelerating, passing, or hill climbing. This allows a smaller, more efficient engine to be used. In some vehicles, the motor alone provides power for low-speed driving conditions where internal combustion engines are least efficient." Moreover, HEV *"Automatically shuts off the engine when the vehicle comes to a stop and restarts it when the accelerator is pressed. This prevents wasted energy from idling"*

(US Department of Energy, 2004e)

Therefore, the total consumption of gas is drastically reduced, while the battery does not have any range limit as it is constantly and automatically recharged while driving.

Industry experts have been working on HEV design and prototypes for already more than 20 years (US Department of Energy, 2004f). Initially, they were conceived as a way to compensate the shortcomings in battery technology when EVs were introduced. It was then commonly assumed that, when batteries will become efficient, the industry would not need Hybrid at all. Nevertheless, in regards of recent developments in the industry, it seems that hybrids are becoming an extremely relevant 'green' alternative.

- HEV Environmental Performances

Information regarding the environmental performances of HEV varies greatly from one source to another. Indeed, the total Life Cycle Assessment[1] of the new Toyota Prius according to the Airborne emissions Index could be summarised as follows (Toyota, ?2004):

Emissions	***Prius Life Cycle***
CO_2	-35%
Nox	-7%
Sox	-8%
PM	+33%
CO	-11%

Table 8 – Toyota Prius Life Cycle Emissions

[1] Life Cycle Emission Assessment corresponds to the total performance of the vehicle in terms of toxic emissions, from fuel production to vehicle use (from 'well to wheel').

These results highlight the potential for HEV to significantly reduce greenhouse gas emissions compared to gasoline. However, contradictory data can be found from diverse sources. Indeed, in terms of tailpipe emissions, the below results could be found (Friedman, 2004);

EPA Emission Standard	***2004 Chevrolet Malibu***	***2004 Toyota Prius***	***Prius reduction***
CO (grams)	51303	12215	76%
Nox (grams)	2443	244	90%
PM (grams)	244	122	50%
CO_2 (lbs)	10470	5330	49%

Table 9 – Comparison Toyota Prius and Chevrolet Malibu Toxic Emissions

The comparison of table 8 and 9 tends to highlight that tailpipe emissions of HEV are dramatically low compared to a conventional gasoline vehicle. However, the manufacturing operations required to produce the vehicle emit more toxic emissions than for conventional vehicles. Nevertheless, the net benefits that can be attained through the HEV alternative remain considerable.

In terms of mileage performance, all major investigations clearly indicate that enormous fuel economy can be achieved thanks to HEV. According to the US Department of Energy, the fuel economy of HEV average 40% compared to conventional ICE. As a result, the dependence on non-renewable resources (petroleum fuel) is reduced by 40% (based on US Department of Energy, 2004 and Friedman 2004). The acceleration and speed of HEV are comparable to a conventional ICE engine. In fact, the Toyota Prius Hybrid system;

"*produces more power from both the gasoline engine and the electric motor, giving the Prius acceleration comparable to a four-cylinder, automatic transmission midsize car. The Prius can accelerate from zero-to-60 mph in about 10 seconds".*

(Toyota North American Pressroom, 2004)

Due to the fact that an HEV require two different powertrains, the incremental production costs are relatively high for the manufacturer. As a result, the retail price of an HEV is much higher than for a conventional vehicle. Many experts have attempted to evaluate the total impact of these costs on the retail price. Delucchi & Lipman (2003) have summarised all major analyses to date. They estimate that the average incremental price of HEV is US$ 3,000. One major breakthrough of the Lipman - Delucchi report is to provide a clear Life Cycle cost analysis and to determine the breakeven price of oil in order for HEV to equal the cost performance of ICE vehicles. In that respect, they estimate that a retail price ranging between, US$ 1.46 and US$ 2.65 (based on the US$ 2,000 rate) for a gallon of gasoline would enable HEV to be as cost effective as a conventional vehicle. More precisely, the Honda Civic Hybrid, one of the most efficient HEV in the market, reaches a breakeven point at a price of US$ 1.74 a gallon. This means that, currently, the Honda Civic will enable the customer to save money on a Life Cycle basis.

- HEV in the automotive industry

The place that HEV will play in the industry is still rather unclear and industry experts have many different opinions regarding the outcome. While it is considered that the Life Cycle total emissions of HEV do not enable Hybrid technology to compete with other alternatives, some experts believe that HEV technology could establish itself as a long term solution (Morris, 2003). Other analysts indicate that HEV will only be a near term alternative until Hydrogen propelled cars penetrate the market in 2010 (Northeast Advanced Vehicle Consortium, 2000). This is of critical importance for car manufacturers, as the costs for developing, implementing and manufacturing any vehicle require tremendous investments. As a result, return on investment requires significant sales volume in order to generate profit. In that respect, many experts believe that the HEV alternative is a dead-end in the medium to long term (Northeast Advanced Vehicle Consortium, 2000). Moreover, the lack of strong political support to HEV tends to discourage manufacturers.

Despite all current analyses available, several major car manufacturers took the decision to introduce HEV on the global market. In that field, Japanese corporations have been the most active business firms. Indeed,

"Japanese car manufacturers are the most aware of the importance of the sustainable mobility issue . . . and Japanese companies are in general more advanced than Western competitors in terms of sustainable product development, both in vehicle safety and energy-efficiency,"

(Morelli, 2004)

Honda and Toyota are leading the way towards HEV introduction to the mass market. However, other major corporations are currently investing into the HEV technology. Nissan and Ford recently announced their intentions to release HEV in the near term by licensing Toyota’s technology. Daimler Chrysler as well as GM also have committed to HEV technology, however in a lesser extent than Toyota or Honda (Brooke, 2003).

4.2.4 Fuel Cell Vehicles (FCV)

- FCV Overview

FCV are currently the main focus of the car industry as well as its stakeholders. Government bodies, consumer lobby groups and diverse associations praise the merits of the Fuel Cell alternative. Indeed, FCV appear to be the ‘Holy Grail’ towards a sustainable automotive industry, since FCV do not produce any toxic emissions. In fact, the only by-products resulting from using a FCV are water and heat.

A FCV results in a radical transformation of conventional vehicles. Indeed, they have very few similarities with conventional vehicles in terms of powertrain. A Fuel Cell is an electrochemical device. Like a battery, it enables to generate electricity in order to propel the vehicle. As such, similar to EVs, FCV do not rely on ICE, but on an electrical motor. Nevertheless, contrary to a battery, the energy is not physically stored in the Fuel Cell. The Fuel Cell converts the energy contained in Hydrogen into electricity. Therefore, whereas batteries will stop to generate electricity when it is discharged, Fuel Cells have the potential to generate electricity as long as they are supplied with fuel.

Until recently, car manufacturers only developed FCV technology as pure R&D applications. Until the early 1990’s it was assumed that Fuel Cell would probably never find physical applications in the automotive industry before a very long term. However, during the 90’s, major improvements in terms of technology enabled manufacturers to build prototypes in order to assess the true potential and merit of Fuel Cell technologies. The year 2000 was a major turning point for the whole industry, as governments suddenly realised the great potential of FCV and of the Hydrogen economy related to it. As a result, massive investments and subsidies were implemented by all major institutions, from the EU to US. Such a signal was interpreted by manufacturers as proof of the high degree of commitment from government bodies, and were encouraged to massively increase R&D efforts in order to bring commercially viable FCV into the market as early as possible (US Department of Energy, 2004g; Morris, 2003).

As a result, it is undeniable that Fuel Cell has been an extremely fast moving technology. The progress and achievements that have been made over the last ten years are tremendous, and many hurdles that seemed critical in 2000 are now cleared (this includes the on-board / off-board reformulation of Hydrogen dilemma; all industry experts now agree that off-board reformulation will be the standard. The FCV will therefore have to be fuelled with pure Hydrogen) (Northeast Advanced Vehicle Consortium, 2003).

- FCV Environmental Performances

As described above, FCV do not emit any pollutants when running. Nevertheless, Hydrogen production as well as vehicle manufacturing do emit a significant amount of CO_2. As observed in the previous section of the report, net advantages in terms of CO_2 emissions differ greatly depending on the manufacturing process of Hydrogen. However, industry experts estimate that total greenhouse gas emissions could be cut by a number ranging from 35% to 85%, either by using Wind Electrolysis or CO_2 capture during Hydrogen manufacturing process (Heywood et al., 2003, Schindler, 2003, Buch et al., 2002).

In terms of performances, an FCV is able to provide more or less the same speed and acceleration as a conventional ICE. However, the main technical hurdle of FCV lies in its operating range. Indeed, current Fuel Cell systems only have a life expectancy of 1,000 hours which represents a driving range of 20,000 miles, whereas ICE have a life expectancy of more than 100,000 miles. Passed this delay, the Fuel Cell will not function and will have to be replaced (Northeast Advanced Vehicle Consortium, 2003). Tremendous R&D efforts are currently leading the industry towards a radical improvement of Fuel Cell life expectancy; however, this technological barrier might be difficult to overcome in the near future.

The high cost of the technology is the second major hurdle towards the implementation of FCV. In the report from Dixon et al. (2002), a review of all major analyses to date regarding incremental costs of production is made. The results suggest that the incremental production costs of FCV, on a mass production basis, would be comprised between US$ 8,300 and US$ 15,200 (Dixon et al., 2002). However, such a conclusion can be discussed, as many different analyses are not that optimistic. For example, the California Air Ressources Board predicts that,

"…the additional cost per fuel cell powered vehicle, now about $1 million will drop to $300,000 in the 2006-8 model years, to $120,000 in 2009-2011, and to $10,000 in 2012-14."
(Morris, 2003)

- FCV applications in the automotive industry

Car manufacturers are highly optimistic regarding the future applications of Fuel Cells in the transportation sector. Even if it is still too early to consider introduction of FCV into the market, all major brands estimate that sales of FCV could start up in the near to mid term through fleet sales to government bodies (Northeast Advanced Vehicle Consortium, 2003).

Being the biggest buyer in the US market and less price sensitive than the private sector, the US government could lay the foundation of the FCV economy by ensuring a considerable market share for car manufacturers. Public transportation is also a hot prospect that could enable car manufacturers to generate considerable return on investments in the medium term (Northeast Advanced Vehicle Consortium, 2003).

However, some industry analysts are more pessimistic regarding the potential success of FCV. In that respect, recent studies are seriously questioning the relevance of developing a Hydrogen economy. As David Morris, Vice President of the Institute for Local Self Reliance stated:

"The hydrogen economy is offered as an all-purpose idea, a universal solution. However, in the short and medium term a crash program to build a hydrogen infrastructure can have unwanted and even damaging consequences. This is especially true for the transportation sector, the transformation of which is the primary focus of hydrogen advocates and the highest priority of federal efforts…The focus on building an national hydrogen…network…ignores shorter term, less expensive and more rewarding strategies"

(Morris, 2003)

This view is share by many other institutions, notably the European Wind Energy Association who estimates that a premature push towards the so-called Hydrogen economy could have a tremendous environmental downside (Morris, 2003). Indeed, as it is today, Hydrogen production would rely exclusively on natural gas, a non-renewable resource. Therefore, one should consider that the Hydrogen economy would make sense only when governments will manage to ensure Hydrogen production through hydro or solar power.

4.3 Green alternatives and New Business Environment Conditions

In light of the empirical evidence presented throughout this section, it seems apparent that there is no easy solution to decrease the dependence on non-renewable resources, while reducing toxic emissions. There is no 'miracle' solution, but one must note the tremendous efforts and breakthroughs that have been achieved by the automotive industry. However, it must be understood that some alternatives present greater potential than other.

In an attempt to fulfil the objective "To determine the degree of compliance between the emerging technologies and the New Business Environment Conditions", the below model has been developed:

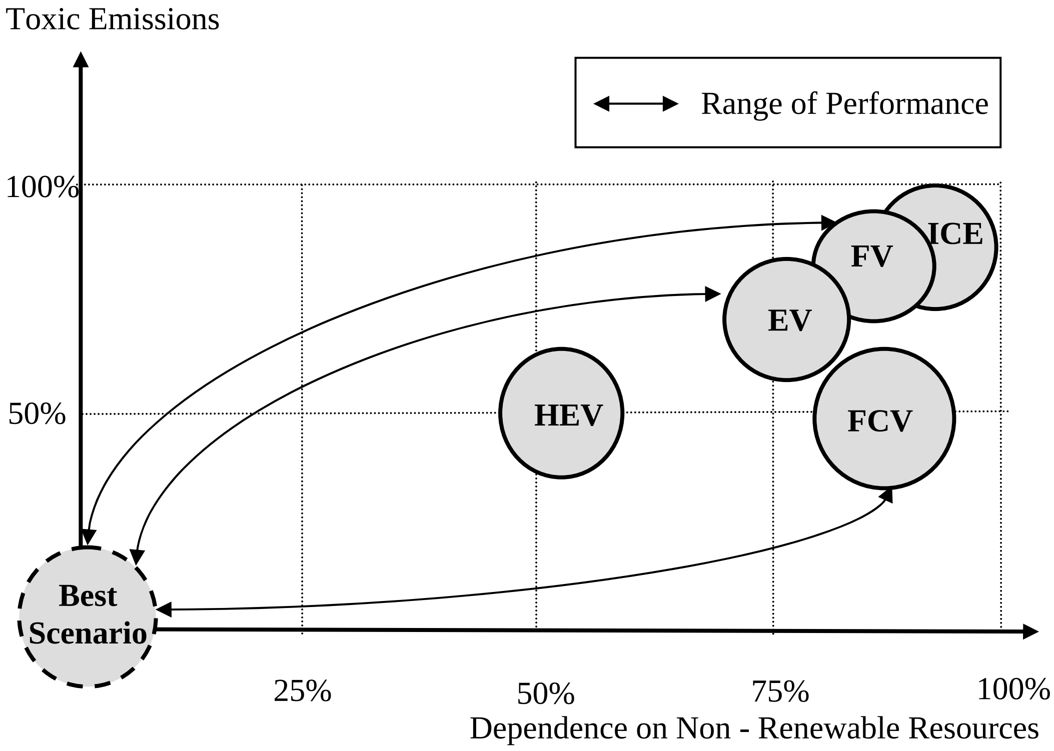

Figure 12 - Eco-friendly technologies compliance with New BEC

This model summarises the major findings in terms of toxic emissions as well as the dependence on non-renewable resources for each “green alternative” on a Life Cycle basis. In that respect, the area ‘ICE’ must be understood as being a highly toxic technology, highly dependent on non-renewable resources. It serves as a basis for comparison with other technologies. The area ‘Best Scenario’ must be understood as the potential performances that could be achieved if fuels were produced in the cleanest way. For example, FV will show poor performances when using low blend fuels (E10-B20); and ultimate performance when using pure Biofuels.

Therefore, the area ‘FV’ reflects the potential to eliminate the use of fossil energy and to reduce toxic emissions while using low blends of Biofuels (E10 and B20). When using low blends, the overall achievements of FV are rather limited, as the fuels remain dependent on oil at a level of 80% and 90% for Biodiesel and Ethanol respectively. Moreover, low blends do not have the potential to drastically reduce toxic emissions as E10 and B20 reduce CO_2 emissions by 10% and 16% respectively. However, when used in their pure form, Biofuels enable to completely eliminate both toxic emissions and the dependence on non-renewable resources. Indeed, the fuel production process actually removes CO_2 from the atmosphere, while no petroleum fuel is required to operate the vehicle. Therefore, in the 'Best Scenario' case, FV appear to be an ideal solution.

EV performances vary greatly depending on which source of energy will be used to produce electricity. In that respect, one must acknowledge the fact that coal is currently the primary material used for electricity generation. It has been shown that an Electric Vehicle running on electricity produced by coal would emit nearly 30% more CO_2 than regular gasoline. In addition, altogether, fossil resources account for more than 80% of electricity generation worldwide, which basically means that EV rely heavily on non-renewable resources. From an aggregated perspective, it has been calculated that EV would currently have the potential to reduce CO_2 emissions by 26%. The EV area, therefore, corresponds to a relatively unclean alternative, highly dependent on non-renewable resources. Nevertheless, it has to be understood that Electricity can be produced through hydro, solar or wind power. These alternative production processes would enable to eliminate the dependence on non-renewable resources, and would also drastically reduce toxic emissions. EV would therefore, in the 'Best Scenario', be one of the most suitable alternatives in regards of the New BEC.

Currently, FCV appear to be among the most suitable alternatives. Even though Hydrogen production still relies heavily on non-renewable resources, the worst scenario analysis estimate that the maximal toxic emissions would amount to 60% of current emissions generated by conventional ICE. However, it is possible to produce Hydrogen by using electrolysis, a production process that enables to eliminate the dependence on non-renewable resources. Moreover, Electrolysis has the advantage of producing an insignificant amount of CO_2. Other processes such as CO_2 sequestration enable to prevent the release of toxic emissions into the atmosphere, when producing Hydrogen. As a result, one could consider that FCV have the potential to eliminate toxic emissions and the dependence on non-renewable resources, in the 'Best Scenario'.

In comparison with all the eco-friendly alternatives that have been reviewed, HEV technology is a unique solution in the sense that it is the only one that will never enable the automotive industry to completely eliminate toxic emissions and the use of non-renewable resources. However, currently, HEV appear to be the most efficient alternative as it reduces CO_2 emissions by at least 40%, and therefore reduces the dependence on oil by 40%. The problem is that, by nature, HEV rely on oil, as a conventional ICE is used to charge an electric motor. In that respect, no 'Best Scenario' can be drawn and one must admit that even if technological improvements could permit to improve the fuel economy achieved by HEV, they will always remain dependent on oil.

5 Analytical Process

5.1 Current Developments

Global warming is often perceived as the most serious threat to our way of life and to some extent life itself. Pollution is the main contributing factor for this destructive phenomenon, where the main instigating factor is greenhouse gases. Encapsulated within the rather generic term of greenhouse gases resides CO_2, which is the main culprit to global warming. Awareness of this trend has brought fear amongst citizen and prompted institutions to act against the spread of CO_2.

The increasing awareness concerning the environmental impacts of $CO_{2,}$ among both consumers and institutional stakeholders, has forced many industries into a state of upheaval. Transparent is also the fact that this pressure shows no signs of depletion but rather the opposite, as pressure augments in line with rising environmental awareness. Undeniably, this pressure is evident in the mounting number of individuals, organisations, politicians, governments and nations who increasingly raise these concerns.

In fact, this is especially notable within the car manufacturing industry, which proportionally stands for a substantial part of the aggregated CO_2 emissions. This negative contribution to the accelerations of global warming in combination with increasing stakeholder awareness has resulted in an increasingly authoritative pressure for change.

The car manufacturing industry not only faces this augmenting environmental pressure, but additional demands for a reduction on the dependence of non-renewable fuels. Noticeably is the growing dependence upon oil. Hence, this dependency negatively influences nations' economies, through the apparent lack of synergy between oil supply and demand. Additional pressure is consequently put upon the car-manufacturing sector, as it has to reduce the dependence on non-renewable resources and its contribution of CO_2 emission.

An effect of these developments was a discontinuity, which shifted the industry from a state of convergence into an era of ferment. As the industry was brought into a state of upheaval, alternative technologies emerged and gained additional attention. Hence, alternative technologies took power and momentum from ICE, and thus altered the scope of competition within the industry. Indeed, prior to these new BEC, investments within alternative technologies could be perceived as minor, as the bulk of development was placed in improving the product and process performance of the entrenched ICE. Differing technological trajectories thus emerged to compete for power and momentum, primarily from ICE but also from one another. These new, so called, eco-friendly alternatives are currently battling for attention and support among involved stakeholders, as the degree of understanding and support varies among the differing alternatives.

The era of ferment represents the period in which emerging technologies compete for stakeholder support. A critical issue is thus to determine which technology has the greatest potential to attract the utmost amount of industry support. The technology that receives the maximum amount of support would emerge as the dominant design, and thus gradually crowd out all other competing technologies. A dominant technology would, therefore, have a superior chance to achieve sustainability. This, in conjunction with the fact that the automotive industry is in an apparent state of upheaval, where the differing eco-friendly alternatives are competing for power and momentum, stresses the apparent need of conducting a dominant design assessment. The authors will, therefore, conduct an analysis using the below model, which builds upon the findings from the theoretical review.

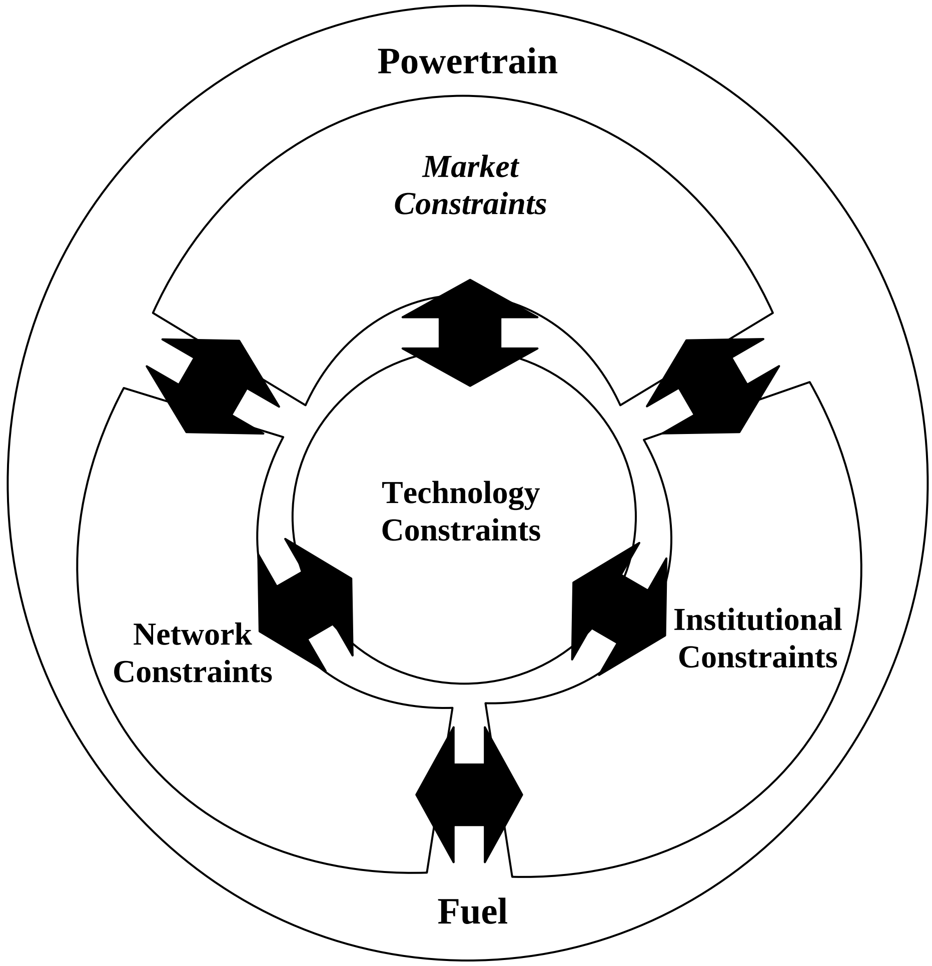

Figure 13 - Constraints for dominance in Automotive Industry

The particularity of this model lies in the fact that the emerging eco-friendly trajectories not only encounter constraints regarding the technology that propels the car, but also the kind of fuel used. As such, an assessment of the overall constraints inherited within each ‘green alternative’, concerning both the fuel and powertrain technologies, need to be conducted. As a result, an evaluation of the constraints inhibiting HEV, FV, FCV and EV from achieving dominant design will hereafter be conducted.

5.2 Technology constraints

There is a critical need to assess the extent to which emerging technologies are competence enhancing or competence destroying. Indeed, when an emerging technology builds upon revolutionary technology, it most likely takes longer for stakeholders to commit to it. In fact, a competence destroying innovation can have impacts on all parts of the value chain, from source of materials until maintenance of the product.

It is therefore important to determine to what extent the eco-friendly alternatives build on existing know-how, as it might postpone and affect the degree of acceptance. As such, there is an importance in evaluating if the emerging technological trajectories are compatible with the entrenched ICE technology. In that respect, the degree of complementarity between all ‘green alternatives’ reviewed within this report and the entrenched ICE can be summarised as follows;

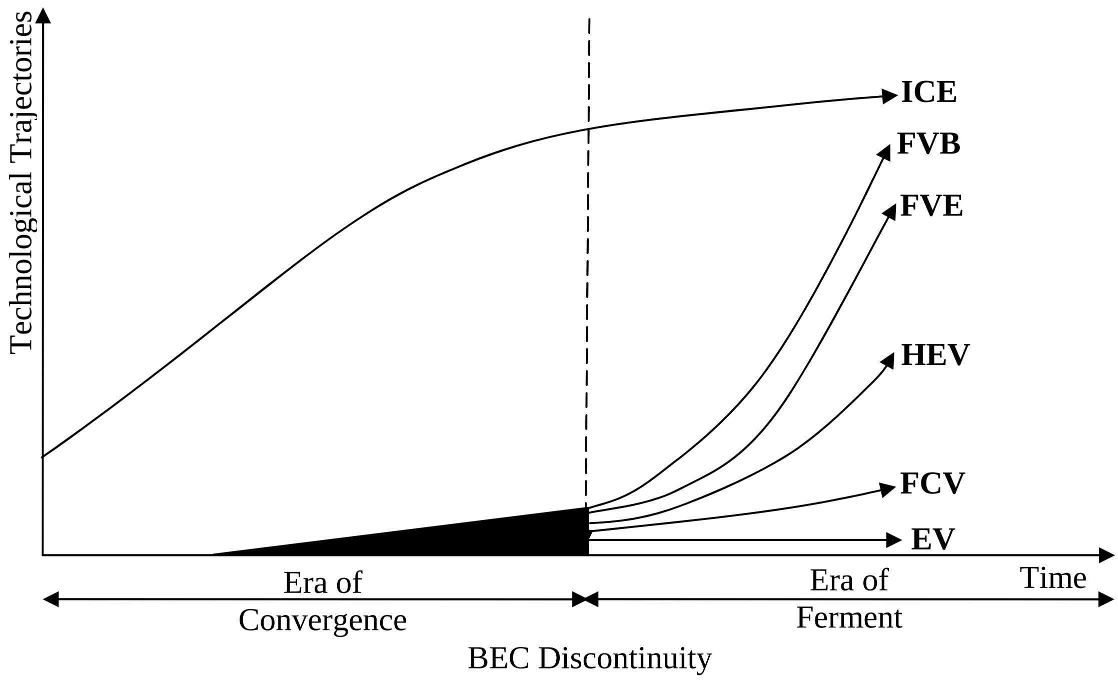

Figure 14 - Technological Trajectories and Complementarity

Figure 14 is an interpretation of the information presented throughout the empirical review. Hence, it reflects the general consensus amongst industry experts regarding the key technological discrepancies between the emerging technologies and ICE. It must be understood that before the emergence of the new BEC discontinuity, the car manufacturing industry was mainly geared towards promoting and developing the conventional ICE. As such, very few efforts, in terms of R&D, were allocated towards the development and introduction of new technologies.

However, the new BEC discontinuity initiated and era of ferment which basically forced the industry to allocate resources into the development of alternative fuel and powertrain technologies. After the wake of this discontinuity five main technological trajectories emerged to compete for power and momentum, namely FVB, FVE, HEV, FCV and EV. These competing technologies proximity to ICE varies significantly, as some builds upon the old whereas others differ considerably. In that respect, it can be said that both FV trajectories are rather closely related to entrenched ICE, as they only require limited modifications in terms of powertrain. The FV trajectories, as such, tend to meet the ICE trajectory within figure 14, highlighting a high degree of complementarity.

On the other hand, HEV complementarity with ICE is less evident, as car manufacturers must develop a new technology in terms of powertrain. This becomes evident with the fact that an electric motor must be inserted in the vehicle, besides the conventional ICE, thereby making the HEV trajectory less compliant with ICE than FV. When it comes to FCV and EV it is clear that the degree of complementarity is low. The powertrain technology required by these vehicles has little to nothing in common with conventional ICE. In that respect, while it can be considered that FCV still require a fuel tank and injection system, EV do not even require such systems as it relies exclusively on batteries that have to be recharged by plugging the vehicles on to the electricity grid.

Consequently, it can be said that, FV are the most competence enhancing alternative amongst the eco-friendly trajectories. HEV appear to be somewhat competence enhancing as they partially rely upon existing technologies, whereas FVC and EV clearly are competence destroying.

However, in order to provide a clear and complete picture of technology constraints, the analysis also needs to consider the extent to which the eco-friendly alternatives are competence-enhancing or destroying regarding the fuel supply. Indeed, while some alternatives imply a completely new set of infrastructures dedicated to fuel production, transportation and supply, other alternatives only require relatively minor adjustment of an existing network.

When considering electricity as a fuel, it is apparent that this technology is, in most cases, widely available all around the world. The infrastructures enabling the production and distribution of it are already available, and one can say that it is possible to find a secure source of electricity at any time and practically everywhere in the world. Electricity as fuel would therefore enhance the current competencies within the fuel industry, as production, transportation and supply systems already exist.

On the other hand, it must be admitted that using Hydrogen as a fuel would require the industry to develop a whole new set of competencies and know how. Not only does Hydrogen still require major R&D efforts to overcome issues related to storage, but also regarding the production and transportation. In fact, it requires the development of new pipelines, refuelling stations and the development of sufficient production facilities to enable large scale supply. In that respect, the current infrastructures used for conventional petroleum gasoline or diesel cannot be used and would have to be replaced. Hydrogen is thus a competence-destroying alternative.

The situation is rather similar for Biofuels, as the current infrastructures and competencies used for petroleum fuels cannot entirely be applied to Biodiesel or Ethanol. Even if recent studies have shown that most of the existing transportation and storage infrastructures are compatible with Biofuels, the production facilities required by Biodiesel or Ethanol are very different from conventional oil refineries. In that respect, Biofuels have to be considered as competence destroying alternative. However, it must not be forgotten that Biofuels could be used as a blend together with conventional fuel. As such, one can say that there is a strong degree of complementarity between Diesel-Gasoline and Biodiesel-Ethanol.

HEV are unique in the sense that they do not require any modification of the current know-how and competencies. As a result, current stakeholders among the supply chain can focus on improving and developing current infrastructures and know-how, rather than creating a new infrastructure. It could therefore be said that HEV technology is a highly competence enhancing alternative.

A matrix (Figure 15, p 78) was created to summarise the above analysis and to provide a clearer understanding of the inherited technological constraints of the emerging eco-friendly alternatives. In that respect, it appears that HEV have the best chances to become dominant and that it is followed by FV alternative. EV have much less chances to become dominant as they are highly competence destroying when it comes to the powertrain technology. Finally, one can conclude that FCV have considerably reduced chances of reaching dominance as it is a highly competence destroying technology.

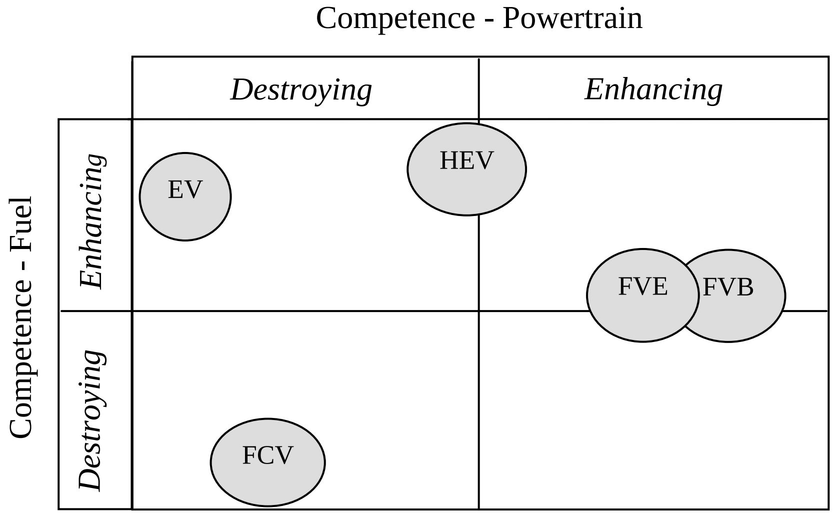

Figure 15 – Competence Destroying vs. Enhancing

5.3 Market Constraints

A clear assessment of market constraints affecting the emerging technologies is a fairly complex task. This is apparent when considering that market demand varies greatly as consumers do not have the same set of expectations or tastes. There is, nevertheless, a set of minimum requirements that an emerging technology must fulfil, in order to be considered acceptable by consumers. Indeed, it has been established that in order to achieve a dominant position, an emerging technology must have similar or superior performance levels as the entrenched technology. In fact, an emerging technology has to overcome two hurdles; the functionality and the net utility thresholds. Hence, a comparison between the emerging technologies and the entranced ICE needs to be conducted.

Nonetheless, functionality must be understood as the combination of several criteria that determine the technical performances of a technology. These criteria include; the life expectancy of a vehicle; the mileage derived from a fully charged vehicle; as well as the speed and acceleration of a vehicle. If an emerging technology shows inferior performance level, in comparison with existing technology (ICE), it will most likely be perceived as rubbish and rejected by consumers. Additionally, for the purpose of this thesis, a key element that must be included within the functional threshold is the extent to which eco-friendly alternatives comply with the New BEC. Indeed, if an eco-friendly alternative is not able to provide better environmental performances than the entrenched ICE, market forces (governments and stakeholders) will most likely reject it.

The net utility threshold is predominantly cost oriented. In the context of this analysis it can be defined as the switching costs a consumer will gain or lose, when changing from the conventional ICE to an emerging alternative. The price of the fuel for equivalent distance as well as the price of the technology will, therefore, be assessed to determine the switching costs each emerging technology has in comparison with ICE.

- Functionality Threshold: technical performances

Although, the acceleration, power and speed of an HEV are comparable to a gasoline engine, it appears to be a highly efficient alternative. Most transparent is the significant advantage in terms of increased mileage. It is widely admitted that the range of an HEV is about 40% more than conventional ICE. Moreover, an indirect functional benefit lies in the fact that the customer will not have to drive to the gas station as often as with a conventional vehicle, thus saving time and mileage. The increased performance level is easily visible by consumers, and might result in an easy acceptance of HEV. HEV thus have low functionality constraints.

The technical performances of FV are rather similar to the conventional ICE, although performance differs whether it is Biodiesel or Ethanol. A general opinion is that FVB tend to outperform FVE. In that respect it is commonly assumed that FVB have the same power, torque, range and payload capacity as Diesel vehicles. However, the mileage achieved by FVE is considered to be at least 25% inferior to a conventional gasoline vehicle. Moreover, there is a fear that Ethanol might accelerate wear on engine, components and fuel lines, which might result in additional maintenance constraints. It could therefore be argued that the functional performance of FVB are similar to ICE, whereas FVE have higher functionality constraints than ICE.

Undeniably, EV are far away from being able to compete with conventional ICE. The mileage of EV rarely exceeds 100 miles per charge. Moreover, it is considered that major technical issues need to be cleared before a mass market introduction of EV is possible. The main hurdle for this is the electric batteries, which still require a long time to be fully recharged and that have rather limited life expectancy.

The performances of FCV are controversial, as it is estimated that FCV offer the same speed and acceleration as ICE. However, in order to achieve the same mileage, the size of the fuel tank would have to be at least 2.5 times bigger than current ones. Thus, one can assume that, for an equivalent length, width and height, FCV would have less room for passengers and cargo, thus reducing the functionality. Moreover, the life expectancy of ‘fuel cell stacks’ is five times shorter (limited to 20,000 miles) than ICE. These factors highlight the lack of functionality inherent in FCV.

- Functionality Threshold: eco-friendly alternatives and new BEC

It has been highlighted that the degree of environmental friendliness varies greatly depending on the production process or raw materials used to manufacture fuel. As such, assessing the market constraints is a fairly complex task, as the result will be completely different whether the analysis is based upon the potential of technology rather than the contemporary situation. For example, under contemporary conditions, electricity production is highly dependent on non-renewable resources, resulting in a rather poor compliance with the New BEC. However, in an ideal scenario, where electricity would be produced through environmental friendly processes, such as wind or solar power, the dependence on non-renewable resources would be eliminated. The situation is rather similar for Hydrogen, which production currently relies heavily upon natural gas. However, the possibility to manufacture Hydrogen through electrolysis and/or capturing CO_2 emissions would enable an elimination of the dependence on non-renewable resources and/or the release of toxic emissions into the atmosphere. When it comes to FV, the compliance with the New BEC is limited if Ethanol or Biodiesle are used as a blend. However, when using pure Biofuels, FV show potential to perfectly match the New BEC.

A matrix (Figure 16) was created to summarise the analysis, which illustrates both the contemporary technological position as well as the ideal situation. It thus becomes clear that HEV seem to be the best alternative. However, it is closely followed by FV, whereas FCV and EV from a functionality’s point of view, both meet the highest degree of constrains.

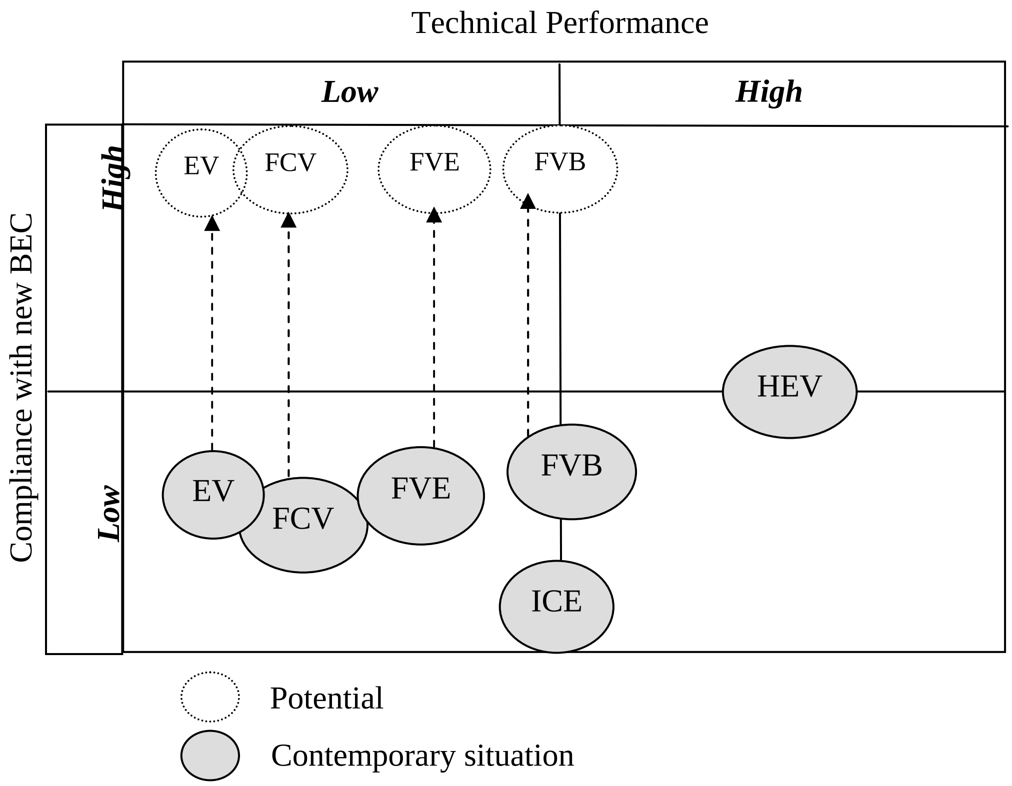

Figure 16 – Functionality Threshold

It is believed that in the future, regulatory bodies will strive for further commitment to developing an eco-friendly transportation sector. It is also believed that stakeholders within the industry will constantly strive to improve current technologies and attempt to develop cleaner and more efficient production processes. Indeed, as markets continuously strive for perfecting themselves, they will naturally try to focus their attention towards perfecting existing technologies. Stakeholders would thus predominantly judge technologies upon their potential rather upon their infancy compliance and performance levels. This, in combination with the objective to assess the potential of the emerging technologies, highlights the importance to focus on the ideal instead of the current situation.

- Net Utility Threshold

The net utility threshold analysis must take into account two variables: the cost of fuel and the cost of the technology. In that respect, each emerging eco-friendly alternative needs to be assessed in comparison with the entrenched ICE using these two variables.

The bulk of the total cost of adopting an emerging technology varies in terms of incremental vehicle production costs and cost of fuel. This becomes apparent with EV technology where the cost of fuel is much lower than conventional fuel, while the high incremental cost of the technology completely upsets this advantage. Biodiesel and Ethanol, on the other hand, only require minimal powertrain upgrading from the conventional ICE, which results in relatively low increase of incremental production cost. However, their relatively low increase in incremental cost is distorted by the high price of fuel, where Biodiesel cost 50% or more and Ethanol approximately 83% more than the conventional fuels in terms of production.

On the contrary, FCV result in both an increase of incremental production cost and a significantly higher price for fuel. Mainly, as Hydrogen fuel made through electrolysis would cost approximately 80% more than conventional petroleum diesel or gasoline.

Despite an increase of incremental production costs, HEV show a unique trend amongst the eco-friendly alternative as the economy in terms of fuel consumption can generally achieve 40%. Henceforth, industry experts estimate that HEV are currently enabling customer to save money on a life cycle basis.

These price discrepancies are compared and highlighted within figure 17 below. The figure clearly illustrates the advantage of HEV in terms of cost benefits, whereas the other technologies show worse cost advantages. The low overall cost of HEV reflects a relatively low or no switching cost involved, which results in a low degree of constraints inhibiting dominant design.

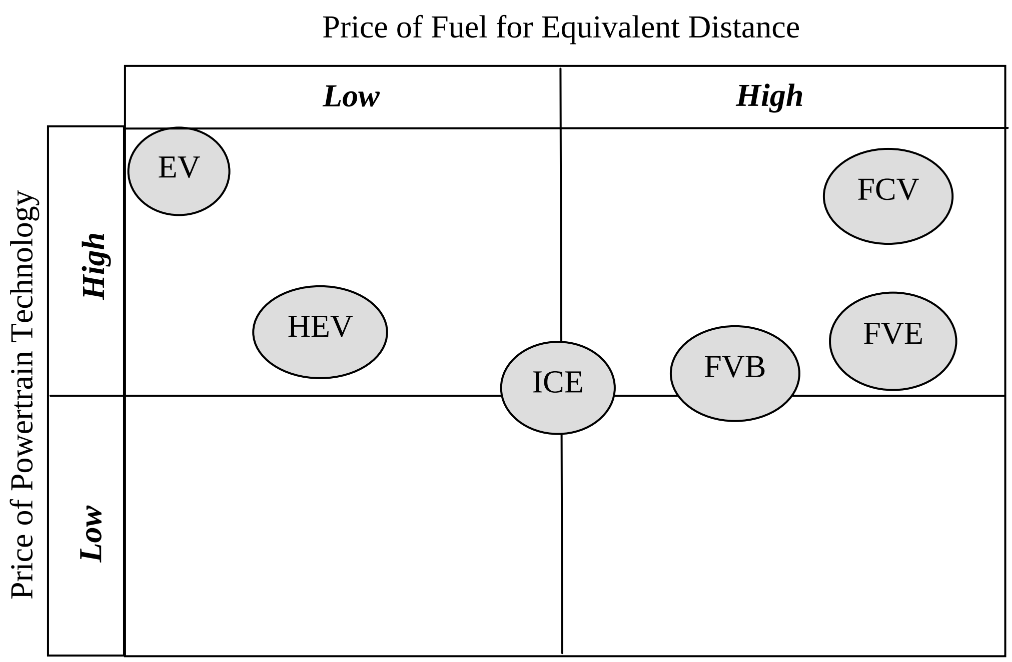

Figure 17 – Net Utility Threshold

5.4 *Institutional constraints*

It must be understood that institutional constraints contain two main forces. On one hand, car manufacturers are playing a vital role, in the sense that they are the only stakeholders that can produce, promote and introduce the 'physical product' onto the market. Therefore, one can consider that the degree of commitment or collusion within the car manufacturing industry will be an important aspect in affecting the outcome of a technological battle.

On the other hand, it can't be denied that government support is a powerful force that might influence or encourage an industry to develop and explore new concepts, products or alternatives. It has already been explained that, in reality, one of the major driving forces behind the development of a 'sustainable' transportation industry is the international regulatory framework, which strives for a significant reduction of CO_2 emissions and the reduction of non-renewable resources. However, it is crucial to determine if the degree of support differs amongst all eco-friendly alternatives.

Assessing clearly the degree of commitment of both governments and business firms is a fairly complex task. Legislation, tax incentives and financial support vary greatly from one country to another. Moreover, different lobby groups promoting different interests currently exist and there is no easy way to measure their relative power. However, this analysis will focus on US institutions, predominantly as it is the biggest market for car manufacturers, and as it is one of the most active regulatory bodies in developing eco-friendly alternatives. Nonetheless, a general analysis of the institutional constraints without differentiating the eco-friendly alternatives will be conducted. This will be followed by a more detailed description of the specific support provided for each eco-friendly alternative.

- Institutional constraints from a general point of view

When looking at car manufacturers' support and commitment, one can say that the multiplicity of alternatives and prototypes developed seems to highlight a high degree of commitment from the whole industry for all alternatives (US Department of Energy, 2004). Indeed, all major brands do offer FV, HEV and have developed FCV prototypes. However, it can be acknowledged that the degree of commitment regarding EV has considerably decreased over the last few years (as illustrated by the decision of Toyota to discontinue the production of its RAV4 EV).

Government bodies and lobby groups generally support all the current eco-friendly alternatives. In that respect it must be noted that a strong focus is made in promoting R&D activities, but financial support is also dedicated to developing all infrastructures related to, and supporting the production of, environmental friendly vehicles. The most significant local legislation that has paved the way towards further improvements seems to be the 1990 'California ZEV (Zero Emissions Vehicles) Regulation', as it marked the beginning of a discussion for alternative technologies (Van Den Hoed, 2004). Before this regulation, the primary focus of the industry and government was the EV (Van Den Hoed, 2004). However, over the years 1990 to 2003, the California ZEV Regulation modified its focus as HEV and FCV were introduced on the agenda. Moreover, a consensus was reached in the industry aiming at reducing the importance and support dedicated to EV programs, and the selection of FCV as the preferred solution (Van Den Hoed, 2004).

As introduced in the empirical review, another key initiative from governments is the 'FreedomCAR', a Co-operative Automotive Research between the US Department of Energy, the US Council for Automotive Research and the energy industry. This initiative focuses government support on fundamental, high risk research that applies to multiple passenger vehicle models and emphasises the development of fuel cells and Hydrogen infrastructure technologies (US Department of Energy, 2004h). Completed by the 'Fuel Partnership' program, the FreedomCAR initiative also attempts to promote the use and development of eco-friendly propulsion systems such as HEV technology, FV and EV (US Department of Energy, 2004h). The FreedomCAR appears to be a major initiative towards sustainable mobility due to the tremendous amount of money that has been invested in it (1.7 billion US$ over the period 2003-2007), and to the participation of several major car manufacturers (Daimler Chrysler, Ford, General Motors) and fuel companies (Chevron Texaco, ConocoPhilips, ExxonMobil, Shell). The US government is currently trying to reinforce such an aggressive action plan, as President Bush urges US authorities to accept a proposal from the National Commission on Energy Policy (Swann, 2004). This proposal involves a US$ 3 billion grant over the next ten years to provide carmakers with incentives to build efficient HEV and advanced diesel vehicles (Swann, 2004).

The EU's initiatives have been fairly modest so far, both in terms of scope and resources. Despite the EU regulation on Biofuels aiming at significantly promoting the use of Biofuels, it seems that massive R&D and infrastructure action plans are yet to be defined. However, over the last few years, the EU commission seems to have realised the need to develop a clear regulatory framework (EU Commission, 2003). It appears clear that the EU is currently focusing on Hydrogen as the future fuel that will be used not only in the energy industry, but also in the transportation sector. Indeed, it is estimated that FCV could penetrate the European markets as early as 2010, and could become the dominant technology in transportation in 2040 (EU Commission, 2003). When it comes to specific regulations for HEV, EV or FV, there is an apparent lack of clear incentives or financial support policies. However, it must be noted that at a government level, tax incentives are provided in order to support the development of HEV sales (Smokers, ?2004).

From an overall perspective, Japan has always been an example of strong co-operation between industry stakeholders and regulatory bodies. As a matter of fact, the METI (Ministry of Economy, Trade and Industry, formerly known as MITI) plays a central role in the development of policies on industry and trade. Both MITI and METI have always strongly encouraged the development of eco-friendly alternatives. More precisely, since 1993, several action plans have been continuously developed and adapted in order to promote an ideal solution for a 'sustainable mobility' (Åhman, 2004). As for the US policy, the Japanese regulations aim mostly at supporting R&D and developing the infrastructures related to a specific eco-friendly alternative. Initially, the main focus of the MITI was to promote EV, which reached its culmination when a basic market expansion plan was established in 1976 (Åhman, 2004). In 1997, MITI altered its strategy to include a strong focus on HEV technology. However, in 2001, the MITI decided to establish a new action plan that will significantly reduce the focus on EV in favour of FCV, which from then on is considered the main strategic focus for achieving 'sustainable mobility'. Indeed, the Japanese Government regards fuel cell development for vehicle use as a national strategic issue in the long term (Åhman, 2004).

- FCV Institutional constraints

The primary focus of the automotive industry today is FCV. All major brands are currently investing considerable amounts of money to develop affordable FCV technology. Government support is exceptionally high as the EU, the US and Japan all perceive the development of an Hydrogen economy as a primary objective for the long term, however, not only for transportation but for electricity generation in general (EU Commission, 2003). Numerous lobby groups representing all industry stakeholders (from suppliers to carmakers) are joining forces in order to request further support from regulatory bodies. For example, the US Fuel Cell Council regroups 43 members and 72 associates, from well know major companies such as Ballard, Daimler Chrysler, General Motors, Argonne National Laboratory or the National Renewable Energy Laboratory (USFCC, 2004). Undeniably, it has to be admitted that FCV are strongly supported by all institutions.

- HEV Institutional constraints

It has been reviewed, that HEV are rather well perceived by all major governments and regulatory bodies. Even if the primary focus of governments is FCV, HEV remain one of the key priorities of the US and Japan. Moreover, tax incentives for consumers buying HEV are rather common. For instance, the US federal government is currently applying a tax deduction of US$ 1500 for Honda Civic, Honda Insight and Toyota Prius owners (NREL, 2004). From a car manufacturer's point of view, the HEV alternative is steadily gaining momentum. This is apparent after the recent success of the Toyota Prius, when General Motors recently announced its plan to make HEV technology available on up to 1 million of its cars and trucks by 2007 (Kelly et al. 2003). Ford and Nissan will also enter a licensing agreement with Toyota, in order to use the Prius technology to introduce the Ford Escape in 2005 and the Nissan Altima in 2006. Honda and Toyota will also introduce more HEV models into the market (Toyota Camry in 2006 and Honda Accord in 2005) (ABIresearch, 2004). Indeed, car manufacturers are trying to catch up with the recent success of Japanese HEV products, and some experts estimate that at least 20 new Hybrid models will appear in America by 2007 (The Economist, 2004). Therefore, it can be admitted that HEV are strongly supported by the car industry and government bodies, however to a lesser extent than FCV.

- EV institutional constraints

Over the last few years it appears that institutional support for EV has considerably been reduced as a result of a stronger focus on developing a Hydrogen economy. Even if programs aiming at improving batteries' efficiency and performances are still active, EV are no more the focus of the stakeholders (Åhman, 2004; Van Den Hoed, 2004). On the contrary, as highlighted with Toyota's decision to discontinue the production of the RAV4 EV, it seems that EV are not anymore considered as a relevant alternative by carmakers. As a result, it must be acknowledged that EV have little support from government and regulatory bodies and nearly no support from the car manufacturers.

- FV institutional constraints

Biofuels are fairly well supported by government bodies. A shining example is the EU directive 2003/30/EC that sets clear and ambitious objectives to be achieved by member states in implementing Biofuels alternative. Indeed, the European Commission's Green Paper 'Towards a European strategy for the security of energy supply' sets the objective of 20% substitution of conventional fuels by alternative fuels in the road transport sector by the year

2020 (EU directive 2003/30/EC). It must be noted that this directive does not attempt to avoid the development of the Hydrogen economy,

"Promoting the use of biofuels in transport constitutes a step towards a wider application of biomass which will enable biofuel to be more extensively developed in the future, whilst not excluding other options and, in particular, the hydrogen option"

(EU directive 2003/30/EC)

This directive also prompts member states to take quick action in order to realise the objective set. In that respect the European Parliament called for a package of measures, including tax exemption or financial assistance for the processing industry and the establishment of a compulsory rate of Biofuels for oil companies (EU directive 2003/30/EC).

The US government is also showing strong support in favour of Biofuels. The Department of Energy is actively supporting a program of research and development of biopower technologies that have the capacity to make important contributions to the US energy supply by 2010 (Duncan, 2001). This program has identified Ethanol as the most promising liquid fuel option for transportation (Duncan, 2001). Moreover, this program supports the development of energy crops and the production, harvesting, handling and conversion-processing technologies needed to make Ethanol commercially successful (Duncan, 2001). The latest development in the US legislation regarding the promotion of Biofuels is rather positive and seems to highlight that the US are now actively supporting not only Ethanol, but also Biodiesel. On December 10th, the US House of Representatives passed a bill that aims at streamlining tax incentives surrounding Ethanol (US Congress, 2004). Moreover, this bill will improve the distribution and availability of both Ethanol and Biodiesel (US Congress, 2004).

Another country that has realised and committed to the potential of using Biofuels is Brazil. Indeed, Brazil is a unique example of a large-scale implementation of using Biofuel in the transportation sector. For more than 20 years Brazil has had an intensive policy for the promotion of Ethanol. In fact, Brazil basic fuels are E28 and E100. Brazil's support of Ethanol becomes transparent when realising that it has contributed to large employment opportunities, for both unskilled and skilled labour, in addition to having a positive effect on the national economy (Falk, ?2004).

Lobby groups are also rather active in promoting the development of Biofuels. Noticeably, the Governor's Coalition currently regroups members from 30 states with international representatives from Brazil, Canada, Mexico, Sweden and Thailand (Governors' Ethanol Coalition, 2004). The primary aim of this association is to share research and development information, explore import and export joint ventures and create an international climate to expand Ethanol's production and worldwide use (Governors' Ethanol Coalition, 2004). Another important association active in promoting Biofuels is the European Biodiesel Board. This association regroups 23 important Biodiesel suppliers from 9 different member states of the EU. This association aims at promoting the use of Biodiesel in the EU while sharing knowledge and information (EBB, 2004).

Car manufacturers have been fairly active in this field and many new model introductions are planned (US Department of Energy, 2004). Indeed, it is undeniable that carmakers have processed with massive investments in order to develop FV and to introduce them in the market. Thanks to a tremendous commitment from government bodies, it is more likely that manufacturers will continue their efforts. As a result it can be said that FV technology is currently a strongly supported alternative from both a governmental as well as an industry perspective. However, more emphasis is currently invested on Ethanol (US Department of Energy, 2004) than on Biodiesel. This phenomenon could be explained by the fact that Ethanol is dedicated to gasoline engines, whereas Biodiesel can only be used in diesel engines. Hence, as gasoline vehicles are more popular worldwide, it is easily understandable that the industry is primarily focusing on Ethanol.

A matrix was devised in an attempt to summarise all the major findings provided through the analysis of institutional constraints. This matrix highlights the fact that FCV have the best chances of achieving dominance from an institutional point of view. HEV and FV are practically at the same level when it comes to institutional support. EV clearly have the worst institutional support, which hamper their ability to become dominant.

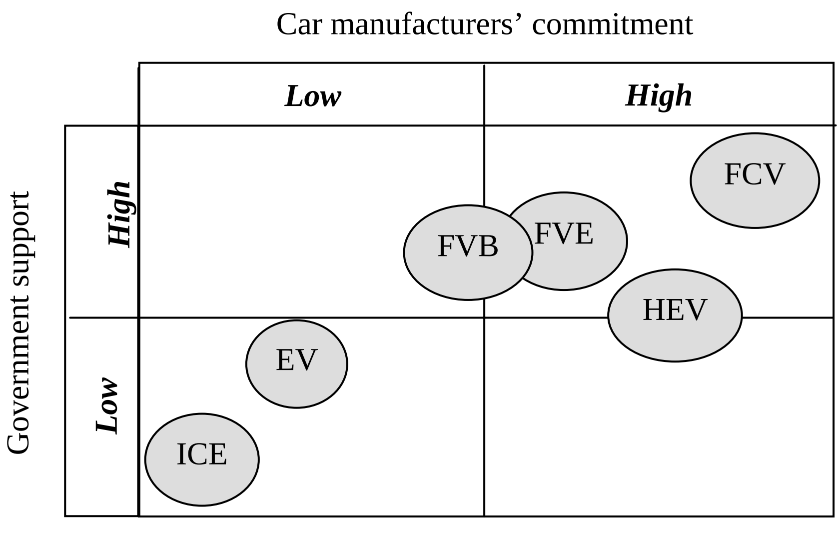

Figure 18 – Institutional Constraints

5.5 Network Constraints

The automotive industry is highly dependent on the supply and accessibility of fuel, as the powertrain and the fuel technologies are cospecialised. In other words, they exist in a state of symbiosis where one can not survive without the other. However, ensuring a smooth continuous supply of fuel is a complex task that requires numerous infrastructures, including production plants, storage and transportation facilities as well as refuelling stations. It must be understood that if these infrastructures are not available today, they will need to be developed before the related eco-friendly alternative can be introduced on the market. As a result, it must be understood that the availability, current state and development of the fuel infrastructures represent a major network constraint inhibiting dominant design. Another vital network factor is the bandwagon effect. This refers to the ‘attractiveness’ a particular technological trajectory has, hence its ability to attract support. In other words, it is the pace to which these eco-friendly alternatives could gain power and momentum amongst the institutional stakeholders.

From a general perspective, each eco-friendly trajectory has different requirements in terms of complementary products. Moreover, the bandwagon effects are not similar amongst all ‘green’ alternatives. As a result, the authors must thoroughly analyse the impacts of network constraints on FV, FCV, HEV and EV.

- FCV Network Constraints

Hydrogen is the technology that currently has the widest institutional support, both from a firm and governmental perspective. This principally stems from the fact that governments are pursuing a holistic solution to the ‘global’ energy problem, and Hydrogen seems to be that solution. In fact, Hydrogen is the most abundant element in the universe and as such, can be extracted from numerous sources. Moreover, the application of fuel cells devices is not limited to the car industry. Using Hydrogen to propel passenger vehicles is only a minor part of all possibilities inherent to Hydrogen. For example, in its vision for the future, the EU Commission assumes that fuel cells will be extensively used to supply power to commercial, residential or tertiary buildings (EU Commission, 2003). Nonetheless, the massive governmental support stimulates car manufacturers to join their cause, through generous financial incentives. This support drove the bandwagon effect and thus resulted in providing FCV with the highest degree of power and momentum within the industry.

However, FCV strong power and momentum is neutralised by several issues, which have to be solved before the technology could become a valid competitive alternative to ICE. Indeed, these problems are related to the required complementary products and infrastructures required by a Hydrogen economy. Dennis Cuneo, a senior vice-president of Toyota North America highlighted these issues, when he said:

"How do you produce the hydrogen in an environmentally sensitive manner? How do you store it? How do you get it into the vehicles? No one in the industry is close to commercialisation yet"

(Mackintosh, 2004)

Although, Cuneo could be perceived as rather subjective, due to Toyota's dedication to HEV, he nonetheless touches upon the critical barriers to FCV implementation. In fact, there resides a difficulty in finding a simple and environmentally friendly way to produce Hydrogen. Further, there resides the technical problem of storage, since Hydrogen, in its pure form, roughly takes up 3,000 times as much space as the same amount of energy of gasoline (Service, 2004). This is advocated by Larry Burns, vice-president oft R&D at GM, who said that:

"Hydrogen storage is still an invention-dependent aspect of the development…"

(Mackintosh, 2004)

Despite these apparent technical barriers to entry, the main obstacle is not the fuel or powertrain itself but the transportation and distribution of the fuel, as Cuneo put it: How do you get it into the vehicles? Further, if Hydrogen is to effectively compete with fossilised fuels there is an apparent need for massive infrastructure development. Indeed, Hydrogen requires enormous amounts of capital investments, as the world's fuel supply infrastructure is extremely complex and vast. In fact, its estimate that Hydrogen has to cover 30% to 50% of the existing filling station infrastructure (Service, 2004). An idea of the massive amounts of investments required is proven with the fact that a 30 percent coverage in the EU would require about 100-200 billion euros (EU Commission, 2003). Additionally, it is estimated that setting up a single Hydrogen fuelling station in the US would cost about US$ 600,000 (Morris, 2003).

Consequently, before FCV technology could become competitively viable it has to overcome the technological hurdles. However, Service (2004) argues that these technical barriers probably would take at least between 10-15 years to overcome in the best scenario. Nonetheless, even if these get solved immediately, there still remains the enormous infrastructural barrier of Hydrogen production. Manufacturing clean and renewable Hydrogen would require governments to completely modify the current electricity production by developing Hydro and Wind power generation stations. Once completed, the construction of Hydrogen production powerplants would then have to be done. One can assume that the sum of money required would be astronomical. This problem is made transparent through the fact that despite the massive industry rally behind Hydrogen, governments only invest a fraction of what would be needed to develop the infrastructures required for the production and distribution of ‘clean’ Hydrogen.

To summarize, it appears clear that the network constraints affecting FCV are rather high. Despite a high bandwagon effect, the currently low availability of complementary competencies, products and infrastructures reflect the hurdles towards a dominant design position.

- HEV Network Constraints

When Toyota first launched its petrol-electric Hybrid car seven years ago, it was met with pessimism within the car manufacturing industry. It even led to the mockery of Toyota. HEV were perceived as ‘too-expensive-to-produce’ cars that would only appeal to a ‘tree-hugging’ minority (Griffiths, 2003). The situation is rather different now, as manufacturers gradually shifted their opinion regarding HEV. Indeed, within the last few years, industry stakeholders have quickly increased their commitment to the HEV alternative, in the fear of losing out if they do not catch the Hybrid technology wave.

This started when Honda entered the market four years ago with its own HEV, the Insight. Currently, other car manufacturers are rushing to catch up as HEV sales continue to rise and even gain pace (Economist, 2004). This becomes apparent when considering that besides the forthcoming widening HEV model range from Toyota and Honda, Ford, DaimlerChrysler, Nissan, Porsche and General Motors are all planning to release their own Hybrid versions. The Hybrid support clearly illustrates that car-manufacturing firms are jumping on the Hybrid bandwagon. As stated within the Economist (2002a); it seems that the automotive industry more or less agrees that hybrids are the next big thing. Indeed, this was proven when General Motors, one of the strongest supporters of FCV, jumped on the Hybrid bandwagon.

Even though the car manufacturing industry shows signs of increasing support towards the Hybrid trajectory it has little governmental support in comparison with FCV. However, it can be argued that the Hybrid technology is less dependent on government’s support, as it doesn’t require any complementary product in terms of fuel infrastructures. HEV would, additionally, even without tax incentives, enable customers to save money on a life cycle basis.

It could consequently be considered that HEV network constraints are primarily related to car manufacturers. The limited regulatory support is therefore not an important issue, as the critical aspect of dominance it is the degree of manufacturers' support. The current pace at which HEV are gaining momentum could therefore be seen as a valuable asset in the current battle for dominant design. Moreover, the numerous introduction of HEV planned over the two coming years suggest that HEV sales would increase as more manufacturers will emphasise efforts in terms of marketing and promotion of HEV technology. As such, it could be concluded that HEV technology is currently gaining power and momentum, and thus faces relatively low network constraints.

- EV Network Constraints

After being the ideal solution towards an environmentally friendly transportation sector, EV have been constantly losing momentum from stakeholders since the late 90's. This probably stems from the previous failures of implementing EV as a mainstream substitute to ICE. These failures are highly correlated with the inherited technical problem that EV face with storage (as the example of the Toyota RAV4 EV). However, the hurdles related to the powertrain technology are not the only concerns.

The Achilles' heel of EV technology resides within its difficulties in finding an environmentally friendly supply of energy. Contrary to first impression, regarding EV strengths, which are the cheap and easily accessible power supply, is the fact that this is actually its main drawback. Indeed, as EV rely upon the established supply of electricity, where there resides a difficulty in assessing whether the supply complies with the New BEC or not. Mainly as the bulk of electricity supply is currently produced using non-environmentally friendly processes that are heavily dependent on non-renewable resources. It would further require significant amounts of capital to completely transform the current power supply network.

The decreasing momentum allocated into the EV technology is also evident within the car manufacturing industry. Today, there is no apparent bandwagon trend. On the contrary, it seems as if car manufacturers are stepping back from the EV alternative. As a result, no model introduction is planned in the foreseeable future, by any major manufacturers. As such, it is unlikely that EV will be able to build an installed base of end-users.

To summarise, the network constraints on EV are enormous. Indeed, the major investments required to develop the necessary complementary infrastructures are not made. This, in combination with the lack of support from stakeholders, results in a high degree of network constraints upon EV.

- FV Network Constraints

The current pace at which FV vehicles are gaining momentum is relatively high. Since the late 90's Government bodies have shown increasing interest in using Ethanol and Biodiesel. Carmakers have been very well aware of such a trend and have embraced the technology. Indeed, it was estimated that in 2001, between one and two million of FV were already on the roads in the US alone (NREL, 2001), which highlights the fact that, currently, FV have the largest installed end-users base. However, it must be noted that the vast majority of these models were FVE, as diesel is not a popular fuel in the US. Carmakers have and are de facto contributing heavily to the bandwagon effect. In 2005, Ford is planning to include four Ethanol dedicated vehicles in its 2005 model's line up (Ford, ?2004). General Motors will also release in 2005 at least three Ethanol dedicated vehicles, a FV version of the Avalanche, Tahoe and Yukon SUVs (GM, ?2004).

Several governments currently support Biofuels and there is an apparent trend towards further dedication within agricultural dependent nations, such as Brazil, the USA and the EU. Mainly because Biofuels could be viewed as a boost to local's agriculture sector by generating an extra source of revenue as well as creating employment. An additional reason for the increasing support for the FV technology is the increasing oil price, which shakes economies and worries several nations. Indeed, an example of this is Brazil's worries concerning the increasing oil price and its balance and foreign debt. Hence, this lead to the dedication and support of FV Ethanol which is competitively produced domestically (Economist, 2002b).

Nonetheless, despite the increasing power and momentum of the FV technological trajectory, as more stakeholders jumps on the FV bandwagon, there still remains the difficulty in establishing a competitive fuel supply network. First, at the agricultural stage Biofuels would necessitate a shift in farming policies in many nations, from the cultivation of food to non-food crops. In addition it would require massive amounts of land to sustain a Biofuel sector. This was highlighted by the EU when stating that for example the Netherlands would not have enough land available for a national production of non-food crops (ATLAS, ?2004). Following this is the problem regarding the associated cost of distributing Biofuels. If Biofuels were to be offered alongside conventional fuels it would require additional fuel storage at petrol stations, additional dedicated pumps, a new delivery system and so fourth. Morris (2003) argues that the implementation of Biofuels as a primary fuel would cost about $50,000 for Biofuel refuelling station. This cost is however only a fraction of the cost of a Hydrogen fuelling station, as transportation and storage infrastructures currently used by petroleum fuels are generally compatible with Biofuels.

To summarise, it seems that the network constraints on Biofuels are rather limited in comparison with FCV. Indeed, an increasing bandwagon has permitted FVE to gain a rather large installed base of end-users. Moreover, the complementary products, technologies and competencies required do not necessitate as many investments as developing a Hydrogen economy.

When concluding network constraints, it becomes apparent that HEV has the best potential to reach dominance from a network perspective. The main reasons are related to the possibility to use existing infrastructures, as well as an increasing manufacturing support. FV also shows a great potential of achieving dominance, as it has a large installed base (compared to the other emerging technologies) and a rapidly increasing momentum. However, this potential is somewhat less inferior to HEV, due to the costs related to the development of supply infrastructures, and the need to secure sufficient land to grow crops. Contrary to HEV and FV, EV and FCV are facing tough network constraints in terms of their huge technical barriers and problems with securing clean sources of fuel supply. As such, HEV and FV possess the best possibilities of achieving dominance from a network perspective, whereas EV and FCV show less potential.

5.6 Overall potential of Eco-friendly alternatives

The separate analyses of each constraint inhibiting dominant design provided a picture regarding each eco-friendly alternatives potential to become dominant in the automotive industry. It has been demonstrated that while a specific technology can achieve an ideal situation within a specific constraint, the same technology might show poor results in another area, hence, eroding a 'competitive advantage'. Therefore, in order to assess the true potential of an eco-friendly alternative to become dominant, its overall degree of compliance with every constraint must be determined. In that respect, the authors have aggregated all the results of the analysis in the below figure (19);

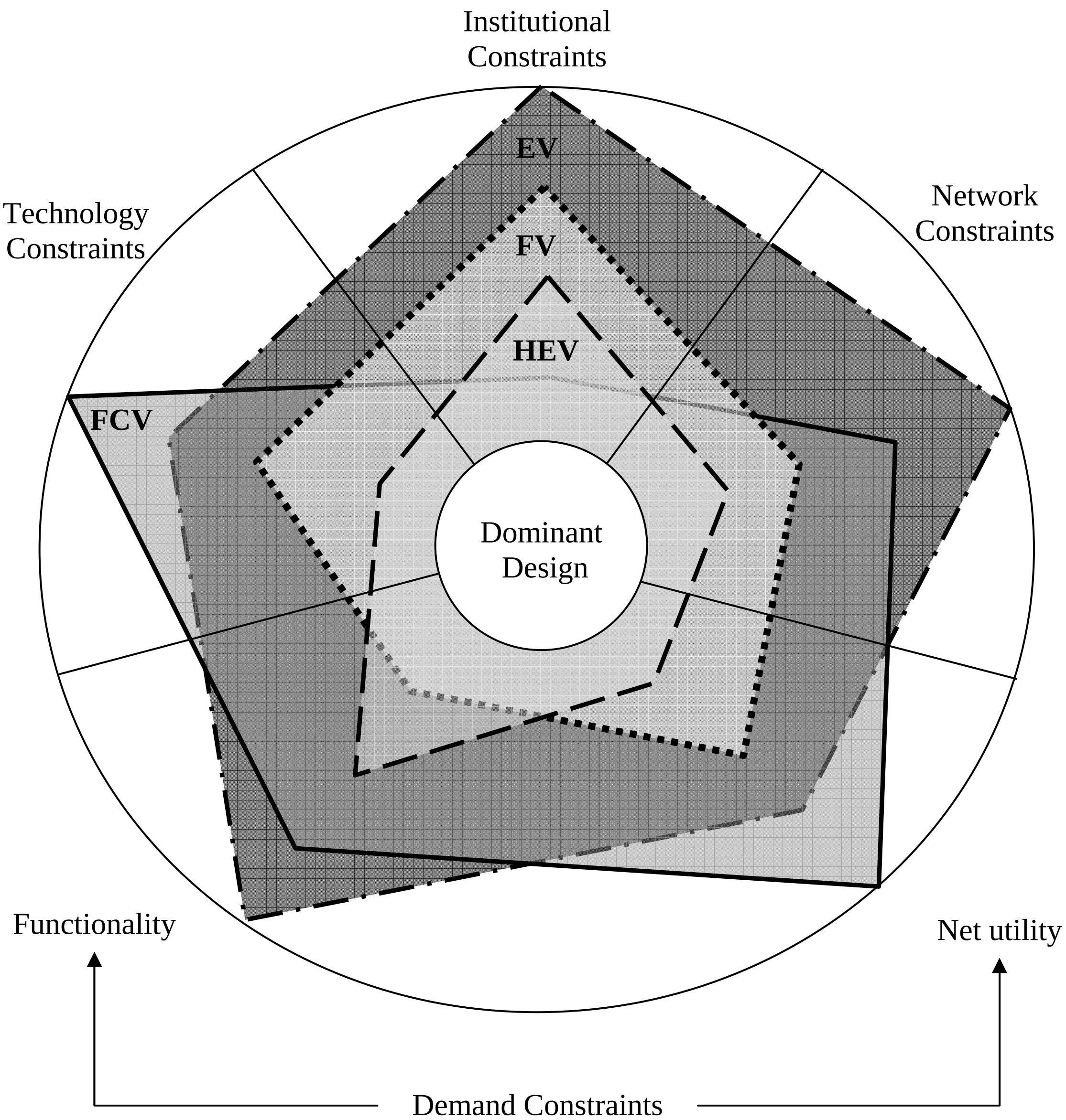

Figure 19 – Degree of Constraints

Figure 19 represents the total weight of the constraints upon a given eco-friendly alternative. As such, it must be understood that the closer a technology is from the 'dominant design' 'frontier', the better are its abilities to become dominant. Hence, the total area that is covered by a technology represents the total constraints it has to face before becoming dominant. Additionally, it must be stressed that all constraints are equally important. Indeed, all constraints interact with each other. For example, strong institutional support will have indirect positive effects on network constraints. Similarly, technology constraints might affect functionality or net utility constraints. Even though it is practically impossible to describe the mechanism that drives these interactions, one must not fall into the trap to assume that some constraints have a bigger power than other ones. Within each constraint, all technologies have been ranked from a qualitative perspective. However, this does not necessarily mean that an eco-friendly alternative ranked last has to face far greater constraints than a technology ranked first. The ranking system simply identifies the degree of facility a given technology has when it comes to overcoming these constraints.

It thus becomes apparent that Hybrid Electric Vehicles seem to have the best potential to become dominant. HEV offer the best results in terms of net utility and do not suffer heavy constraints in terms of technology. Moreover, the ecological as well as technical performances of HEV are impressive, and have the advantage to be clearly visible from an end-user's perspective. Indeed, car manufacturers are becoming increasingly aware of the relevance of Hybrid technology, which results in positive network effects.

FV are performing rather well from an overall perspective, and can be classified as second best alternative for achieving dominant design. Even though the institutional support and net utility benefits of FV are relatively limited in comparison with HEV, the outstanding potential in terms of functionality suggests that Flexible Vehicles would constitute a very good alternative.

Even if FCV currently benefit from strong institutional support, the hurdles towards the development of Fuel Cell Vehicles are enormous. Indeed, both the fuel and powertrain technological barriers suggest that tremendous efforts in terms of R&D and the development of supply infrastructures are still required before the introduction of FCV is feasible. Moreover, the potential outcomes in terms of net utility or functionality are rather uncertain. Therefore, FCV do not seem to have a strong potential to become a dominant design.

When it comes to EV, one can be sceptical regarding the true potential of the electric alternative to become the dominant design. Firstly, it must be stressed that the institutional support has constantly decreased over the last decade. Moreover, the strong technological constraints as well as the poor potential of EV to show benefits in terms of net utility and functionality suggest that Electric Vehicles have the lowest potential to become dominant.

5.7 The true potential of HEV

It now appears clear that the Hybrid technology has the best potential to become the dominant design amongst all the competing technologies. It must therefore be admitted that the HEV alternative could be sustainable over a certain period of time. However, it is important to question how long this sustainability can last, and what the true potential of Hybrid technology is.

In fact, the real sustainability of HEV is highly questionable. As a matter of fact, amongst all eco-friendly alternatives, HEV is the only one that will never be able to fully match the new BEC. Hybrid technology is a concept relying on a conventional ICE engine running on regular gasoline or diesel. What will happen if in the next 30 to 50 years, when all the required infrastructures for a clean Hydrogen transportation industry become available? Undeniably, there will be no barriers in implementing FCV as an ultimate solution for a ‘sustainable mobility’. Therefore, one must wonder if Hybrid technology is not simply a ‘stepping-stone’ towards a cleaner alternative. In fact, under contemporary conditions, the legal framework does not impose car manufacturers to provide end-users with purely clean vehicles relying entirely on non-renewable resources. However, from the moment the automotive industry will be able to comply with environmental friendliness, it can be assumed that regulatory bodies will strive to promote the use of a ‘green alternative’. In that respect, one can say that tomorrow’s legislation might be more constraining than the so-called ‘New BEC’.

One can argue that it is practically impossible to determine how long it will take for FV, FCV or EV alternatives to be able to fully match the new BEC, while offering great advantages in terms of net utility and functionality. Such an analysis depends on many intangible variables, and even if several mathematical models enable to extrapolate on probable outcomes, the degree of uncertainty does not enable these analyses to be highly reliable.

In that respect, the dominant design paradigm, based on the power, momentum and potential that can be allocated to emerging trajectories, provides a unique view upon the topic. As such, while mathematical studies speculations are based on probable market size, production capacities and underlying costs, the authors believe that a speculation based upon power, momentum and support that can be allocated to emerging trajectories would provide industry stakeholders with vital and complementary conclusions. Such an analysis would require determining how the technological trajectories will evolve between each other in the future, and how the total power, momentum and support will be shared amongst all trajectories. As such, the analysis of the overall potential of eco-friendly alternatives available in section 5.6 provides a clear overview of the current situation, form which relevant speculations can be drawn.

Figure 20 (p 98) was, therefore, developed to highlight the probable evolution of all eco-friendly alternatives, and what their potential degree of power, momentum and support would be.

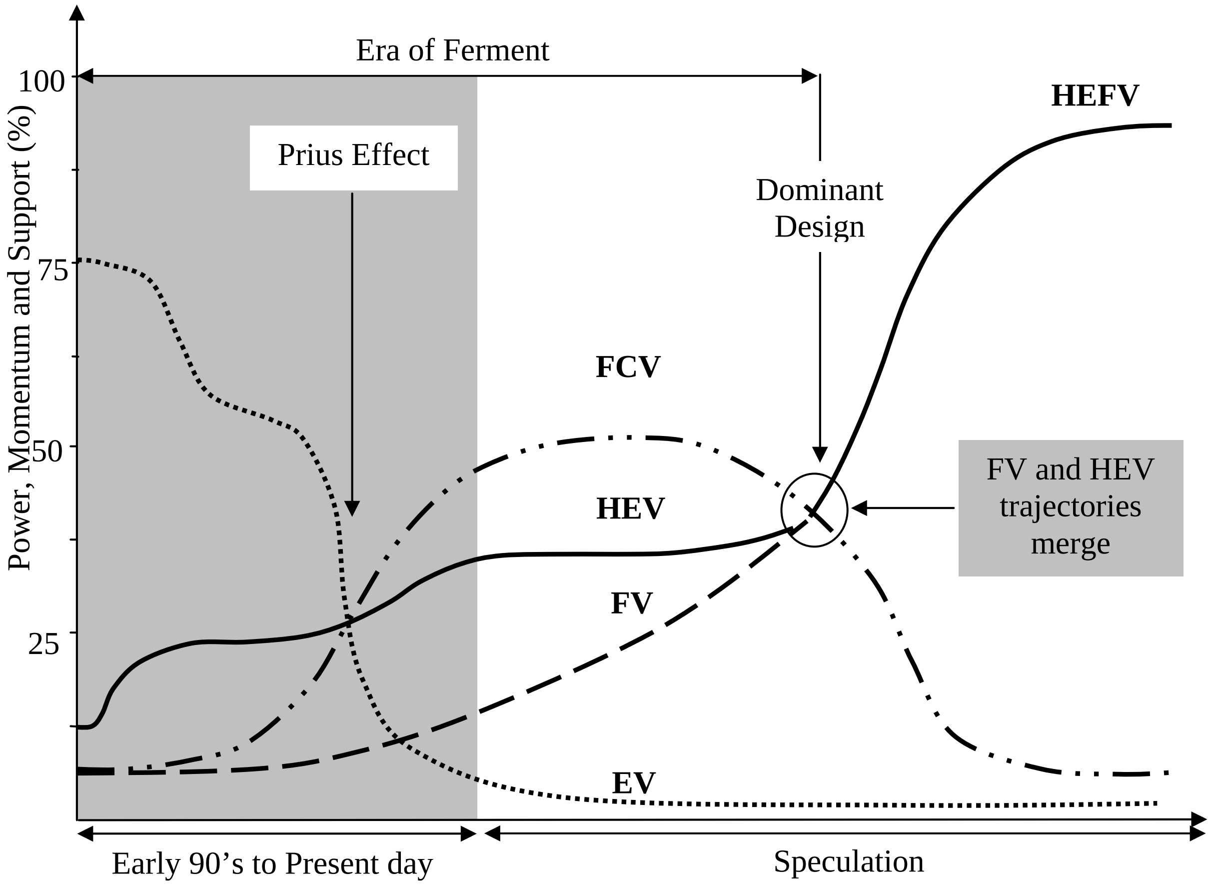

Figure 20 – Evolution of the Emerging eco-friendly alternatives

- Early 90's to present day

In the early 90's the focus of the automotive industry's stakeholders was the development of EV as the key towards 'sustainable mobility'. However, market forces soon realised the considerable technological hurdles that EV had to face. As such, the early 90's saw the emergence of an alternative solution that would enable the automotive industry to overcome the shortcomings of EV technology. As a result, a part of the support dedicated to EV was allocated to HEV. Initially, HEV were only supposed to be present until the hurdles towards the implementation of EV would have been cleared. However, during the late 90's the automotive industry started to show tremendous interests into developing fuel cell cars, and in the very beginning of the 21st century, regulatory bodies as well as car manufacturers initiated massive investments into the promotion of Hydrogen. Soon enough, Hydrogen was to be seen as the ultimate solution towards an environmentally friendly transportation industry. During the same period, HEV were introduced in the market by Japanese carmakers. Despite criticism and the disbelief of many experts towards the relevance and potential profitability of the HEV market, the success of the new Prius initiated a boost in the degree of support from all stakeholders for the Hybrid technology. In fact, while HEV were once considered as a step towards EV, it is now commonly believed that HEV will fill the 'gap' before FCV' related technical issues are solved, and that all required infrastructures have been implemented.

Simultaneously, the FV trajectory has gradually gained power and momentum since the early 90's as Flexible Vehicles became increasingly popular in several markets around the world. While Brazil was heavily promoting the use of Ethanol as a basic fuel, Germany decided to support Biodiesel. In the US, all major carmakers developed FV and in 2001, it was estimated that between 1 and 2 millions vehicles were on the US roads. In fact, regulatory bodies including the EU Commission and the Federal US government are currently actively supporting Biofuels.

As a result of the emergence of the HEV, FCV and FV trajectories, Electric Vehicles have seen their degree of support power and momentum dramatically reduced during the past two decades. In fact, it has been highlighted that EV currently have very little chance to compete with other alternatives as the whole industry seems to have decided that EV will most likely not be the best candidate towards an eco-friendly transportation sector.

- Forecasted events

Following the conclusion of the dominant design analysis, it is apparent that only three major trajectories will compete in the future for the dominant design position. Within these three, HEV have the best chances followed by FV and FCV. It is therefore believed that the degree of power and momentum will not decrease for these trajectories. However, the degree of support for EV will gradually disappear. It is also believed that, in regards of the new BEC, the HEV will gain very little support, as it is believed that HEV will never enable an environmentally friendly alternative. As a result, the only trajectories that might gain power support and momentum will be FV and FCV. Within these two alternatives, it has been proven that FV have the best chances to become dominant, and as such will further improve their power and momentum. However, FCV benefit from a tremendous institutional support which results in enormous subventions in order to promote not only the development of all the required infrastructures, but also encourage R&D activities in order to overcome the technological barriers. It is uncertain that, in the future, the technological and network constraints of FCV can be overcome. However, one can say that FV and FCV will fiercely compete for dominance.

A fundamental difference between Biofuels and Hydrogen propelled vehicles is the fact that Ethanol or Biodiesel can be used in combination with traditional gasoline or gasoline in any kind of blends. Therefore, it must be admitted that the infrastructures required for implementing the FV alternative could be set up gradually. Indeed, Biofuels could be used in combination with conventional ICE until all the other constraints related to the introduction of FV are cleared. As such, the investments related to the development of a fuel supply for FV can be recovered in a gradual and constant manner. On the contrary, the FCV alternative is rather static. Hydrogen can only be used in FCV. As a result, while the investments required are enormous, the industry will only be able to recover from sunk costs after all infrastructures are completed and FCV widely used. At first sight, it seems that FV would have a competitive advantage compared to FCV as Biofuels can be introduced on the market at any time, gradually paving the way for the feasibility of FV.

This is where HEV show their true competitiveness. Indeed, the biggest advantage of HEV is the flexibility of the technology, as it combines the characteristics of a conventional ICE with an electric powertrain. Hence, there is a high degree of complementarity between FV and HEV as the Hybrid electric powertrain can be used in a FV. Moreover, as low blends of Biofuels gradually become available on the market, they will be compatible with HEV. Moreover, the FV technology will enable HEV to overcome the only hurdle towards true sustainability; the combination of FV and HEV will facilitate a perfect match with the New BEC.

HEV and FV being the most likely alternatives to become dominant, it is strongly believed that by merging the two trajectories, the automotive industry will be provided with an ultimate solution towards ‘sustainable mobility’.

6 Conclusion

In order to conclude this thesis, the authors would like to review all the objectives that assisted in conducting the research and which have permitted the authors to formulate an answer to the research problem.

The first area of investigation was devoted to the identification of the technological requirements that enable a technology to become sustainable, from a theoretical perspective. In that respect, it was first necessary to determine the evolution and competitive nature of emerging technologies in order to understand the motives that could force an industry to introduce a new technology into the market.

As a matter of fact, the internal activities and capabilities within individual firms, as well as historical necessities, traditionally result in a technological shift within an industry. More precisely, technology evolution can be defined as a bit-by-bit cumulative process, which is ultimately punctuated by a major advance that could either consist in a 'genius' technological breakthrough, or result from a new set of rules dictated by regulatory bodies or historic necessity. Consequently, at any given time, an industry can be pushed into a state of upheaval, characterized by the emergence of several trajectories that all compete to become the new 'standard'. The main problem of business firms is therefore to identify, amongst differing trajectories, the alternative that offers the best potential to win the technological battle and to establish itself as the only relevant solution.

The theoretical review clearly highlighted the difficulties that corporations face when trying to identify the most relevant trajectory, which often results in a high degree of inertia. However, a striking finding of this thesis lies in the fact that a technology battle ends with the selection of a dominant design that all stakeholders firmly support. Consequently, the dominant design will become the new standard of the industry, and as such, will show a strong potential to develop into a sustainable alternative. Hence, a striking finding of this thesis is to highlight the strong correlation between 'dominant design' and 'sustainability'. Therefore, one must conclude that the technological requirements to become sustainable are strongly dependent on the requirements to become dominant. A major contribution of this thesis has been to clearly identify the major constraints inhibiting the dominant design. It has been identified that network effects, institutional support as well as demand and technological constraints play a vital role in enabling a specific trajectory to attain a dominant position.

The description of the evolution and competitive nature of emerging technologies enabled to better understand the current dilemma that the automotive industry is facing. In fact, the need to reduce toxic emissions, while reducing the dependence on non-renewable forces, represents the historic necessity that resulted in a stage of upheaval. The automotive industry responded by developing several alternatives, including the Hybrid technology, that currently competes for power and momentum in order to become dominant. Therefore, it became apparent that in order to assess the true potential of HEV to become a sustainable alternative, it was first necessary to determine the potential of hybrid technology to become dominant.

However, analyzing the constraints inhibiting dominant design and determining the potential of HEV to win the technological battle would not provide sufficient evidence to answer the research problem. Indeed, for the purpose of this thesis, a strong focus was put on the so-called New Business Environment Conditions. As such, to be truly sustainable, the Hybrid technology had to prove that it can outperform all the emerging trajectories in reducing toxic emissions and the dependence on non-renewable resources. In that respect, the second area of investigation focused on providing all the empirical evidence that enabled to determine, not only the hurdles towards the physical implementation of the emerging technologies, but also the degree of compliance between the different technologies and the New Business Environment Conditions.

In terms of compliance with the new BEC, a striking finding was the high degree of uncertainty related to the true performance and relevance of all emerging trajectories. However, under contemporary conditions, it is clear that the Hybrid technology is the best alternative. Indeed, the hurdles towards the implementation of fully eco-friendly Fuel Cell Vehicles, Electric Vehicles and Flexible Vehicles are immense, especially when it comes to building the infrastructures necessary to develop a massive supply of ‘clean’ fuel. In fact, one could even conclude that FCV, FV or EV will never be able to outperform the Hybrid technology, at least not before several decades, if ever. Nonetheless, the empirical review enabled the conclusion that the major shortcoming of the hybrid technology lies in its inability to completely eliminate toxic emissions and will therefore always remain dependent on oil. The empirical review therefore suggested that, in regards of the New Business Environment Conditions, the true potential for HEV to constitute a sustainable alternative is relatively uncertain. As a result, in order to provide a complete answer to the question, it became necessary to compare the overall potential of all the emerging technologies to become dominant.

As such, the third area of investigation shed further light into the potential sustainability of the hybrid technology. By aggregating all the empirical evidence collected, it was possible to clearly assess the effects of the constraints inhibiting dominant design upon each trajectory. In fact, a striking finding of this research is to clearly demonstrate that the HEV alternative will most likely become the dominant design, and would therefore have the best chances to become sustainable. The analytical process also permitted to conclude that the potential of FV to become dominant is rather high. Finally it became clear that FCV and EV have very little chances to become the dominant technology.

A major breakthrough of the analysis was also to provide an insight on the probable evolution of the different trajectories in the future. Indeed, based upon the past and current evolution of the emerging trajectories, it has been possible to conclude that the hybrid technology will truly become a sustainable alternative. In fact, by combining the potential to become dominant and outstanding environmental performances, the hybrid managed to gain a tremendous degree of support from all stakeholders of the industry. Moreover, HEV have a unique competitive advantage that will most likely be the key in the selection of the Hybrid design as the technology that will propel tomorrow's cars: a high degree of flexibility and adaptability.

Indeed, while the HEV alternative currently has the best potential to become dominant in the near to medium term, it also shows potential to completely eliminate toxic emissions and the dependence on non-renewable resources by merging with Flexible Vehicles. As a matter of fact, the Hybrid technology is the only alternative that can adapt itself to its environment as it can be used in combination with any kind of Internal Combustion Engine. Flexible Vehicles, which show potential to eliminate toxic emissions and the dependence on non-renewable resources, is a technology that relies on the entrenched ICE. As such, a Hybrid Electric powertrain can be inserted into a Flexible Vehicle.

Therefore, it is apparent that HEV and FV are highly complementary and can provide the automotive industry with a truly sustainable alternative: a Hybrid Electric Flexible Vehicle that has the potential to outperform all other emerging trajectories. In fact, the reason why Hybrid technology can outshine its rivals lies in its strong potential to adapt itself to better fit the business environment conditions. Indeed, as Charles Darwin stated;

"In the struggle for survival, the fittest win out at the expense of their rivals because they succeed in adapting themselves best to their environment."

(Charles Darwin, 1859)

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