İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

TECHNOLOGY DEVELOPMENT ENVELOPE APPROACH FOR THE ADOPTION OF FUTURE POWERTRAIN TECHNOLOGIES: A CASE STUDY ON FORD OTOSAN ROADMAPPING MODEL

M.Sc. Thesis by
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Department : Mechanical Engineering

Programme : Automotive

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

GELECEK AKTARMA ORGANLARI TEKNOLOJİLERİNİN BELIRLENMESI ICIN "TEKNOLOJI GELISTIRME ZARFI" METODOLOJISI: FORD OTOSAN YOL HARITASI UYGULAMASI

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FOREWORD

In this study, a new methodology has been applied to automotive industry and new powertrain technologies were assessed according to a company's objective. Automotive industry is a new territory for this methodology and its application required extensive interest from many experts.

First, I would like to thank all the experts who have provided me their precious inputs and contributed highly to my study. I would like to express my deep appreciation and thanks for my advisor, Prof. Dr. Metin Ergeneman and for Dr. Murat Yildirim, Ford Otosan R&D Manager for his guidance. Dr. Tugrul Daim has introduced me to this methodology and helped me through each step. Without his interest, this work would not be complete in time. Finally, I would like to thank my family and fiancé who have always provided their unsparing support.

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ABBREVIATIONS

AHP	: Analytic Hierarchy Process
BSFC	: Brake Specific Fuel Consumption
BTDC	: Before Top Dead Center
BTU	: British Thermal Unit
CAFE	: Clean Air for Europe
CI	: Compression Ignition
CO	: Carbon Monoxide
CR	: Compression Ratio
CRS	: Common Rail System
CVT	: Continuously Variable Transmission
DI	: Direct Injection
DISI	: Direct Injection Spark Ignition
ECU	: Electronic Control Unit
EDU	: Electronic Injection Driver Unit
EGR	: Exhaust Gas Recirculation
EIVC	: Early Intake Valve Closing
EPA	: Environmental Protection Agency
FC	: Fuel Cell Vehicle
GDI	: Gasoline Direct Injection
GDP	: Gross Domestic Product
GHG	: Greenhouse Gases
HC	: Hydrocarbons
HCCI	: Homogeneous Charge Compression Ignition
HD	: Heavy Duty
HEV	: Hybrid Electric Vehicle
ICE	: Internal Combustion Engine
IG	: Improvement Gap
IMEP	: Indicated Mean Effective Pressure
IP	: Improvement Priority
IPCC	: Intergovernmental Panel on Climate Change
ISFC	: Indicated Specific Fuel Consumption
IVC	: Intake Valve Closing
LCV	: Light Commercial Vehicle
LEV	: Low Emission Vehicle
LIVC	: Late Intake Valve Closing
LNT	: Lean NOx Trap
MPI	: Multi Port Injection
NEDC	: New European Driving Cycle
NiMH	: Nickel Metal Hydride
NOx	: Nitrogen Oxide
PEM	: Polymer Electrolyte Membrane
PFI	: Port Fuel Injection
PHEV	: Plug-in Hybrid Electric Vehicle

PM : Particulate Matter
ROHR : Rate of Heat Release
R&D : Research & Development
SCR : Selective Catalytic Reduction
SFC : Specific Fuel Consumption
SOFC : Solid Oxide Fuel Cell
SULEV : Super Ultra Low Emission Vehicle
TC : Turbocharger
TDE : Technology Development Envelope
TDP : Technology Development Profile
TRM : Technological Roadmapping
TWC : Three Way Catalyst
UC : Ultracapacitor
ULEV : Ultra Low Emission Vehicle
VCR : Variable Compression Ratio
VVT/A : Variable Valve Timing/Actuation
WETO : World Energy Technology and Climate Policy Outlook
WOT : Wide Open Throttle

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TECHNOLOGY DEVELOPMENT ENVELOPE APPROACH FOR THE ADOPTION OF FUTURE POWERTRAIN TECHNOLOGIES: A CASE STUDY ON FORD OTOSAN ROADMAPPING MODEL

SUMMARY

Industry, government, and academia have started to adopt the technology roadmapping concept to setup their technology strategy, identify gaps and opportunities in their R&D activities. Automotive industry, facing fierce competition with continuous technological breakthroughs and improvements, should have roadmaps with respect to their company objectives that has flexible features so that organizations can reassess and adjust their roadmaps in a timely manner according to the impacts of the changes.

This study focuses on future powertrain systems with the aim of defining the most probable implantation road map for the different alternatives to improve powertrain efficiency. A new methodology called Technology Development Envelope (TDE) for transforming the roadmapping approach to the level in which it is dynamic, flexible and operationalizable is recognized for a case study of Ford Otosan's technological planning concept.

In the first section of the study, following the introduction, roadmapping process is explained in detail. Second section includes the explanation of the TDE methodology and details its application. Third section addresses why the automotive industry requires prompt actions to determine its R&D activities. Later, some of the state-of-the-art technologies are investigated. Fifth section includes the case study application of the TDE methodology.

As a first step, experts provide inputs to an Delphi questionnaire, which is also explained in details, and define technologies to be assessed. A series of criteria and sub-factors have been defined with the aim to compare the different powertrain systems to identify the best solutions. A specific weight has been assigned to each indicator according to its influence on the barriers encountered during its market introduction.

All technologies are reviewed with respect to these factors and assigned with a "Technology Value" for the related time period. This value marks the improvement of a technology by years and with respect to others.

After the calculation of Technology Values, all the selected powertrain technologies are assessed. Finally, a TDE has been developed for the case study, which will direct the company to its most ideal technology.

GELECEK AKTARMA ORGANLARI TEKNOLOJİLERİNİN BELIRLENMESI ICIN "TEKNOLOJI GELISTIRME ZARFI" METODOLOJISI: FORD OTOSAN YOL HARITASI UYGULAMASI

ÖZET

Sanayi, hükümet ve akademi; teknoloji stratejilerini geliştirmek, Ar-Ge aktivitelerinde boşluk ve fırsatları belirlemek için teknoloji yok haritalarını oluşturmaya başlamışlardır. Otomotiv endüstrisi de, süregelen teknolojik gelişmeler ve iyileşmeler sayesinde şiddetli bir rekabete sahne olmaktadır. Bu rekabet, ilgili şirketlerin kendilerine uygun, devamlı düzenlenebilir ve değiştirilebilir, yani oldukça esnek bir yapıya sahip yol haritalarına sahip olmalarını gerekli kılar.

Bu çalışma gelecek aktarma organları teknolojileri üzerine yoğunlaşarak, en verimli sistemlerin seçilmesi ve en olası bir yol haritasına uygulanmasını hedeflemektedir. Dinamik ve esnek yapısı ile yol haritası yaklaşımını daha uygulanabilir kılan yeni bir metodoloji, Teknoloji Geliştirme Zarfı (TDE) adıyla, örnek vaka olarak seçilen Ford Otosan'ın teknoloji planlama konseptine uygulanmıştır.

Girişin hemen ardından, teknoloji yol haritası oluşturma işlemleri incelenmiştir. Bir sonraki bölümde, ilgili metodoloji ayrıntılarıyla açıklanmıştır. Daha sonra, bu metodolojinin otomotiv endüstrisindeki uygulama sebepleri belirtilmiş ve güncel teknolojiler özetlenmiştir. Bir sonraki bölümde, örnek vaka üzerinden metodoloji uygulanmıştır.

Uygulama adımlarının ilki, karşılaştırılacak teknolojilerin belirlenmesi; hemen ardından, sıralanan bu teknolojileri karşılaştırabilmek için çeşitli kriter ve faktörlerin seçilmesidir. Bu safhalarda, bilgi toplamak için kullanılan Delphi metodu da ayrıntılanmış ve açıklanmıştır. Belirlenen kriter ve ilgili faktörlere gore teknolojiler değerlendirilerek, her bir teknolojinin "Teknoloji Değeri" oluşturulmuştur. Bu değer, bir teknolojinin hem seneler bazında nasıl değişeceğini, hem de diğer teknolojiler ile farkını ortaya koymaktadır.

Seçilen tüm teknolojiler için Teknoloji Değerleri'nin oluşturulmasının ardından, bu değerler kullanılarak teknolojiler değerlendirilmiş ve son olarak, örnek firma için Teknoloji Geliştirme Zarfı oluşturulmuştur. Oluşturulan bu grafiğe göre ilgili firma, gelecekte kendisi için izlemesi en uygun yolu belirleyebilir.

1. INTRODUCTION

Energy consumption in the developing world has grown far more rapidly over the last twenty years According to World Energy Outlook (WEO) 2007, with the emerging giants such as India and China, if governments around the world stick with current policies the world's energy needs would be well over 50% higher in 2030 than today. China and India together account for 45% of the increase in demand in this [1]. Global oil demand, which continues to form the largest component of total energy demand, is expected to show a similar increasing pattern. Growing demand will be overwhelmingly (84%) met by fossil fuels, while greenhouse gas emissions will rise by 57%, with the United States, China, India, and Russia contributing two-thirds of the increase.

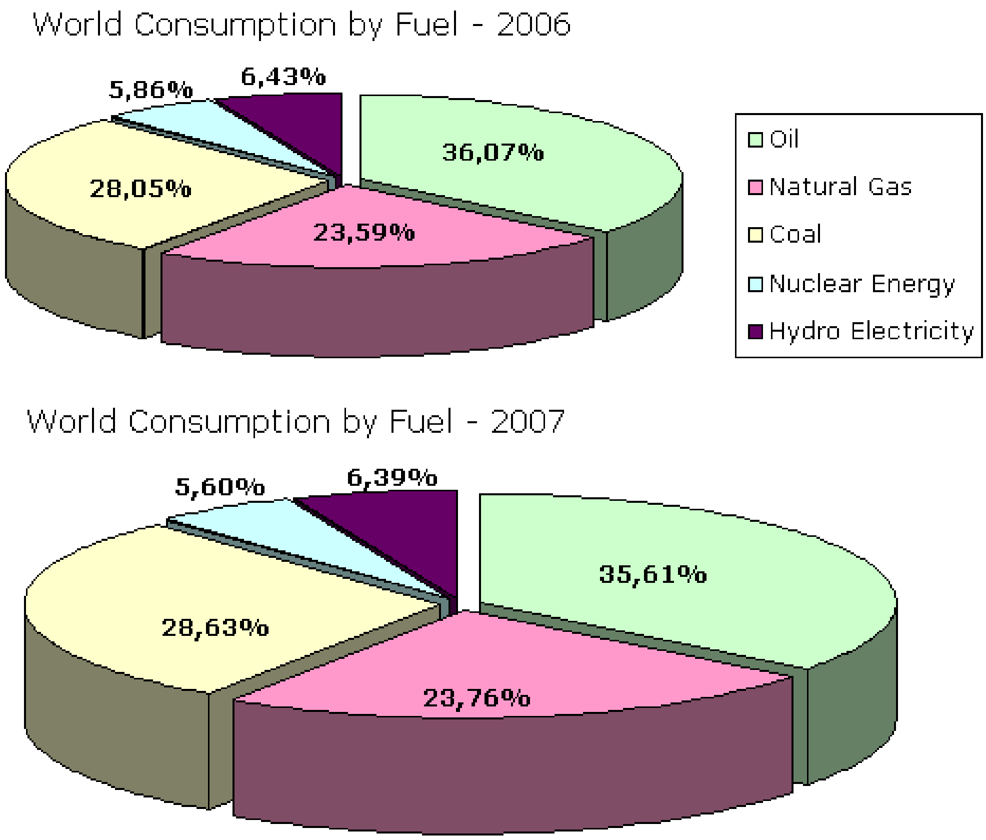

Figure 1.1 : World fuel consumption according to WEO 2007

Because of dependence on fossil fuels, the ever-increasing energy demand will eventually lead to a change in world's oil supplies. In 1956, Peak oil theory was created stating that in time, the maximum rate of global petroleum extraction will be reached, after which the rate of production enters terminal decline [2]. The logistic model, now called Hubbert peak theory, and its variants have been shown to be descriptive with reasonable accuracy of the peak and decline of production from oil wells, fields, regions, and countries [3].

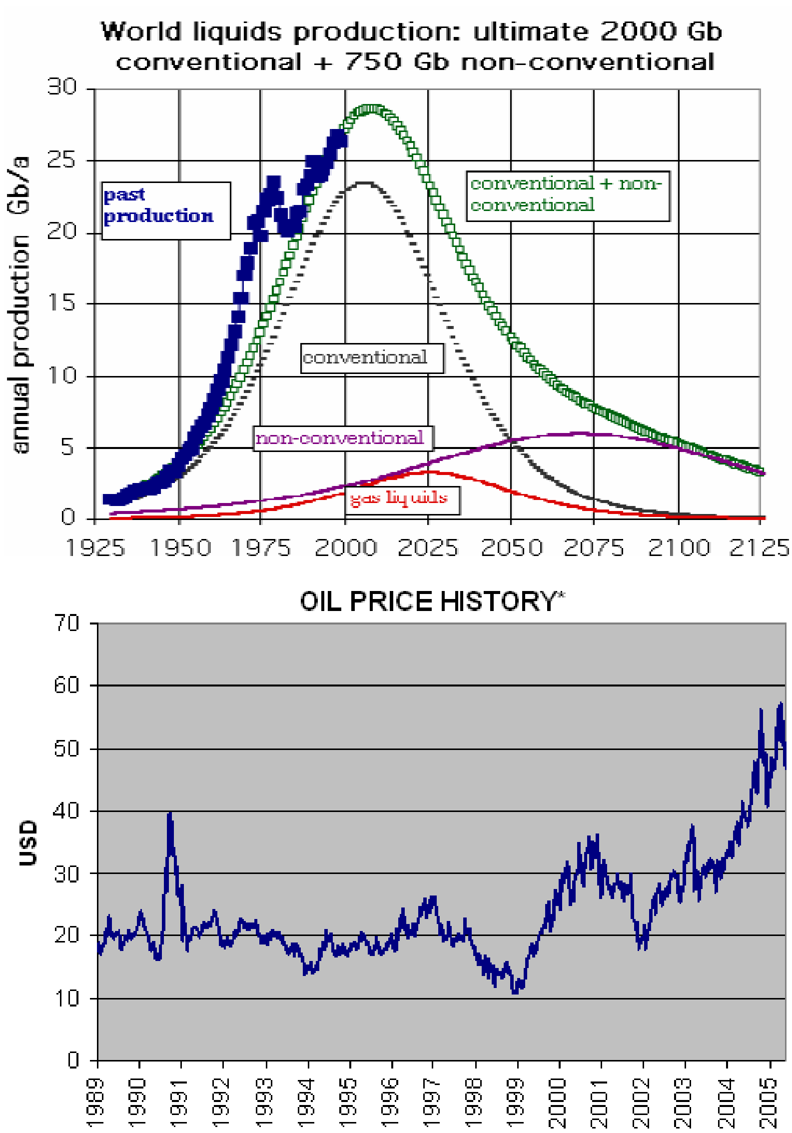

Figure 1.2 : World oil production is projected to peak [4]

Some observers believe the high dependence of most modern industrial transport, agricultural and industrial systems on the relative low cost and high availability of oil will cause the post-peak production decline and possible severe increases in the price of oil to have negative implications for the global economy.

Wide use of fossil fuels in internal combustion engines also causes air pollution and risks human health, because of emitting pollutants. Air pollutants like CO, NOx, etc. can be toxic and pose a threat at even very low levels. In addition, greenhouse gases released into the atmosphere directly affects global warming. The regulations of European Union on motor vehicle emissions force car manufacturers to develop new technologies reducing undesired vehicle emissions. Moreover, market competition due depleting fossil fuel resources, forces car manufacturers search for ways of improving engine efficiency or adopting new technologies while staying within the limits stipulated by the legislated standards. Figure 1.3 shows the regulations getting more stringent with every passing year.

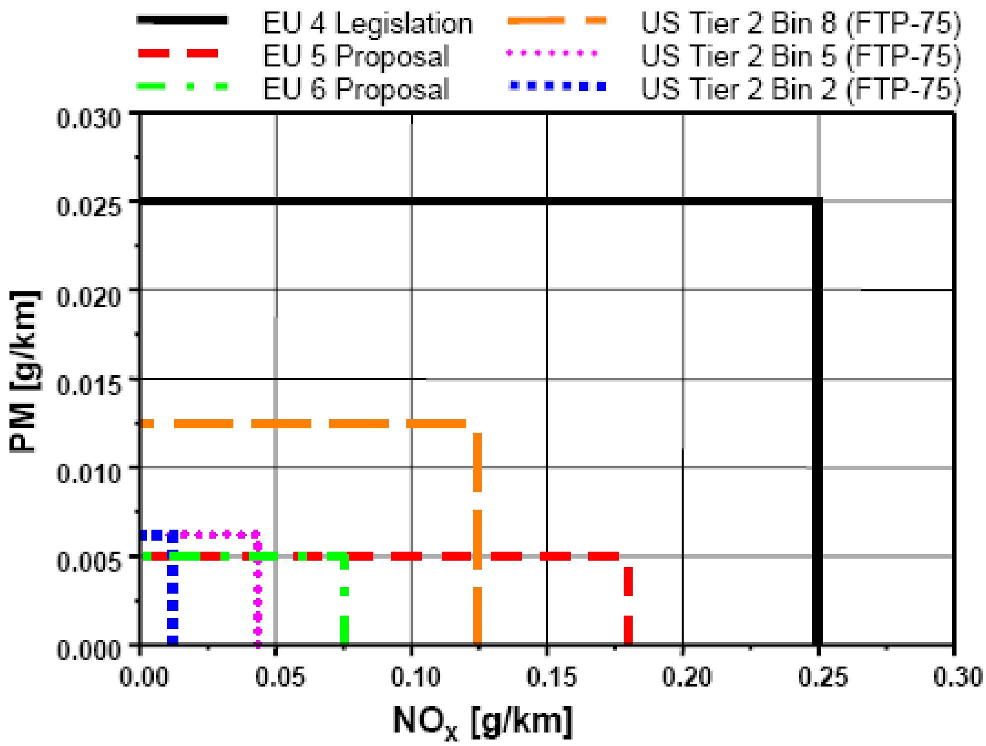

Figure 1.3 : Emission regulations for diesel passenger cars

Current studies indicate that radiative forcing by greenhouse gases is the primary cause of global warming [5,6]. According to these studies, the greenhouse effect, which is the warming produced as greenhouse gases trap heat, plays a key role in regulating Earth's temperature. CO_2 production from increased industrial activity and other human activities such as cement production and tropical deforestation has increased the CO_2 concentrations in the atmosphere [7].

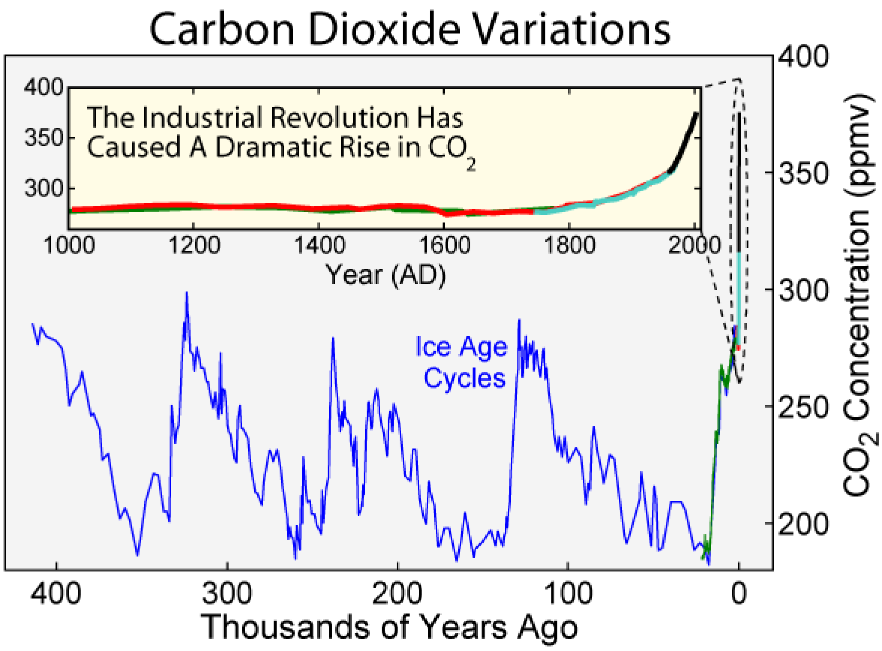

Figure 1.4 : Changes within atmosphere due to CO_2 emissions

In general, increases in developing-country energy demand have been underpinned by growth in population, in economic activity and in per capita incomes; and underlying the growth in economic output has been rapid expansion in industrial activity. Combined with the increasing rates of urbanization evident throughout the developing world, these factors have led to sharp increases in the demand for motorized transport. In most countries, the growth in energy demand has outpaced that of GDP, leading to increases in aggregate energy intensities.

Automotive industry is going through difficult times, as radical changes are expected in order to overcome above problems. Therefore, it is very important for a company to review their positions and form a strategy to decide how to act on future necessities.

1.1 Purpose of the Thesis

This purpose of this thesis is to carry out a roadmapping methodology for automotive industry, with respect to future powertrain systems. This methodology will create a roadmap for the case study company and any other similar company, and due to its flexible nature, it has a chance to be reviewed and changed continuously and quickly. As a result, several future powertrain technologies will be evaluated, and their technological value with respect to several criteria and factors will be calculated.

1.2 Technology Planning Background

There are many published definitions of ‘technology’. Examination of these definitions highlights a number of factors that characterize technology, which can be considered as a specific type of knowledge. The key characteristic of technology that distinguishes it from more general knowledge types is that it is applied, focusing on the ‘know-how’ of the organization. While technology is usually associated with science and engineering, the processes that enable its effective application are also important - for example new product development and innovation processes, together with organizational structures and supporting knowledge networks.

Similar to ‘technology’, there are many definitions of ‘technology management’ in the literature. For the purposes of this study, definition is adopted, proposed by the European Institute of Technology Management (EITM) [8]:

"Technology management addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies (product, process and infrastructural) needed to maintain a market position and business performance in accordance with the company’s objectives".

Technology Management, as defined by Floyd [9], is set of management disciplines that allow organization to manage its technological fundamentals to create competitive advantage. Typical concepts used in technology management are technology strategy (a logic or role of technology in organization), technology mapping (identification of possible relevant technologies for the organization), technology roadmapping (a limited set of technologies suitable for business), technology project portfolio (a set of projects under development) and technology portfolio (a set of technologies in use).

Role of technology management function in organization understands the value of certain technology for the organization. Continuous development of technology is valuable as long as there is a value for the customer and therefore technology management function in organization should be able to argue when to invest on technology development and when to withdraw.

Whipp, Steele and Roussel [10-12] also define technology Management as the integrated planning, design, optimization, operation and control of technological products, processes and services, a better definition would be the management of the use of technology for human advantage.

Perhaps the most authoritative input to our understanding of technology is the diffusion of innovations theory developed in the first half of the twentieth century. It suggests that all innovations follow a similar diffusion pattern - best known today, as described by Bowen [13], in the form of an "s" curve though originally based upon the concept of a standard distribution of adopters. In broad terms, the "s" curve suggests four phases of a technology life cycle - emerging, growth, mature and aging, as seen on Figure 1.5.

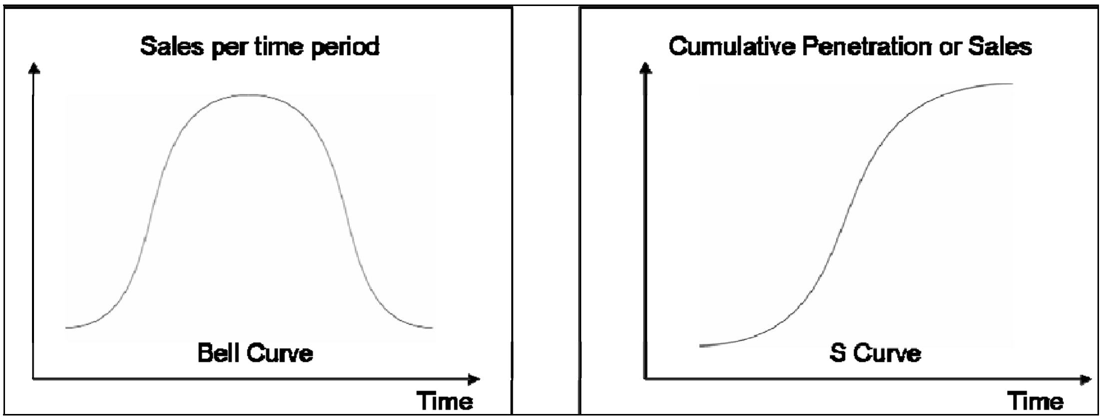

Figure 1.5 : The adoption curve becomes an s-curve.

1.2.1 Technology Roadmapping

In order for companies to face fierce competitive problems, it is highly important to depend on technology management and planning [14]. When a project is initiated, it is crucial to decide which of the relevant and available technologies to employ. In addition to technological choices made for the project itself, it may be necessary to forecast the technologies with which our technological choices and our project results will interact. Our systems must be reasonably compatible with those in the environment that do or will exist across their expected life.

Both reasons for forecasting technology go beyond the obvious need to plan for the technological future. Such planning may or may not be the subject of a special project. For many organizations, technological planning is an ongoing function of management. Nevertheless, whether planning is done as a routine or on a project basis, technological forecasting is required [15].

The generic roadmap is a time-based chart, comprising a number of layers that typically include both commercial and technological perspectives. The roadmap enables the evolution of markets, products and technologies to be explored, together with the linkages between the various perspectives.

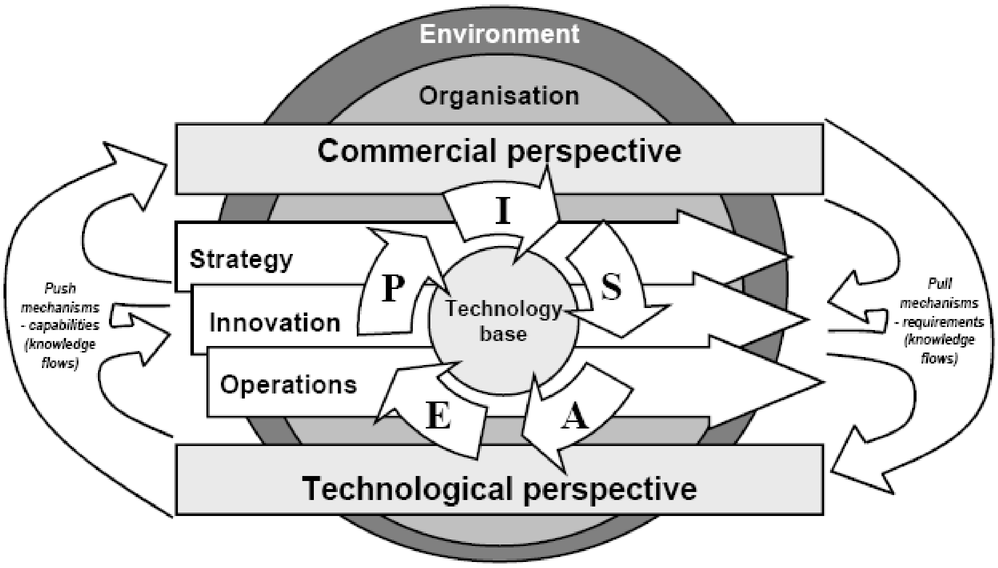

Figure 1.6 : Technology management framework

Phaal et al. [16] describes technology roadmapping as a needs-driven technology planning process to help, identify, select, and develop technology alternatives to satisfy a set of product needs. It brings together a team of experts to develop a framework for organizing and presenting the critical technology-planning information to make the appropriate technology investment decisions and to leverage those investments.

Given a set of needs, the technology roadmapping process provides a way to develop, organize, and present information about the critical system requirements and performance targets that must be satisfied by certain periods. It also identifies technologies that are to be developed to meet those targets. Finally, it provides the information needed to make trade-offs among different technology alternatives.

Roadmapping can be done at either of two levels, industry or corporate. These levels require different commitments in terms of time, cost, level of effort, and complexity. However, for both levels the resulting roadmaps have the same structure although with different levels of detail. Technology roadmapping within a national laboratory is essentially corporate-level roadmapping, although a national laboratory may participate in an industry roadmapping process.

At both the individual corporate and industry levels, technology roadmapping has several potential uses and resulting benefits. First, technology roadmapping can help develop a consensus about a set of needs and the technologies required to satisfy those needs. Second, it provides a mechanism to help experts forecast technology developments in targeted areas. Third, it can provide a framework to help plan and coordinate technology developments within both a company and an entire industry.

The main benefit of technology roadmapping is that it provides information to help make better technology investment decisions. First, identifying critical technologies or technology gaps that must be filled to meet product performance targets. Finally, ways to leverage R&D investments through coordinating research activities either within a single company or among alliance members must be identified.

An additional benefit is that as a marketing tool, a technology roadmap can show that a company really understands customer needs and has access to or is developing the technologies to meet their needs. Industry roadmaps may identify technology requirements that a company can support.

Science and technology roadmapping provides several benefits [17]:

- Clearly defines the technical risks associated with the project or program baseline,
- Develops a vision and consensus among science and technology users, providers and management about the capabilities needed to most effectively accomplish baselines and the knowledge and technologies required to satisfy those needs,
- Develops a consensus forecast among science and technology users and management for developments in targeted areas,

- Provides a framework to plan and coordinate science and technology developments within a project or program.

A recent survey by Phaal and Farrukh [18] of 2,000 UK manufacturing firms indicates that about 10% of companies (mostly large) have applied the technology roadmapping approach, with approximately 80% of those companies either using the technique more than once, or on an ongoing basis. However, application of the TRM approach presents considerable challenges to firms, as the roadmap itself, while simple in structure and concept, represents the final distilled outputs from a strategy and planning process. Key challenges reported by survey respondents included keeping the roadmapping process 'alive' on an ongoing basis (50%), starting up the TRM process (30%), and developing a robust TRM process (20%).

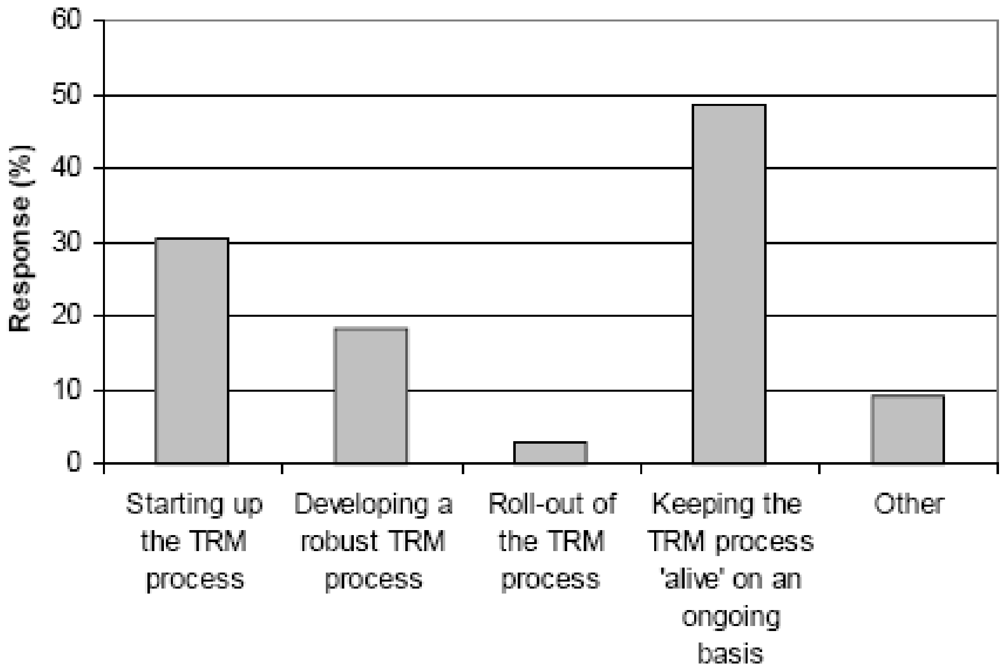

Figure 1.7 : Key technology roadmapping challenges

Several companies may struggle with the application of roadmapping since there are many specific forms of roadmap, which often have to be tailored to the specific needs of the firm and its business context. Furthermore, there is little practical support available and companies typically re-invent the process, although there have been some efforts to share experience.

Factors that contribute to successful technology roadmapping are shown in Figure 1.8 below, as described by Gerdsri and Rinne [17]. Factors that are particularly important for successful roadmapping include a clearly articulated business need, the desire to develop effective business processes, having the right people involved and commitment from senior management.

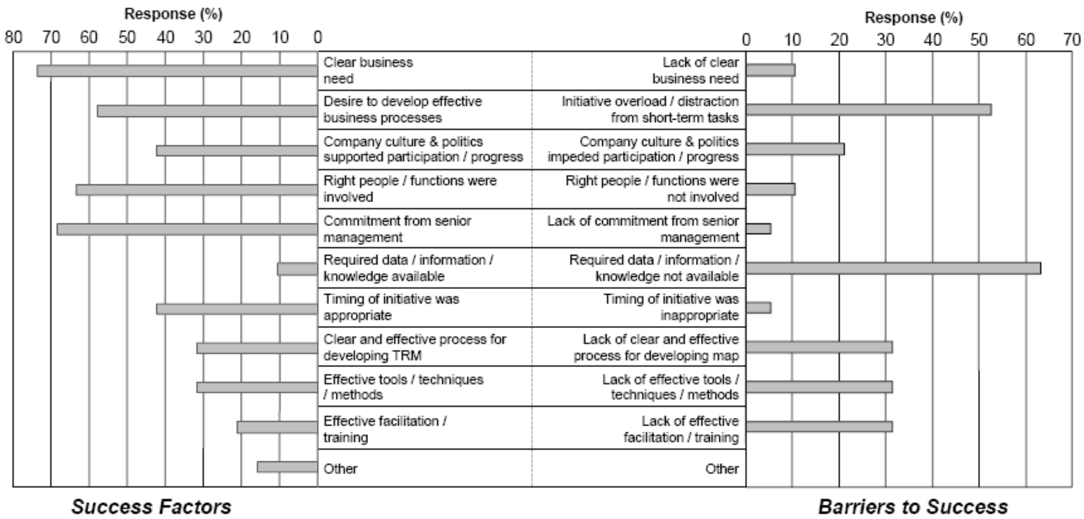

Figure 1.8 : Roadmapping success factors and barriers to success

The technology roadmapping approach is very flexible, and the terms ‘product’ or ‘business’ roadmapping may be more appropriate for many of its potential uses. Examination of a set of approximately 40 roadmaps has revealed a range of different aims, clustered into the following eight broad areas, based on observed structure and content.

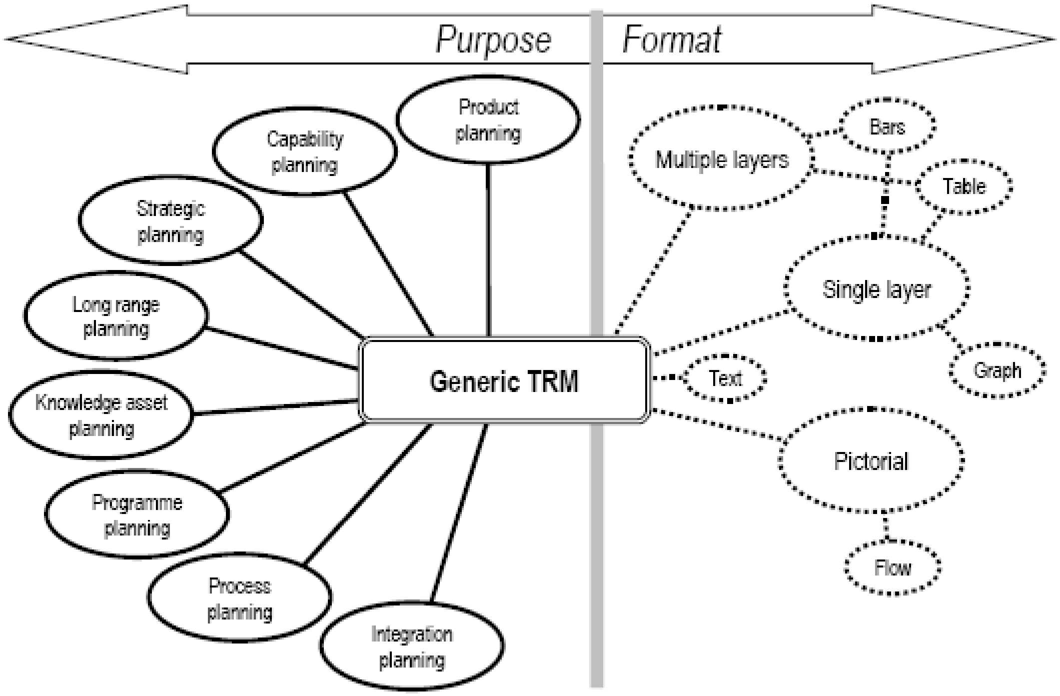

Figure 1.9 : Characterization of roadmaps

1.2.2 Key requirements for roadmap construction

According to Phaal and Gerdsri [16-18], from the preceding discussion of the functions of technology roadmaps, a number of key requirements emerge. The following list provides a starting point for addressing current shortcomings and for anticipating requirements for the more advanced functions of roadmaps such as virtual innovation and innovation factories.

Persistence: Roadmap elements and their attributes and relationships must be persisted. All other aspects of roadmap construction presuppose it and virtual innovation requires it. Without persistence of roadmap elements, technologies and products that are envisioned, but not developed, cannot influence further envisioning.

Manipulation: Manipulation ranks right after persistence as an enabler of roadmapping. It simplifies updating and maintaining roadmaps.

Collaboration: With persistence and manipulation, roadmaps would become robust technology management tools within a small circle of developers. In its most primitive form, collaboration would enable different users to manipulate the same roadmap. At the very least, this would require roadmapping tools to negotiate concurrent changes to roadmaps much like simultaneous access to databases. For large-scale collaborations and cases where collaborators do not wish to share entire roadmaps, various messaging schemes can facilitate the exchange of roadmap elements.

Integration and Cohesion: Perhaps an outcropping of collaboration, roadmap integration stresses the need to bring elements from different roadmaps together. The objective of integration is to widen the field by drawing in otherwise unrelated technologies. The ultimate expression of roadmap integration would take the form of seamlessly linked roadmaps that connect to all the other roadmaps. Such an integrated roadmap would be particularly useful for searching for new disruptive technologies.

Metrics: One of the challenges of technology roadmaps is to develop measures of the value of different nodes and paths on the technology roadmap. Metrics are of particular importance for technology selection. Technology providers would like to know which product path provides the greatest benefit for their business.

Organization: Technology roadmaps are organized from the perspective of the creators and users of the roadmap. Even a collaborative roadmap reflects the, albeit aggregated, perspective of its users. Metrics that valuate paths through a roadmap still reflect the valuations of users, organizations, and so on, individually or taken together. If the metrics inform the organization of the roadmap, that organization is still imposed externally. At the same time, especially the larger technology roadmaps convey a sense of the emergence of technologies. In fact, large roadmaps can show regularities that reflect some of the patterns of the evolution of products and technologies. One such pattern is the growth of sustaining technologies that is punctuated by the rise of disruptive technologies. If the technology and product elements of roadmaps were aware of these patterns, they could contribute another dimension to the organization and structure of roadmaps. In fact, if products and technologies adjusted their own relationships according to such patterns, the resulting technology roadmaps would show a degree of self-organization.

1.2.3 Technology roadmapping process

Technology roadmapping is an iterative process that fits within the broader corporate strategic planning, technology planning, and business development context. Planning activities must link three critical elements; customer/market needs, products/services, and technologies. The corporate vision drives the strategic planning effort, which generates high-level business goals and directions. Given a corporate vision, strategic planning involves decisions that identify and link at a high level the customer/market needs a company wants to address and the products and services to satisfy those needs. Given this strategic plan, technology planning involves identifying, selecting, and investing in the technologies to support these products and service requirements. Business development involves planning for and implementing certain aspects of the strategic plan, specifically those involving the development of new products and services and/or new lines of business. Figure 1.10 summarizes the steps of the technology roadmapping process.

Phase I. Preliminary activity

1. Satisfy essential conditions.
2. Provide leadership/sponsorship.
3. Define the scope and boundaries for the technology roadmap.

Phase II. Development of the Technology Roadmap

1. Identify the "product" that will be the focus of the roadmap.
2. Identify the critical system requirements and their targets.
3. Specify the major technology areas.
4. Specify the technology drivers and their targets.
5. Identify technology alternatives and their time lines.
6. Recommend the technology alternatives that should be pursued.
7. Create the technology roadmap report.

Phase III. Follow-up activity

1. Critique and validate the roadmap.
2. Develop an implementation plan.
3. Review and update.

Figure 1.10 : The three phases in the technology roadmapping process [19]

To summarize, there is a wide range of research available on technology forecasting and roadmapping as well as many industrial roadmaps [20-29]. Furthermore, most forecasting and assessment methods, such as Delphi, are investigated thoroughly [30-32]. However, there are only a limited number of studies concentrating on combining Delphi forecasting method and technology roadmapping for technologic forecasting.

Furthermore, in most of the studies, technology forecasting is usually focused on existing technologies and not on emerging technologies [33-35]. According to Walsh [36], it should be noted that it is rather difficult to gather information on emerging technologies, especially when both quantitative and qualitative measures must be included in the study. Therefore, another approach is required to conduct a roadmap.

Phall [36] states that current roadmaps on automotive industry focus on general aspects of the future technologies and reflect an overall evaluation.

During the constitution of a product or an industry roadmap, the work is carried out either by colleagues within a company or external technology developers across industries. However, as Gerdsri [37] discussed, it is highly important to form a link between both external and internal technology developers and researchers.

Roadmaps are stationary by nature and need to be re-constructed each time a change is required. However, it is highly important for a company to keep the roadmap dynamic and ready to change accordingly. Therefore, it is crucial to "keep the roadmap alive", as Gerdsri [39] defines in another study.

It also should be noted that even though almost every transport industry player has already constituted their roadmaps, a flexible and dynamic roadmap created by technology developer and technology implementer experts on emerging powertrain technologies has never been studied before.

All these roadmapping gaps require a more flexible approach that can evaluate emerging technologies by gathering data from both technology developers and technology implementers.

Therefore, a new methodology called Technology Development Envelope is introduced [37-39].

2. TECHNOLOGY DEVELOPMENT ENVELOPE METHODOLOGY

TDE is a new concept and methodology for identifying the optimum path in developing technology strategies and combining them with business strategies and/or policy decisions [37-38].

TDE helps companies to identify emerging technologies, evaluate the value of those technologies with respect to the organization's objective. As Gerdsri describes, the connection of technologies from one period to the next results the technology development path, containing technologies with the highest value in each period is considered as TDE [38]. Once the best path is identified, it can be used to structure the technology elements in a roadmap, making it more flexible and alive.

The TDE framework is structured by obtaining strategic information on the development of technologies and then using this information to evaluate the value of each technology based on the impacts of its characteristics on the organization's objective in each period. A technology development envelope is formed by connecting technologies that have the highest value in each period throughout the specified period.

As shown in Figure 2.1, development of a TDE framework can be summarized in 3 phases:

- Gathering strategic information on the development of emerging technologies from experts,
- Evaluation of emerging technologies through a generalized hierarchical model in which contributions of each technology to company objective are calculated by different values that are determined through a series of pair-wise judgment quantifications,
- Formation of TDE from the graphical results of emerging technologies and creating connecting lines between those to represent technology development paths.

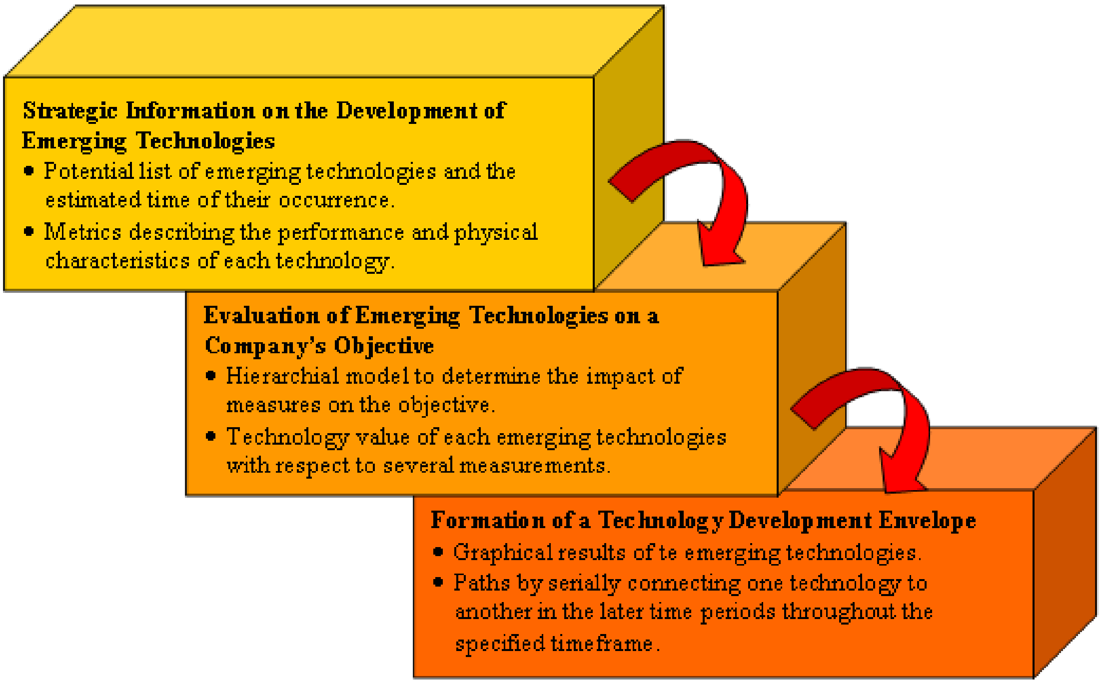

Figure 2.1 : TDE Framework

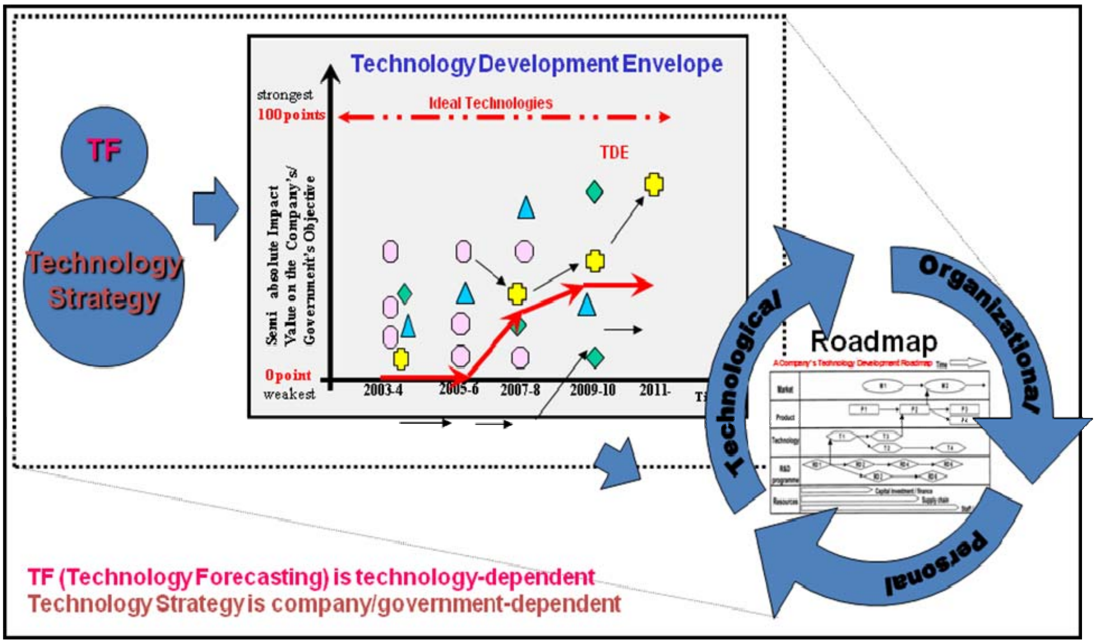

Figure 2.2 : TDE Hierarchical Model [37]

The methodology involves forecasting, identification, assessment, evaluation and selection of emerging technologies. In order to develop a methodology to build a TDE, with its hierarchical model is shown in Figure 2.2; a research objective should be selected by fulfilling five research goals. Table 2.1 explains the overall reconstructing questions of the TDE model.

Table 2.1 : Research goals and questions to fulfill research objective

QUESTIONS TO BE ANSWERED	RESEARCH GOALS	
Trends of emerging technology development in the industry?	RG1:	Developing a forecasting model for identifying the trends of emerging technologies
Significant criteria and technology factors to satisfy the objective?	RG2:	Developing a judgment quantification model for measuring the relative impact of measures of effectiveness on the objective
Measures of effectiveness applied to each factor?		
Relative priority of each criterion?		
Relative importance of each technological factor under each criterion?		
Assessment of emerging technologies based on their measures of effectiveness?	RG3:	Assessing technological factors of each emerging technology
Evaluation of emerging technologies in terms of relative impacts of their measures of effectiveness?	RG4:	Evaluating technological factors
Creation of a technology development envelope?	RG5:	Constructing the technology development envelope
Constructing the paths of technology development?		

The development of a TDE is designed to be completed through six model development steps: technology forecasting, technology characterization, technology assessment, technology evaluation, hierarchical modeling and formation of technology development envelope [38]. The flow of information to the model and within the model is shown in the Figure 2.3, while each step is summarized in Table 2.2.

Table 2.2 : Summarizing each step to achieve research objective [38]

RESEARCH OBJECTIVE		
Step 1:	**Technology Forecasting**	Develop a forecasting model using Delphi for identifying the trend of emerging technologies
Step 2:	**Technology Characterization**	Identify criteria and technological factors satisfying a company's objective
Step 3:	**Technology Assessment**	Assess emerging technologies based on the measures of effectiveness
Step 4:	**Hierarchical Modeling**	Develop a hierarchical model to determine the relative impact of measures of effectiveness on a company's objective
Step 5:	**Technology Evaluation**	Evaluate the impact of emerging technologies on a company's objective by using the semi-absolute value
Step 6:	**Formation of TDE**	Construct the technology development envelope and technology development paths

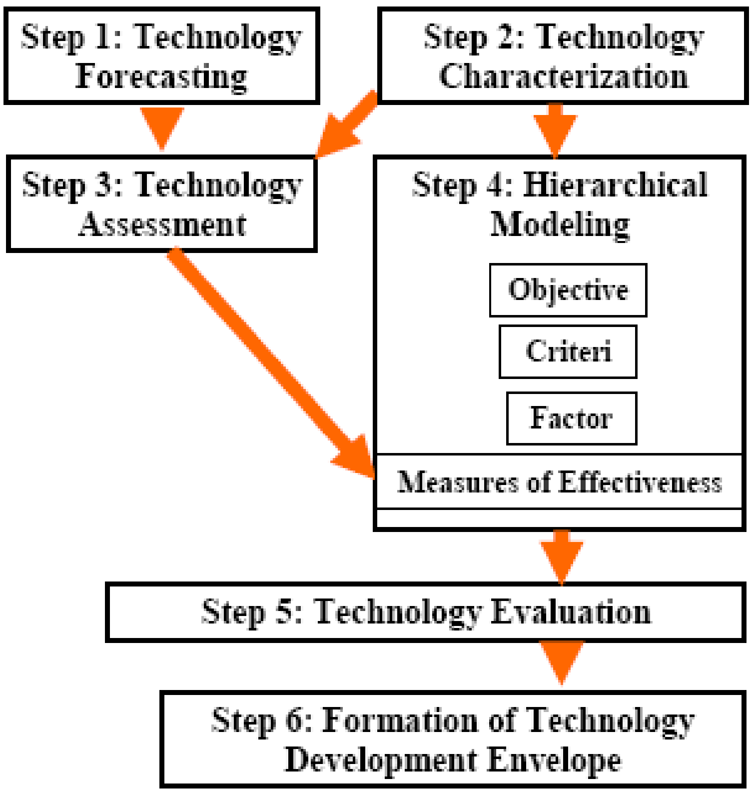

Figure 2.3 : Flowchart representing the six model development steps [38]

2.1 Technology Forecasting

The main purpose of this step is to forecast the future trend of emerging technologies and to define the timing of their occurrences. Emerging technologies, in definition, represent new and significant developments within a field. It is a general term used to denote significant technological developments that in effect, broach new territory in some significant way. Due to unavailability of strategic information, it is always challenging to obtain data on emerging technologies. Therefore, forecasting methods should be applied in order to derive reliable information. In this study, Delphi method has been selected to overcome this challenge and receive data on both quantitative and qualitative aspects of the technologies.

Delphi may be characterized as a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem. The most common Delphi is commonly referred to as a "Delphi Exercise." In this situation, a small monitor team designs a questionnaire, which is sent to a larger respondent group. After the questionnaire is returned the monitor team summarizes the results and, based upon the results, develops a new questionnaire for the respondent group. The respondent group is usually given at least one opportunity to reevaluate its original answers based upon examination of the group response. [40]

The Delphi method allows experts to deal systematically with a complex problem or task. The essence of the technique is straightforward. It comprises a series of questionnaires sent to a pre-selected group of experts. These questionnaires are designed to elicit and develop individual responses to the problems posed and to enable the experts to refine their views as the group's work progresses in accordance with the assigned task. The group interaction in Delphi is anonymous, in the sense that comments, forecasts, and the like are not identified as to their originator but are presented to the group in such a way as to suppress any identification. Anonymity, controlled feedback and statistical response are the main characteristics that identify Delphi method [41].

Fowles [41] describes the following ten steps for the Delphi method:

1. Formation of a team to undertake and monitor a Delphi on a given subject,
2. Selection of one or more panels to participate in the exercise. Customarily, the panelists are experts in the area to be investigated,
3. Development of the first round Delphi questionnaire,
4. Testing the questionnaire for proper wording,
5. Transmission of the first questionnaires to the panelists,
6. Analysis of the first round responses,
7. Preparation of the second round questionnaires (and possible testing),
8. Transmission of the second round questionnaires to the panelists,
9. Analysis of the second round responses,
10. Preparation of a report by the analysis team to present the conclusions of the exercise.

In this study, expert opinions were obtained from separate expert panels; such as universities (Istanbul Technical University, Sakarya University, Boğaziçi University, etc.), a research center (TUBITAK) and industry (Ford Otosan, Ford Motor Company, etc). The experts can be grouped into two, technology developers and technology implementers. Throughout the study, expert opinion is required through Step 1 to Step 4. During these steps, technology developers are responsible from identifying a list of emerging technologies with the expected timing of their occurrence and to provide the measures of effectiveness of each emerging technology; while technology implementers are responsible from identifying a set of criteria and the technological factors associated with each criterion, to satisfy the objective of achieving technological competitiveness.

They determine the relative importance of criteria, the relative impact of technological factors on each criterion, and the relative impact of measures of effective on each technological factor.

For the technology forecasting step, two sets of Delphi process is conducted. In round one, the experts are asked to modify the pre-developed list and the definition of emerging technologies which will be available during the pre-determined time scale and then to estimate their timing of occurrences. In round two, the experts are asked to verify and modify their first round results, as appropriate, with the explanation of their response.

The results of this step are the list of potential technologies and their timing presented in the time-series format called technology development profile (TDP) [37].

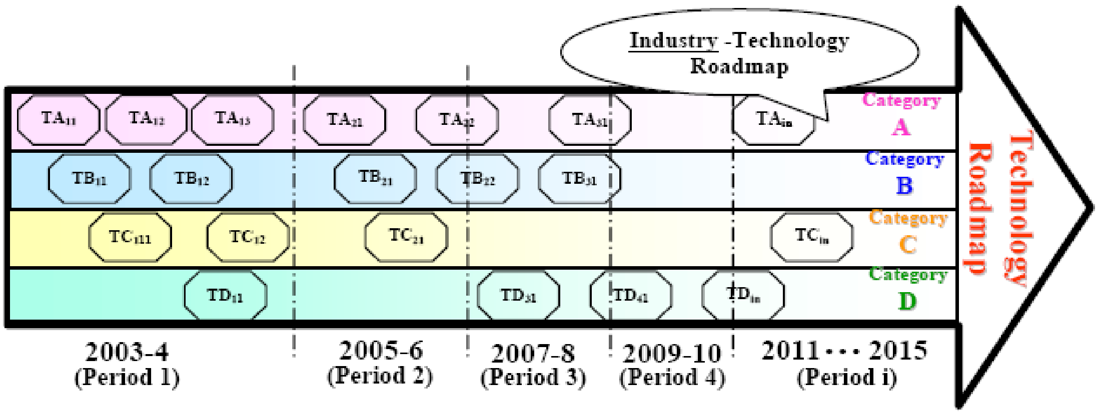

Figure 2.4 : Technology Development Profile constituted by expert opinions

Figure 2.4 explains the constitution of an TDP, where TA_{in} indicates the occurrence of technology "n" categorized in group "A" and estimated to be available in the period "i" and TB_{in} indicates the occurrence of technology "n" categorized in group "B" and estimated to be available in the period "i".

2.2 Technology Characterization

The main objective of this step is to define and verify the company's objective for evaluating technologies and to identify the criteria and technological factors that satisfy the company's objective. It is highly important to align the objective with the company's strategy. The expert panel is asked to modify the pre-identified list of criteria and technological factors associated with each criterion to satisfy the objective of achieving technological competitiveness. The group is also asked to define the measures of effectiveness used to directly measure the contribution of emerging technologies according to each technological factor.

The process can be summarized as below:

1. Defining the company objective according to the company strategy (by expert opinion)
2. Identifying criteria to evaluate the emerging technologies in accordance with the company objective.
3. Identifying technological factors under each criterion to directly measure the contribution of each technology.
4. Obtaining quantitative and qualitative parameters for each factor, either acquiring the numerical values or by defining a 5 point scale, depending on the means used in measuring the contribution of technologies toward factors.
5. Defining the measures of effectiveness used to directly measure the contribution of emerging technologies according to each technological factor.

The identification of components placed in the criteria and technological factors level is accomplished based on the focus of their preferential independence even though some components may share their technical dependency.

2.3 Technology Assessment

In this step, emerging technologies are assessed based on the measures of effectiveness. The experts are asked to provide the values of the measures of effectiveness of each emerging technology with which they are familiar according to the technological factors. Since technological factors can be classified as qualitative or quantitative parameters, the contribution of each technology toward factors could be subjectively or objectively measured.

Technology 1:						
Criteria	Factors	Units	2008-2015	2015-2025	2025--	Comments
C1	F11:					
	F21:					
	F31:					
	F41:					
C2	F12:					
	F22:					
	F32:					
	F42:					
	F52:					

Figure 2.5 : Evaluation of each technology according to criterion and factors

Figure 2.5 shows a base excel chart to send to the expert for technology assessment based on their measures of effectiveness with respect to criterion and their respective factors.

For the evaluation of emerging technologies, the relative impact values of technologies on the objective are calculated by determining the criterion priorities, the relative importance of factors on each criterion, and the relative impact of technologies on each factor.

Technology assessments address the improvement of the technological characteristics over time.

2.4 Hierarchical Modeling

For this step, a hierarchical model is developed to determine the relative impact of measures of effectiveness on a company's objective. A generalized hierarchical model can be constructed with a four-level hierarchy; objective, criteria, factors, and technologies.

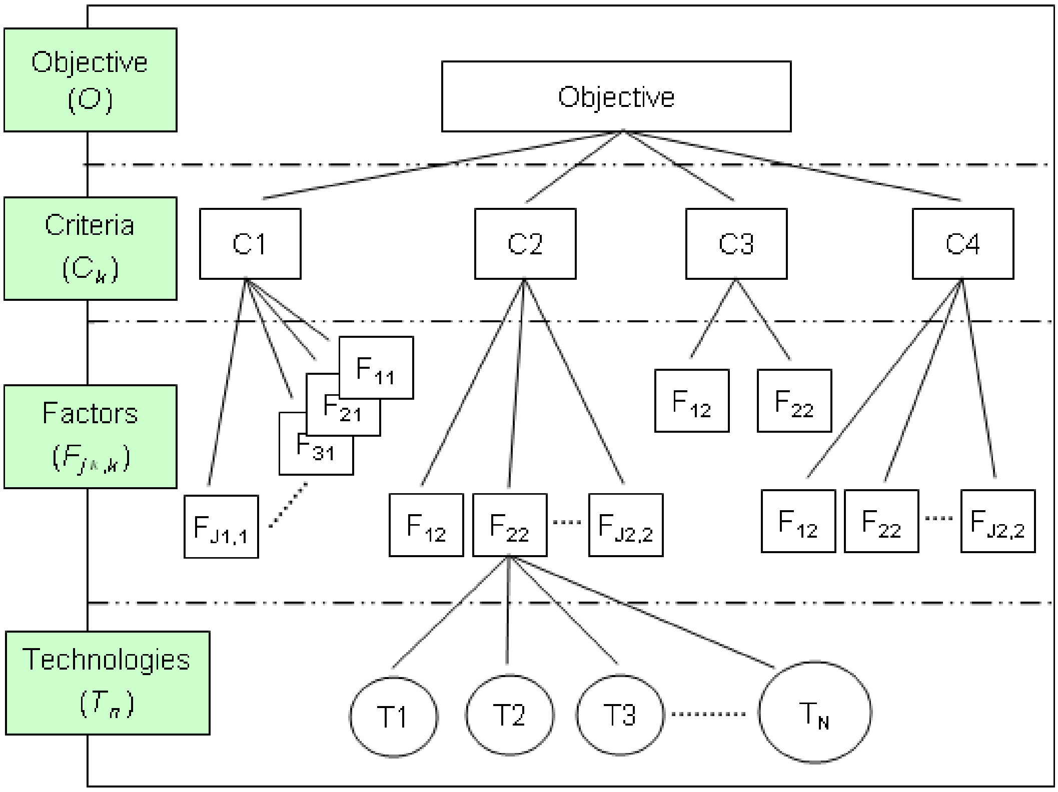

Figure 2.6 : A hierarchical model developed for evaluating emerging technologies

At this point, the reason to choose a hierarchical process in this study should be examined. The Analytic Hierarchy Process (AHP) is a structured technique for helping people deal with complex decisions. Rather than prescribing a "correct" decision, the AHP helps people to determine one that suits their needs and wants.

Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem; tangible or intangible, carefully measured or roughly estimated, well or poorly understood, anything at all that applies to the decision at hand.

Once the hierarchy is built, the decision makers systematically evaluate its various elements, comparing them to one another in pairs. In making the comparisons, the decision makers can use concrete data about the elements, or they can use their judgments about the elements' relative meaning and importance. It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations.

The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another in a rational and consistent way. This capability distinguishes the AHP from other decision making techniques [42].

In the final step of the process, numerical priorities are derived for each of the decision alternatives. Since these numbers represent the alternatives' relative ability to achieve the decision goal, they allow a straightforward consideration of the various courses of action [43].

A hierarchical decision model has a goal, criteria that are evaluated for their importance to the goal, and alternatives that are evaluated for how preferred they are with respect to each criterion. The model is shown in Figure 2.7. The goal, the criteria and the alternatives are all elements in the decision problem, or nodes in the model. The lines connecting the goal to each criterion means that the criteria must be pairwise compared for their importance with respect to the goal, as described by Ra [44]. Similarly, the lines connecting each criterion to the alternatives mean the alternatives are pairwise compared as to which is more preferred for that criterion. Thus in the hierarchy that is shown there are six sets of pairwise comparisons, one for the criteria with respect to the goal and 5 for the alternatives with respect to the 5 criteria [45].

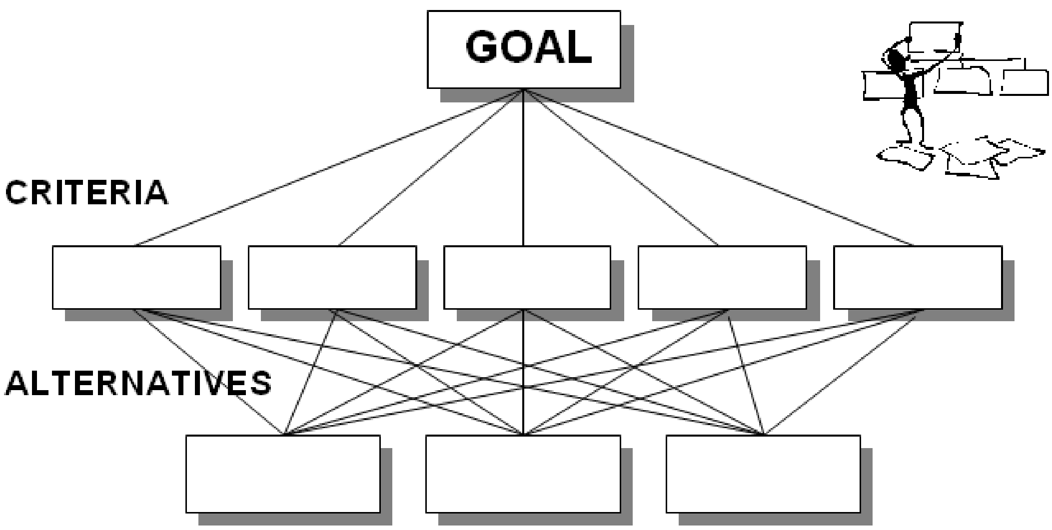

Figure 2.7 : Simplest decision model

The model in Figure 2.6 represents the hierarchical structure in which the relative contributions of technologies to the objective are calculated by determining the priorities of the criteria, the relative importance of factors on each criterion, and the relative impact of technologies on each factor [46]. The relative values of components in a given level are determined through a series of pairwise judgment quantifications with respect to the elements in the next higher level.

With the essence of this research to deal with emerging technologies, this hierarchical model is not appropriate because the comparison process need to be repeated every time new technologies are added. Therefore, the use of a semi-absolute scale was introduced as the alternative approach so that technologies would be evaluated through how much their characteristics value with respect to the measures of effectiveness specifically associated with each factor. In below Figure 2.8, a hierarchical model for determining the relative impact of measures of effectiveness is shown.

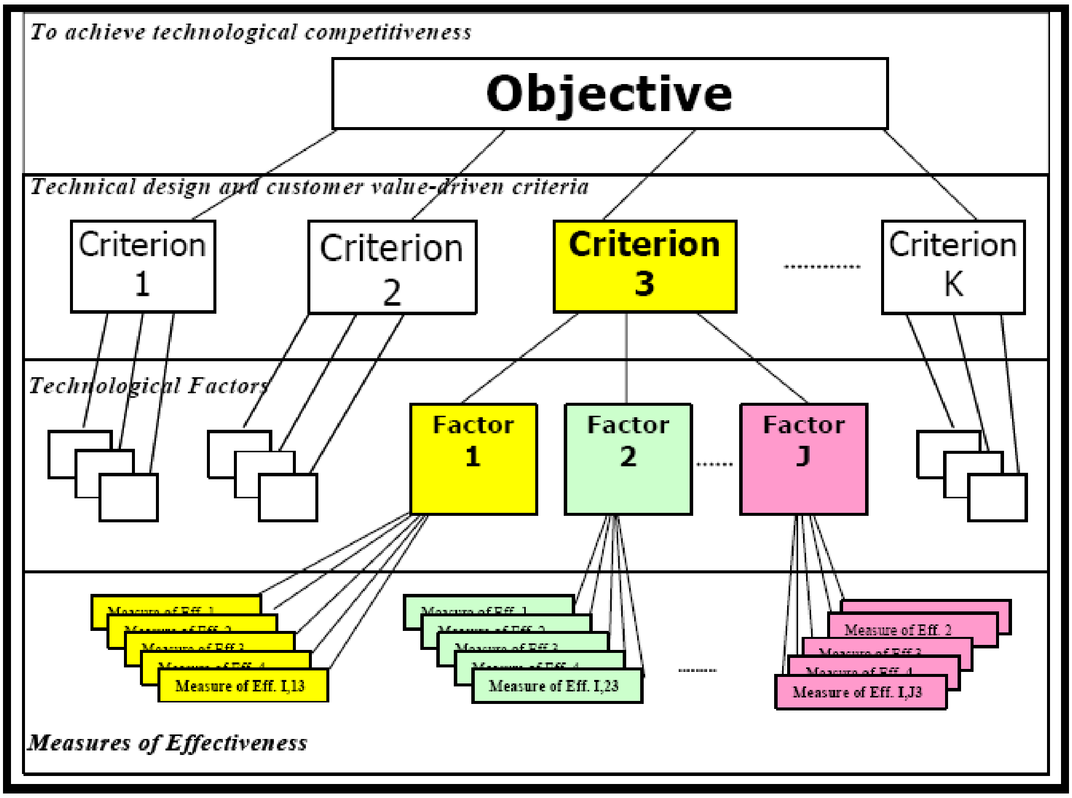

Figure 2.8 : Hierarchical model for determining measures of effectiveness [37]

2.5 Mathematical Model

Even though consisting of a mathematical model is included in Step 4, Hierarchical Modeling, calculations step of this model should be explained thoroughly.

During the development of the hierarchical model, an index called "technology value" is defined. As Gerdsri et al.[47] and Rinne et al. [48] presented, for the hierarchical model in Figure above, the technology value of an emerging technology (*TVn*) can be calculated with the formula below:

$$TVn = \sum_{k=1}^{K} \sum_{k_k=1}^{J_k} w_k \cdot f_{j_k,k} \cdot V\left(t_{n,j_k,k}\right) \quad \textbf{(2.1)}$$

TVn is the technology value of technology (*n*) determined according to a company's objective.

w_k is the relative priority of criterion (*k*) with respect to the company objective.

$f_{j_k,k}$ is the relative importance of factor (j_k) with respect to criterion (*k*).

$t_{n,j_k,k}$ coefficient describes the performance and physical characteristics of technology (*n*) along with factor (j_k) for criterion (*k*).

$V(t_{n,j_k,k})$ is the desirability value of the performance and physical characteristics of technology (*n*) along factor (j_k) for criterion (*k*).

Above formula for measuring the value of emerging technologies, can be estimated by five measurements as described below:

2.5.1 Criteria Evaluation

The mean values among all experts' judgment for each criterion are calculated to represent the group's judgment. Figure 2.9 represents the weight of criteria on a hierarchical model.

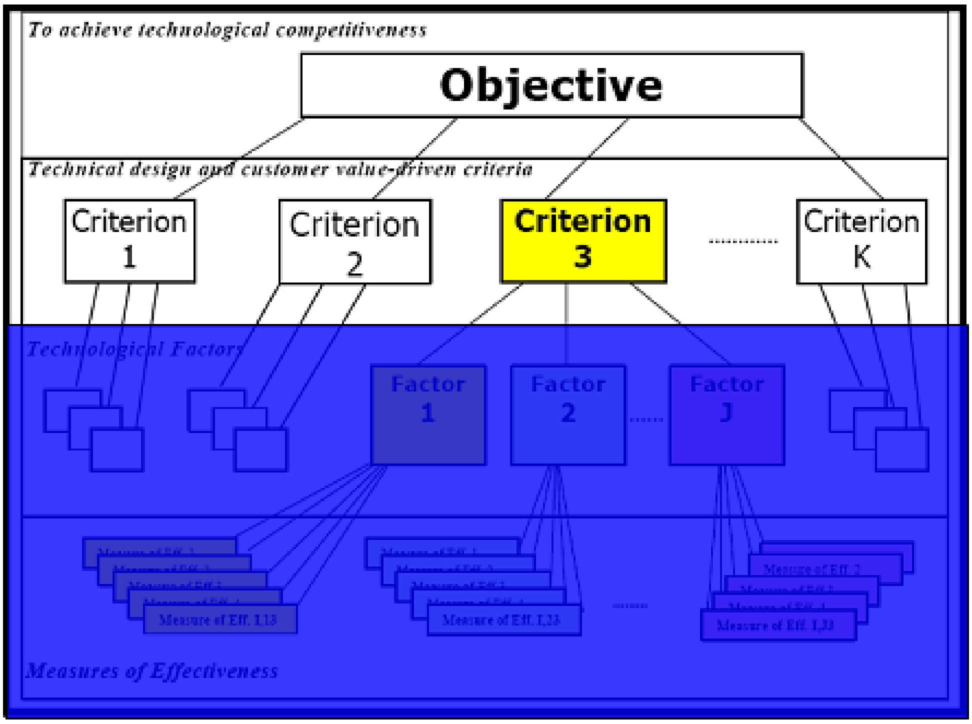

Figure 2.9 : Evaluating the weight of the criteria on a hierarchical model

$$\sum_{k=1}^{K} w_k = 1.0 \text{, where } w_k > 0 \tag{2.2}$$

The series of comparative judgments are obtained from experts through the allocation of 100 points between two criteria at a time. This method is called the Constant-Sum Method [45,46]. The judgments are converted to a normalized measure of relative priority values in ration scale for the criteria.

For example, below table represents the Constant-Sum values showing comparative judgment on each pair of criteria obtained an expert to determine the relative priority of the four criteria.

According to Table 2.3, the relative priority of the seven criteria to which this expert assigned can be determined as in Table 2.4.

Table 2.3 : Example of constant-sum values gathered from one expert

C1	20	C2	40	C3	75
C2	80	C3	60	C4	25
C1	10	C2	60		
C3	90	C4	40		
C1	50				
C4	50				

Table 2.4 : Priority of the four criteria from values gathered from an expert

Criteria	C1	C2	C3	C4	Σ
Relative importance (w_k)	0,13	0,30	0,38	0,19	1,00

By combining the relative priority values given by all experts, the mean value can be calculated to represent the group decision on the relative priority.

2.5.2 Factors Evaluation

For this calculation step, the series of comparative judgments on technological factors with respect to each criterion are obtained and the relative importance of those factors under each criterion is calculated.

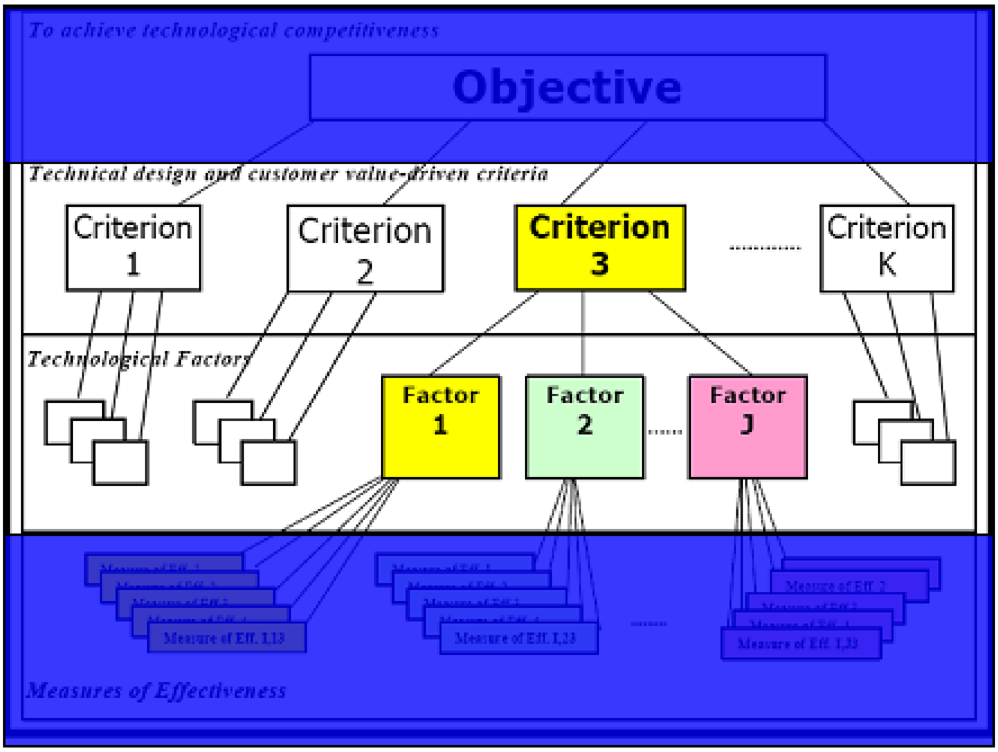

Figure 2.10 : Evaluating the weight of the factors based on criteria

$$\sum_{j_k=1}^{J_k} f_{j_k,k} = 1.0 \quad \text{where,} \quad f_{j_k,k} > 0 \tag{2.3}$$

The relative importance of factors can be calculated by values gathered from experts, or by using the Constant-Sum method applied in criteria evaluation step.

Continuing the example above, below table represents the results for the normalized relative importance of factors under each criterion:

Table 2.5 : Relative importance of factors

Factors under C1	F11	F21	∑		
Rel. Importance	*0,43*	*0,57*	**1,00**		
Factors under C2	F12	F22	F32	∑	
Rel. Importance	*0,12*	*0,46*	*0,42*	**1,00**	
Factors under C3	F13	F23	F33	F43	∑
Rel. Importance	*0,34*	*0,40*	*0,22*	*0,04*	**1,00**
Factors under C4	F14	F24	∑		
Rel. Importance	*0,23*	*0,77*	**1,00**		

2.5.3 Relative Desirability of Measures of Effectiveness

This measurement is required to determine the relative desirability of measures of effectiveness under each combination of factor and criterion. Gerdsri and Kocaoglu [49] explain the process in four steps:

1. Identification of the best and worst limiting metrics that each factor can take on,
2. Identification of the metrics whose desirability is linearly proportional to their numerical value between the two limits,
3. Development of a semi-absolute scale by assigning 0 point to the worst and 100 points to the best limiting metrics under each factor,
4. Calculation of the relative desirability of the intermediate values between the two limits,

$$0 \le V(m_{i_{jk},j_k,k}) \le 100 \tag{2.4}$$

Above formula applies to each factor (j_k) and criterion (k).

There are two approaches to complete the process [49];

1. If a characteristic of a factor can be verified as a linearly proportional function, the relative desirability of the measures of effectiveness between the worst and best metrics is determined as linearly proportional to its numerical values between the limits.
2. If a characteristic of a factor cannot be verified as a linearly proportional function, the non-linear functional relationships between the numerical values of the metric and their desirability value need to be developed.

Each expert assigned a value between 0 and 100 representing his/her judgment on the relative desirability of each measure of effectiveness as a ratio of the desirability of the "best" limiting metric. The mean values were calculated among the relative values given by each expert to represent the group decision. As a result, the desirability curves were developed according to the approaches above. Some examples of the desirability curves are shown in Figure 2.11.

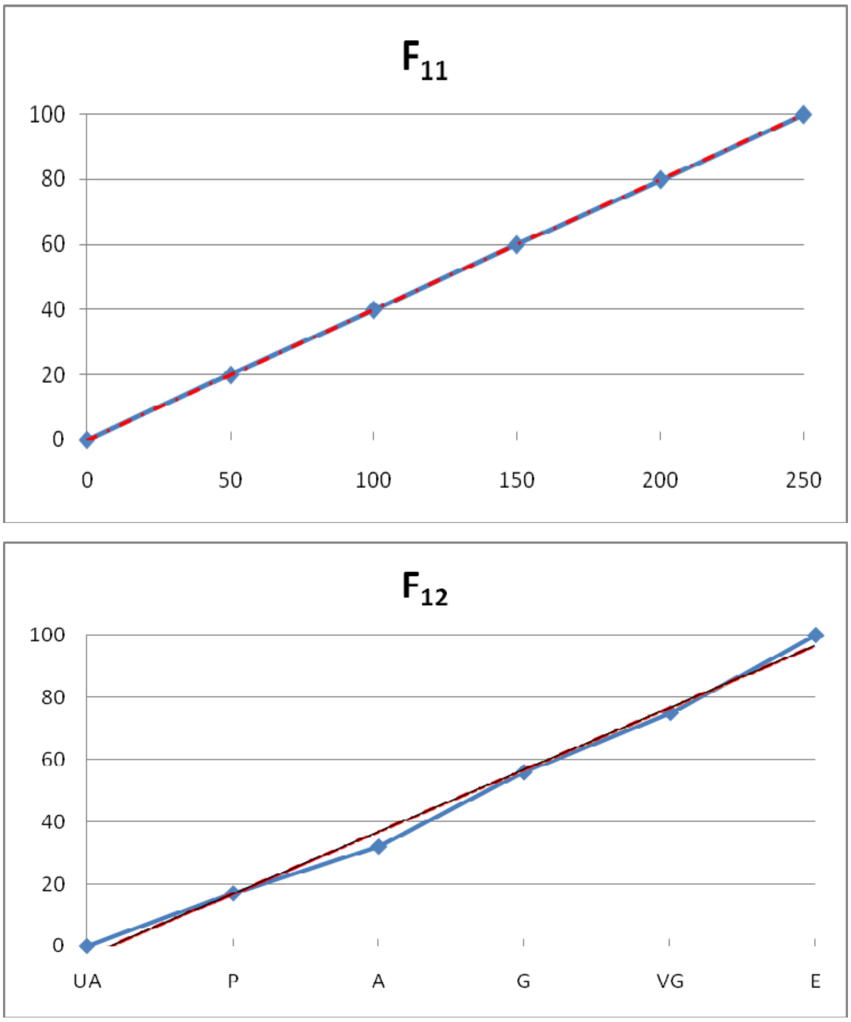

Figure 2.11 : Desirability curves according to relative values given by experts

2.5.4 Mapping Metrics

The calculation includes the mapping of technological metrics ($t_{n,j_k,k}$) to the desirability values [$V(t_{n,j_k,k})$] using the relative desirability value of measures of effectiveness [$V(m_{j_k,k})$] resulting from Step 3.

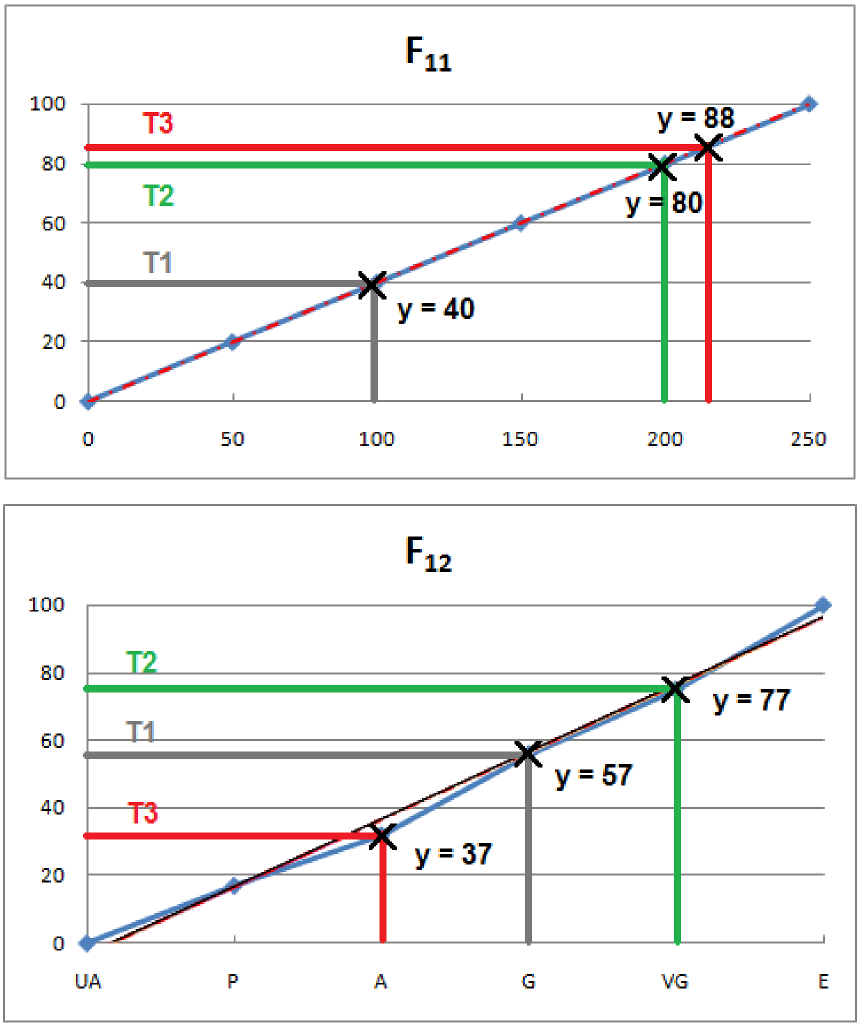

Figure 2.12 : Distribution of the desirability values on desirability curves

Figure 2.12 and Table 2.6 shows the mapping the performance metrics of technology (*n*) along factor (j_k) for criterion (*k*) to the relative desirability values.

Table 2.6 : Metrics and desirability values of different technologies

Criteria	Factors	Units	Technological Metrics $t_{n,j_i,k}$ T1	T2	T3	Desirability Values $V(t_{n,j_i,k})$ T1	T2	T3
C1	F11:		100	200	220	40	80	88
	F21:		G	VG	A	57	77	37
C2	F12:							
	F22:							
	F32:							

2.5.5 Quantification of Technology Value

This last step calculates the Technology Value for each emerging technology by applying Equation 2.1, the technology value is calculated through the matrix computations among the criteria priorities (Step 1), the relative importance of factors on each criterion (Step 2), and the desirability value of technologies to factors (Step 4). The outcomes are the technology values of emerging technologies according to a company's objective. The ideal technology from a company's point of view would represent the technology value of 100.

Below table summarizes the calculation of a hypothetical technology value for an emerging technology:

Table 2.7 : Calculation of technology value for an hypothetical Technology No: 1

Criterion	Factors	Desirability Value	Technology Value
C1: 0,13	F11: 0,43	$V(t_{1,11})$ 40	2,24
	F21: 0,57	$V(t_{1,21})$ 57	4,22
C2:	F12:	$V(t_{1,12})$	
	F22:	$V(t_{1,22})$	
	F32:	$V(t_{1,32})$	
C3:	F13:	$V(t_{1,13})$	
	F23:	$V(t_{1,23})$	
	F33:	$V(t_{1,33})$	
	F43:	$V(t_{1,43})$	
C4:	F14:	$V(t_{1,14})$	
	F24:	$V(t_{1,24})$	
			54.15

2.6 Technology Evaluation

This step is conducted by the researcher. First, the researcher converts the relative impact of the measures of effectiveness to the semi-absolute ratio scale by assigning the value of 10 points to the measure of effectiveness, which has the highest relative impact, and proportional values to the other measures of effectiveness according to their relative impacts. Then, transforming the hierarchical model used for measuring the relative impact of measures of effectiveness to the one used for evaluating the semi-absolute impact of emerging technologies on the company's objective.

Gerdsri [38] presents that with the hierarchical model for technology evaluation, the researcher then determines the overall impact of "technology n" based on the result as shown below.

$$T_n = \sum_{k=1}^{K} \sum_{j=1}^{J} [W_k][F_{jk}][T_{n,jk}] \tag{2.5}$$

$\lfloor T_{n,jk} \rfloor$ represents the matrix of the semi-absolute value of emerging technology "n" on the factor "j" under the criterion "k",

$\lfloor F_{jk} \rfloor$ represents the matrix of the relative impact of factor "j" on the criterion "k",

$[W_k]$ represents the matrix of the relative importance of criterion "k" on the objective,

T_n donates the overall semi-absolute value of emerging technology "n".

A technology whose semi-absolute impact value is 10 is perfect technology for satisfying a company's objective.

Technologies are grouped together according to their timing of occurrence and stacked up according to their impacts on the company's objective from the highest to the lowest value.

2.7 Formation of TDE

All the results derived from earlier steps are collected to constitute a diagram and to show paths that connect one technology to another in the later time periods throughout the specified timeframe. The technology development path which sequentially connects all the strongest impact values of emerging technology candidates in each time period throughout the specified timeframe is considered as the TDE, as shown in Figure 2.13 [38].

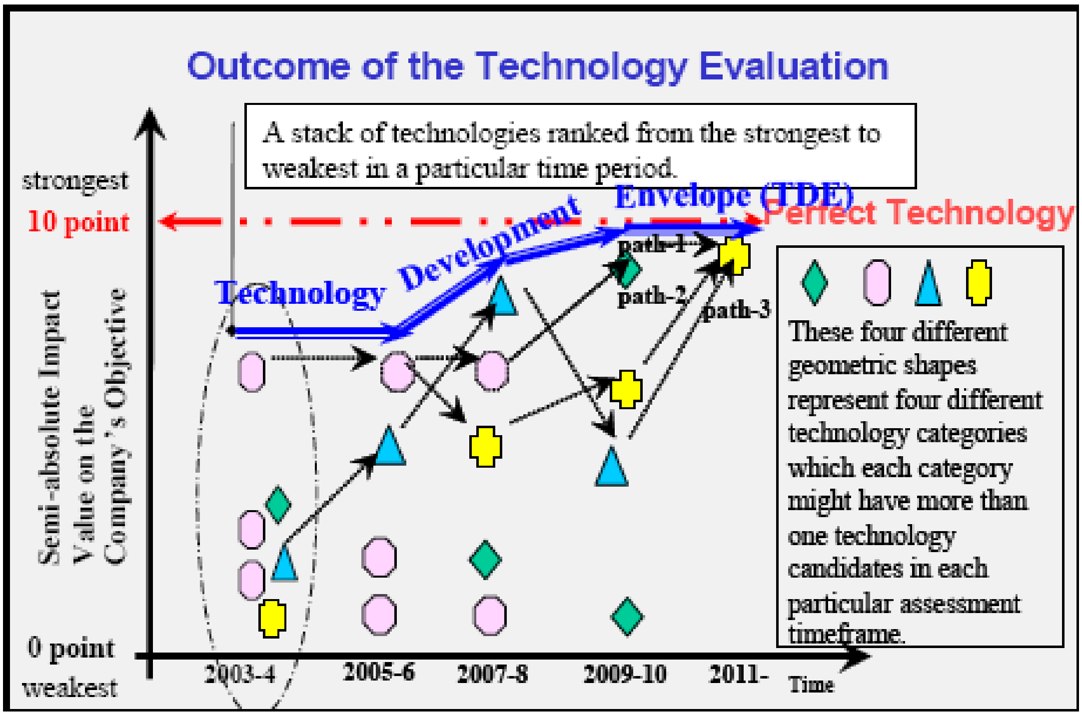

Figure 2.13 : TDE diagram representing paths of technology development

3. CHALLENGES AFFECTING AUTOMOTIVE INDUSTRY

Automotive industry expects a breakthrough in energy systems for the upcoming decades due to unavoidable depletion of world fossil fuel resources. Furthermore, CO_2 and other pollutants are becoming more and more dangerous for global warming and human health. In order to reduce these emissions, governments adopt stricter exhaust emission regulations all over the world. In order to overcome these challenges, various powertrains have been developed and launched to improve fuel economy and reduce exhaust emissions.

3.1 Energy Trends

Worldwide energy demand is increasing alarmingly. The European “World Energy Technology and Climate Policy Outlook” (WETO) predicts an average growth rate of 1.8% per annum for the period 2000-2030 for primary energy worldwide. This demand contradicts with shrinking fossil fuel supplies, which emit greenhouse gases, causing the negative impacts of global climate change and air pollution.

World fossil fuel sources may not be able to meet future energy demand. To date, it has been estimated that 95% of the oil reserves have been identified. The rate of oil discovery peaked in the early 1960's, and the rate of discovery has dropped off significantly. With the use of any finite commodity, production starts and rises at a peak level and will ultimately decline to zero. Hubbert's peak is the term used to describe the production function for oil. Named after the famous geologist, this production curve is useful to understand the changes to come in the petroleum business.

In 1956, Hubbert proposed that fossil fuel production in a given region over time would follow a roughly bell-shaped curve without giving a precise formula; he later used the Hubbert curve, the derivative of the logistic curve, for estimating future production using past observed discoveries.

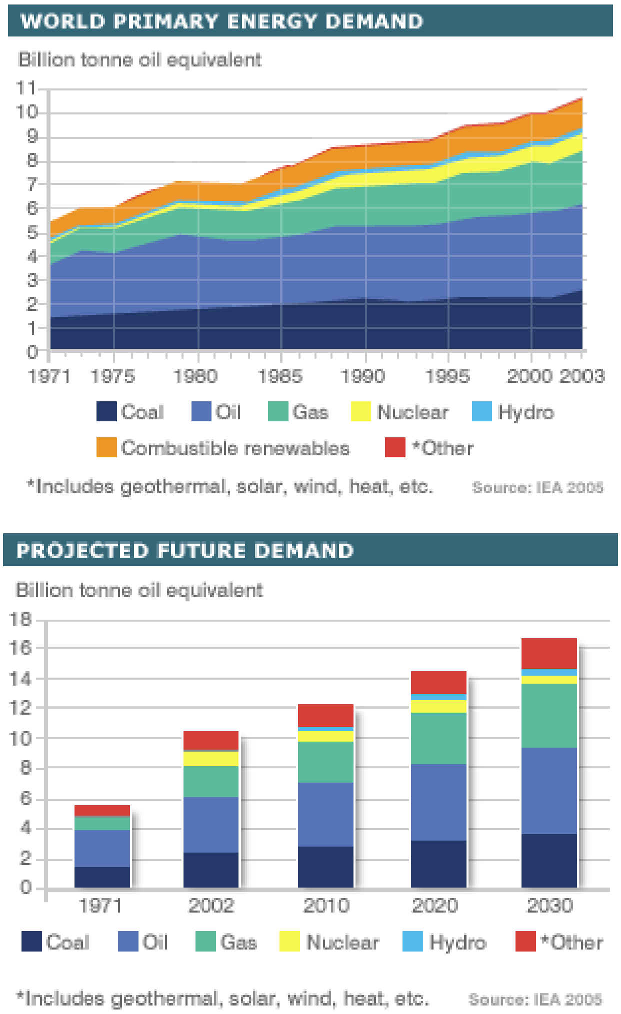

Figure 3.1 : World's current and projected future energy demand

Hubbert assumed that after fossil fuel reserves (oil reserves, coal reserves, and natural gas reserves) are discovered, production at first increases approximately exponentially, as more extraction commences and more efficient facilities are installed. At some point, a peak output is reached, and production begins declining until it approximates an exponential decline.

The Hubbert curve satisfies these constraints. Furthermore, it is roughly symmetrical, with the peak of production reached when about half of the fossil fuel that will ultimately be produced has been produced. It also has a single peak.

Given past oil discovery and production data, a Hubbert curve that attempts to approximate past discovery data may be constructed and used to provide estimates for future production. In particular, the date of peak oil production or the total amount of oil ultimately produced can be estimated that way. Cavallo [50] defines the Hubbert curve used to predict the U.S. peak as the derivative of:

$$Q(t) = \frac{Q_{\max}}{1 + ae^{bt}} \quad \textbf{(3.01)}$$

where $Q_{\max}$ is the total resource available (ultimate recovery of crude oil), *Q(t)* is the cumulative production, and *a* and *b* are constants. The year of maximum annual production (peak) is:

$$t_{\max} = \frac{1}{b}\ln\left(\frac{1}{a}\right) \quad \textbf{(3.2)}$$

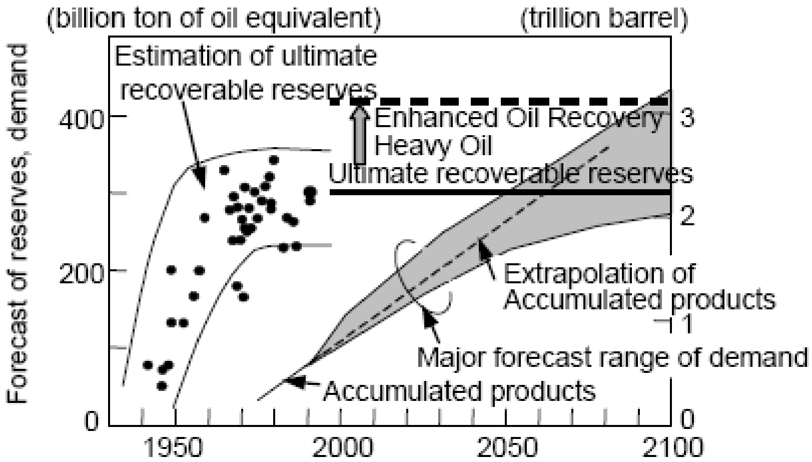

Figure 3.2 : World reserves forecast [51]

In 1940, the forecasted volume of petroleum reserves was around 0.6 trillion barrels but was recently changed to 2.2 trillion barrels and now seems to be stable. Assuming that the consumption keeps the same pace, it is projected that the petroleum supply will be exhausted around 2060. This means that petroleum will probably be a leading automobile energy source for the next couple of decades or more. However, there is no doubt that petroleum resources are limited.

3.2 Exhaust Emission Reduction

Over decades, global pollution concerns have increased and air quality targets have been established in programs, like the Clean Air Act in the USA or the Clean Air For Europe program (CAFE). Triggered by local air pollution problems, many countries have gradually imposed increasingly stringent automotive emissions regulations in the past years. America, Europe and Japan, as the key automotive technology developers, have established engine and exhaust after-treatment technologies for extremely low emission levels.

America, Europe and Japan have developed their own emission regulations with different test cycles and limits, but with similar procedures. The core of all procedures is the measurement methods formulated by the US EPA (Environmental Protection Agency). Today all developed countries and most of the developing countries have emission regulations implemented and other countries are catching up fast.

Most of the development of new regulations in 2007 occurred in Europe, with the finalization of the light-duty Euro 5 and 6 emissions standards, and a proposal from the Commission for Euro VI heavy-duty standards [52].

The first date of implementation of Euro 5 for new vehicle types is September 1, 2009 and the date of implementation for all vehicles is January 1, 2011. Meanwhile, the first date of implementation of Euro 6 for new vehicle types is September 1, 2014 and the date of implementation for all vehicles is September 1, 2015.

Table 3.1 : EU Emission Standards for Passenger Cars and LCVs, g/km [53]

Tier	Ref. Mass	Fuel Type	CO	HC	HC+NOx	NOx	PM
Euro 4	< 1305 kg	Diesel	0.50	-	0.30	0.25	0.025
		Petrol	1.0	0.10	-	0.08	-
	1305-1760 kg	Diesel	0.63	-	0.39	0.33	0.04
		Petrol	1.81	0.13	-	0.10	-
	> 1760 kg	Diesel	0.74	-	0.46	0.39	0.06
		Petrol	2.27	0.16	-	0.11	-
Euro 5	< 1305 kg	Diesel	0.50	-	0.23	0.18	0.005[b]
		Petrol	1.0	0.10	-	0.06	0.005[a,b]
	1305-1760 kg	Diesel	0.63	-	0.295	0.235	0.005[b]
		Petrol	1.0	0.10	-	0.06	0.005[a,b]
	> 1760 kg	Diesel	0.74	-	0.350	0.280	0.005[b]
		Petrol	2.27	0.16	-	0.082	0.005[a,b]
Euro 6	< 1305 kg	Diesel	0.50	-	0.17	0.08	0.005[b]
		Petrol	1.0	0.10	-	0.06	0.005[a,b]
	1305-1760 kg	Diesel	0.63	-	0.195	0.105	0.005[b]
		Petrol	1.81	0.13	-	0.075	0.005[a,b]
	> 1760 kg	Diesel	0.74	-	0.215	0.125	0.005[b]
		Petrol	2.27	0.16	-	0.082	0.005[a,b]

a - applicable only to vehicles using DI engines
b - proposed to be changed to 0.003 g/km using the PMP measurement procedure

Figure 3.3 and Figure 3.4 compare the European regulations with the US Tier 2 regulations.

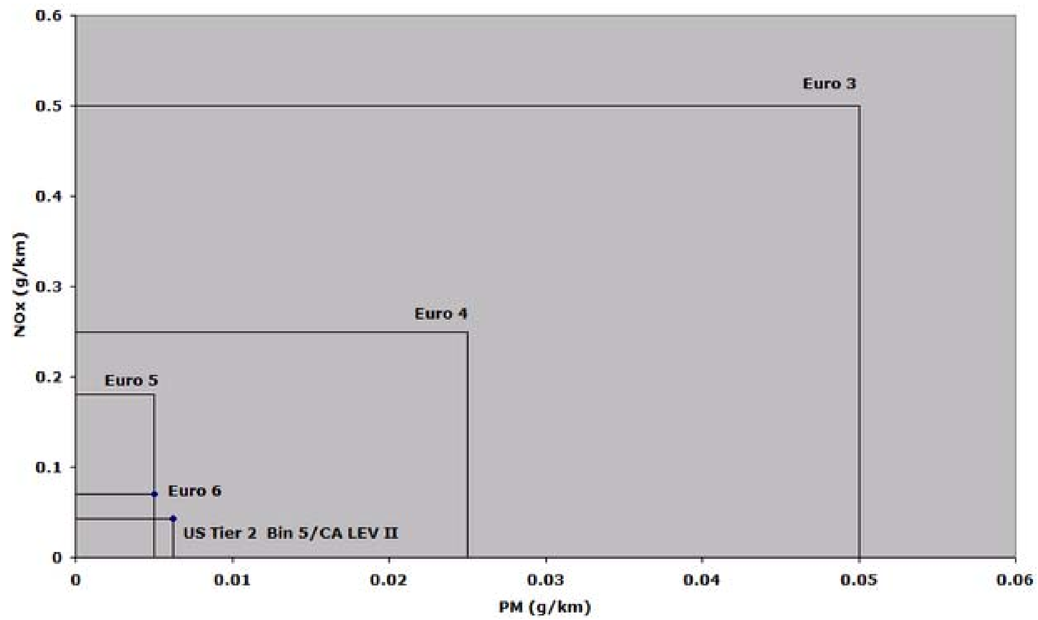

Figure 3.3 : PM and NOx emission limits for diesel cars

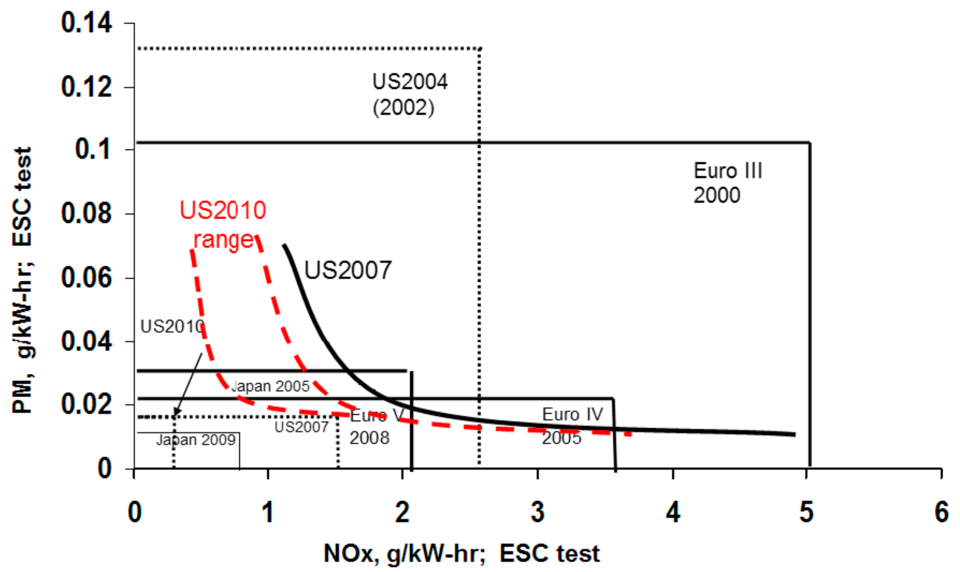

Figure 3.4 : Comparison of on-road HD standards in the US, Japan, and Europe

The Japanese 2009 NOx and PM standards are numerically identical to the Euro 5 standards but are measured on a different test cycle [54].

It is expected that the Euro 5 NOx regulations will largely be met without NOx aftertreatment, however that is not the case for Euro 6 regulations. Additional exhaust emission control strategies will be required for Euro 6 vehicles to be developed in 2009 and 2010 [55].

California State emission requirements are usually more stringent than set by EPA (Environment Protection Agency), however developed from with similar procedures.

In 1998, CARB (California Air Resources Board) has adopted LEV II (Low Emission Vehicle II) regulations following a less strict LEV I regulations. These standards set the limit for NOx and PM emissions even lower than European exhaust emission standards. In Figure 3.5, a comparison of LEV standards with ULEV (Ultra Low Emission Vehicle) and SULEV (Super Ultra Low Emission Vehicle) standards.

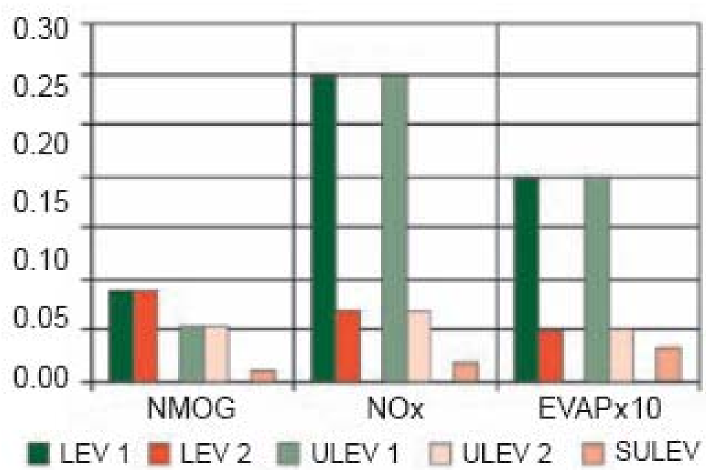

Figure 3.5 : LEV emission standards comparison

3.3 CO_2 Emissions

Below figure shows recent monthly mean carbon dioxide globally averaged over marine surface sites.

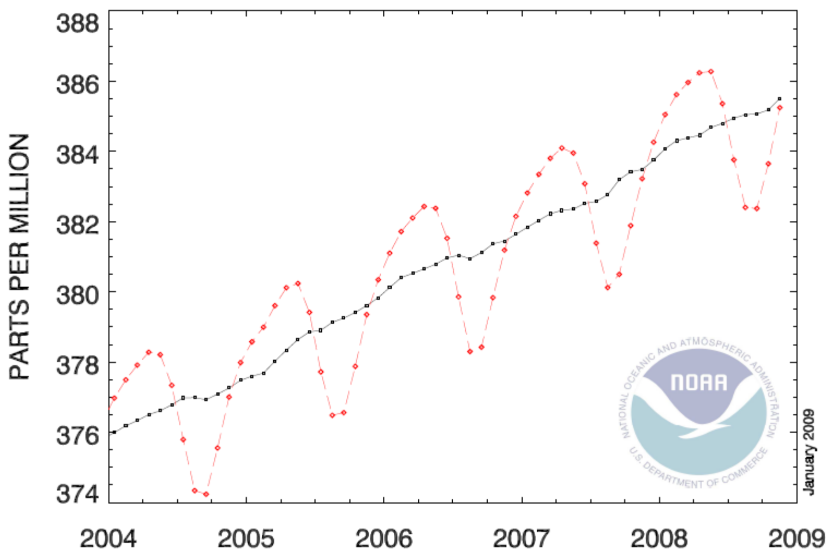

Figure 3.6 : Monthly mean CO_2 globally averaged over marine surface sites [56]

The Global Monitoring Division of NOAA/Earth System Research Laboratory has measured carbon dioxide and other greenhouse gases for several decades at a globally distributed network of air sampling sites [57]. A global average is constructed by first fitting a smoothed curve as a function of time to each site, and then the smoothed value for each site is plotted as a function of latitude for 48 equal time steps per year. A global average is calculated from the latitude plot at each time step [58].

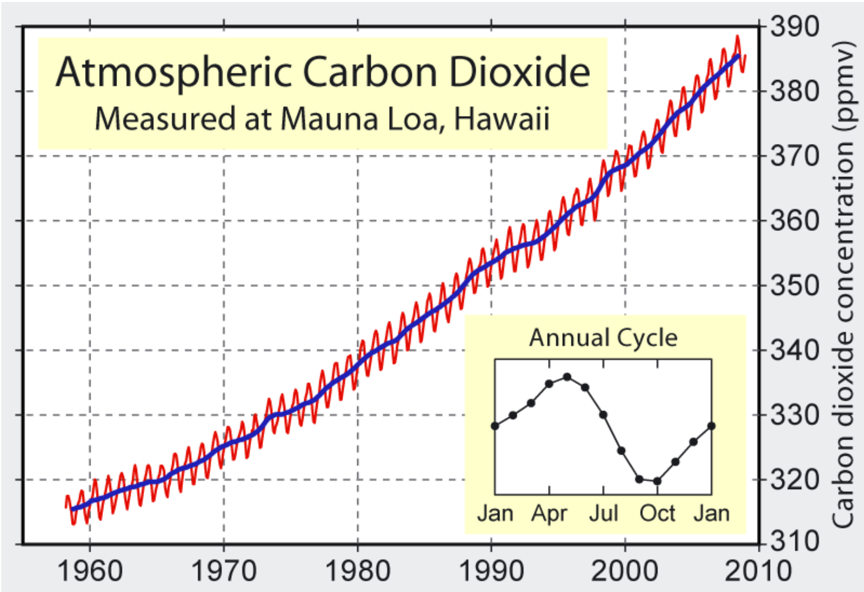

Figure 3.7 : Atmospheric CO_2 emissions

Figure 3.7 shows the history of atmospheric carbon dioxide concentrations as directly measured at Mauna Loa, Hawaii. This curve is known as the Keeling curve, and is an essential piece of evidence of the man-made increases in greenhouse gases that are believed to be the cause of global warming. The longest such record exists at Mauna Loa, but these measurements have been independently confirmed at many other sites around the world [59].

Due to rapid industrilization and human activities such as the combustion of fossil fuels and deforestation, the concentration of atmospheric carbon dioxide has increased by about 35% since preindustrial times [60]. The Intergovernmental Panel on Climate Change (IPCC) has predicted an average global rise in temperature of 1.4°C to 5.8°C between 1990 and 2100 [61]. In order to avoid wide-ranging consequences due to CO_2 emission concentration in atmosphere exceeding the threshold level, the international experts believe that it is essential to limit the global temperature rise within 1.5°C to 2.5°C. The climate change has gained great momentum due to Kyoto protocol to the United Nations Framework Convention on Climate Change (UNFCCC or FCCC), an international environmental treaty produced at the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro, Brazil, from 3–14 June 1992. Under Kyoto, industrialized countries agreed to reduce their collective GHG emissions by 5.2% compared to the year 1990 [62].

Table 3.2 : Transportation GHG Emissions by mode [63]

Mode of Transportation	GHG emission contribution (2000) [%]
Passenger cars	36
Light trucks	19
Heavy Trucks	16
Aircraft	10
Marine	5
Rail	2
Buses	1
Other	11

The transportation GHG emission contribution is shown in Table 3.2. It is clearly seen from the table that cars, trucks and buses contributes about 70% GHG emission from total transportation sectors. There is an urgent need to reduce GHG emission from all sectors including transport sector in order to avoid global warming consequences. In this direction, European Union has taken a lot of initiatives to control CO_2 emission from transport vehicles.

The CO_2 emission reduction in vehicles is directly related with improving the fuel economy. Improvement of fuel efficiency can be achieved in many ways such as, reducing vehicle weight, reducing aerodynamic losses and improving the energy efficiency of car components.

Due to several challenges that the automotive industry is facing, as described above, global strategies and action plans for the future alternative and sustainable energy sources are being prepared and adopted continuously. These policies advocate to raise the share of renewable energies and to develop measures relating to energy efficiency and sustainable energy sources while promoting alternative fuels. In this respect, alternative powertrain technologies and fuels are sought to be adopted to support these global strategies.

4. STATE-OF-THE-ART POWERTRAIN TECHNOLOGIES

Increasing shortages of energy resources as well as emission legislation is increasing the pressure to develop more efficient, environmentally friendly propulsion systems for vehicles. Due to its more than 125 years of history with permanent improvements, the internal combustion engine (ICE) has reached a very high development status in terms of efficiency and emissions, but also drivability, handling and comfort. Therefore, the IC engine is considered be the dominant propulsion system for future generations. However; considering the ever-tightening regulations, global approach to reduce greenhouse gases and the need to reduce the dependency on fossil fuels, will lead the propulsion system road to other emerging and disruptive technologies such as fuel cells.

Future products and technologies must meet social, economic and environmental goals, satisfying market requirements for mobility, safety, performance, cost and desirability, with the objectives of improving the quality of life and wealth creation.

Investment in road vehicle technology and research should be considered in terms of the contribution that the investment is expected to make towards the primary social, economic and environmental goals:

- Socially sustainable road transport system, providing equitable, safe and secure road transport that meets the needs and aspirations of society.
- Economically sustainable road transport system, supported by a dynamic and successful automotive industry.
- Environmentally sustainable road transport system, with a low environmental impact in terms of energy consumption, global warming, waste and health.

4.1 Diesel Engines

Currently, Diesel engines achieve a high customer acceptance in Europe, due to their superior real world fuel economy, durability and excellent driving performance. The continuously increasing sales numbers, especially in the heavier vehicle classes, reflects this high acceptance.

The quality of the fuel-air mixture formation is a very important factor in reducing emissions. A better mixture formation can be achieved through the optimization of nozzle parameters, the increase of injection pressure, and the optimization of the injection rate scheduling. An improvement of the mixture formation can allow for more fuel being brought into the combustion chamber so that a higher engine power can be achieved [64]. Another very import objective of state-of-the-art research is the reduction of NOx and PM emissions through low temperature combustion [65-67]. A prerequisite to achieve this is the control of the combustion by means of a variation of the scheduling for multiple injections. Engine experiments have also shown that with multiple injections per power cycle it is possible to reduce both NOx and soot emissions significantly [68].

In order to balance increased power output and compliance with EURO V and subsequent regulations, diesel engines require modern variant of direct fuel injection system. Common rail system features a high-pressure fuel rail feeding individual solenoid valves, as opposed to low-pressure fuel pump feeding unit injectors, or high-pressure fuel line to mechanical valves controlled by cams on the camshaft. Third-generation common rail diesels now feature piezoelectric injectors for increased precision, with fuel pressures up to 2.000 bars.

Figure 4.1 shows the configuration of a 2nd-generation 180MPa piezo CRS. The feed pump suctions fuel from the fuel tank and supplies it to the pumping chambers of the supply pump where pressure is increased to rail pressure. The common rail is equipped with a pressure sensor to detect the fuel pressure and a pressure relief valve to lower the fuel pressure during deceleration etc. The common rail distributes fuel to the piezo injectors, which inject fuel into the engine combustion chamber. The electronic control unit (ECU) controls the injection quantity, timing and the number of injections accurately and electronic injector driver unit (EDU) based on the information from various sensors.

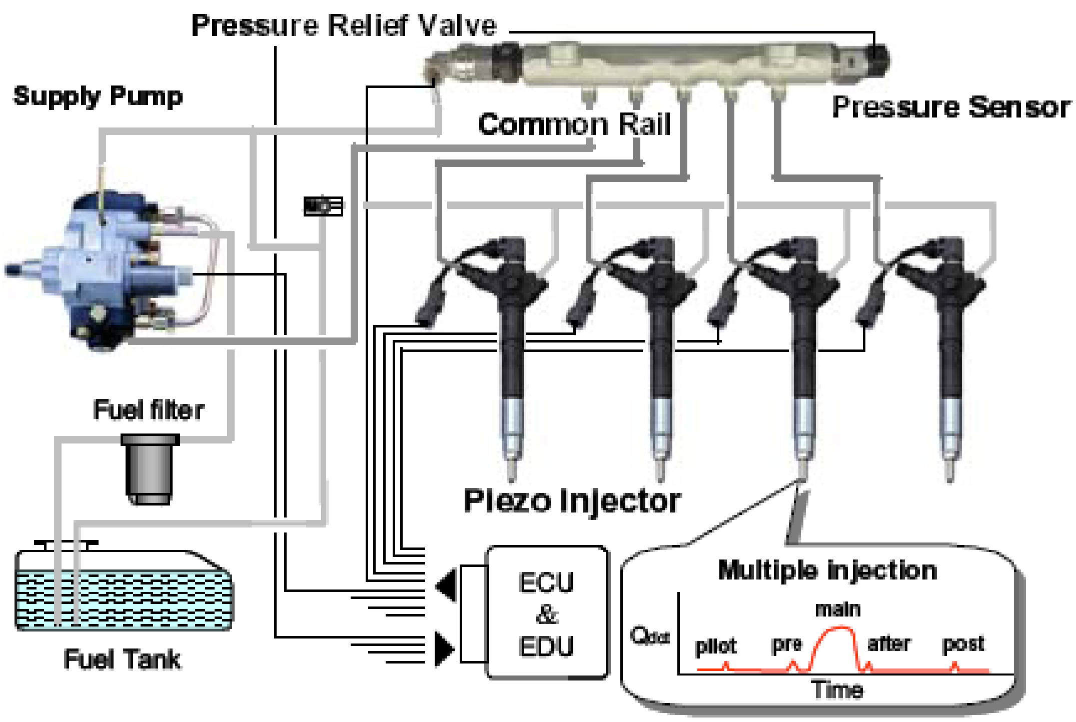

Figure 4.1 : Second Generation 180MPa Piezo CRS

Compared to a solenoid injector, the piezoelectric injector brings the following advantages [69]:

- A more efficient rate of injection,
- A higher dynamic allowing to reduce the minimum time between two consecutive injections, thus making it possible to use multiple injection strategies, especially close pilot injection and double pilot injection schemes,
- A substantial reduction of the minimum fuel quantity with a favorable impact on soot emissions at part load,
- Improved emission robustness for mass production and increased engine stability.

By contrast with other injection systems, pressure generation and injection are separate from each other in Common Rail technology. A separate high-pressure pump continuously feeds fuel into the rail. While other diesel direct-injection systems have to build up the high fuel pressure anew for each injection cycle, the Common Rail System permanently has at its disposal a fuel pressure matched to the operating conditions of the engine, even at low engine speeds.

In addition, Common Rail technology differs from conventional systems by providing multiple injections per working cycle. This cycle is divided into pre-injection (pilot injection) for quiet engine running, main injection for ideal power deployment and secondary injection for reduced emissions. The fuel reaches the injector via short pressure lines and then through the injection nozzles into the combustion chamber.

The higher the injection pressure, the finer the injection system vaporizes the fuel, thus permitting combustion that is even more efficient. However, as Dohle and Eimers-Klose [70] stated, modern common rail diesel systems are quite complex, with injectors capable of injecting very small quantities in extremely short time intervals with the help of pressures up to 2000 bar, the rail and the high pressure pump. High speed and multi-injections enables not only an economic combustion but also noise reduction and exhaust gas aftertreatment.

Dohle et al. presents the system requirements for future diesel injection systems and their investigations show that a full flexible rate shape in the whole engine map leads to the required performance. A study conducted by Vanegas et al. [71] shows that a Common-Rail fuel system allows for variable pressures (up to 1600 bar), timing, and numbers of injections. As a result, for three injections (pilot, main, and post), the NOx emissions slightly decreased for compared to the split injection strategy. Thus, they were also lower than for the single injection strategy. The CO and HC emissions approximately remained constant when applying a post injection, while the smoke emissions decreased when applying an early post injection.

Continuously variable transmissions (CVT) have been proposed and applied to cars since the early days of the automotive vehicles. However, CVTs were finally displaced by geared transmissions. Nevertheless, the fuel saving potential of CVTs has been clearly recognized. For example, Dorey [72] found that if CVTs could produce a similar efficiency to that of manual gearboxes, 35% of fuel savings in urban driving and 30% savings in Highway were possible. Unfortunately, Micklem and Soltic [73,74] investigated that these performances have not been achieved to date, mainly because the lower efficiency of currently available CVTs almost decompensate all advantages of operating the engine at its optimum curve. As the number of teeth of a gear has to be an integer figure, only rational transmission ratios can be achieved which do not provide a continuous set. It is therefore impossible to get a continuously variable transmission by using purely geared CVTs. Using other coupling devices to allow a continuously varying transmission comes on cost of a reduced efficiency. Further studies show the limits of the efficiency , such as Guebeli's [75] for belt CVTs, Tejinder's [76] for half toroidal CVTs, Tanaka's [77] for rubber V-belt CVTs, Chen's [78] for toroidal CVTs, and Shelley and Zhang's [79,80] for further types of CVTs.

The efficiency of power split CVTs also has been studied by Mangialardi [81,82] and Mantriota [83-85]. There are several conclusions, but the obvious and most important one is that the less the amount of power is transmitted via the CVT-branch, the more is transmitted directly via gears, which is much better.

Mucino et al [86] proposed to add an external gearbox to a power split CVT. This arrangement can reduce power transmitted via the CVT branch at will by adding sufficient numbers of gears. However, this solution has a huge drawback in that the system has to be declutched during gearshift. Gear shifts, however, last for a long period because they require changing transmission ratio from one extreme to the other.

In Greenwood's [87] studies a multi mode mechanism that can change gears while still transmitting torque is disclosed. Even gearshifts can be performed very fast. Unfortunately, this mechanism does not allow optimizing ratios of every mode and power cannot be reduced at will.

It is well known that diesel fuel has a higher energy density than gasoline. On average, 1 gallon (3.8 L) of diesel fuel contains approximately 155x106 joules (147,000 BTU), while 1 gallon of gasoline contains 132x106 joules (125,000 BTU). This, combined with the improved efficiency of diesel engines, explains why diesel engines get better mileage than equivalent gasoline engines. However, in terms of the environment, diesel has some pros and cons. Diesel emits very small amounts of CO, HC and CO_2, emissions that lead to global warming, releasing high amounts of NOx and PM at the same time. Therefore, in order to fulfill the future emission limits, it is mandatory to use new combustion technologies and to use such complex exhaust after-treatment systems, like particulate filters, exhaust gas recirculation (EGR), selective catalytic reduction (SCR) and lean NOx traps (LNT).

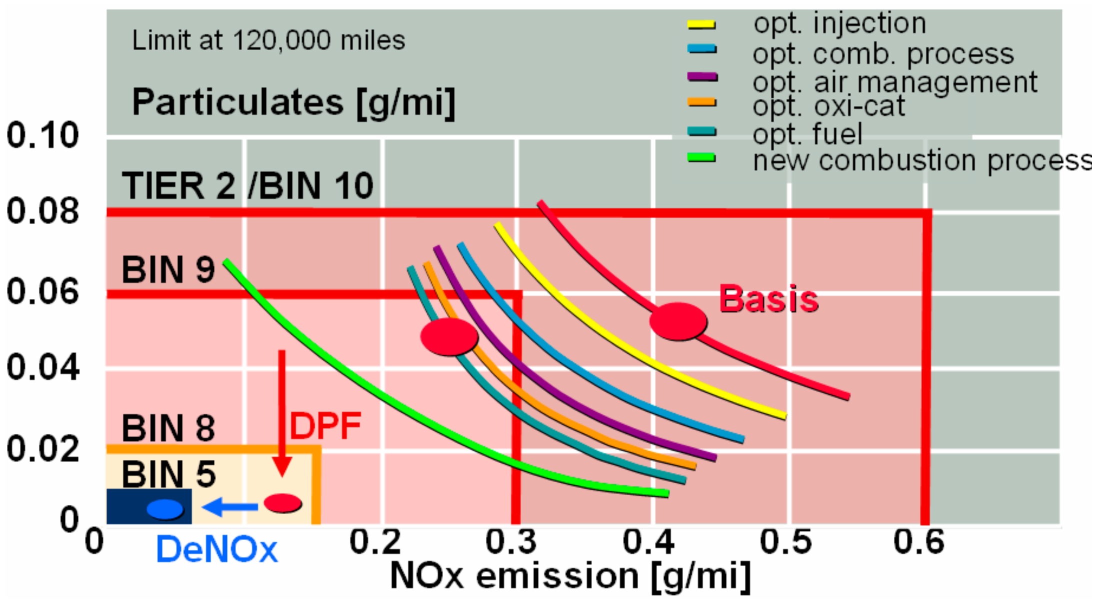

Figure 4.2 : Emissions results for a US Tier 2 Bin 5 technology package

Johnson [54] explains that Figure 4.2 depicts the PM/NOx trade-off curve for a light duty diesel technology package to meet the US Tier 2 Bin 5 standards. A similar package was shown for Euro 6, but with a different engine calibration. In both systems, the deNOx efficiency is nominally 75%, but more NOx has to be removed in Europe (~85 mg/km) than in the US (40 mg/km) presumably resulting in a higher urea consumption for SCR, or a higher fuel penalty for an LNT (lean NOx trap); which is likely more than offset by the fuel consumption advantage of running at the higher NOx level.

NOx control is focusing on SCR for diverse applications. Focus is on cold operation, durability, secondary emissions, and system optimization. Aged LNTs (lean NOx traps) are effective up to about 60-70% deNOx efficiency, and are being considered for light-duty and some light heavy-duty applications. According to Lambert et al. [88], there is growing interest in supplementing LNT performance with integrated SCR, which utilizes ammonia generated in the LNT during rich regenerations, to improve efficiency and reduce costs. Very little was in the literature in 2006 regarding lean NOx catalysts. Johnson [89,90] and Rohr et al. [91] discussed that lean NOx traps offer an attractive NOx solution for light duty applications and those HD applications in which an extended urea infrastructure might be problematic.

There is significant motivation to improve low temperature SCR performance; SCR is emerging in the light-duty sector where reduced cold start emissions are critical, further NOx reductions in the HD sector are needed, and greater NOx reductions are desired in urban driving or other low load conditions. Urea decomposition is one barrier to good low temperature SCR performance. Kroecher [92] shows NO2 affects the decomposition of urea, in that the decomposition efficiency of a catalyst dropped from 70 to 40% at 150°C in the presence of NO2. Urea evaporation and decomposition can be strongly dependent on getting good mixing. There are several papers on modeling to improve urea injection and mixing using a variety of devices [93-96].

In the tailpipe, SCR efficiencies are approaching 90%+, with better mixing and control. Low temperature deNOx efficiency is being addressed with increased understanding on limitations, such as ammonium nitrate formation at T<200°C, and with urea decomposition catalysts. Advances are also being made on liquid urea substitutes [97].

Cooper [98] summarizes that DPFs have been applied to production vehicles since 1999, and are now standard equipment on most European diesel cars and all US and Japanese cars. All 2007 HD truck engines in the US and all but the long haul trucks in Japan use them. Moving into the future, it is clear that DPFs will be as significant a part of the diesel engine as direct injection and turbocharging is today.

Increased boosting levels at part load operation allow a leaner combustion at the same NOx-emission level. The main challenge is to realize higher boosting levels at upper part load operation without generating excessive gas exchange losses. This requires the implementation of improved boosting systems.

Arnold et al. [99,100] show that turbocharged can diesels give a %31 to %36 reduction in CO_2 emissions and downsizing trend and its benefits are also being realized in diesel engines due to the increase in power and torque density result from advances in turbocharger and injection system technology.

4.2 Gasoline Engines

The increasing fuel cost and the demand for reduction of CO_2 emission require a significant improvement of fuel economy in the next years. Contradictory to this target are continuously increasing customer demands with regard to vehicle performance and driveability, and the requirement to meet future exhaust emission regulations.

A very effective measure to reduce the fuel consumption is to shift the engine operation towards higher loads, i.e. into operating areas of higher efficiency. This can be managed by downsizing of an engine and/or by choosing a longer gear ratio. In combination with turbocharging such a concept allows achieving a very attractive vehicle performance. Current turbocharged gasoline engines with port injection offer high power output and nominal torque, but due to their conceptual layout they have disadvantages with regard to fuel economy, exhaust emission capability and transient response.

The combination of turbo-charging with suitable state-of-the-art technologies, like homogeneous gasoline direct injection or variable valve timing, allows to utilize synergy effects for achievement of a highly fuel efficient engine concept suitable for low emission. The full load performance characteristics of such a concept are focused on low-end-torque end transient response and therefore excellent vehicle drivability. Such a GDI Turbo engine concept can be also utilized as basis for a cost effective hybrid system.

Gasoline direct injection offers a significant potential for improving the fuel economy and CO_2 emissions from spark ignited engines, whilst maintaining or improving the high specific power output of current MPI engines. In this respect, the GDI engine promises a mixture of the benefits of both current gasoline and Diesel engines.

According to Harada et al [101] and Kume et al [102], the distinctive feature of recent direct injection (DI) gasoline engines is to mix various operating regimes. The engines are operated in stratified mode at part load and homogeneous mode at or near full load. Charge stratification is achieved by injecting fuel during the compression stroke to provide a mixture cloud around the spark plug. This enables stable combustion to be achieved while the overall mixture is ultra lean. Besides this strategy, Andriesse et al. [103] and Anderson et al. [104] consider another strategy to employ stoichiometric operation even at part load. Absence of liquid fuel in the intake port and availability of conventional three-way-catalyst give an excellent potential to reduce pollutant emissions.

Thus, DI gasoline engines have very attractive potential for improving gasoline engine's advantage of power density, and for improving their disadvantage of increased fuel consumption at part load.

Landenfeld et al. [105] states that lean stratified GDI concepts need and extra catalytic converter in the exhaust tract to effectively treat NOx emissions that are being generated in the engine due to the presence of excess air during combustion. If high demands on compliance of emission regulations are made, currently available lean fuel economy concepts are not successful. GDI is then to be applied as pure stoichiometric version and thus dispense with expensive aftertreatment for NOx. Yet GDI can still offer improved fuel economy over conventional SI engines.

Turbocharging and downsizing gasoline engines offers a potent mechanism of reducing CO_2 emissions. Arnold et al [100] investigated that In gasoline engines, turbocharging is estimated to give more than 10% reduction in global warming gas emissions. It appears that the first cost of turbocharging can be more than offset with cost reductions in engine downsizing and engine family rationalization. In addition, because the technologies that control global warming gas emissions also reduce fuel consumption, the lifetime cost of a turbocharged gasoline engine powered car is estimated to be even lower. There are open issues to be considered such as thermal durability, cold start emissions and turbo lag/response.

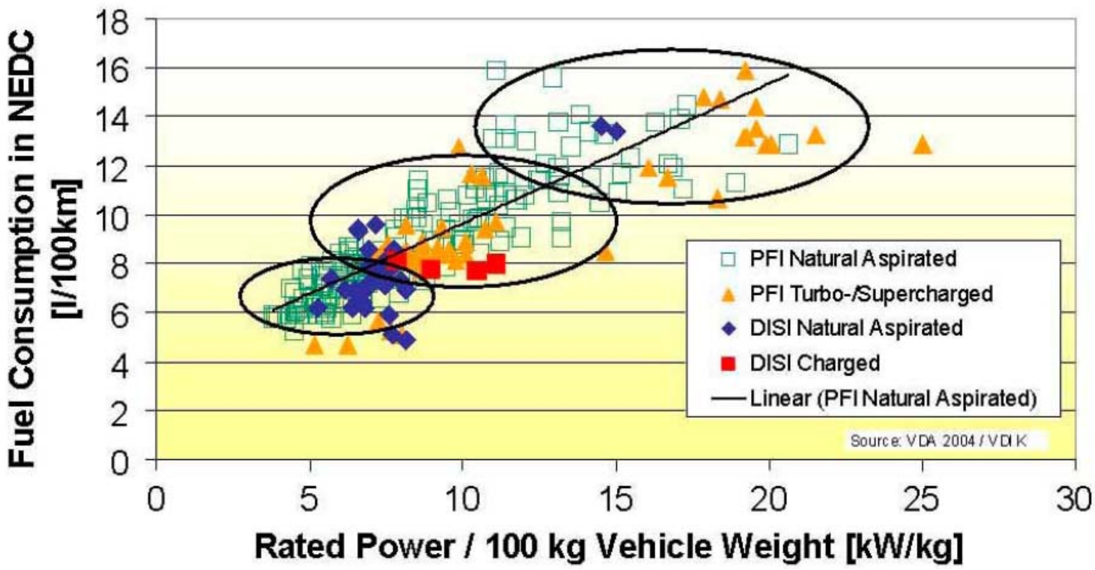

Figure 4.3 : NEDC Consumption vs. Power to Weight Ratio [105]

In above Figure 4.3, the German vehicle market is analyzed with respect to New European Driving Cycle consumption and power/weight ratio, where the advantages in consumption become clear, in particular when used for niche or sports concepts.

However, higher volumes are only realized in upper middle class vehicles, by manual transmission. A basic weakness of these engines - the engine torque at low engine speeds, the "low-end-torque" becomes apparent. Particularly, with turbocharged engines, the BMEP that can be reached at 1000 rpm only lies slightly above that of naturally aspirated engines.

Being a downsizing concept, the Turbo DISI engine has to be compared to a larger naturally aspirated engine. The measured BSFC map and full load curve of the 1.8L turbocharged direct-injected engine and of a 2.6L naturally aspirated engine with intake cam phasers are compared in Figure 4.4, taken from Arnold's [100] study.

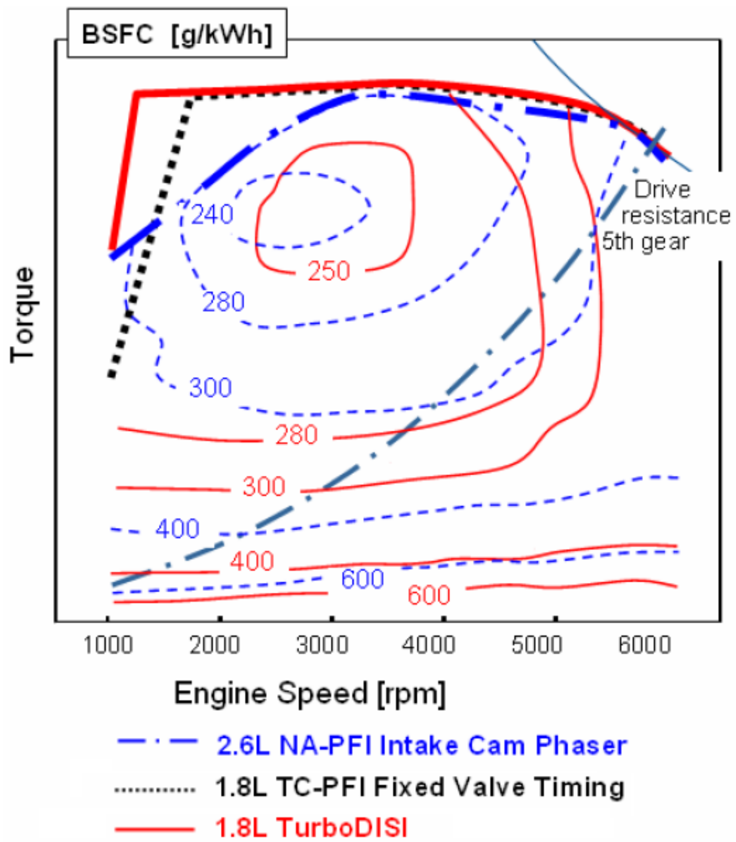

Figure 4.4 : Comparison of BSFC maps

The minimum BSFC of the Turbo DISI engine is approximately 244 g/kWh, nearly at the same level as the naturally aspirated engine. At 2000 rpm/2 bar BMEP, the

Turbo DISI reaches a remarkable BSFC of only 368 g/kWh which is significantly better than today's turbocharged PFI engines. The Turbo DISI engine can be operated with a relatively high compression ratio of 10,5:1 compared to 9,0:1 for the PFI turbocharged engine and 10,0:1 for the 2.6L NA engine. This higher compression ratio is a key reason for the improved BSFC. The decreased charge air temperature of direct injection reduces knock sensitivity, allowing an increased compression ratio.

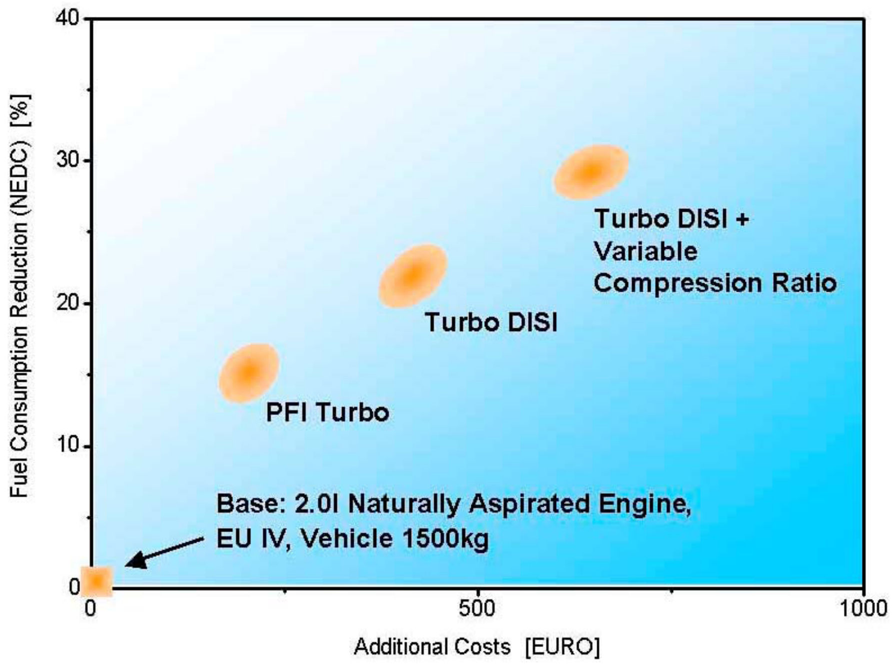

Figure 4.5 : Development Strategy and Cost/Benefit Assessment [106]

The assessment of the fuel saving potential for the Turbo DISI engine is performed with regard to the estimated extra costs. For this purpose, the fuel saving in the New European Driving Cycle is shown in Figure 4.5.

Niefer and Kramer [107] observe that the most important restriction regarding direct gasoline injection is the fact that although the engine concept offers large fuel consumption advantages in the NEDC, they offer minimal or even no fuel saving in everyday driving of most customers.

In ICEs, variable valve timing (VVT) allows the lift, duration or timing of the intake or exhaust valves (or both) to be changed while the engine is in operation. Prior to VVT, camshafts were synchronized through gears or timing chains. VVT is applied to the timing sprockets or gears so that the relationship between the toothed element and camshaft are adjusted based on engine variables.

Both GDI and VVA are being viewed as the future-oriented SI engine concepts, which are expected to make essential contributions towards reducing CO_2 emissions from automobiles. Combining the two technologies creates a series of synergies, which in total represent great potential to reduce fuel consumption. An estimation based on simulations and test-bench results conducted by Salber et al. [108] shows saving of up to 23% compared to a conventional PFI engine. In addition, the two technologies complement each other ideally concerning the exhaust emissions limited by law. A qualitative assessment of the individual potentials and the anticipated synergies is given in Figure 4.6.

	Fully VVT	DISI	Combination
Dethrottling	+	+	+
Lean Burn Combustion	O	+	+
EGR Control	++	O	++
Charge Motion Control	+	O	+
Low Idle Speed	+	O	+
Transient Operation	+	+	++
EGT Management	+	O	+
Cold Start Emissions	+	+	++
Low End Torque	+	+	++
Knock Tolerance	+	+	++
Fuel Economy Benefit incl. Cyl. Deact.	8 - 10% 14 - 16%	10 - 14%	15 - 18% 19 - 23%

Figure 4.6 : Synergies between Fully VVT and DI for SI-Engines

Boosting is nearly standard for diesel engines in passenger cars and commercial vehicles. Traditionally, boosted gasoline engines frequently occurred in connection with a performance enhancement of an existing vehicle model. Recently, however, an increasing number of boosted engines have become available as options to compete with larger capacity engines with similar driving performance. The resulting downsizing factor ranges between 25-35%. The particular advantage of downsizing is related to the fact that a smaller engine has a correspondingly higher specific load and lower pumping and friction losses. The additional advantages arising from the reduced weight and volume of the basic power unit, however, are partially reduced due to the presence of the boosting components.

When downsizing is realized by shifting the engine operating point, fuel consumption is reduced due to de-throttling and reduced friction. However, these benefits are partly counterbalanced by losses associated with reduced displacement and compression ratio.

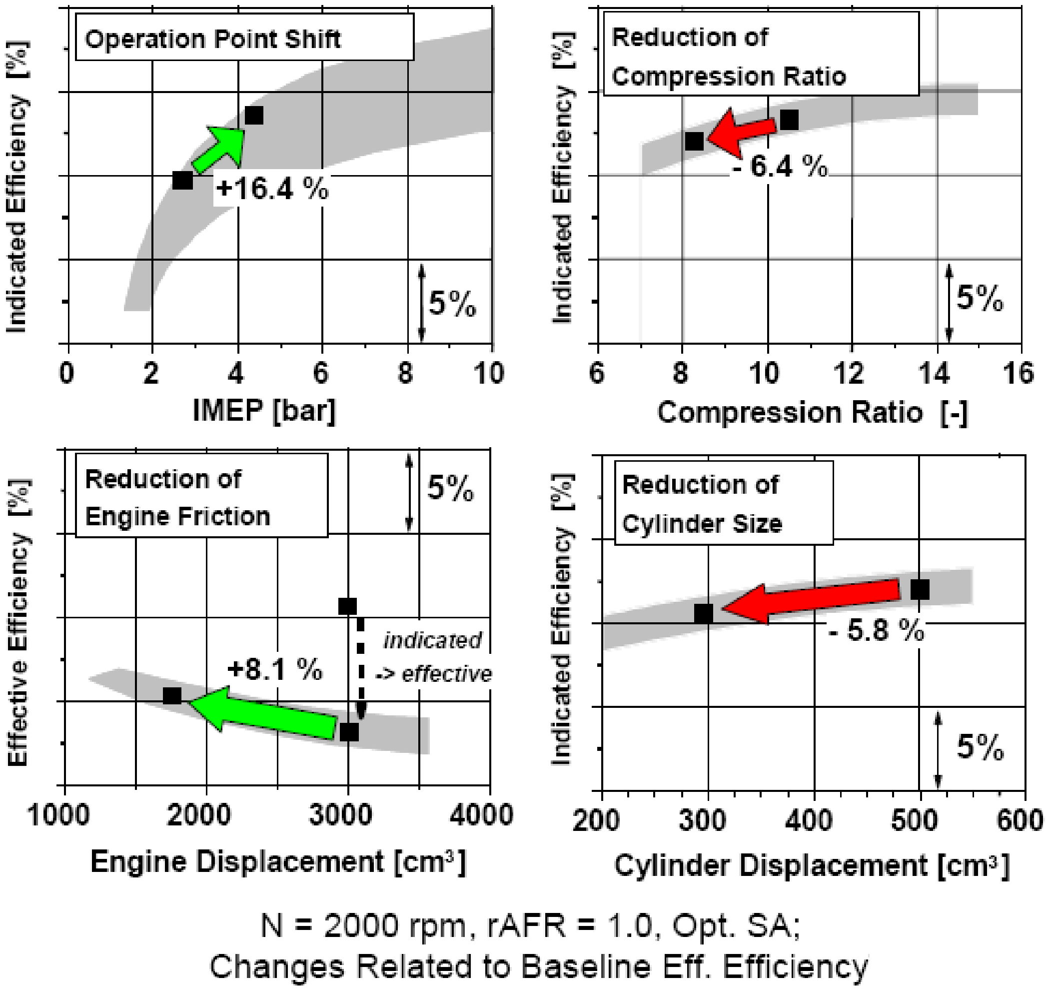

Figure 4.7 : Downsizing of Gasoline Engines

Figure 4.7 shows the indicated efficiency as a function of the indicated mean effective pressure (IMEP) for engines measured by Schwaderlapp et al [109]. According to their study, de-throttling causes a significant rise in the internal efficiency of about 16.4%. An efficiency loss is caused by the compression ratio (CR) reduction, which is a function of the boost rate. The boost rate is determined by the downsizing factor. Ultimately, a CR decrease from 10.5 to 8.5 yields a disadvantage in fuel consumption of 6.4%.

In general, the thermal efficiency of automotive engines improves with a higher compression ratio, resulting in lower fuel consumption and higher power output.

However, in practice, the occurrence of knocking at low speeds or under high loads gives rise to the problem. There is a natural limit on how high the compression ratio can be raised if an engine is to be operated at the same fixed compression ratio in all load and speed ranges. Consequently, it is desirable to vary the compression ratio so that it optimally matches the engine operating conditions.

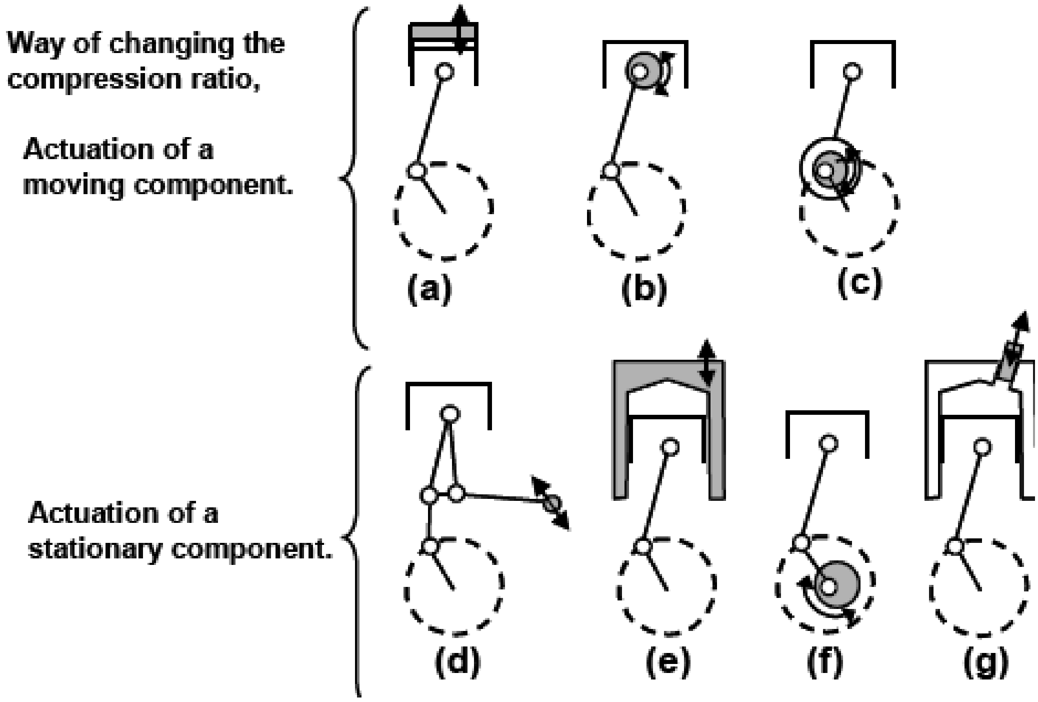

Figure 4.8 : Classification of VCR mechanism [110]

Moteki et al. [110] derives the different types of variable compression ratio (VCR) mechanism that have been proposed so far, in Figure 4.6, according to the component that is actuated to vary the compression ratio. Examples (a), (b) and (c) are for mechanisms in which a part that is normally moving under steady-operation at the same fixed compression ratio is actuated to vary the compression ratio. Conversely, examples (d), (e), (f) and (g) are for mechanisms in which a part that is normally stationary under steady-state operation at the same fixed compression ratio is actuated only at the time the compression ratio is varied.

The former types were proposed at a relatively early stage and offer the advantage that few engine modifications are needed to make the compression ratio variable. Parts that are normally moving under steady state operation include the piston crown in (a) as Wirbeleit, et al.[111], Wallace and Lux [112], Ashley [113] and Arai, et al. [114] investigates; the piston pin in (b), and the crankpin in (c) as derived from

Wardznski and Rychter's [115], Rychter and Teodorczyk's [116] and Kajiwara's [117] studies. These parts are subject to the effects of inertia force that vary dynamically according to the engine speed and act directly on the parts themselves. In addition, the actuation force for varying the compression ratio must be transferred from outside the mechanism via other moving components to the part that is actuated.

Types (d), (e) and (f), which have been proposed recently, are especially advantageous for suppressing any increase in compression ratio variation among the cylinders when applied to an in-line multi-cylinder engine. This is because the part that is actuated for varying the compression ratio is shared in common among all the cylinders. The parts involved in these types are the control shaft in (d), the head and cylinder in (e), the structure supporting the crankshaft main bearings in (f) and a part of combustion chamber in (g). These parts were investigated in numerous studies [118-125].

Moteki et al. [110] also discuss multi-link mechanism (d) in their study. By optimizing the link geometry of the multi-link mechanism, 2nd order vibration has been reduced and the total friction loss of the engine has been equivalent to the conventional one due to lowering the piston-side thrust load. These effects proved to be the potential for obtaining additional dynamic benefits apart from VCR capability.

4.3 HCCI Engines

Homogeneous charge compression ignition (HCCI) is a form of internal combustion in which well-mixed fuel and oxidizer (typically air) are compressed to the point of auto-ignition. As in other forms of combustion, this exothermic reaction releases chemical energy into a sensible form that can be translated by an engine into work and heat.

HCCI has characteristics of the two most popular forms of combustion used in IC engines: homogeneous charge spark ignition (gasoline engines) and stratified charge compression ignition (diesel engines). As in homogeneous charge spark ignition, the fuel and oxidizer are mixed together. However, rather than using an electric discharge to ignite a portion of the mixture, the density and temperature of the mixture are raised by compression until the entire mixture reacts spontaneously.

Stratified charge compression ignition also relies on temperature and density increase resulting from compression, but combustion occurs at the boundary of fuel-air mixing, caused by an injection event, to initiate combustion.

The defining characteristic of HCCI is that the ignition occurs at several places at a time which makes the fuel/air mixture burn nearly simultaneously. There is no direct initiator of combustion. This makes the process inherently challenging to control. However, with advances in microprocessors and a physical understanding of the ignition process, HCCI can be controlled to achieve gasoline engine-like emissions along with diesel engine-like efficiency. In fact, HCCI engines have been shown to achieve extremely low levels of NOx emissions without an aftertreatment catalytic converter. The unburned hydrocarbon and carbon monoxide emissions are still high (due to lower peak temperatures), as in gasoline engines, and must still be treated to meet automotive emission regulations.

To summarize the development of the HCCI technology, Onishi, et al. proposed new combustion concept with two-stroke cycle gasoline engine in 1979 [126]. Najt, et al. tested the first HCCI four-stroke engine in 1983 [127]. Ryan, et al. showed that diesel-HCCI had a potential to achieve ultra low NOx and PM emission with high thermal efficiency [128]. Yanagihara, et al. proposed the UNIBUS concept [129] and showed that PCCI combustion was able to control start of combustion and achieve very low NOx and PM emission at medium load. They introduced this concept to a production vehicle. Okude, et al. showed that high-load PCCI combustion was achieved with controlled split injection and reduced compression ratio [130]. Hardy, et al. achieved medium load high-speed PCCI operation with complying with US2010 emissions regulation for heavy-duty on-road diesel engines [131].

According to Fuquan et al. [132], HCCI provides up to a 15-percent fuel savings, while meeting current emissions standards. Since HCCI engines are fuel-lean, they can operate at a Diesel-like compression ratios (>15), thus achieving higher efficiencies than conventional spark-ignited gasoline engines

Homogeneous mixing of fuel and air leads to cleaner combustion and lower emissions. In fact, because peak temperatures are significantly lower than in typical spark ignited engines, NOx levels are almost negligible. Additionally, as Jurgen et al. [133] state, the premixed lean mixture does not produce soot.

Baumgarten [134] investigates that in regards to gasoline engines, the omission of throttle losses improves HCCI efficiency.

Despite several advantages stated above, there are few unsolved problems with HCCI engines. High in-cylinder peak pressures may cause damage to the engine, while high heat release and pressure rise rates contribute to engine wear. Rolf et al. [135] study the difficulty of the auto-ignition event control, unlike the ignition event in spark ignition (SI) and Diesel engines, which are controlled by spark plugs and in-cylinder fuel injectors, respectively.

Stanglmaier [136] shows that HCCI engines have a small power range, constrained at low loads by lean flammability limits and high loads by in-cylinder pressure restrictions. Furthermore, Aceves et al. [137] investigates that CO and HC pre-catalyst emissions are higher than a typical spark ignition engine, caused by incomplete oxidation due to the rapid combustion event and low in-cylinder temperatures and trapped crevice gases, respectively.

Controlling HCCI is a major hurdle to more widespread commercialization. HCCI is more difficult to control than other popular modern combustion engines, such as Spark Ignition (SI) and Diesel. In a typical gasoline engine, a spark is used to ignite the pre-mixed fuel and air. In Diesel engines, combustion begins when the fuel is injected into compressed air. In both cases, the timing of combustion is explicitly controlled. In an HCCI engine, however, the homogeneous mixture of fuel and air is compressed and combustion begins whenever the appropriate conditions are reached. This means that there is no well-defined combustion initiator that can be directly controlled. Engines can be designed so that the ignition conditions occur at a desirable timing. To achieve dynamic operation in an HCCI engine, the control system must change the conditions that induce combustion. Thus, the engine must control either one of the compression ratio, inducted gas temperature, inducted gas pressure, fuel-air ratio, or quantity of retained or re-inducted exhaust. Several control approaches are discussed below.

There are several methods of modulating both the geometric and effective compression ratio. The geometric compression ratio can be changed with a movable plunger at the top of the cylinder head. The effective compression ratio can be reduced from the geometric ratio by closing the intake valve either very late or very early with some form of variable valve actuation (i.e. variable valve timing permitting Miller cycle). Both of the approaches mentioned above require some amounts of energy to achieve fast responses. Additionally, implementation is expensive. The effect of compression ratio on HCCI combustion has also been studied extensively, as in Pitz et al. [138] and Christensen et al. [139] studies. Control of an HCCI engine using variable compression ratio strategies has been shown effective. According to Haraldsson et al. [140], higher CR can replace inlet air preheating. Brake thermal efficiency increases and NOx emissions decrease, with CR up to 17:1. The drawback of increasing CR is increased CO emission, due to the faster expansion, i.e. shorter reaction time. Cylinder size has an effect on the need for inlet air heating and CR, due to cylinder wall heat losses. Smaller combustion chamber volume to area ratio increases heat losses and the need for inlet air heating and higher CR.

Variable valve actuation (VVA) has been proven to extend the HCCI operating region by giving finer control over the temperature-pressure-time history within the combustion chamber. VVA can achieve this via two distinct methods:

- Controlling the effective compression ratio: A variable duration VVA system on intake can control the point at which the intake valve closes. If this is retarded past bottom dead center (BDC), then the compression ratio will change, altering the in-cylinder pressure-time history prior to combustion.
- Controlling the amount of hot exhaust gas retained in the combustion chamber: A VVA system can be used to control the amount of hot internal exhaust gas recirculation (EGR) within the combustion chamber. This can be achieved with several methods, including valve re-opening and changes in valve overlap. By balancing the percentage of cooled external EGR with the hot internal EGR generated by a VVA system, it may be possible to control the in-cylinder temperature.

While electro-hydraulic and camless VVA systems can be used to give a great deal of control over the valve event, the componentry for such systems is currently complicated and expensive. Mechanical variable lift and duration systems, however, although still being more complex than a standard valvetrain, are far cheaper and less complicated. If the desired VVA characteristic is known, then it is relatively simple to configure such systems to achieve the necessary control over the valve lift curve.

It is well-known that high EGR ratio is effective in controlling HCCI combustion. As EGR ratio increases, maximum cylinder pressure increases, ROHR peak decreases and ROHR peak timing is retarded. As EGR ratio increases, NOx decreases, because dilution by EGR gas leads to lower combustion temperatures. Smoke is extremely low on this test condition regardless of EGR ratio. Increase in EGR ratio also leads to improve ISFC. Because heat release occurs later as higher EGR ratio, ROHR peak is shifted toward TDC just like constant volume cycle.

Kodama et al. [141] investigates the control strategy effects on the HCCI combustion in heavy-duty engines. Figure 4.9 shows effect of EGR ratio on cylinder pressure and ROHR, where Figure 4.10 shows effect of EGR ratio on engine performance, as summarized above. From the viewpoint of extending HCCI operation, high EGR ratio is more desirable to prevent high ROHR peak However, extremely high EGR ratio causes misfire and deterioration of ISFC. It also requires higher intake manifold pressure to keep AFR constant. From these results, desirable EGR ratio is about 50-60% in medium and high load.

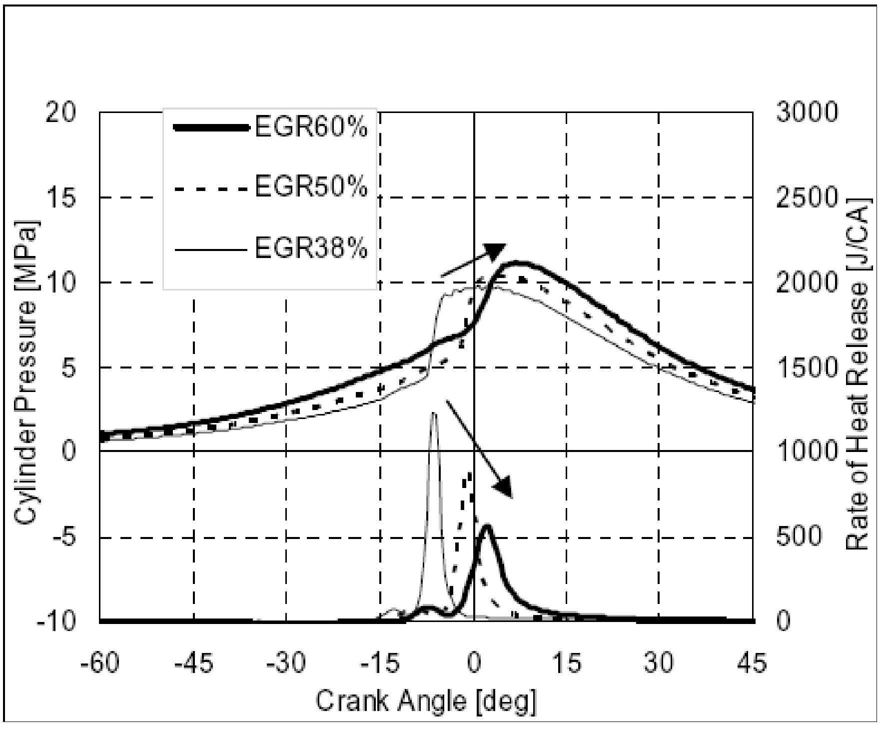

Figure 4.9 : Effect of EGR ratio on cylinder pressure and ROHR

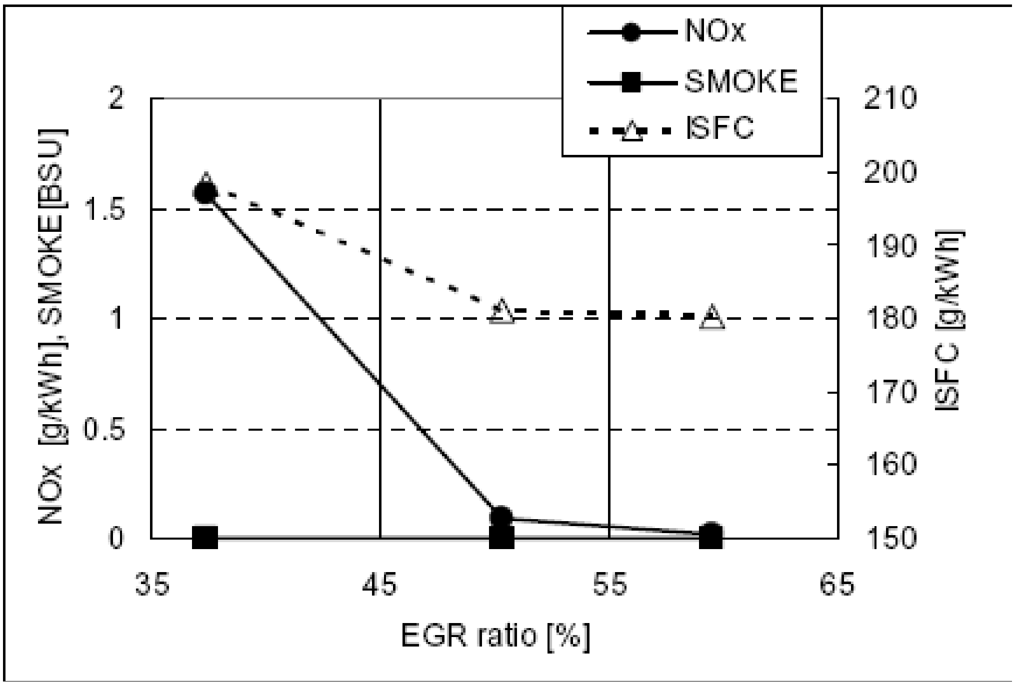

Figure 4.10 : Effect of EGR ratio on engine performance

Kodama reduced CR from 16.8 to 13 and 10 to increase load with peak cylinder pressure within the allowable limit. Figure 4.11 shows cylinder pressure and ROHR with CR of 16.8 and 13 at 20% load. In case of 16.8 CR, maximum cylinder pressure was about 18 MPa, which was upper limit of the test engine. To extend operation range, CR was reduced from 16.8 to 13. Maximum cylinder pressure and ROHR peak was substantially decreased and ROHR peak timing was retarded. However, even with 13 CR, achieved operation range was up to 50% load when maximum cylinder pressure reached to 18MPa.

As a next step, CR was further reduced from 13 to 10. Figure 4.12 shows the comparison between CR of 13 and 10 at 50% load. Maximum cylinder pressure was reduced from 18 to 12.5 MPa and ROHR peak became low, which allowed operating over 50% load. However, it was stated that engine startability became worse than before.

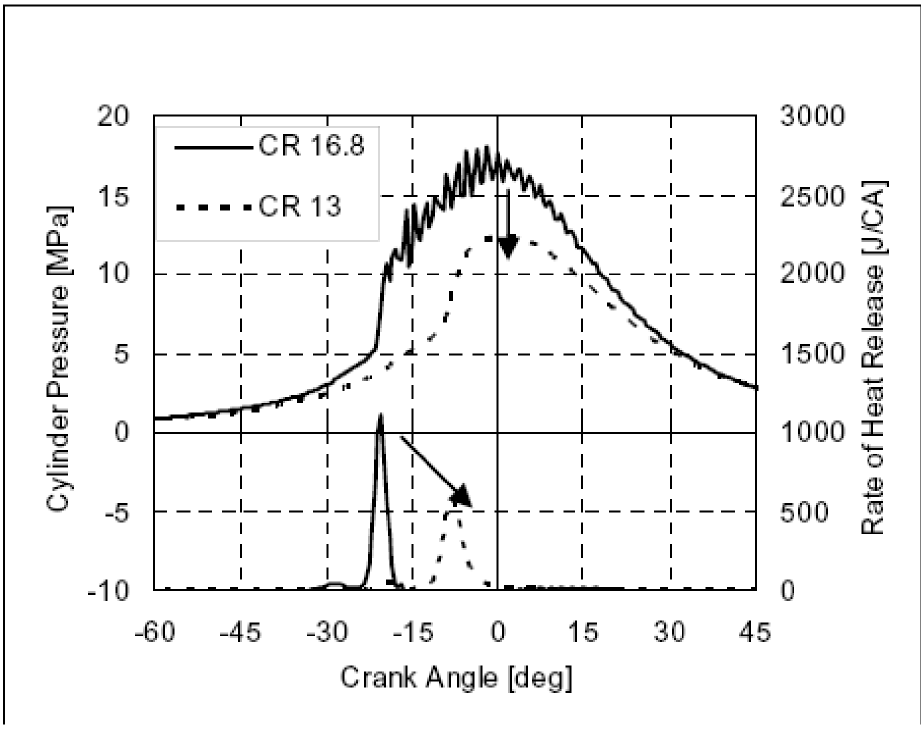

Figure 4.11 : Effect of CR on cylinder pressure and ROHR for CR 16.8 and 13

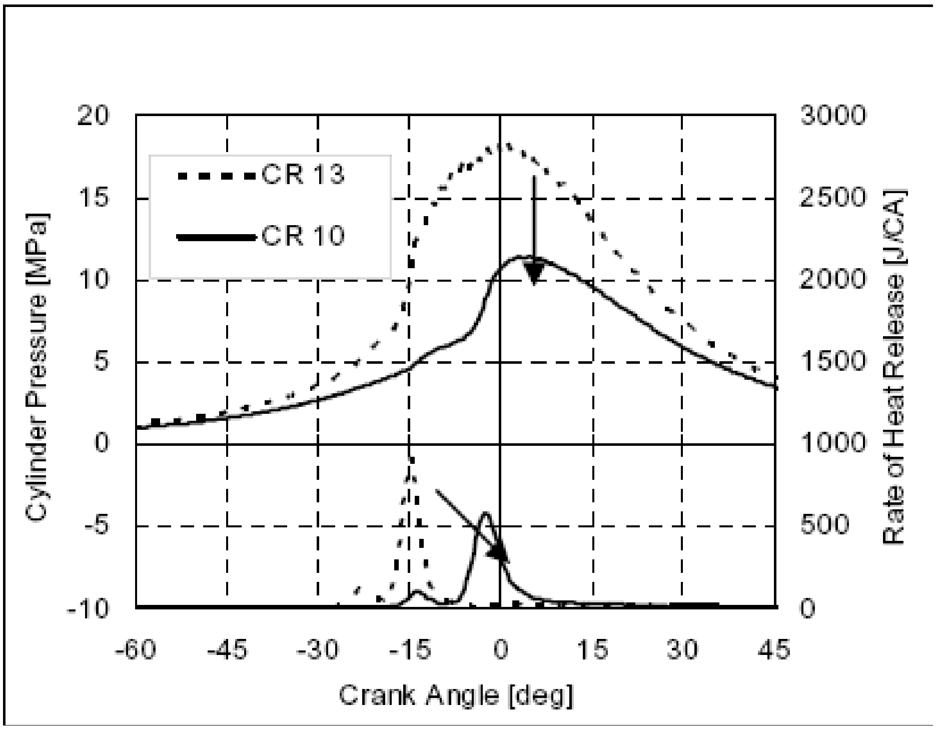

Figure 4.12 : Effect of CR on cylinder pressure and ROHR for CR 13 and 10

In Kodama's study, the effect of intake valve closing was also investigated, as IVC is considered another key variable for HCCI operation range [142].

Late or early IVC timing is desirable in terms of reducing maximum cylinder pressure and ROHR peak within allowable limit for extending operation range.

However, in medium and low load, maximum cylinder pressure and ROHR peak are low relatively; hence it is desirable to control IVC timing so that ISFC becomes better. When controlling IVC timing in relation to engine condition, VVA is considered an effective device because of changing maximum cylinder pressure and ROHR peak more quickly than EGR ratio and CR.

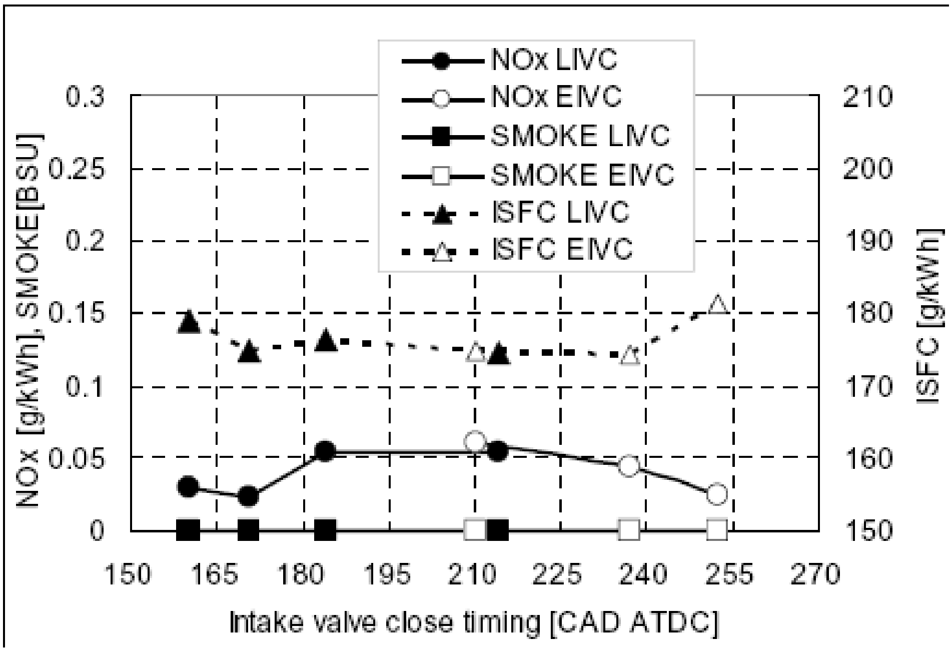

Figure 4.13 : Effect of EIVC and LIVC on engine performance

Figure 4.13 shows effect of EIVC and LIVC on engine performance. When IVC timing 30 CAD later or earlier than standard timing, NOx was decreased. Smoke remained almost zero on this test condition regardless of IVC timing. From a view point which is better between EIVC and LIVC, these tests revealed that ISFC of EIVC was somewhat better than LIVC at same NOx level.

4.4 Hybrid Electric Vehicles

Due to the high energy density and low cost of petroleum, ICE has been the power source of choice for vehicle propulsion. An acceptable range and performance are achieved even with peak tank to wheel efficiency of less than 30%. However, rising prices and environmental concerns about the impact of petroleum combustion have led to a push for the development of more efficient and less polluting vehicles. Drivetrain electrification is seen as the short-term means to reduce oil consumption. Simultaneously, the number and electric power draw of "convenience" hotel loads are increasing, leading to larger energy consumption. Both of these competing requirements make a larger energy storage unit necessary.

A hybrid system is defined as “a system with 2 or more means of propulsion of differing operating principle operated in combination with each other” [143,144]. Practical developments have been achieved with combinations of internal combustion engines, electric motors and hydraulic motors; but given the background development of electric vehicles, electric motors, batteries and their controlling technologies developed rapidly, and ICE-electric hybrids are currently becoming mainstream.

In a hybrid vehicle, by running these two different power sources at different conditions, a wide range of working modes and power train systems can be designed. However, optimizing these two power sources to make them run in the most efficient operating conditions is also a very complicated problem. Because of these, American National Renewable Energy Laboratory (NREL) and Argonne National Laboratory [145] develop a simulation software called ADVISOR and PSAT. In literature there are also too many papers about fuel consumptions and exhaust emissions of different hybrid vehicle designs which these software calculates.

Engine maps, which are shown in Figure 4.1, show the contradictions between fuel economies and exhaust emissions. In the software ADVISOR; vehicle parameters, exhaust emission and fuel consumption maps are given as inputs, and running simulations in predicted drive cycles give results about exhaust emissions and fuel consumptions. The help of these results can do optimization of control strategies easily.

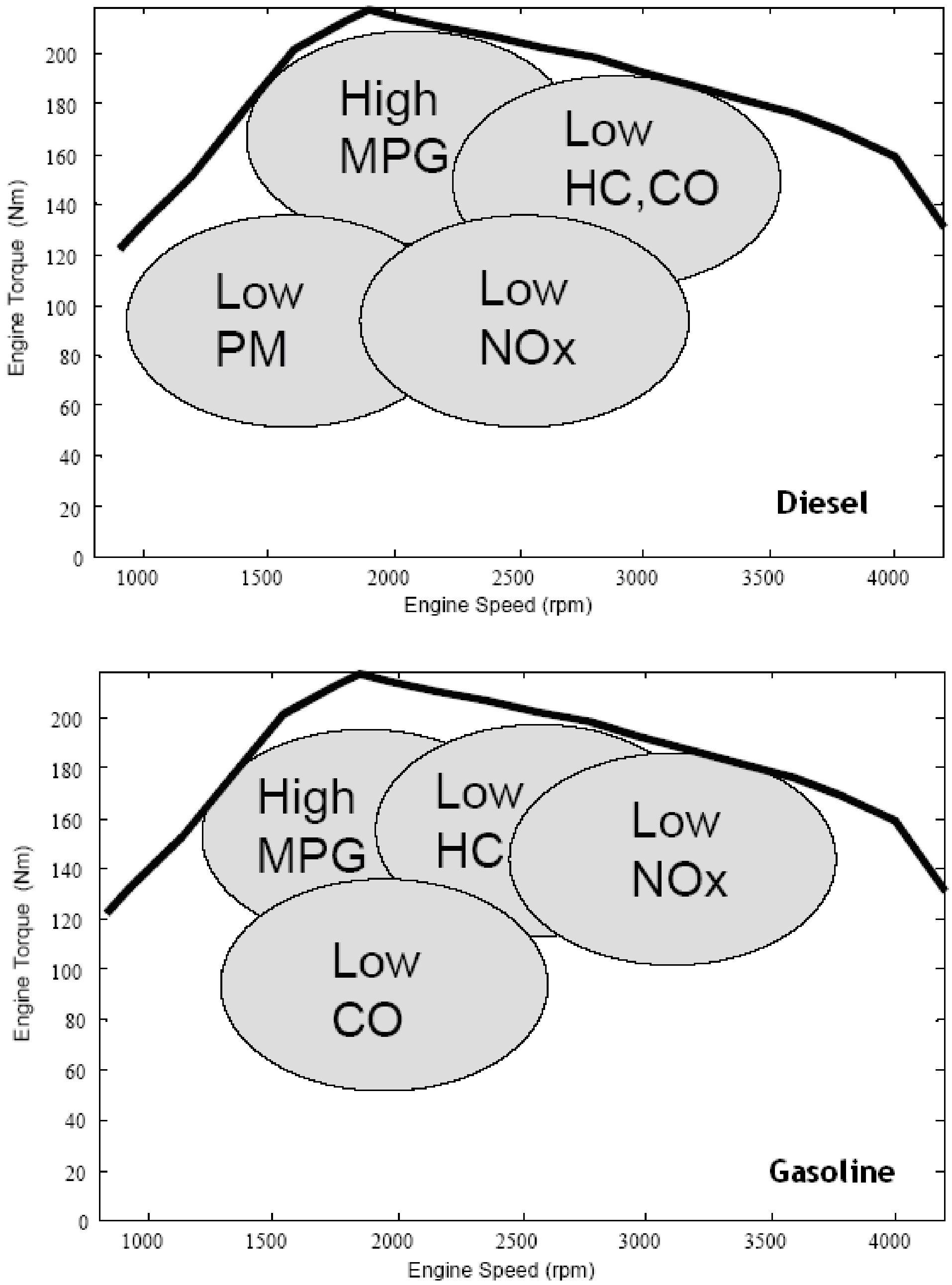

Figure 4.14 : Contradiction between fuel economy and exhaust emissions

4.4.1 Hybrid Classifications

4.4.1.1 Classification According to Their Driveline

A series configuration is the first attempt to circumvent the large size of batteries for an extended travel. This is achieved by an ICE, dedicated solely to the purpose of charging batteries. The ICE (being detached from wheels) working point is chosen freely. The main drawback of this configuration is reduced efficiency as the energy losses are encountered twice. In contrast, in a parallel HEV, the electric motor and

ICE both can drive the vehicle in parallel. Due to fewer power conversions, vehicle efficiency is expected to be higher. In this configuration, four modes of operation are possible: pure electrical, pure ICE and power operation with both the sources with batteries being drained or being charged in regenerative way. A single motor capable of doubling up as a generator also suffices. Figure 4.15 and Figure 4.16 shows the structure of a parallel and a series hybrid electric vehicle, respectively.

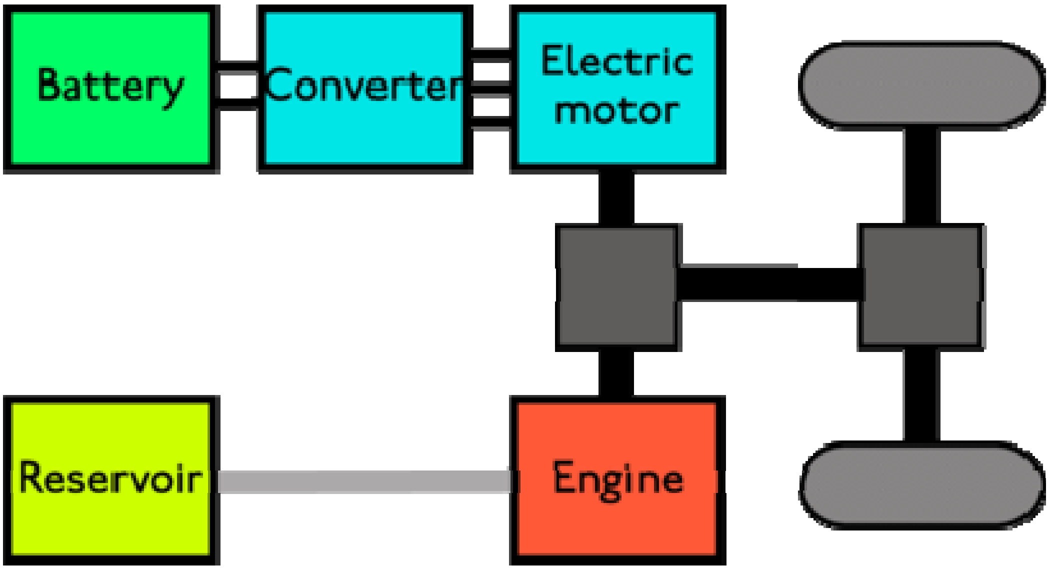

Figure 4.15 : Structure of a parallel hybrid electric vehicle

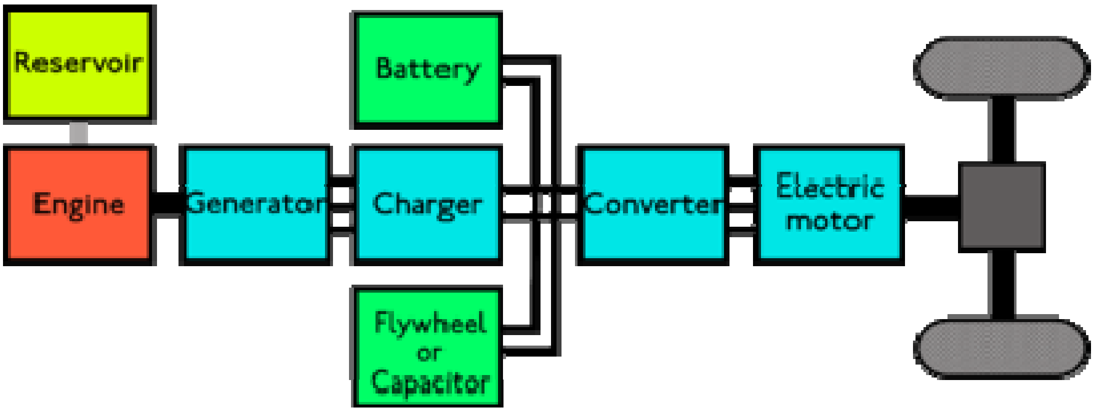

Figure 4.16 : Structure of a series hybrid vehicle

A variant of parallel HEV – the power split hybrid comprises of a planetary gearbox connecting the two electrical machines and the ICE. The traction motor is connected to the ring wheel, the generator to the sun gear and finally the ICE is connected to the carrier and thereby possible to switch off and the vehicle can drive in a pure electric mode. Owing to the connection of the sun wheel and the planet wheels, the speed of the engine can simply be adjusted by varying the speed of the generator. The drawback with this arrangement is the need for two electrical machines and inability to transmit the entire ICE torque to the output shaft, hence the name power split [146].

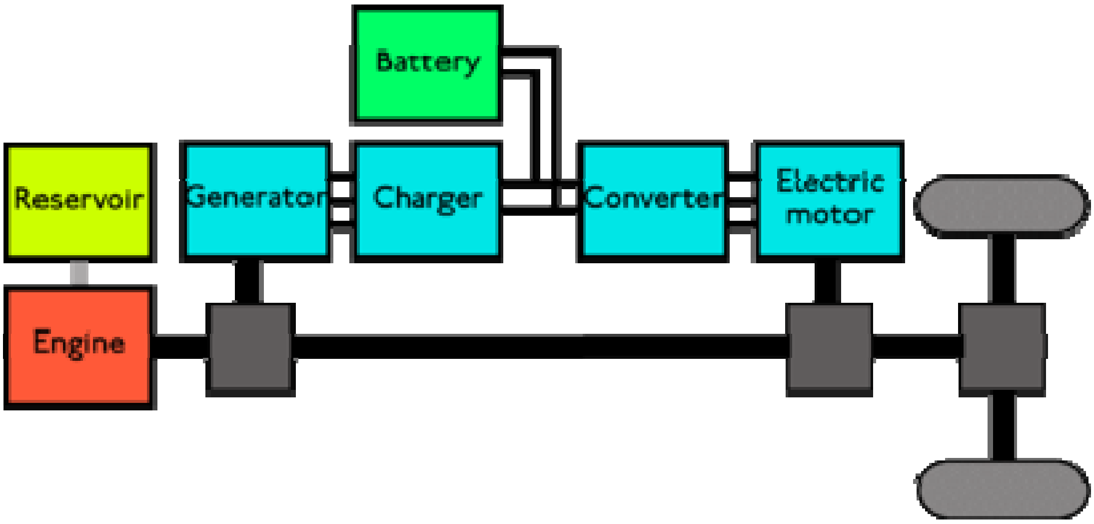

Figure 4.17 : Structure of a combined hybrid electric vehicle

Figure 4.17 shows the structure of a power split hybrid electric vehicle.

The technical literature describing advances in HEVs is mostly limited to patent databases. Bowen [147] and Sherman [148] both describe transmissions, which use torque converter to connect ICE to transmission. Such torque converters are known to be inefficient. Bowan [147] and other inventors [149-155] describe the use of Power Split Hybrid configuration for HEVs, whose disadvantages have been mentioned above.

4.4.1.2 Classification by Degree of Hybridization

A full hybrid, sometimes also called a strong hybrid, is a vehicle that can run on just the engine, just the batteries, or a combination of both large, high-capacity battery pack is needed for battery-only operation. These vehicles have a split power path that allows more flexibility in the drivetrain by interconverting mechanical and electrical power, at some cost in complexity. To balance the forces from each portion, the vehicles use a differential-style linkage between the engine and motor connected to the head end of the transmission.

Power assist hybrids use the engine for primary power, with a torque-boosting electric motor also connected to a largely conventional powertrain. The electric motor, mounted between the engine and transmission, is essentially a very large starter motor, which operates not only when the engine needs to be turned over, but also when the driver "steps on the gas" and requires extra power. The electric motor may also be used to re-start the combustion engine, deriving the same benefits from shutting down the main engine at idle, while the enhanced battery system is used to power accessories.

Mild hybrids are essentially conventional vehicles with oversized starter motors, allowing the engine to be turned off whenever the car is coasting, braking, or stopped, yet restart quickly and cleanly. Accessories can continue to run on electrical power while the engine is off, and as in other hybrid designs, the motor is used for regenerative braking to recapture energy. The larger motor is used to spin up the engine to operating rpm speeds before injecting any fuel.

A plug-in hybrid electric vehicle (PHEV) has two defining characteristics,

- It can be plugged in to an electrical outlet to be charged,
- It has some range that can be traveled on the energy it stored while plugged in.

They are full hybrid, able to run in electric-only mode, with larger batteries and the ability to recharge from the electric power grid and can be parallel or series hybrid designs. Their main benefit is that they can be gasoline-independent for daily commuting, but also have the extended range of a hybrid for long trips. They can also be multi-fuel, with the electric power supplemented by diesel, biodiesel, or hydrogen. The "well-to-wheel" efficiency and emissions of PHEVs compared to gasoline hybrids depends on the energy sources of the grid.

In general, hybrid vehicles improve fuel economy in four different ways. First, with the existence of the secondary power source (the battery pack and electric motor), hybrid vehicles require a substantially smaller ICE than do conventional vehicles, and they can reduce reliance on the ICE when it is least efficient (e.g., in low-speed, stop-and-go traffic). Second, because battery power is available, ICE engines can be turned off at idle, offering a 5-10 percent improvement in fuel economy [156]. Third, hybrids employ regenerative braking to capture much of the energy otherwise lost in braking. With a larger battery pack and motor, more energy can be recaptured, but increasing the size adds weight. Existing systems can recapture most of the braking energy, which results in greater fuel economy gains. Fourth, most hybrids use more efficient electric pumps, which adds to a significant reduction in accessory loads.

Yet in exchange for their benefits, current hybrids have considerably greater cost and complexity, less acceleration if the IC engine is downsized, greater weight, and questions about their long-term reliability. Their higher cost may prevent HEVs from eventually dominating the new car market. There are examples where conventional cars can achieve the same or better gas mileage and/or emissions ratings as hybrids, raising questions over whether the benefits of hybrids are really worth the cost. Yet, the relative benefits of improved gas mileage versus costs could be greater on larger vehicles, like SUVs and large pickup trucks. Finally, HEVs are considered stepping-stones from today's gasoline-powered cars to fuel cells and a hydrogen economy [156].

Harris and Ventimeglia [157] express that the two areas of technology bottlenecks for hybrid electric vehicles are energy storage and energy conversion.

Batteries are the prevalent ESS in the market due to their low cost, portability, and ruggedness. They produce electricity by releasing the potential energy stored in the chemicals of the battery.

Fetcenko et al. [158] study NiMH batteries, which are composed of nickel hydroxide on the positive electrode and a multicomponent, engineered alloy consisting of vanadium, titanium, nickel, and other metals on the negative electrode. This technology has experienced great advances in the past 15 years, as evidenced by a threefold increase in energy and tenfold increase in specific power. The distinct advantages of the technology include safe operation at high voltage; excellent volumetric energy and power; tolerance to abusive overcharge and overdischarge; and excellent thermal properties.

In the past, main hurdles to widespread use of the technology were limited capacity at low temperatures and limited charge acceptance at elevated temperatures. Progress has been made in improving the performance of the batteries at temperature extremes. On the other hand, the issue with price is a more serious one. The raw materials used are very expensive and will not become much cheaper in mass production. To keep NiMH technology competitive in the long term, more frugal use of precious metals or the use of cheaper substitutes is a must.

Li-ion batteries are an attractive technology for HEV applications thanks to their high energy density, four times the lead-acid batteries, and high cell voltage

[159,160]. However, Li-ion technology has a thermal stability problem, especially for larger cells that are a necessity for HEV applications. In addition, the performance of Li-Ion batteries erodes drastically at extreme temperatures (above 65ºC or below 0ºC) [160,161]. The chemical reaction in Li-ion cells is highly exothermic when discharged and endothermic when charged. Therefore, there is a net accumulation of heat at the center of the battery pack since heat cannot be dissipated effectively. Al-Hallaj and Selman [162] investigate that temperature variations lead to different internal resistances for different cells. This leads to uneven discharge of the cells and, eventually, thermal runaway. To avoid thermal runaway in Li-ion cells, a good thermal management system must be designed. All of the solutions offered thus far, to the best of our knowledge, incorporate forced circulation of air or liquid [163]. This complicates the thermal management system, while adding to the cost.

To summarize, as in Chalk and Miller's study, the promising aspects of the Li-Ion chemistry are its low memory effect, high specific energy of 100 Wh/kg, high specific power of 300 W/kg, and battery life of 1000 cycles. The key barriers are the following: calendar life, cost, operation at temperature extremes, and abuse tolerance. A breakthrough in the development of advanced electrodes is needed to further increase the specific energy [164].

A step for solution first proposed by Lukic et al. [165] and then by Al-Hallaj and Selman [166], is to use a Phase Change Material (PCM) for thermal management. Here, each cell of the battery pack would be surrounded by PCM. When the battery is discharging, the PCM absorbs the heat; and, when it is charging, the PCM returns heat to the pack. For a well-designed battery pack, the temperature of the PCM will be uniform throughout.

Capacitors store electric energy by physically separating and accumulating unlike charges. The charges are stored on two parallel plates divided by an insulator. UCs are special capacitors which are able to store a substantial amount of energy at a low voltage. This is achieved by having a high surface area and high permittivity dielectric. These design parameters lead to a low-voltage withstand capability, according to Ribeiro et al. [167].

Current trends indicate that higher energy densities are achievable with a carbon composite electrode using an organic electrolyte rather than carbon/metal fiber composite electrode devices with an aqueous electrolyte. UC stores energy physically separating unlike charges. This has a major implication on the properties of UCs such as cycle life, efficiency, energy and power density, and voltage. UCs have a long cycle life due to the fact that (ideally) there are no chemical changes on the electrodes in normal operation. Efficiency is superior: it is only a function of the ohmic resistance of the conducting path. Power density is exceptional, since the charges are physically stored on the electrodes. Conversely, energy density is low since the electrons are not bound by chemical reactions. This lack of chemical bonding also implies that the UC can be completely discharged.

There is also research regarding increasing the surface area of the electrodes to further improve energy storage capability. Finally, researchers such as Lam and Louey [168] are making efforts to combine the properties of a capacitor and a battery into one device.

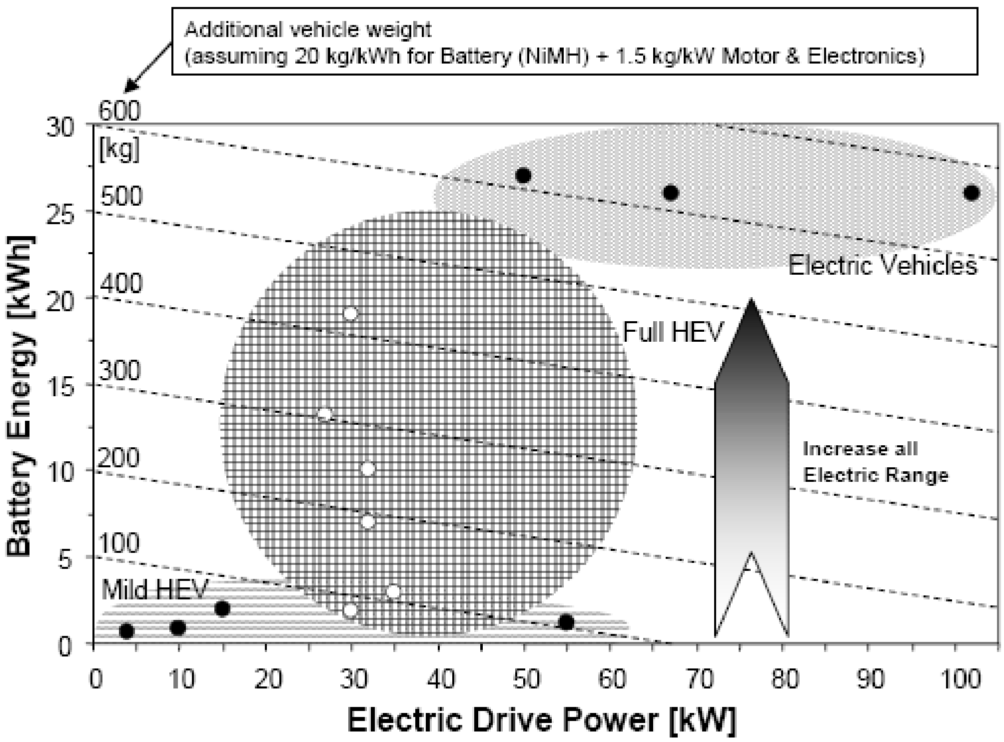

Figure 4.18 : Hybrid electric vehicles – battery energy vs. electric drive power

Battery capacity and electric motor power are shown for various production and concept electric vehicles in Figure 4.18 above, taken from Pischinger, Lang and Kemper's [169] study.

Assuming competitive values for specific weight of battery (20 kg/kWh) and electric motor/power electronics (1.5 kg/kW) lines for constant additional vehicle weight are included in the diagram. Battery capacity, which is the dominant factor for the all electric driving range, is the major contributor to vehicle weight increase. Additional vehicle weight, in return, has an adverse effect on fuel economy. A drawback of about 0.4l / 100kg can be expected. Cost increase runs in the same direction. Therefore, a large all electric driving range will not be suitable for mass production unless battery technology is improved considerably.

Brake energy recovery is one major potential of fuel economy improvement to be achieved by hybrid operation. Here, moderate electric motor power with low battery storage capacity is sufficient to achieve considerable benefits. Even though mild hybrids with a ratio of battery capacity to electric power of 1/20 kWh/kW are sufficient, the weight increase with increasing electric power is considerable. Therefore, the total achievable benefit can only be increased up to a certain extent, as shown in Figure 4.19.

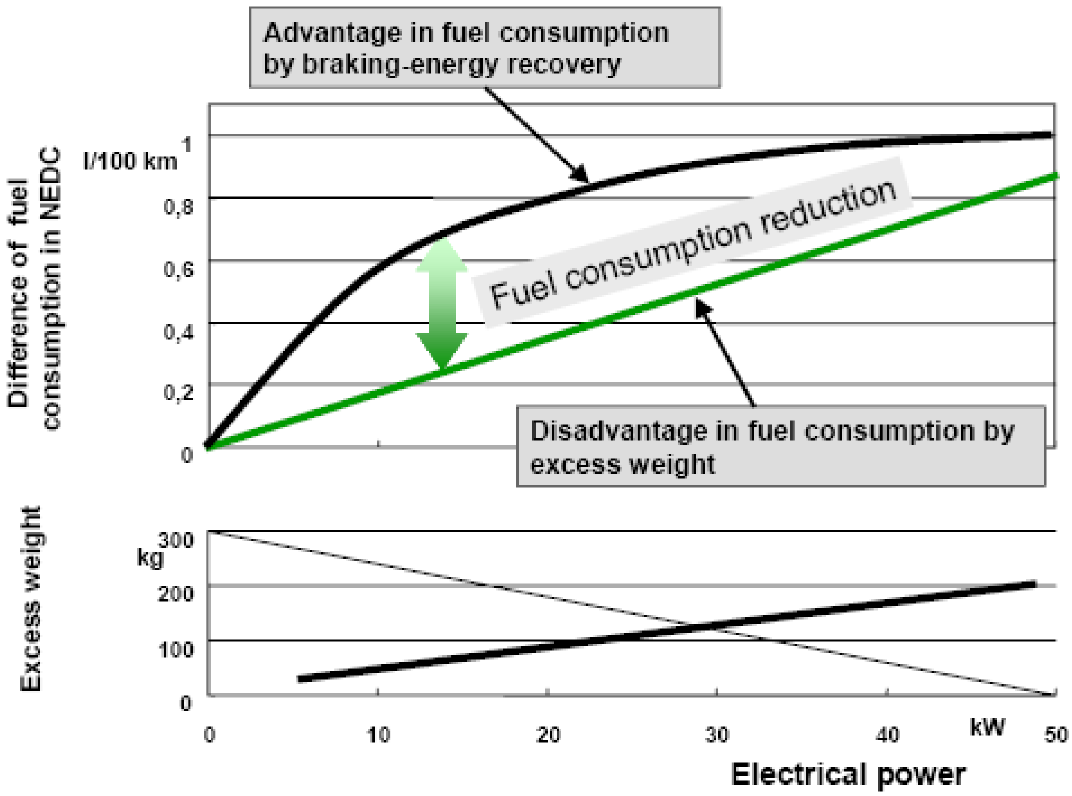

Figure 4.19 : Fuel consumption improvement by braking energy recovery [169]

Hybrid vehicles offer a unique advantage by collecting the vehicle kinetic energy during vehicle deceleration. In addition, operating the engine in most thermodynamically efficient condition and to transfer the engine energy to wheels in most efficient manner are also critical to achieve real improvements in fuel economy.

Hybrids have made great progress, but their future as a competitive alternative power technology depends on overcoming several remaining challenges including:

- Improving battery technology by reducing cost and increasing power density and durability,
- Lowering the cost of electric motors and motor controllers,
- Using advanced gasoline and diesel engine technology,
- Cutting the weight and improving performance,
- Reducing the complexity,
- Cutting the overall price.

4.5 Hydrogen as a Fuel

The present energy situation has stimulated active research interest in non-petroleum, renewable and non-polluting fuels. Much of the present world's energy demand is being met by the exhaustible fossil fuels (natural gas, oil and coal), which are also the material basis for the chemical industry. It is well known that combustion of fossil fuel causes air pollution in cities and acid rain, which damage forests, and leads to the build-up of carbon dioxide, changing the heat balance of earth. In recent years, the concern for cleaner air, along with stricter air pollution regulations and the desire to reduce the dependency on fossil fuels have rekindled the interest in hydrogen as an automobile fuel. Hydrogen has been considered for many years as an alternative fuel for the future to replace the fuels derived from the rapidly depleting petroleum resources. Generally, the arguments for and against hydrogen as an alternative fuel is based on some of its characteristics.

Hydrogen is by far the most abundant element in the universe, making up 75% of the mass of all visible matter in stars and galaxies. Hydrogen can be produced from water. The electrolysis of water is one of the most obvious sources of hydrogen. Its advantages are the possible recycling characteristics coupled with the production of high purity fuel.

However, electrolysis requires electrical work, which is of much higher quality than heat or internal energy and hence is very expensive. Hence, fossil fuels are the common sources of hydrogen at present. These fossil fuels can be poor quality carbon or hydrocarbon fuels and carbon monoxide is necessarily associated with the hydrogen produced. Sakthinathan and Jeyachandran [170] study other ways to produce hydrogen as well as a new approach to use hydrogen as a fuel. Renewable sources of energy such as photovoltaic cells, wind, hydro and geothermal are increasingly being used to produce electricity. That electricity, in turn, can be used in a process called electrolysis, to split water into hydrogen and oxygen. Hydrogen can also be extracted from energy crops and agricultural waste, so called biomass. Once produced, the hydrogen can be stored and used, when needed, to generate electricity.

As the normal boiling point is very low for hydrogen, it cannot be stored conveniently like gasoline. Furthermore, as the critical temperature is also very low, hydrogen cannot be liquefied easily. Very low temperature refrigeration is required to liquefy hydrogen and to maintain it in the liquid phase. An alternative method of storage is in the gaseous phase in highpressure cylinders. The compression of the gas to such high pressures requires the expenditure of much expensive compression work and the provision of the necessary infrastructure. Also, these hydrogen gas cylinders would add significantly to the total weight, cost and bulkiness of the fuel installation. Padiyar [171] gives the combustion characteristics of hydrogen as in Table 4.1.

Gaseous hydrogen can be transported in pipelines or under high pressure in steel cylinders. Hydrogen becomes a liquid if cooled below its boiling point of 20 K (-423°F). Liquid hydrogen is transported by truck or rail in highly insulated containers. Pipeline transmission is the cheapest and most energy efficiency way to move gaseous hydrogen over long distances. Even if the end-use requires liquid hydrogen, it is better to pipe gaseous hydrogen to a liquefaction facility located near the demand than to use truck or rail delivery. Long distance truck delivery is used today only because the demand is not large or concentrated enough to justify a pipeline, as Kukkonen investigates in his study [172].

Hydrogen can be carried on board vehicles and installations in the form of various metallic hydrides that would permit the controlled release of hydrogen by supplying heat, often from the engine exhaust gas or its cooling water. These methods are of limited use as they add much cost and weight while reducing the flexibility of the fuel system and contributing to an increase in undesirable emissions. In this research work, an approach is attempted to store the hydrogen in the nano-materials as a solid storage device.

Table 4.1 : Combustion characteristics of hydrogen fuel.

Properties	Hydrogen	Gasoline
Flammabilty limits [% by volume]	4-75	1,1-3,3
Minimum ignition energy [mJ]	0,02	0,24
Laminar flame speed at NTP [m/s]	1,90	0,37
Adiabatic flame temperature [K]	2318	2277
Auto ignition temperature [K]	858	340
Queching gap at NTP [mm]	0,64	2,0
Density at NTP [g/m^3]	83,764	4400
Calorific value [kJ/kg]	141.790	47.300
Normal boiling point (NBP) temperature [K]	20,268	310-478
Critical temperature[K]	32,976	540-569

There are three potentially practical ways to store hydrogen in an automobile: as a gas "dissolved" in a metal (metal hydride), as a cryogenic liquid or as a constituent in a chemical compound such as methanol (CH_3OH). Strickland [173] shows that the hydride storage is the simplest and the safest, but the hydrides available today store only 1 to 5% hydrogen by weight. The hydride fuel system for an ICE vehicle can increase vehicle weight by more than 50% and result in a severe fuel economy penalty. Liquid hydrogen is light, but due to its low energy density occupies three times as much volume as gasoline. Cryogenic fueling and storage present problems of fuel boil off, and the increased fuel volume raises questions about safety. The main problem, however is the high dollar and energy cost of liquefaction.

The fire and explosion hazards involved with hydrogen are qualitatively the same as those encountered with natural gas and gasoline. Hydrogen is more dangerous than these fuels in some circumstances and less dangerous in others [174-177]. Metal hydride storage on a vehicle has the potential to be extraordinarily safe; much safer than gasoline. This is because the metal hydride is a stable system and the hydrogen is released only upon application of heat. Hord [177] conducted tests by firing incendiary bullets into several containers containing metal hydrides and in to a gasoline tank. In the worst case, a flare, one meter in diameter, was produced upon rupture and a small hydrogen flame burned for a short time. In contrast, the gasoline tank burned fiercely for 5 minutes.

As far as the environment is concerned, hydrogen can be the cleanest burning fuel available. The primary combustion product is water. Oxides of nitrogen (NOx) are produced when any fuel is burned in air. The amount of NOx produced depends on the flame temperatures encountered. With stoichiometric hydrogen/air mixtures, NOx emissions are high. However, hydrogen's wide flammability limits allow the use of lean mixtures with reduced temperatures and insignificant NOx emissions. Therefore the end-uses of hydrogen generate little pollution and any environmental problems associated with hydrogen are concentrated in the production phase [171].

Hydrogen offers many attributes as a transportation fuel. It can be derived from various sources. This diversity means that different geographic regions can obtain hydrogen from whatever feedstock is available which would tend to reduce concerns over regional energy security. Hydrogen is a "clean burning" fuel, contributing to significantly reduced local emissions where it is used. If hydrogen is derived from renewable resources, if carbon is successfully sequestered, or if environmentally benign nuclear power sources can be developed, the total environmental impact of hydrogen as a fuel would be minimal.

Establishing the required hydrogen retail infrastructure will be an immense and expensive proposition. From an auto manufacturer's perspective, the existence of an expansive refueling infrastructure is critical to management commitment to high volume vehicle production. Some, as well as Ford Motor Company [178], have estimated that hydrogen fuel will need to be available at 25-50% of urban and 50-70% of rural filling stations before consumers will feel confident enough to purchase a hydrogen vehicle. The estimated costs of creating this infrastructure exceed tens of billions of U.S. dollars.

Means for hydrogen transportation and delivery need to progress to the same extent as the gasoline distribution system today. Today's usual transport of compressed gaseous or liquid hydrogen by tube tanker trucks will have to be replaced by significantly higher capacity transportation systems that may require a mix of local, regional and central hydrogen production facilities feeding the transportation and delivery system. Similarly, international harmonization or homologation of hydrogen codes and standards is needed.

4.6 Hydrogen ICE

For the transportation sector, much of the discussion of hydrogen as a fuel has been centered on the fuel cell. While this is the most likely "end game" for sustainable transportation, in the shorter-term hydrogen is attractive since it can be efficiently burned in conventional internal combustion engines. Hydrogen has a wide combustion range, which means that hydrogen fueled engines can operate on a wider range of air-fuel mixtures than gasoline engines, and can run lean for more efficiency with minimal pre-ignition or knock.

Converting existing engines to run on hydrogen requires modifications to the engine such as new fuel injectors designed to handle hydrogen gas, revised ignition system, new high compression pistons, modifications to the engine controls software and adding a supercharger. These engine changes would leverage the large manufacturing infrastructure already in place to produce gasoline- and diesel-fueled engines, which can affordably be converted to run on hydrogen. In addition, key vehicle subsystems needed for fuel cell vehicles, such as on-board hydrogen storage, fuel handling, instrumentation and sensors, could be developed first on a hydrogen ICE vehicle.

Taking the hydrogen ICE vehicle one step further along the evolutionary path by adding a hybrid electric powertrain provides further efficiency improvements. Here again, technologies such as durable and efficient batteries, electric motors, electronic inverters/converters and controls developed for H_2ICE HEVs would also support development of fuel cell vehicles.

Thus, a H_2ICE could serve as a bridging action, providing significantly lower tailpipe emissions and better fuel efficiency, while helping to provide an economically viable path towards hydrogen fuel cell vehicles [156]. H_2ICEs could also help develop vehicular demand for the installation and expansion of a hydrogen refueling infrastructure, the lower cost of a H_2ICE means that for the same cost, more ICEs than fuel cell vehicles could be produced and put into the market.

Many issues must be resolved before hydrogen can become a viable fuel alternative. In general, for any new hydrogen fueled vehicle to be viable for high volume sales, it will need to provide equal or better function than a conventional vehicle at comparable cost very soon after public introduction. Although there will be a few "early implementers" who are willing to pay a premium price for new technologies, the automobile is becoming a commodity to customers who are uncompromising in their demand for performance, function, quality and affordability. The hydrogen vehicle is faced with many challenges, many of which will require technical breakthroughs rather than simply further development of existing technology:

H_2 storage provides the largest vehicular challenge to the viability of a hydrogen-fueled vehicle. A minimum of a 300-mile range is required which results in storage goals of [178],

- 2010: 2.0 kWh/kg (6 weight percent), 1.5 kWh/liter, $4/kWh
- 2015+: 3.0 kWh/kg (9 weight percent), 2.7 kWh/liter, $2

Technologies being investigated include compressed gaseous hydrogen tanks, chemical hydrides, metallic hydrides, and carbon nanotubes, but none can meet these aggressive targets yet. Because H_2ICEs are less efficient than fuel cells, their range will be somewhat less. This, however, was considered when the FreedomCAR Hydrogen Storage goals were set with the expectation that a storage system meeting the 2015 goals, in particular, will provide acceptable range to either customer.

Furthermore, as discussed in Section 4.5, establishing the required hydrogen retail infrastructure will be an immense and expensive proposition.

Hydrogen fueled ICEs have the potential for an increased engine efficiency, with a demonstrated indicated efficiency of 52% for a hydrogen fueled spark-ignition engine and a power generation efficiency of 49% for a hydrogen fueled compression-ignition engine, as shown by Tang et al. [179] and Akagawa et al., [180], respectively. Furthermore, Verhelst, Verstraeten and Sierens [181] investigates that hydrogen is a very versatile fuel, allowing several load control strategies for optimization of the efficiency and emissions (NOx) throughout the load range. The practical consequence is widely varying ranges for the equivalence ratio and recycled exhaust gas fraction (EGR), which is an important distinction between hydrogen engines and other homogeneous charge, spark ignition engines.

Hydrogen, by many of its properties, is inherently suited to SI engines. The wide ignition limits of hydrogen make it possible to use less throttling compared to the operation on gasoline. This reduces the pumping losses and increases the thermal efficiency.

The high burning velocity of hydrogen makes the engine operation to approach the ideal Otto cycle. It also enables the hydrogen SI engine to be operated at higher speeds. Hydrogen, by fast burning rates and slow pre-ignition reactivity, can have a high effective octane number. Therefore it is highly resistant to knocking even when combusted under very lean conditions.

The high auto-ignition temperature of hydrogen makes it knock resistant. But this makes it difficult to ignite a hydrogen/air mixture using heat alone without some additional ignition source. There is a substantial increase in the thermal efficiency due to the factors said above, but there is also a considerable loss of power due to hydrogen displacing a lot of air.

Less cyclic variations are encountered with hydrogen than with other fuels, even for very lean mixture operation. This leads to a reduction in emissions, improved efficiency, and a quieter and smoother operation of the engine. Hydrogen exhaust emission consists only of oxides of nitrogen and water vapor. Also, with lean operation the NOx level tends to be significantly smaller than those encountered with operation on diesel fuels.

Sakthinathan's study [170] investigates the modifications on a conventional (carbureted) SI engine as followed:

- The hydrogen was inducted into the inlet manifold after the carburetor with a T-pipe junction.
- The spark advance was reduced to 6° bTDC on account for the high rate of flame propagation of hydrogen fuel.
- The hot rated spark plug used for gasoline operation was replaced with cold rated spark plug for avoiding the pre-ignition of charge.
- The spark plug gap also reduced to 0.389 mm to reduce the spark intensity, since the hydrogen fuel requires less energy to ignite.
- Hydrogen stored at a pressure of 150 bar in a gas cylinder was reduced to 3.5 bar pressure through a pressure regulator.

- A flow meter is used to regulate the amount of hydrogen entering into the engine.
- Water filled flame trap was utilized to suppress any backfire from traveling to the hydrogen storage cylinder from the engine cylinder.

The results are summarized in Figure 4.20 and 4.21.

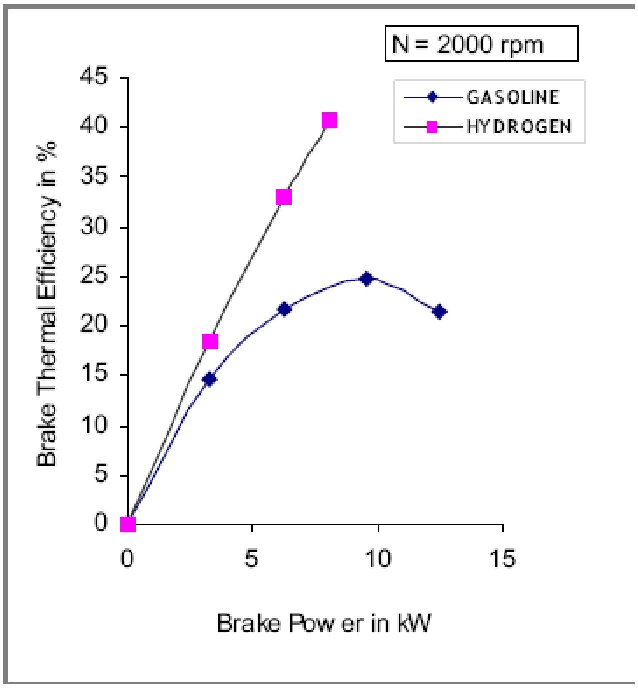

Figure 4.20 : Variation of brake thermal efficiency with brake power

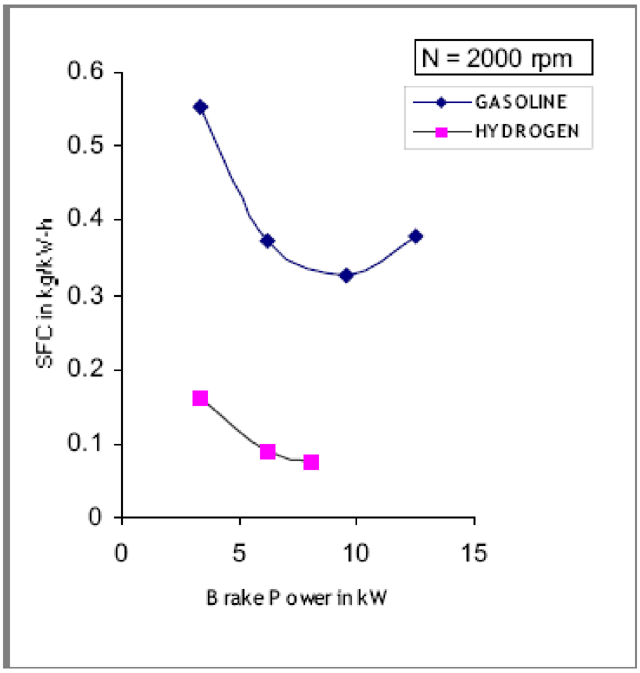

Figure 4.21 : Variation of specific fuel consumption with brake power

In the research, the maximum thermal efficiency for hydrogen-fueled operation is 40.87%, whereas it is 24.66% in the case of gasoline-fueled operation. Power developed by the engine running with hydrogen fuel was reduced by 35.29% compared with gasoline operation. That means the hydrogen engine develops only 65% of power when compared with gasoline engine. This is due to the less energy density of hydrogen fuel on volume basis.

It is also observed that the Specific Fuel Consumption (SFC) for hydrogen operation is lower over the entire region when compared to gasoline-fueled operation. The wide ignition limits of hydrogen make it possible to use less throttling compared to that during gasoline operation. This property helps in running the hydrogen engine at very lean mixtures, causing less specific fuel consumption in hydrogen engine.

Variation of NOx emissions with brake power is shown in Figure 4.22.

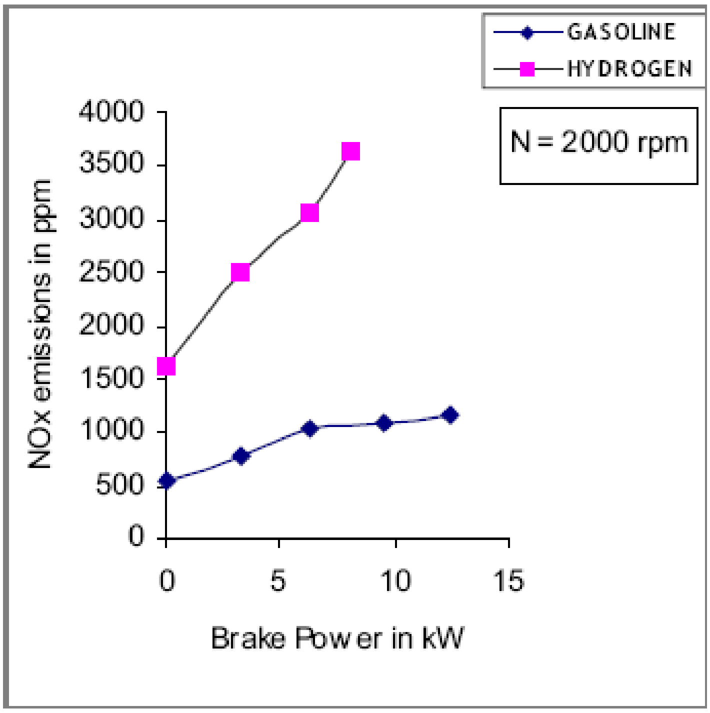

Figure 4.22 : Variation of NOx emissions with brake power

At 50% load the NOx emissions of hydrogen-fueled operation was 3068 ppm whereas it was 1025 ppm with gasoline-fueled operation. The high burning rates of hydrogen produce high pressures and temperatures during combustion in engines. This is the reason for high concentrations of oxides of nitrogen in the exhaust.

Hydrogen is a very interesting fuel when it comes to load control [181,183]. The high flame speeds of hydrogen mixtures and its wide flammability limits permit very lean operation. Where possible, wide-open throttle (WOT) operation is used, regulating load with the mixture richness (qualitative control) instead of volumetric regulation (quantitative control) and thus avoiding pumping losses [184].

In a search for high power densities, high efficiencies and most importantly, low NOx emissions, several combustion strategies have to be considered. One can choose for a lean burn strategy where the quality-based mixture control is used, but in this case NOx emissions are problematic for intermediate to high loads [185].

Verhelst et al. [186] investigate lean burn and stoichiometric operation with EGR for hydrogen fuelled ICEs. For low load conditions (power output or fuel flow rate) the lean burn strategy is definitely a better strategy as the raw NOx emissions are below the trade-off of acceptable NOx concentration (NOx ≤100 ppm) and the efficiency of the lean burn strategy is better than for the EGR strategy. At high EGR rates (for this engine around 35% EGR) the combustion becomes unstable (very high COV values), with also a decrease in power output and efficiency.

For all conditions, the raw NOx emissions are higher for the lean burn strategies. Previous tests [187-190] have shown that the efficiency of the TWC under lean burn conditions is poor. In the tests presented here, the efficiency of the TWC is also not very high, probably due to the location of the TWC, which is too far away from the engine exhaust (temperatures of the gases in the TWC just around the light-off temperature).

The H_2ICE offers near-zero emissions, using nearly conventional engine technology and creating a bridge to the hydrogen fuel economy. Current near-zero emission H_2ICEs have limited performance and, increasing the level of performance with today's gasoline ICE, could result in a NOx emission problem. Furthermore, the primary drawback with hydrogen fuel is insufficient storage. Acceleration performance is also an issue, because hydrogen is a very light gas, and it is difficult to achieve high volumetric efficiencies with it. Some other technical challenges include a need for significant sealing and tubing upgrades to prevent leaks, upgrading fuel injectors, improving cylinder head cooling and oil management (lubricants are still needed), and a special ventilation system.

Still, H_2ICE might be used to help create demand for hydrogen, allowing a nascent, yet cost effective hydrogen fuel infrastructure to develop before fuel cell power plants become commercially viable.

4.7 Fuel Cells

Concerns over the health impacts of small particle air pollution, climate change, oil supply security and oil price volatility, as described in early sections, have combined to encourage radical changes in automotive engine and fuel technologies that offer the potential for achieving near zero emissions of air pollutants and greenhouse gas (GHG) emissions, and diversification of the transport sector away from its present heavy reliance on oil. Cockroft and Owen [191] investigate that the hydrogen fuel cell vehicle is one technology that offers the potential to achieve all of these goals, provided the hydrogen is derived from a non-fossil fuel source or, if derived from a fossil fuel, CO_2 sequestration is a financially viable technology.

Fuel cells have provided electrical power on spacecraft since the 1960s, but it was only in the late 1990s that the automakers began to seriously consider them as a replacement for the internal combustion engine. Fuel cells offer higher fuel efficiency than IC engines can ever produce by using hydrogen and oxygen as fuel (not petroleum) while emitting only water vapor.

At their simplest, fuel cells are electrochemical devices that convert the chemical energy of gaseous hydrogen and oxygen into electricity, heat and water. They have three major advantages over current internal combustion engine technology in the transport sector:

- Gains in energy efficiency: The IEA [192] reports that the average overall on-road efficiency of gasoline and diesel internal combustion engines vehicles is at or below 23%, depending upon the specific engine technology. Average fuel consumption of a FCV ranges from a factor of two to three times lower than ICEs in highway and urban traffic respectively (with hybrid FCVs achieving an additional 10-15% efficiency), although these values are sensitive to the drive cycle characteristics. Both the efficiency of FCVs and ICEVs are expected to improve over time. A comparison of their future efficiency is complicated by a number of factors relating to the range of potential new technologies in vehicle design.

- Near-zero tailpipe emissions of greenhouse gases.
- Very low emissions of local air pollutants: Irrespective of the fuel, fuel cells largely eliminate emission of particulates and oxides of sulphur and nitrogen. All of these pollutants are associated with conventional engines.

Fuel cells are regarded as the most promising power sources for zero-emission, high efficiency and low noise. A fuel cell consists of two electrodes separated by an electrolyte. In most cases, hydrogen fuel is fed into the anode of the fuel cell. Oxygen (or air) enters the fuel cell at the cathode. Encouraged by a catalyst, the hydrogen splits into protons and electrons. The protons pass through the electrolyte. The electrons create a separate current that can be utilized before they return to the cathode, to be reunited with the hydrogen and oxygen to form a molecule of water. Individual cells are “stacked” together to generate useful quantities of power [193].

In past studies, MacLean and Lave [194] examined the life cycle implications of a wide range of fuels and propulsion systems. However, the effect of different hydrogen storage options was not studied. Ananthachar and Duffy [195] compared fuel cell vehicles with different types of storage but the effect of drive cycle and the weight of different tanks on the hydrogen consumption were not considered. Ogden et al. [196] compared hydrogen, methanol and gasoline as fuels for fuel cell vehicles. Ristovski et al. [197] carried out comparison of compressed natural gas with petrol as the transportation fuel, but their study was limited to ICE powered vehicle only and did not consider fuel cell powered vehicle technology. Manish and Banerjeeb investigated that at current technology, fuel cell vehicles are not economically viable and improvement in both fuel cell life and price is critical towards fuel cell vehicle’s viability. At current life of fuel cell (approximately 5 years), the fuel cell price has to be reduced by 90%. However, at fuel cell life of 20 years, fuel cell vehicles will be viable at 70% price reduction.

Because of their fuel flexibility, fuel cells can promote energy diversity and a transition to renewable energy sources. A fuel cell system that includes a fuel reformer can utilize the hydrogen from any hydrocarbon fuel – natural gas, ethanol, methanol, and even gasoline. Hydrogen can also be produced using solar-powered electrolysis, or it can be extracted from novel feedstock such as landfill gas or anaerobic digester gas from wastewater treatment plants.

A variety of fuel cells is in different stages of development. The most common classification of fuel cells is by the type of electrolyte used in the cells:

1. Polymer electrolyte fuel cell (PEFC),
2. Alkaline fuel cell (AFC),
3. Phosphoric acid fuel cell (PAFC),
4. Molten carbonate fuel cell (MCFC),
5. Solid oxide fuel cell (SOFC) [193].

Broadly, the choice of electrolyte dictates the operating temperature range of the fuel cell. The operating temperature also plays an important role in dictating the degree of fuel processing required. In low-temperature fuel cells, all the fuel must be converted to hydrogen prior to entering the fuel cell.

A fuel cell works by catalysis, separating the component electrons and protons of the reactant fuel, and forcing the electrons to travel through a circuit, hence converting them to electrical power. The catalyst typically comprises a platinum group metal or alloy. Another catalytic process puts the electrons back in, combining them with the protons and oxidant to form waste products (typically simple compounds like water and carbon dioxide).

A typical fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. Voltage decreases as current increases, due to several factors:

- Activation loss
- Ohmic loss (voltage drop due to resistance of the cell components and interconnects)
- Mass transport loss (depletion of reactants at catalyst sites under high loads, causing rapid loss of voltage) [198]

To deliver the desired amount of energy, the fuel cells can be combined in series and parallel circuits, where series yield higher voltage, and parallel allows a stronger current to be drawn. Such a design is called a fuel cell stack. Further, the cell surface area can be increased, to allow stronger current from each cell.

4.7.1 Proton Exchange Fuel Cells

Proton exchange membrane fuel cells, also known as polymer electrolyte membrane (PEM) fuel cells (PEMFC), are a type of fuel cell being developed for transport applications as well as for stationary fuel cell applications and portable fuel cell applications. Their distinguishing features include lower temperature/pressure ranges (50-100°C) and a special polymer electrolyte membrane. Figure 4.23 shows the construction of a PEMFC.

In the archetypal hydrogen–oxygen proton exchange membrane fuel cell (PEMFC) design, a proton-conducting polymer membrane, (the electrolyte), separates the anode and cathode sides. On the anode side, hydrogen diffuses to the anode catalyst where it later dissociates into protons and electrons. These protons often react with oxidants causing them to become what is commonly referred to as multi-facilitated proton membranes (MFPM). The protons are conducted through the membrane to the cathode, but the electrons are forced to travel in an external circuit (supplying power) because the membrane is electrically insulating. On the cathode catalyst, oxygen molecules react with the electrons (which have traveled through the external circuit) and protons to form water — in this example, the only waste product, either liquid or vapor [199].

Design issues of a PEMFC are as summarized below:

1. **Costs:** In 2002, typical cells had a catalyst content of $1000 per kilowatt of electric power output. In 2008, UTC Power has 400kw Fuel cells for $1,000,000 per 400kW installed costs. The goal is to reduce the cost in order to compete with current market technologies including gasoline internal combustion engines. Many companies are working on techniques to reduce cost in a variety of ways including reducing the amount of platinum needed in each individual cell. Ballard Power Systems have experiments with a catalyst enhanced with carbon silk, which allows a 30% reduction (1 mg/cm^2 to 0.7 mg/cm^2) in platinum usage without reduction in performance [200]. Monash University, Melbourne uses PEDOT instead of platinum [201]. The Nafion membrane currently costs €400/m^2. In 2005 Ballard Power Systems announced that its fuel cells will use Solupor, a porous polyethylene film patented by DSM [202,203].

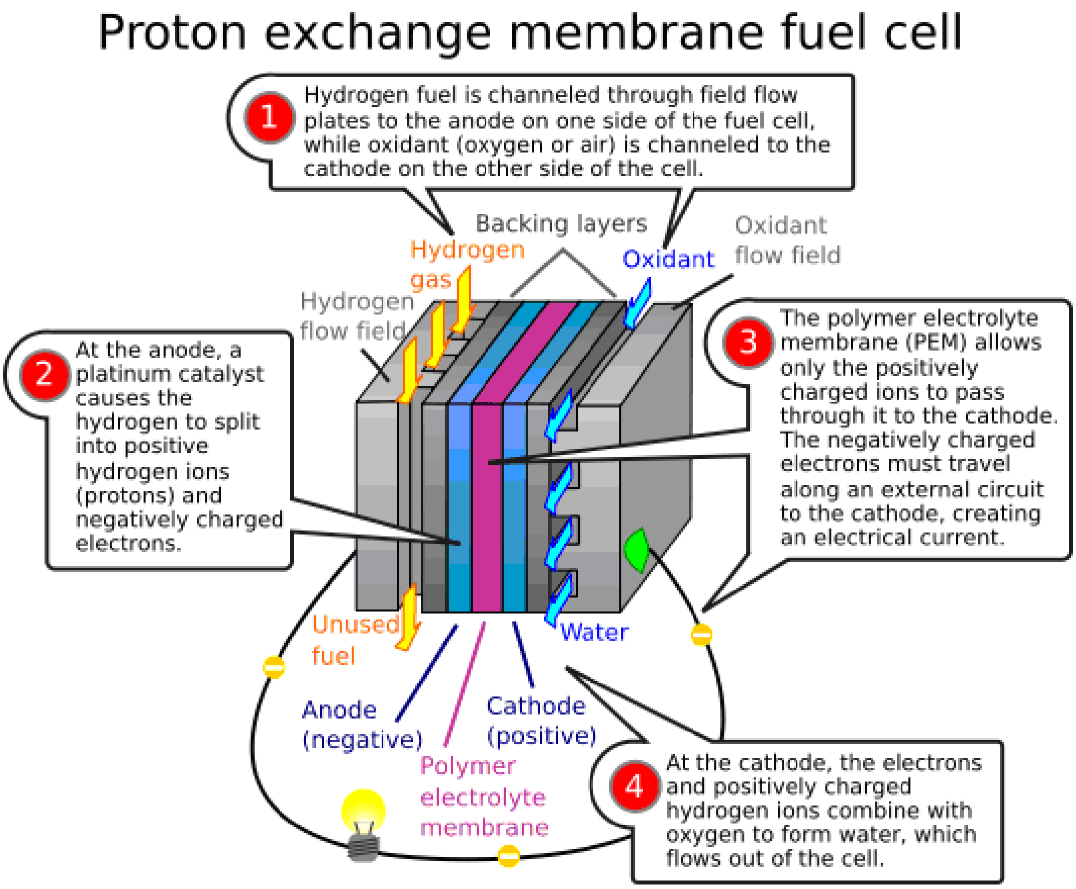

Figure 4.23 : Construction of a high temperature PEMFC

2. **Water and air management:** In this type of fuel cell, the membrane must be hydrated, requiring water to be evaporated at precisely the same rate that it is produced [204]. If water is evaporated too quickly, the membrane dries, resistance across it increases, and eventually it will crack, creating a gas "short circuit" where hydrogen and oxygen combine directly, generating heat that will damage the fuel cell. If the water is evaporated too slowly, the electrodes will flood, preventing the reactants from reaching the catalyst and stopping the reaction. Methods to manage water in cells are being developed like electroosmotic pumps focusing on flow control. Just as in a combustion engine, a steady ratio between the reactant and oxygen is necessary to keep the fuel cell operating efficiently.

3. **Temperature management:** The same temperature must be maintained throughout the cell in order to prevent destruction of the cell through thermal loading. This is particularly challenging as the $2H_2 + O_2 \rightarrow 2H_2O$ reaction is highly exothermic, so a large quantity of heat is generated within the fuel cell.

4. **Durability, service life, and special requirements:** Stationary fuel cell applications typically require more than 40,000 hours of reliable operation at a temperature of -35°C to 40°C (-31°F to 104°F), while automotive fuel cells require a 5.000 hour lifespan under extreme temperatures. Current service life is 7.300 hours under cycling conditions [205]. Automotive engines must also be able to start reliably at -30°C (-22°F) and have a high power to volume ratio (typically 2,5 kW per liter).

The efficiency of a fuel cell is dependent on the amount of power drawn from it. Drawing more power means drawing more current, this increases the losses in the fuel cell. As a rule, the more power (current) drawn, the lower the efficiency. Most losses manifest themselves as a voltage drop in the cell, so the efficiency of a cell is almost proportional to its voltage. For this reason, it is common to show graphs of voltage versus current (so-called polarization curves) for fuel cells. A typical cell running at 0.7 V has an efficiency of about 50%, meaning that 50% of the energy content of the hydrogen is converted into electrical energy; the remaining 50% will be converted into heat. (Depending on the fuel cell system design, some fuel might leave the system unreacted, constituting an additional loss.)

For a hydrogen cell operating at standard conditions with no reactant leaks, the efficiency is equal to the cell voltage divided by 1.48V, based on the enthalpy, or heating value, of the reaction. For the same cell, the second law efficiency is equal to cell voltage divided by 1.23V. (This voltage varies with fuel used, and quality and temperature of the cell.) The difference between these numbers represents the difference between the reaction's enthalpy and Gibbs free energy. This difference always appears as heat, along with any losses in electrical conversion efficiency.

Fuel cells do not operate on a thermal cycle. As such, they are not constrained, as combustion engines are, in the same way by thermodynamic limits, such as Carnot cycle efficiency. At times this is misrepresented by saying that fuel cells are exempt from the laws of thermodynamics, because most people think of thermodynamics in terms of combustion processes (enthalpy of formation). The laws of thermodynamics also hold for chemical processes (Gibbs free energy) like fuel cells, but the maximum theoretical efficiency is higher (83% efficient at 298K [206]) than the Otto cycle thermal efficiency (60% for compression ratio of 10 and specific heat ratio of 1,4). Comparing limits imposed by thermodynamics is not a good predictor of practically achievable efficiencies. Also, if propulsion is the goal, electrical output of the fuel cell has to still be converted into mechanical power with the corresponding inefficiency. In reference to the exemption claim, the correct claim is that the "limitations imposed by the second law of thermodynamics on the operation of fuel cells are much less severe than the limitations imposed on conventional energy conversion systems" [207]. Consequently, they can have very high efficiencies in converting chemical energy to electrical energy, especially when they are operated at low power density, and using pure hydrogen and oxygen as reactants.

For a fuel cell operating on air (rather than bottled oxygen), losses due to the air supply system must also be taken into account. This refers to the pressurization of the air and dehumidifying it. This reduces the efficiency significantly and brings it near to that of a compression ignition engine. Furthermore, fuel cell efficiency decreases as load increases.

The tank-to-wheel efficiency of a fuel cell vehicle is about 45% at low loads and shows average values of about 36% when a driving cycle like the NEDC (New European Driving Cycle) is used as test procedure [208]. The comparable NEDC value for a Diesel vehicle is 22%. In 2008, Honda released a car with fuel stack claiming a 60% tank-to-wheel efficiency [209].

It is also important to take losses due to fuel production, transportation, and storage into account. Fuel cell vehicles running on compressed hydrogen may have a power-plant-to-wheel efficiency of 22% if the hydrogen is stored as high-pressure gas, and 17% if it is stored as liquid hydrogen [210].

Fuel cells cannot store energy like a battery, but in some applications, such as stand-alone power plants based on discontinuous sources such as solar or wind power, they are combined with electrolyzers and storage systems to form an energy storage system. The overall efficiency (electricity to hydrogen and back to electricity) of such plants (known as round-trip efficiency) is between 30 and 50%, depending on conditions [211]. While a much cheaper lead-acid battery might return about 90%, the electrolyzer/fuel cell system can store indefinite quantities of hydrogen, and is therefore better suited for long-term storage.

Nowadays low temperature fuel cell stacks proton exchange membrane fuel cell (PEMFC), direct methanol fuel cell (DMFC) and phosphoric acid fuel cell (PAFC) make extensive use of platinum catalysts. Impurities create catalyst poisoning (reducing activity and efficiency) in these low-temperature fuel cells, thus high hydrogen purity or higher catalyst densities are required [212]. Although platinum is seen by some as one of the major "showstoppers" to mass-market fuel cell commercialization companies, most predictions of platinum running out and/or platinum prices soaring do not take into account effects of thrifting (reduction in catalyst loading) and recycling. Recent research at Brookhaven National Laboratory by Johnson [213] could lead to the replacement of platinum by a gold-palladium coating, which may be less susceptible to poisoning and thereby improve fuel cell lifetime considerably. Current targets for transport PEM fuel cells are 0.2 g/kW Pt – which is a factor of 5 decreases over current loadings – and recent comments from major original equipment manufacturers (OEMs) indicate that this is possible. In addition, it is fully anticipated that recycling of fuel cells components, including platinum, will kick in. High-temperature fuel cells, including molten carbonate fuel cells (MCFC's) and solid oxide fuel cells (SOFC's), do not use platinum as catalysts, but instead use cheaper materials such as nickel and nickel oxide, which are considerably more abundant They also do not experience catalyst poisoning by carbon monoxide, and so they do not require high-purity hydrogen to operate. They can use fuels with an existing and extensive infrastructure, such as natural gas, directly, without having to first reform it externally to hydrogen and CO followed by CO removal. Instead, they can more efficiently use the same fuels that are used to make hydrogen for low-temperature fuel cells.

Table 4.2 summarizes the major challenges to be overcome before fuel cell technology is ready for commercialization in the automotive industry.

Table 4.2 : Major technical challenges for PEM fuel cells

Fuel Cell Engine • Long life, lower cost membranes • Low cost catalysts • Low cost designs and manufacturing	**Fuel Processors** • Better catalysts • Small heat exchangers • Sulfur removal or sulfur tolerant
Fuels • Large investment in methanol producers • Development of petroleum distillates for fuel cells	**Hydrogen Production** • Cost reduction for natural gas reforming • Cost reduction for electrolysis of water • Using solar, wind and other renewables
Storage • Higher capacity storage devices • Lower cost storage devices • Improved Safety	

With progress in fuel cell technology and an increasing availability of hydrogen fuels, the power of fuel cells can be increased, leading to a higher share of fuel cell power for vehicle propulsion. Eventually, provided the necessary technological progress takes place, the fuel cell can serve as primary propulsion unit for vehicles. Today, this step appears to be more than a decade into the future.

5. APPLICATION OF THE MODEL – FORD OTOSAN CASE STUDY

For the purpose of illustration, the proposed model is applied to the strategic evaluation of emerging powertrain technologies. The outcomes of technology value will indicate which technology of the case study company, Ford Otosan in this case, should consider for R&D investment in developing new vehicles.

Ford Otosan, established at the end of 1950s, is one of the most innovative research-intensive companies and the sales leader in Turkey. Within a short time, Ford Otosan has joined the ranks of Ford of Europe top production plants, with strong international reputations. Today, Ford Otosan has the technology and the know-how to design a complete vehicle for the domestic and international markets.

Ford Otosan Product Department was formed in 1961 and, as of today can develop almost a complete vehicle in house. Engineers utilize the state of art engineering tools to develop parts and systems, simulate crash tests or cooling performance and have gained extensive knowledge and experience from countless hours and kilometers of engine and vehicle testing. Engineering resources include Design Studio (concept development, digital modeling, A-class surfacing, clay generation & modeling, rapid prototyping, color & harmony analysis, craftsmanship, design aid manufacturing) 6 Test Cells (with TUV & TSE accreditation capable of measuring performance, emissions, T/C Matching and Turbo Transient Response), Material Lab (to support material characterization, failure root cause and micro structure analysis), Vehicle Performance Measuring Equipments (to measure speed, acceleration, brake performance, fuel consumption and noise & vibration), Fatigue Test Rigs (with programmable 6 hydraulic cylinders and SINCOTEC Resonance Frequency Fatigue Rig Test Rig), Durability Rig Test Laboratory (to support key life tests). As of April 2009, the number of engineers working in Product Development has reached 596. The PD has 12 PhD and 474 MSc. and BSc. degree level engineers who are internationally recognized in their area of expertise. 110 technician and supporting workers form the competitive employee body of the company.

R&D department of Ford Otosan, established in 2002, is known to be the leading structure of "pre-competitive level actions" in Turkey, leads most of the vital projects with universities, research centers and other companies, and plays a key role in driving forward the whole process to reach the results compatible with the truly integrated European approach. R&D Department is the first automotive industry partner that has involved in a project funded by FP6 program of EC (GREEN Integrated Project). Turkey's first fuel cell package has been designed and developed with and consortium led by Ford Otosan. In the first quarter of 2006, Ford Otosan designed and produced its first hybrid vehicle, FOHEV (Ford Otosan Hybrid Electric Vehicle) again working with universities and research centers in Turkey.

A state of the art plant, carefully initiated product development projects, projects being worthy of funding from Turkish government as well as European Commission, exceptional human resources – all these components enable Ford Otosan to thrive as a dynamic and innovative institution of high level design and development.

As an OEM, Ford Otosan foresees its future in well-developed investments in R&D, therefore requires a dependable, applicable, practical and yet flexible roadmap.

The technological improvements of existing and emerging technologies are explained in Section 4. There are many roadmaps, international, national and industry wise, with respect to future vehicle technologies. Furthermore, different technologies were assessed with respect to their efficiencies and some performance features [169,214-218]. However, most of the studies do not acquire any methodologies to assess these technologies and only list specific attributions of those. Several studies that assess advanced powertrain technologies with a specific methodology only include main specifications such as efficiency, fuel consumption, exhaust and CO_2 emissions, but do not have a more detailed review of other features.

5.1 Technology Forecasting

In order to shape the powertrain technologies, a Delphi questionnaire is prepared and allocated to separate expert panels. First group of experts represent the university side of the research as they focus on powertrain development and technological gaps. Second group is a panel of research center experts, focusing on advanced technologies and control strategies. Third group represents the industry that involves in powertrain development and production. After receiving first round of reviews, the panels were united to be separated once again in two panels. First panel represents an industry-wide group of experts, who involve in the development of future vehicle technologies. This panel is formed in a way that experts' biases in the outcomes of emerging technologies and differences in their ideas across industry, academic, and government background are well balanced. Second panel consisted of members from the company and partners. Therefore, after two rounds of Delphi study, a list of seven technologies was listed as Table 5.1. Delphi Questionnaire is detailed in Appendix A, while the distributions of the experts are shown in Appendix B.

Table 5.1 : List of future vehicle technologies

T1:	Diesel engine + CVT + Common Rail 3rd Gen (1800 bar) + TC + SCR + DPF
T2:	GDI engine + Downsizing + VVT + VCR + TC
T3:	Diesel HCCI + VCR + VVT + EGR
T4:	Hydrogen ICE + Liquid H2 storage (cyrogenic) + VVT + TC
T5:	Diesel engine + Li-ion battery + Starter/charger motor + Electric motor
T6:	PEM Fuel Cell + Li-ion battery + Electric motor + Compressed hydrogen storage

The surveys point out that gasoline and diesel ICEs will still be dominant, however, their market share will be diminished due to increasing shares of hybrids and hydrogen vehicles. Today, the greatest challenge that ICEs are facing is considered the limitation of further development. In the upcoming decades, diminishing resources and environmental issues will be the number one challenge against their improvements. Experts believe that SCR together with LNT will be used in the future for the reduction of exhaust emissions. In addition, further increase in injection pressure for next generations of Common Rail is expected. Combustion chamber optimization may show some promising progress in the coming few years, however, most of the experts underlined that it has reached its boundaries.

With respect to hybrids and fuel cells, system components are the biggest challenges. They are open for further technological development and must overcome cost, weight, complexity and control issues. Nevertheless, hydrogen infrastructure and on-board hydrogen storage units will require further development.

In addition to the questionnaire, experts also provided their estimates on the technological metrics indicating the future development progress of each technology along twenty-two factors.

5.2 Technology Characterization

The objective of the company is defined as "to achieve technological competitiveness with respect to powertrain systems", with which the second round-second panel experts agreed on. In accordance with the pre-defined technologies, a table was created to categorize them according to design criteria and technological factors associated with each criterion. Seven criteria and factors associated with each criterion along with their limiting values on the measure of effectiveness were finalized. All the criteria are explained in detailed in Appendix C, as a small portion is shown in Table 5.2; whereas the descriptions of all 5-point scales defined for each factor are explained in Appendix D.

Table 5.2 : Description of criteria and technological factors

Criterion 1:	**Cost Effectiveness**	**Units**
Description:	Overall expenses of powertrain systems	
F11:	**Vehicle cost**	[$]
Description:	Overall system cost and production expense.	
Example:	Additional cost of the vehicle compared to reference vehicle	
F21:	**Maintenance cost**	[% of capital cost]
Description:	Maintenance cost of the systems; affected from system complexity, availability and characteristics of the system components	
Example:	Spare parts of some systems or components may be extremely expensive	

These tables are very flexible according to the nature of TDE and can be reviewed according to the future expert feedbacks of the Delphi Questionnaire. For the first round of Delphi, ten experts provided feedback where on the second round this number has decreased to four.

Table 5.3 below shows the criteria and set of factors along with the limiting values of the measures of effectiveness applied for each factor.

Table 5.3 : List of criteria and factors associated with each criterion

		Units:	Measure of effectiveness	
			Worst:	Best:
C1: Cost effectiveness				
F 11:	Additional vehicle cost	$	40000 or higher	0
F 21:	Maintenance cost	% of capital cost	10 or higher	0
C2: Performance				
F 12:	System efficiency	%	0	100
F 22:	Peak power output	kW	0	250
F 32:	System control technologies	5 pt scale	UA	E
F 42:	Power density	kW/l	0	250
F 52:	Additional weight	kg	500 or higher	0
F 62:	Durability	Km	0	250000 or higher
C3: Emissions				
F 13:	NOx	g/km	0,30 or higher	0
F 23:	PM	g/km	0,01 or higher	0
F 33:	HC	g/km	0,40 or higher	0
F 43:	CO	g/km	1,5 or higher	0
C4: Fuel Consumption				
F 14:	Fuel consumption	l/100km	30 or higher	0
F 24:	CO2 emissions	g CO2/km	300 or higher	0
C5: Fuel Specifications				
F 15:	Fuel infrastructure availability	5 pt scale	UA	E
F 25:	Fuel infrastructure cost	million $	1000 or higher	0
F 35:	Energy density by mass	MJ/kg	0	150 or higher
C6: System Evaluation				
F 16:	Materials availability	5 pt scale	UA	E
F 26:	Components availability	5 pt scale	UA	E
F 36:	Technology development state	5 pt scale	UA	E
F 46:	Regulations / incentives	5 pt scale	UA	E
F 56:	Complexity	5 pt scale	UA	E
F 66:	System safety	5 pt scale	UA	E
C7: Market				
F 17:	Availability of vehicles	5 pt scale	UA	E
F 27:	Sales volume	%	0	100

5.3 Technology Assessment

In this step, emerging technologies are assessed based on the measures of effectiveness. The experts are asked to provide the values of the measures of effectiveness of each emerging technology with which they are familiar according to the technological factors.

5.3.1 Methodology Assumptions

Several papers by Santini [215] have emphasized the need for a defined set of rules that should be adopted to ensure a fair and consistent assessment. To fulfill the recommendations, the following hypotheses have been made:

- All vehicles are considered to be based upon the same platform, a light commercial vehicle. Therefore, cost and weight differences arise from powertrain and component changes.
- Vehicle aerodynamic drag, tire rolling resistance, and glider mass have been kept constant throughout the configurations. The differences between each vehicle are only due to their configurations and control strategies.
- All of the components are based on current technology. The gasoline engine is a single overhead camshaft, two valves per cylinder; the diesel engine is a high-pressure direct injection engine and has two valves per cylinder.
- The results for a powertrain configuration or technology are dependent on the driving schedule; NEDC is selected for reference vehicle to allow easy evaluation of each powertrain anywhere in the world.
- No cold start has been taken into account, for the configurations with either an engine or fuel cell.
- Because the goal of this research is to focus more on the impact of drivetrain configurations rather than fuel production, we will only consider one hydrogen production path: from reforming at a station, which is the solution that is expected to be used first.

Experts were asked to provide estimates for the technologies of their expertise indicating the future development of the technology using the factors that were sent to them as a "Powertrain Technology Evaluation" document, taking a Euro 4 level, 1,9 Gasoline Engine Light Commercial Vehicle as reference. Reference values and the evaluation of an expert is given in Table 5.4. Experts used the reference values and were asked to fill out the form in accordance with them.

Table 5.4 : Powertrain technology evaluation example

Criteria	Factors	Units	Reference Vehicle - 1,9 L. EURO 4 Gasoline Engine		DIESEL ENGINE + CVT +COMMON RAIL (1800 BAR) + TC + SCR + DPF		
			2009	Comments	2009-2015	2015-2025	2025--
C1:Cost Effectiveness	F11: Vehicle cost (additional)	$	21.000	A conventional light duty SI vehicle price	7.000	4.000	2.000
	F21: Maintenance cost	% of capital cost	2		5	4	3
C2: Performance	F12: System efficiency	%	14	Well-to-wheel efficiency	15	16	17
	F22: Peak power output	kW	95		100	110	125
	F32: System control technologies	5 pt scale	E		G	VG	E
	F42: Power density	kW/l	75		75	78	80
	F52: Additional weight	kg	1.400	A conventional light duty vehicle weight	50	20	10
	F62: Durability	km	100.000	Euro 4 stage	100.000	160.000	200.000
C3: Emissions	F13: NOx	g/km	0,1	N_1, Class II, Euro 4 stage	0,22	0,15	0,05
	F23: PM	g/km	0	N_1, Class II, Euro 4 stage (not available)	0,005	0,005	0,003
	F33: HC	g/km	0,13	N_1, Class II, Euro 4 stage	0,003	0,002	0,001
	F43: CO	g/km	1,81	N_1, Class II, Euro 4 stage	0,63	0,55	0,4
C4: Fuel Consumption	F14: Fuel consumption	l/100 km	10	An average light duty vehicle fuel consumption	9	7,5	6
	F24: CO2 emissions	gCO2/km	263	An average light duty vehicle CO2 emissions	238	198	159
C5: Fuel Specifications	F15: Fuel availability	5 pt scale	E	Fuel is available everywhere for every vehicle	E	E	VG
	F25: Fuel infrastructure cost	billion $	0	No further infrastructure is required	0	0	0
	F35: Energy density by mass	MJ/kg	43	Regular gasoline	42	42	42
C6: System Evaluation	F16: Materials availability	5 pt scale	E		E	E	E
	F26: Components availability	5 pt scale	E		VG	E	E
	F36: Technology dev. state	5 pt scale	A		VG	G	P
	F46: Regulations/legal framework	5 pt scale	E		E	E	E
	F56: Complexity	5 pt scale	VG		G	VG	E
	F66: System safety	5 pt scale	G		VG	E	E
C7: Market	F17: Availability of vehicles	5 pt scale	E		A	VG	E
	F27: Sales volume	%	45	Sales of gasoline vehicles were %45 of total LCVs	2	4	10

5.4 Hierarchical Modeling

As explained in Section 2, a generalized hierarchical model can be constructed with a four-level hierarchy; objective, criteria, factors, and technologies. This model represents the hierarchical structure in which the relative contributions of technologies to the objective are calculated by determining the priorities of the criteria, the relative importance of factors on each criterion, and the relative impact of technologies on each factor.

However, this approach poses two disadvantages. First, the judgment quantification approach becomes very difficult when the number of technologies increases. Second, the whole series of comparative judgments need to be repeatedly quantified every time a new technology is added to the list.

To overcome these difficulties, a composite index called "technology value" is developed to quantify the impact of each technology on the objective based on the semi-absolute values instead of the relative values.

With the new approach of quantifying the technology value, the generalized model has to be transformed to an operational model by replacing the technologies with their measures of effectiveness as shown in Figure 5.1. Set of measures of effectiveness (metrics) is defined for each technological factor so that the performance and physical characteristics of emerging technologies could be directly evaluated.

The impact relationships of measures of effectiveness associated with each factor are determined through the quantification of judgments for the desirability of each measure of effectiveness.

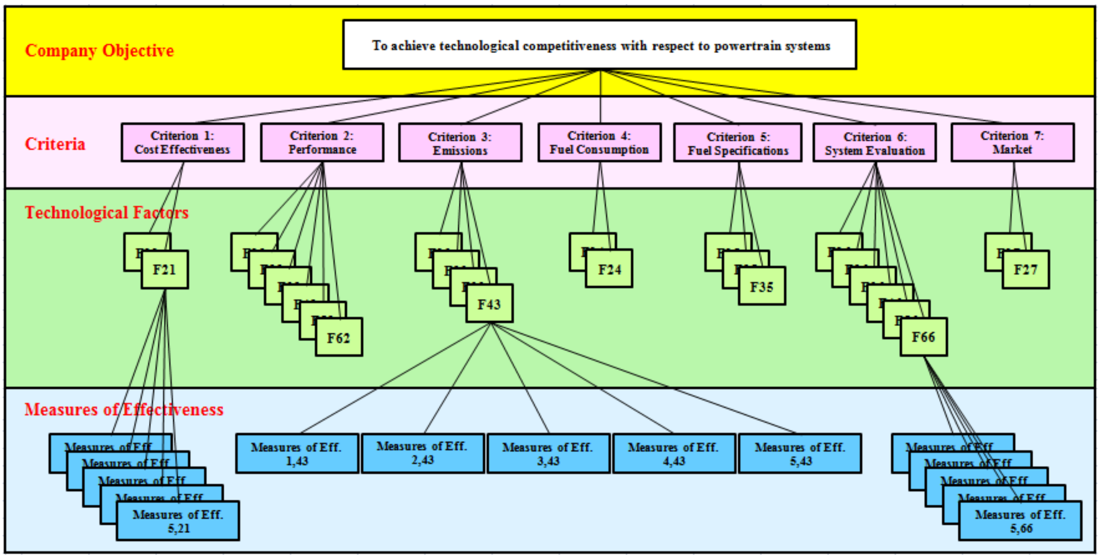

Figure 5.1 : The hierarchical model developed for evaluating technologies

5.5 Mathematical Modeling

5.5.1 Measurement 1- Criteria Evaluation

This step shows the determination of [w_k], the relative priority of criteria (*k*) with respect to objective. The values representing comparative judgment on each pair of criteria were obtained from each expert to determine the relative priority of the seven criteria, according to Equation 5.1 below.

$$\sum_{k=1}^{K} w_k = 1.0 \text{, where } w_k > 0 \qquad \textbf{(5.1)}$$

The below table represents the 21 comparison provided by one expert.

Table 5.5 : Example of values in comparative judgments provided by one expert

C1: *60* C2: *40*	C1: *70* C3: *30*	C1: *65* C4: *35*	C1: *80* C5: *20*	C1: *70* C6: *30*	C1: *90* C7: *10*	C2: *60* C3: *40*
C2: *55* C4: *45*	C2: *75* C5: *25*	C2: *75* C6: *25*	C2: *90* C7: *10*	C3: *45* C4: *55*	C3: *70* C5 *30*	C3: *75* C6: *25*
C3: *90* C7: *10*	C4: *85* C5: *15*	C4: *85* C6: *15*	C4: *90* C7: *10*	C5: *30* C6: *70*	C5: *20* C7: *80*	C6: *60* C7: *40*

Using PCM software[1], the relative priority of the seven criteria to which this expert assigned can be determined as:

Table 5.6 : Relative priority of the criteria by one expert

Criteria	C1	C2	C3	C4	C5	C6	C7	∑
Rel. Importance [w_k]	0,26	0,22	0,16	0,22	0,04	0,07	0,04	**1,0**

Figure 5.2 shows the PCM software during priority inputs. Afterwards, combining the relative priority values given by all six experts, the mean value was calculated. The result is shown in Figure 5.3.

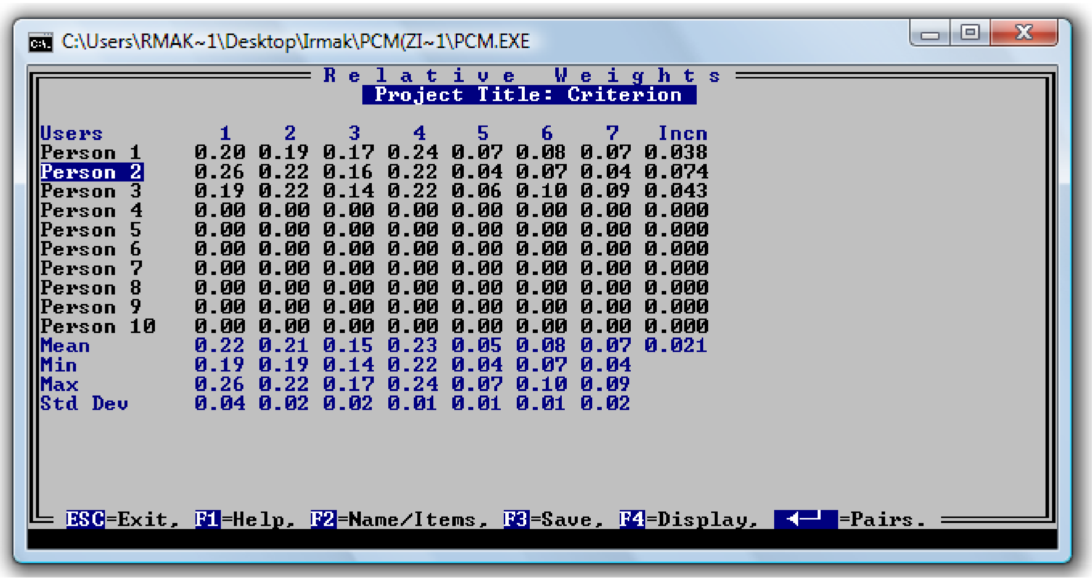

Figure 5.2 : Screenshot of the PCM software during addition of expert inputs

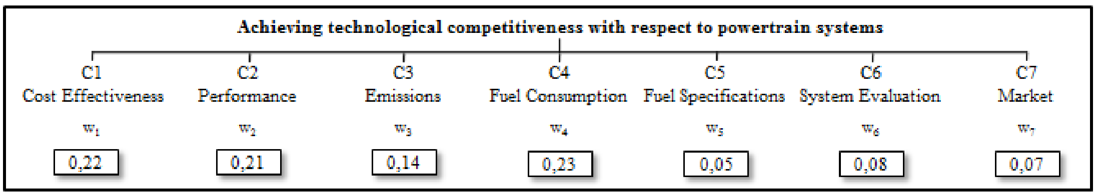

Figure 5.3 : The relative priority of seven criteria

The mean values among all experts' judgment for each criterion are calculated to represent the group's judgment. In this case, the group results indicate that Cost Effectiveness and Fuel Consumption are the leading criteria, Performance following right behind. The least important criterion was selected as Fuel Specifications, where

[1] PCM software is developed by Dundar F. Kocaoglu and coded by Bruce J. Bailey. The software is used to facilitate the computation process of Constant-Sum Pairwise comparison method by converting judgments into numerical values [219]

fuel availability and infrastructure features are assessed. This result also supports the literature in future and alternative powertrain technologies.

Fuel Consumption, therefore Fuel Economy and CO_2 Emissions are considered the most important factors for assessment. This result is compatible with all the studies that assess future vehicle technologies with respect to fuel economy and CO_2 emissions. The main reason for Emissions criteria to receive 4th place in the ranking is that exhaust emissions should be reduced due to stringent regulations no matter what the technology is.

5.5.2 Measurement 2 - Factors Evaluation

This step shows the determination of [$f_{j_k,k}$], the relative impact of factors (f_k) associated with each criterion (k), in accordance with the Equation 5.2 below:

$$\sum_{j_k=1}^{J_k} f_{j_k,k} = 1.0 \quad \text{where,} \quad f_{j_k,k} > 0 \qquad \textbf{(5.2)}$$

The values representing comparative judgments on the set of factors associated with each criterion were obtained from four experts. The relative importance of the factors with respect to the criterion, which they are associated with, was calculated by following the same approach as Measurement 1 above.

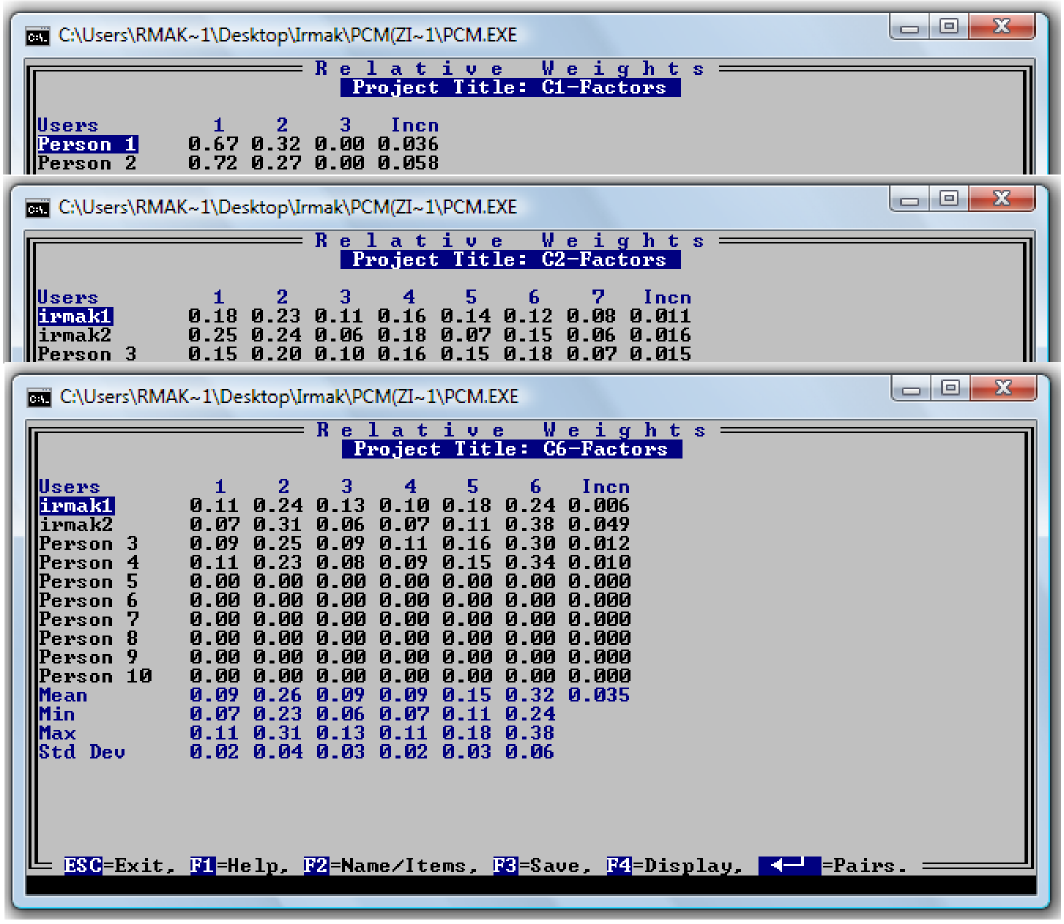

Figure 5.4 : Examples of factor inputs associated with each criterion

The results are represented in the Table 5.7 below:

Table 5.7 : The relative importance of factors under each criterion

Factors under C1	**F11**	**F21**	Σ				
Rel. Importance	0,70	0,30	1,00				
Factors under C2	**F12**	**F22**	**F32**	**F42**	**F52**	**F62**	Σ
Rel. Importance	0,21	0,20	0,12	0,16	0,13	0,18	1,00
Factors under C3	**F13**	**F23**	**F33**	**F43**	Σ		
Rel. Importance	0,32	0,32	0,19	0,17	1,00		
Factors under C4	**F14**	**F24**	Σ				
Rel. Importance	0,53	0,47	1,00				
Factors under C5	**F15**	**F25**	**F35**	Σ			
Rel. Importance	0,37	0,45	0,18	1,00			
Factors under C6	**F16**	**F26**	**F36**	**F46**	**F56**	**F66**	Σ
Rel. Importance	0,09	0,26	0,09	0,09	0,15	0,32	1,00
Factors under C7	**F17**	**F27**	Σ				
Rel. Importance	0,59	0,41	1,00				

Below table summarizes the importance of factors, with respect to their criteria:

Table 5.8 : Distribution of the relative importance of factors

CRITERIA	FACTORS		IMPORTANCE PERCENTAGE
C1: Cost effectiveness	F11:	Vehicle cost	70%
	F21:	Maintenance cost	30%
C2: Performance	F12:	System efficiency	21%
	F22:	Peak power output	20%
	F32:	System control tech.	12%
	F42:	Power density	16%
	F52:	Weight	13%
	F62:	Durability	18%
C3: Emissions	F13:	NOx emissions	32%
	F23:	PM	32%
	F33:	HC	19%
	F43:	CO	17%
C4: Fuel Consumption	F14:	Fuel consumption	53%
	F24:	CO2 emissions	47%
C5: Fuel Specifications	F15:	Fuel inf. availability	37%
	F25:	Fuel infrastructure cost	45%
	F35:	Energy density by mass	18%
C6: System Evaluation	F16:	Materials availability	9%
	F26:	Components availability	26%
	F36:	Technology dev. state	9%
	F46:	Regulations	9%
	F56:	Complexity	15%
	F66:	System safety	32%
C7: Market	F17:	Availability of vehicles	59%
	F27:	Sales volume	41%

According to Table 5.8, Vehicle Cost, System Efficiency, NOx and PM emissions, Fuel Consumption, System Safety and Availability of Vehicles are the main factors that stand out while assessing a technology.

5.5.3 Measurement 3 – Relative Desirability of Measures of Effectiveness

This step shows the determination of $[V(m_{j_k,k})]$, the relative desirability of measures of effectiveness (metrics) under each combination of factor $[j_k]$ and criterion $[k]$.

Resenting his/her judgment on the relative desirability of each measure of effectiveness as a ratio of the desirability of the "best" limiting metric. The mean values were calculated among the relative values given by each expert to represent the group decision. As a result, 25 desirability curves were developed.

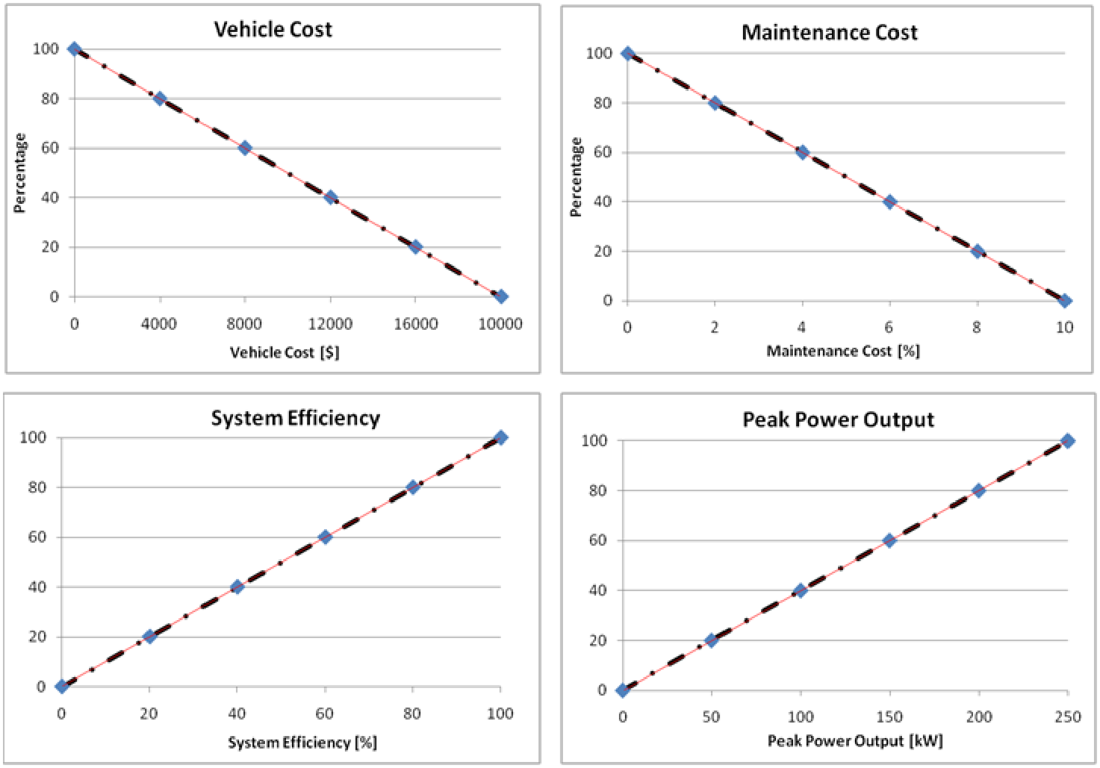

Figure 5.5 : Desirability curves

Figure 5.5 shows some examples of desirability curves developed for vehicle cost, maintenance cost, system efficiency and peak power output. The desirability curves for the other 21 factors are shown in Appendix E.

5.5.4 Measurement 4 – Mapping Metrics

This step includes the mapping of technological metrics $[t_{n,j_k,k}]$ to the desirability values $[V(t_{n,j_k,k})]$ using the relative desirability value of measures of effectiveness $[V(m_{j_k,k})]$ resulting from Measurement 3 as presented in Table 5.9 and Appendix F.

Table 5.9 : Metrics and desirability values estimated for 2009-2015

			Technological Metrics						Desirability Values					
Criteria	**Factors**	**Units**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
C1: Cost Effectiveness	F11: Vehicle cost (additional)	$	7.000	6.000	19.000	17.000	9.500	39.500	82,50	85,00	52,50	57,50	76,25	1,25
	F21: Maintenance cost	% of capital cost	5	7	9	8	5	6	50,00	30,00	10,00	20,00	46,67	40,00
C2: Performance	F12: System efficiency	%	15	15	45	30	21	22	15,00	15,00	45,00	30,00	20,50	22,00
	F22: Peak power output	kW	125	120	100	120	118	75	50,00	48,00	40,00	48,00	47,00	30,00
	F32: System control technologies	5 pt scale	VG	A	A	G	VG	A	80,00	40,00	40,00	60,00	80,00	40,00
	F42: Power density	kW/l	75	80	80	90	108	69	30,00	32,00	32,00	36,00	43,00	27,60
	F52: Additional weight	kg	50	50	200	210	275	325	90,00	90,00	60,00	58,00	45,00	35,00
	F62: Durability	km	100.000	100.000	80.000	80.000	100.000	125.000	40,00	40,00	32,00	32,00	40,00	50,00
C3: Emissions	F13: NOx	g/km	0,220	0,100	0,290	0,150	0,133	0,000	26,67	66,67	3,33	50,00	55,56	100,00
	F23: PM	g/km	0,005	0,005	0,000	0,005	0,017	0,000	95,00	95,00	100,00	95,00	82,67	100,00
	F33: HC	g/km	0,003	0,130	0,380	0,040	0,035	0,000	99,25	67,50	5,00	90,00	91,17	100,00
	F43: CO	g/km	0,630	1,810	1,100	0,001	0,710	0,000	68,50	9,50	45,00	99,95	64,50	100,00
C4: Fuel Consumption	F14: Fuel consumption	l/100 km	9	9	5	11	5	5	40,00	40,00	70,00	26,67	65,00	68,33
	F24: CO2 emissions	gCO2/km	238	238	140	1	143	0	20,67	20,67	53,33	99,71	52,33	100,00
C5: Fuel Specifications	F15: Fuel availability	5 pt scale	E	E	A	UA	E	UA	100,00	100,00	25,00	0,00	100,00	0,00
	F25: Fuel infrastructure cost	billion $	0	0	0	100	0	10	100,00	100,00	100,00	90,00	100,00	99,00
	F35: Energy density by mass	MJ/kg	42	42	46	120	42	120	28,00	28,00	30,80	80,00	28,00	80,00
C6: System Availability	F16: Materials availability	5 pt scale	E	E	G	VG	G	P	100,00	100,00	60,00	80,00	60,00	20,00
	F26: Components availability	5 pt scale	G	VG	G	A	A	UA	60,00	80,00	60,00	40,00	40,00	0,00
	F36: Technology development state	5 pt scale	VG	VG	VG	E	E	E	80,00	80,00	80,00	100,00	100,00	100,00
	F46: Regulations/incentives	5 pt scale	G	G	E	E	E	E	60,00	60,00	100,00	100,00	100,00	100,00
	F56: Complexity	5 pt scale	G	A	VG	VG	G	UA	60,00	40,00	80,00	80,00	60,00	0,00
	F66: System safety	5 pt scale	VG	VG	VG	VG	VG	A	80,00	80,00	80,00	80,00	80,00	40,00
C7: Market	F17: Availability of vehicles	5 pt scale	A	P	A	P	A	UA	40,00	20,00	40,00	20,00	40,00	0,00
	F27: Sales volume	%	10	3	1	1	5	1	10,00	3,00	0,50	1,00	4,67	0,75

All the tables featuring the metrics and desirability values of future powertrain technologies estimated for 2015-2025 and 2015 and forward are presented in Appendix E. Table 5.10 shows the total responses for two separate Delphi rounds to create the metrics table.

Table 5.10 : Delphi feedbacks on technology metrics

ROUND 1				
Technologies	University	Industry	Research Centers	TOTAL
T1	2	2	2	5
T2	1	2	1	4
T3	1	-	1	2
T4	1	-	1	2
T5	3	3	4	10
T6	2	2	3	7
OVERALL				30

ROUND 2				
Technologies	University	Industry	Research Centers	TOTAL
T1	1	1	-	2
T2	1	-	1	2
T3	1	-	-	1
T4	1	-	-	1
T5	1	2	1	4
T6	2	1	-	3
OVERALL				13

5.5.5 Measurement 5 – Quantification of Technology Value

The technology value is calculated through matrix computations among the criteria priorities (Measurement 1), the relative importance of factors on each criterion (Measurement 2), and the desirability value of technologies for each factor (Measurement 4), by applying Equation 2.1.

Table 5.11 : Calculation of the technology value of Technology 1 for 2009-2015

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	(0,22)	F11	(0,70)	$V(t_{1,11})$	(82,50)	12,71
		F21	(0,30)	$V(t_{1,21})$	(50,00)	3,30
C2: Performance	(0,21)	F12	(0,21)	$V(t_{1,12})$	(15,00)	0,66
		F22	(0,20)	$V(t_{1,22})$	(50,00)	2,10
		F32	(0,12)	$V(t_{1,32})$	(80,00)	2,02
		F42	(0,16)	$V(t_{1,42})$	(30,00)	1,01
		F52	(0,13)	$V(t_{1,52})$	(90,00)	2,46
		F62	(0,18)	$V(t_{1,62})$	(40,00)	1,51
C3: Emissions	(0,14)	F13	(0,32)	$V(t_{1,13})$	(26,67)	1,19
		F23	(0,32)	$V(t_{1,23})$	(95,00)	4,26
		F33	(0,19)	$V(t_{1,33})$	(99,25)	2,64
		F43	(0,17)	$V(t_{1,43})$	(68,50)	1,63
C4: Fuel Consumption	(0,23)	F14	(0,53)	$V(t_{1,14})$	(40,00)	4,88
		F24	(0,47)	$V(t_{1,24})$	(20,67)	2,23
C5: Fuel Specifications	(0,05)	F15	(0,37)	$V(t_{1,15})$	(100,00)	1,85
		F25	(0,45)	$V(t_{1,25})$	(100,00)	2,25
		F35	(0,18)	$V(t_{1,35})$	(28,00)	0,26
C6: System Evaluation	(0,08)	F16	(0,09)	$V(t_{1,16})$	(100,00)	0,72
		F26	(0,26)	$V(t_{1,26})$	(80,00)	1,25
		F36	(0,09)	$V(t_{1,36})$	(80,00)	0,58
		F46	(0,09)	$V(t_{1,46})$	(60,00)	0,43
		F56	(0,15)	$V(t_{1,56})$	(60,00)	0,72
		F66	(0,32)	$V(t_{1,66})$	(80,00)	2,05
C7: Market	(0,07)	F17	(0,59)	$V(t_{1,17})$	(40,00)	1,65
		F27	(0,41)	$V(t_{1,27})$	(10,00)	0,29
						54,63

Table 5.11 shows the calculation of the technology value for Technology No:1, future diesel engine system. Below table represents all the results derived from all the calculations. Rest of the calculations of the technology values are detailed in Appendix G.

Table 5.12 : Technology values for all technologies for each time period

	2009-2015	2015-2025	2025-
T1	54,63	65,33	70,80
T2	51,36	61,75	63,14
T3	48,12	58,21	65,77
T4	53,80	63,31	67,54
T5	59,25	69,14	77,60
T6	48,57	67,22	79,48

The outcomes are the technology values of emerging technologies according to a company's objective. The ideal technology from a company's point of view would represent the technology value of 100.

5.5.6 Interpretation of Calculations

Each technology was evaluated in each period by measuring how well their technological metrics meet the company's desirability level and then factored that by the relative importance of factors and the relative priority of criteria. By constructing the data in this manner, the proposed model can be used to evaluated any technology as long as the natures of those technologies can be described along 25 factors or even for concealed technologies which their names and identities could be kept secret.

The technology values for Technology 1 is shown in Figure 5.6, rest of the development of each technology is detailed in Appendix H.

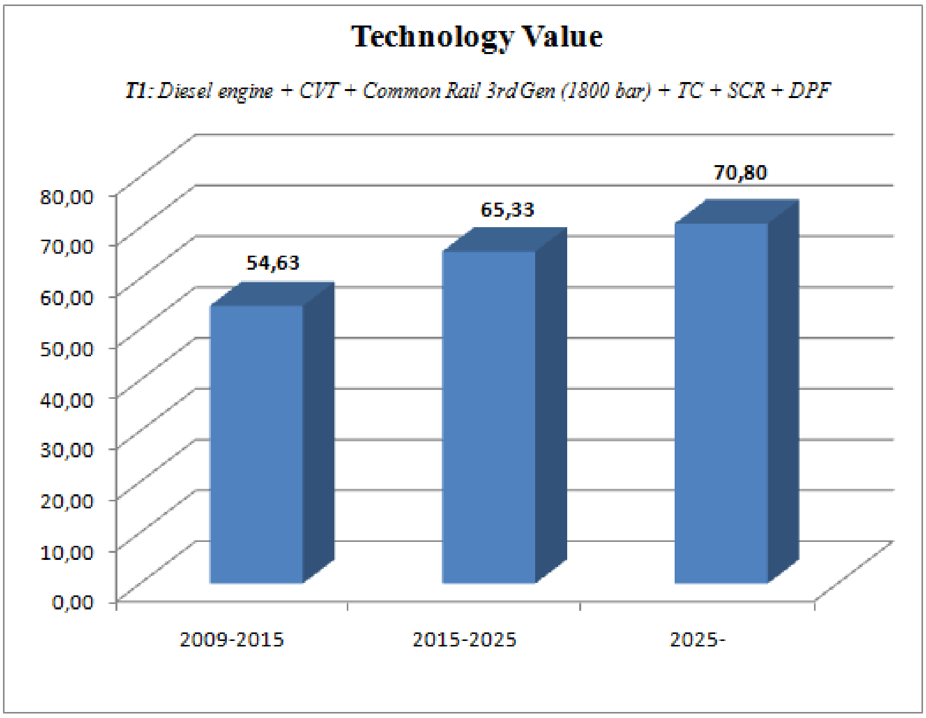

Figure 5.6 : Technology value of Technology 1 for each time period

The results indicate that the technology value of Fuel Cell technology would be significantly improved overtime as the development of this technology goes on. And eventually, this technology would become a dominant technology by the end of 2025. Even though Hybrid technology is not the dominant technology adopted by the company, it is and will be the most efficient technology for a decade, before the fossil economy transition to hydrogen is achieved. The current technologies, diesel and gasoline engines, will not be attractive any more even though the costs will continue dropping and specifications will be improved.

The evaluation of all technologies is shown in Figure 5.7. It can be easily seen that the technologies that stand out for the upcoming decades are Fuel Cell and Hybrid technologies.

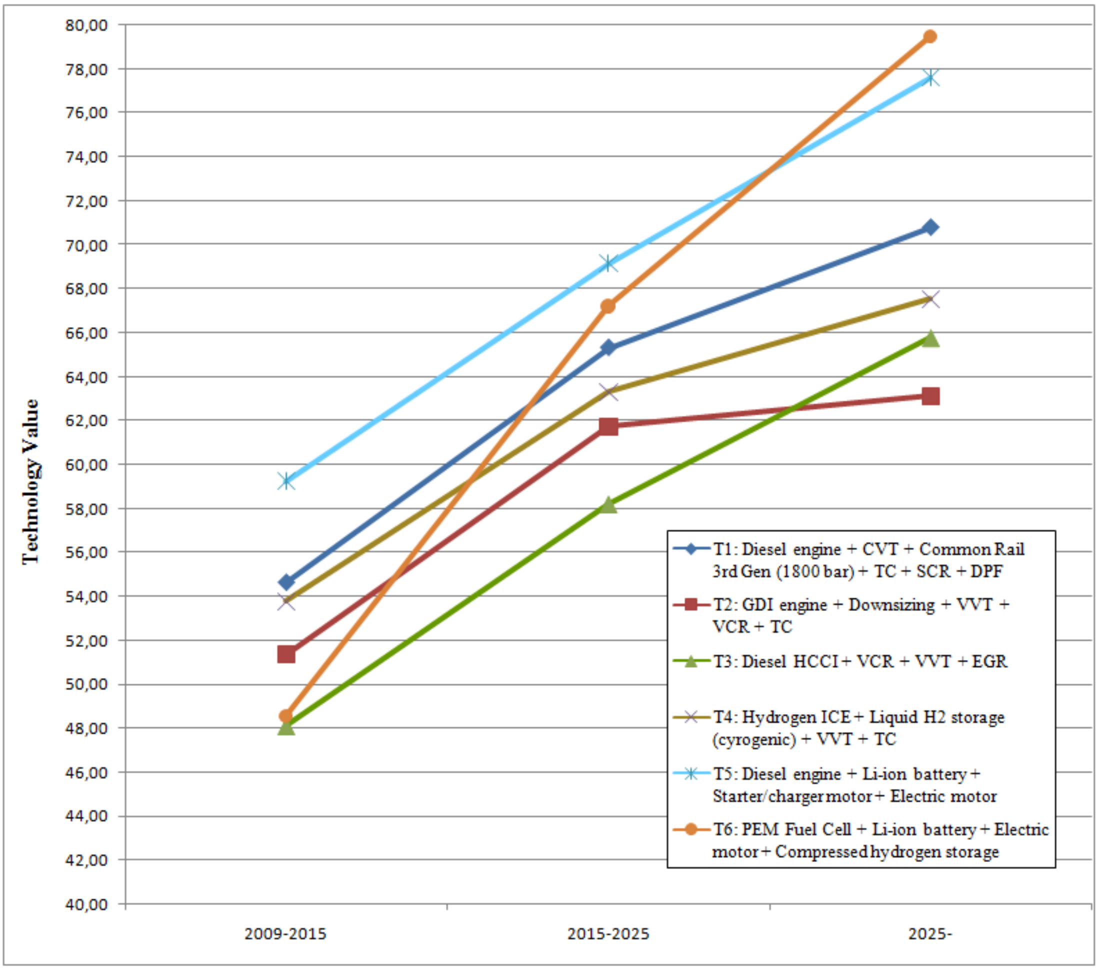

Figure 5.7 : Evaluation of all technologies

5.6 Formation of TDE

The path linking technologies that have the highest impact on a company's objective in each time period is called the Technology Development Envelope (TDE). The connection of one technology to the next results in the technology develop path. The path connecting the technology, which has the strongest impact value on the objective, is called the TDE. If the development of technologies follows the TDE, the technological benefits to company from the development would be maximized. Figure 5.8 shows alternative paths of technologies for Ford Otosan.

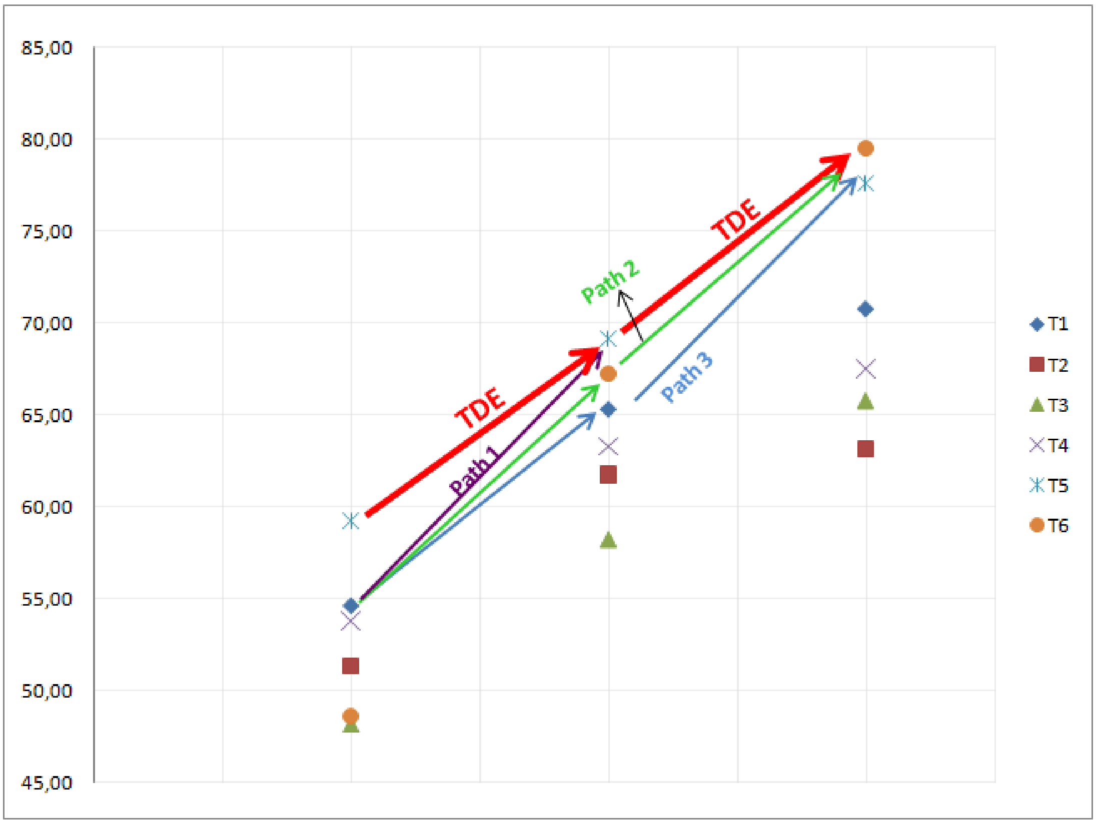

Figure 5.8 : Formation of TDE for Ford Otosan

A comparison of the technology values of six different technology alternatives indicates that GDI technology will no longer be satisfying the Company's objective. The company should follow paths as summarized in Table 5.13 below.

Table 5.13 : The TDE paths to maximize technological benefits

TDE Paths		
T5 →	T5 →	T6
T1 →	T5 →	T6
T1 →	T6 →	T6
T1 →	T1 →	T6

5.7 Improvement Gap and Improvement Priority

These two measures are developed to determine which of technologies to focus on as well as which of factors to improve.

5.7.1 Improvement Gap

Improvement Gap (IG) is the weighted gap between the performance of each technology along a factor and the upper bound for the ideal technology along that factor as calculated from the expert judgments. It is defined as;

$$IG_n = \sum_{k=1}^{K} \sum_{j_k=1}^{J_k} w_k \cdot f_{j_k,k} \cdot \left[100 - V\left(t_{n,j_k,k}\right)\right] \qquad \textbf{(5.3)}$$

where; the performance gap along factor is (j_k), $\left[100 - V\left(t_{n,j_k,k}\right)\right]$ is is weighted by the product of the relative value of the criterion (k) and the factor (j_k).

5.7.2 Improvement Priority

A Improvement Priority (IP) is the rank order of the factors according to the IG value of the technologies determined along those factors.

5.7.3 Analysis of IG and IP

The technology values of T1, T5 and T6 (Diesel engine, Battery Hybrid and Fuel Cell) technologies are close to each other. Table 5.14 represents the improvement gap (IG) and improvement priority (IP) of each of these technologies along 25 factors.

Table 5.14 : IG and IP of the three technologies along 25 factors for 2025

		T1			T5			T6		
Criterion	**Factors**	**Desirability Value**	**IG**	**IP**	**Desirability Value**	**IG**	**IP**	**Desirability Value**	**IG**	**IP**
C1 0,22	F11 0,70	70,00	4,62	3rd	98,13	0,29		87,50	1,93	
	F21 0,30	17,00	5,48	2nd	70,00	1,98		75,00	1,65	
C2 0,21	F12 0,21	64,00	1,59		29,00	3,13	1st	29,00	3,13	1st
	F22 0,20	100,00	0,00		52,00	2,02	4th	33,60	2,79	2nd
	F32 0,12	32,00	1,71		100,00	0,00		100,00	0,00	
	F42 0,16	98,00	0,07		52,00	1,61		33,00	2,25	3rd
	F52 0,13	64,00	0,98		66,00	0,93		92,50	0,20	
	F62 0,18	83,33	0,63		64,00	1,36		70,00	1,13	
C3 0,14	F13 0,32	96,00	0,18		80,00	0,90		100,00	0,00	
	F23 0,32	99,75	0,01		97,00	0,13		100,00	0,00	
	F33 0,19	80,00	0,53		96,46	0,09		100,00	0,00	
	F43 0,17	53,33	1,11		76,67	0,56		100,00	0,00	
C4 0,23	F14 0,53	43,33	6,91	1st	80,00	2,44	3rd	83,33	2,03	5th
	F24 0,47	75,00	2,70		72,67	2,95	2nd	100,00	0,00	
C5 0,05	F15 0,37	100,00	0,00		100,00	0,00		100,00	0,00	
	F25 0,45	28,00	1,62		100,00	0,00		20,00	1,80	
	F35 0,18	100,00	0,00		28,00	0,66		80,00	0,18	
C6 0,08	F16 0,09	100,00	0,00		100,00	0,00		80,00	0,14	
	F26 0,26	20,00	1,66		100,00	0,00		100,00	0,00	
	F36 0,09	40,00	0,43		80,00	0,14		100,00	0,00	
	F46 0,09	100,00	0,00		80,00	0,14		100,00	0,00	
	F56 0,15	100,00	0,00		80,00	0,24		80,00	0,24	
	F66 0,32	100,00	0,00		100,00	0,00		100,00	0,00	
C7 0,07	F17 0,59	22,00	3,22	4th	80,00	0,83		80,00	0,83	
	F27 0,41	0,00	2,87	5th	30,00	2,01	5th	22,50	2,22	4th

IP is shown for the top five factors for each of the three technologies in Table 5.15.

Table 5.15 : Top factors that the technologies most depend on

IP	Factor	
1st	F12	System efficiency
2nd	F14	Fuel consumption
3rd	F22	Peak power output
4th	F27	Sales volume
5th	F24	CO2 emissions
	F21	Maintenance cost

The decision on which technology should be selected will significantly depend on successful improvement of system efficiency and fuel consumption, as these factors have the highest improvement priority. This result will change for other periods of the study, as detailed in Table 5.16 below.

Table 5.16 : IP ranking of factors for different time periods

IP	2009-2015 Factor		2015-2025 Factor		2025- Factor	
1st	F14	Fuel consumption	F24	CO2 emissions	F12	System efficiency
2nd	F24	CO2 emissions	F12	System efficiency	F14	Fuel consumption
3rd	F11	Vehicle cost	F14	Fuel consumption	F22	Peak power output
4th	F21	Maintenance cost	F21	Maintenance cost	F27	Sales volume
5th	F12	System efficiency	F11	Vehicle cost	F24	CO2 emissions
					F21	Maintenance cost

Fuel consumption and CO_2 emissions are and will be the main factors that the technology selection will depend on. As the vehicle costs are expected to decrease by technology improvement in time, its importance will fade in time. Nevertheless, performance and efficiency will also remain as important.

5.8 Results

The results are summarized as below:

- Today, almost all of the technologies represent close values of the ideal technology. However, a limit can be drawn to %50, and any technology below this can be eliminated due to their remoteness from being the strongest technology. Therefore, HCCI engines and Fuel Cells are not good technologies to be adopted before the necessary technological progress takes place. Battery hybrid technology represents the value of %59,25 of the ideal technology alternative according to the company's preferance. Following closely is Diesel technology, with a value of %55,63, is currently the main product of the company. The results indicate that the company should start investing in hybrids, but for the short run, diesel technology will still be dominant.
- For the next decade, Fuel Cell technology makes an impressive improvement and closes the difference with Battery Hybrid technology, with values of %67,22 and %69,14, respectively. All the technologies, except for the HCCI engine, make progress and rank below %60 line. However, it should be noted that the assumptions are done with respect to the experts expectance of the continuous progress and to overcome each bottlenecks of the mentioned technologies.

- For the long term, the experts evaluating the Fuel Cell technology expect to overcome energy storage, cost and weight issues. This technology represents the value of %79,48, with the closest followers Battery Hybrid and Diesel technologies, representing the values of %77,60 and 70,80, respectively. The computation of the Fuel Cell technology in Appendix G indicates that further improvements of Fuel Consumption, Cost Effectiveness and Emissions aspects would not yield any greater contribution to its technology value since the desirability values of the factors associated with those three criteria are already approaching the full scores.
- Figure 5.7 shows that each technology value increases with a decreasing rate after 2015-2025 time period. This results from the fact that the technologies are expected to show better technological progress to a degree, until they reach technological maturity. For instance, the line representing the Fuel Cell technology has a wider angle for the periods between "2002-2015" and "2015-2025". However, this increase in development slows down between "2015-2025" and "2025-", decreasing from approximately 49° to 39°. Nevertheless, this decreasing rate is still high enough for the technology to become dominant. When the GDI technology is reviewed, it shows some potential for the current market, however its increase cannot compete with other technologies, increasing rate angle decreasing from approximately 35° to 5°.

5.9 Research Validation

Three tests were conducted to validate this research for: content validity, construct validity, and criterion-related validity.

Content validity was tested in the research preparation phase and the development of research instrument to ensure that all information can be captured as intended. Construct validity was tested when the hierarchical decision model was developed to assure unidirectional hierarchical relationships among decision levels, and independence among decision elements. Criterion-related validity was tested after the completion of the model to see how adequately the results represent the reality.

It should be noted that each expert that has evaluated a technology of his or her own expertise, and believes that the mentioned technology will develop and become a dominant technology, as expected. This case shows itself more specifically in the "Sales volume" factor associated with "Market" criterion. Table 5.17 represents the first review of the sales volumes of the technologies. It can be easily seen that even though the study do not cover all the technologies, the sales volume are above %100. The second row shows the renewed and final numbers.

Table 5.17 : The re-evaluation of the Sales Volume factor

Factors	Units	T1	T2	T3	T4	T5	T6	TOTAL
2015-2020								
F27: Sales volume – *1st round*	%	30	8	15	15	25	10	%103
F27: Sales volume - *REVIEWED*	%	18	6	1	8	16	9	%58
2025-								
F27: Sales volume – *1st round*	%	40	10	25	20	40	40	%197
F27: Sales volume - *REVIEWED*	%	22	7	2	9	30	23	%93

5.10 Lessons Learned

During the development of the study, some changes and arrangements in the methodology application were required in order to improve the evaluation and results.

5.10.1 Corrections during Criteria Selection

During the first round of Delphi Review of Criteria, Safety was a separate criterion. However, 18 experts out of 22 evaluators criticized this selection by mentioning that "Active Safety" and "Passive Safety" factors associated with this criterion cannot evaluate the powertrain systems but are involved with the overall vehicle.

Criterion 6 was named "System Availability" at first. However, after several warnings from the experts for including "Regulations and Incentives", "System Complexity" and "System Safety" factors which do not qualify for an availability assessment, the title was renewed as "System Evaluation".

5.10.2 Corrections during Factors Selection

Below factors were removed from their associated criteria:

- "Material costs" factor was removed from Criteria 1, as the cost for the materials required for the development of the powertrain is included in the overall vehicle cost.
- "Energy storage costs" factor was removed from Criteria 1 for the same reason as above, the component cost is considered to be included in the overall vehicle cost.
- "Cold start up" factor was removed from Criteria 2, and it was added to the assumptions that no cold start has been taken into account for either technologies.
- "Operating temperature" factor were first used in Criteria 2, in order to emphasize the temperature limitations for several technologies. However, this factor can be considered to be evaluated within the "System Complexity" and "System Control Technologies" factors due to that the operating temperature limitations increase the importance of system control and cause it to be more complex.

6. CONCLUSION AND FUTURE WORK

6.1 Major Highlights of the Thesis

This study represents a robust quantitative model for evaluating the impact on current and emerging technologies on a company's objective. A methodology, named as "Technology Development Envelope", has been applied to a company, and with respect to its objective, several powertrain technologies are investigated.

Six technologies are selected; two currently dominant technologies, Diesel and Gasoline engines, two in development phase, HCCI and Hydrogen ICE engines and finally two require to overcome some bottlenecks before a large scale market introduction, Battery Hybrid and Fuel Cell.

Seven criteria and 25 factors associated with these criteria are selected to assess these technologies. Each step has been conducted with the imputs from experts, as a requirement of the Delphi method. All the imputs were gathered together and evaluated with respect to the methodology's mathematical model. Each technological metrics were calculated into desirability values and the total of these values constitutes technology values for each technology. Once the technology value is known, then the technology can readily be incorporated into the model and compare with all other available and emerging technologies. The change of the values for each time periods shows the state of development for each technology.

Currently, Battery Hybrid and Diesel technologies are considered to be the closest to be the ideal technologies according to the company's preference. However, in the upcoming decades, Fuel Cell technology makes an impressive progress and becomes the dominant technology after 2025.

6.2 Recommendation for the Future Work

Due to its flexible nature, the TDE developed for this study can be reviewed and updated with improved criteria and factors, and can be applied to other current and emerging technologies.

Biofuels were not adressed in this study. Technologies should be assessed with addition of biofuels or by running with biofuels only.

For Diesel technology, asides from the CVT transmission, a 6-speed automotic transmission was intented to be assessed. However, not enough input were received, therefore was removed from final technologies.

The difference between compressed and liquid hydrogen storage could not be explained within the limits of this study. This subject requires further assessment.

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APPENDICES

APPENDIX A

1. Fuel and powertrain systems for the future: Please estimate the percentage of the vehicles using fuels / powertrains below. Please include comments below.

	TODAY	2015	2025
Gasoline	50	38	25
Diesel	30	30	25
CNG	4	5	6
LPG	3	4	5
Biodiesel	4	5	8
Ethanol	3	4	5
Hydrogen	3	4	7
Electric	3	10	18
Solar	0	0	1

	TODAY	2015	2025
Spark ignition	53	41	29
Diesel	33	26	26
Full electric	3	5	8
Fuel cell	2	4	6
Full hybrid	2	6	8
Mild hybrid	1	5	6
Plug-in hybrid	0	3	5
HCCI	4	5	5
Hydrogen ICE	2	5	7

2. Energy storage systems: Please estimate the percentage of the energy storage systems to be used in the future. Please include comments below.

	TODAY	2015	2025
Lithium – ion battery	17	32	39
Lead – acid battery	51	33	29
Lithium Polymer battery	7	10	14
Nickel-Cadmium battery	12	8	4
Nickel-Metal Hydride battery	10	12	6
Zinc-Air battery	0,5	1	1
Ultracapacitor	2	3	5
Flywheel	0,5	1	2

3. Required technologies for the sustainability of ICEs: Please estimate the percentage of ICE technologies to be used in the future. Please include comments below.

	TODAY	2015	2025
High pressure injection	5	5	5
Injection optimization	4	4	4
Combustion chamber optimization	4	3	2
Aftertreatment systems			
EGR	3	3	3
SCR	4	5	5
LNT	2	3	3
Cooled EGR	2	3	4
DPF	4	5	5
Variable valve timing	2	4	5
LTC strategies (low temp. combustion)	2	3	4
VCR (variable compression ratio)	3	5	5

4. What are the greatest challenges for ICEs in the future? Please rank the following in order of greatest challenge to smallest challenge (**1: Smallest challenge - 5: Greatest challenge**). Please add others if necessary and include your comments below.

	TODAY	2015	2025
Diminising resources	2	3	4
Environmental issues	2	3	4
Technological improvement threshold	3	3	4

5. What are the greatest challenges for hybrid systems to be used in the future? Please rank the following in order of greatest challenge to smallest challenge (**1: Smallest challenge - 5: Greatest challenge**). Please add others if necessary and include your comments below.

	TODAY	2015	2025
Components			
Batteries	3	2	1
Power control unit	2	1	1
Power-split device	3	1	1
Electric motor	3	1	1
Generators	3	1	1
Other challenges			
Cost vs payback	3	2	1
Vehicle weight	3	1	1
Pollution control	3	1	1
Vehicle control	2	1	1
Complexity	3	2	1
Auxiliary systems	3	2	1
Engine choice	3	2	1

6. What are the greatest challenges for fuel cell systems to be used in the future? Please rank the following in order of greatest challenge to least challenge (**1: Smallest challenge - 5: Greatest challenge**). Please add others if necessary and include your comments below.

	TODAY	2015	2025
Components			
Fuel cell engine unit	4	3	2
Fuel storage	5	3	2
Batteries	3	2	1
Electric motor / generator	3	1	1
Power control unit	2	1	1
Power-split device	3	1	1
Other challenges			
Hydrogen infrastructure	5	3	1
Hydrogen source	3	2	2
Cost	5	4	3
Durability	5	4	3
Precious metals	3	3	3

APPENDIX B

Table B.1 : Distributions of experts

University	Industry	Research Centers	TOTAL
20	15	6	41

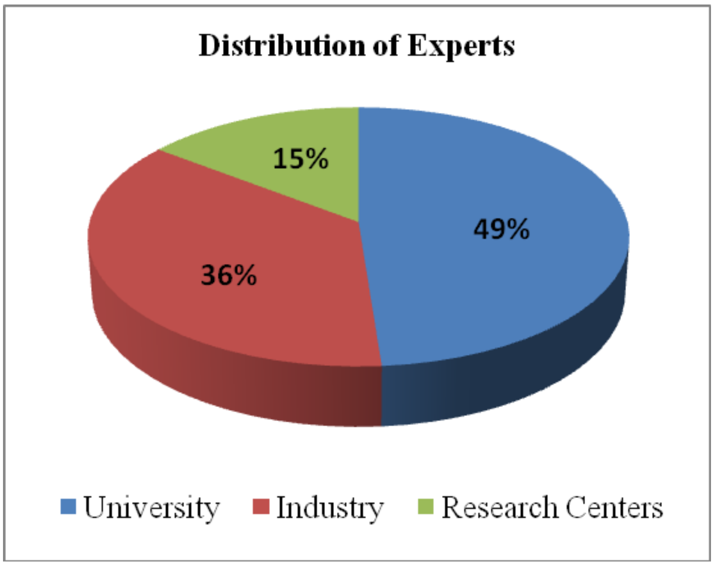


Figure B.1 : Distribution of experts by percent

Table B.2 : Distribution of experts by work premises

	University		Industry	Research Centers
TOTAL	20		15	6
Prof.	7	Manager	2	-
Assoc. Prof.	4	Expert	5	4
Ass. Prof.	3	Chief Engineer	7	-
Dr.	6	Engineer	1	2

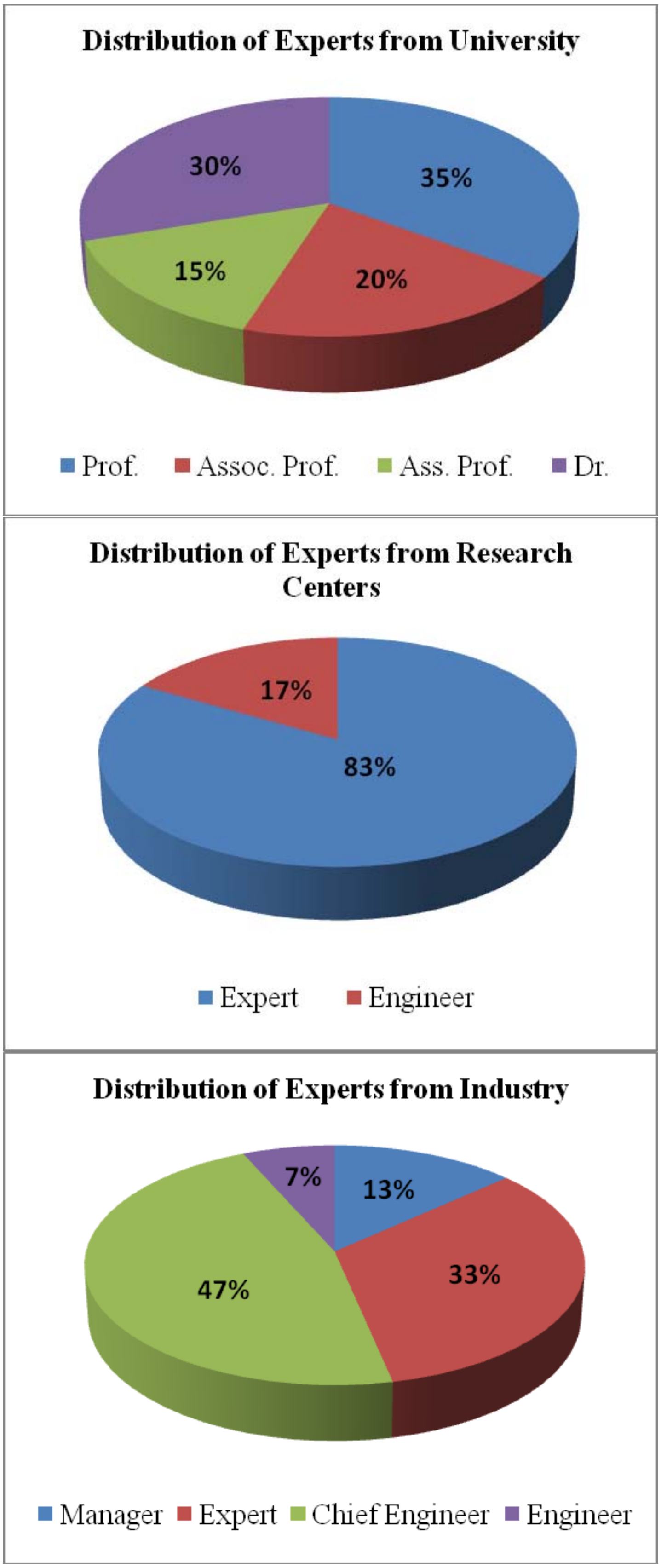


Figure B.2 : Distribution of experts by work premises

APPENDIX C

Table C.1 : Description of Criteria and Factors for Criteria 1 to Criteria 5

Criterion 1: **Description:**	**Cost Effectiveness** Overall expenses of powertrain systems	
F11: **Description:** *Example:*	**Vehicle cost** Overall system cost and production expense. Additional cost of the vehicle compared to referance vehicle	[$]
F14: **Description:** *Example:*	**Maintenance cost** Maintenance cost of the overall vehicle Spare parts of some systems or components may be extremely expensive	[$]
Criterion 2: **Description:**	**Performance** Comparison of system requirements for powertrains	
F12: **Description:** *Example:*	**System efficiency** The measure of the effciency and completeness of combustion of the fuel Well-to-wheel efficiency of the overall system	[%]
F22: **Description:**	**Peak power output** Maximum level of work or energy output during an observation period	[kW]
F32: *Example:*	**System control technologies** Control strategies required to work in the most efficient area	[5-pt scale]
F42: **Description:**	**Power density** Ratio of the power to volume of a device	[kW/l]
F52: **Description:** *Example:*	**Additional weight** Additional powertrain system weight compared to conventional vehicle Weight is a critical factor for vehicles which should be reduced	[kg]
F62: **Description:**	**Durability** Ability of something to perform its function repeatedly	[km]
Criterion 3: **Description:**	**Emissions** Emissions standards to be fulfilled before market introduction	
F13: **Description:** *Example:*	**NOx emissions** Nitrogen oxides are usually emitted from high temperature combustion Can be seen as the brown haze dome above or plume downwind of cities	[gr/km]
F23: **Description:**	**PM emissions** Tiny particles of solid or liquid suspended in a gas	[gr/km]
F33: *Example:*	**HC emissions** Contributes to enhanced global warming	[gr/km]
F43: **Description:** *Example:*	**CO emissions** Product by incomplete combustion of fuel such as natural gas, coal or wood Colourless, odourless, non-irritating but very poisonous gas	[gr/km]
Criterion 4: **Description:**	**Fuel Consumption** Fuel consumption and respective CO2 emission values	
F14: **Description:** *Example:*	**Fuel consumption** Total output of a vehicle as a ratio of range units per a unit amount of input fuel In direct proportion with CO2 emissions	[l/100km]
F24: **Description:**	**CO2 emissions** Emitted due to carbon content of the fuel	[g CO2/km]
Criterion 5: **Description:**	**Fuel Specifications** Comparison of the systems with respect to their fuels	
F15: *Example:*	**Fuel infrastructure availability** Is the fuel infrastructure available for each driver?	[5-pt scale]
F25: **Description:**	**Fuel infrastructure cost** Total cost for fuel distribution & fuelling infrastructure	[million $]
F35: **Description:**	**Energy density by mass** Amount of energy stored in a given system or region of space per unit mass	[MJ/kg]

Table C.2 : Description of Criteria and Factors for Criteria 6 to Criteria 7

Criterion 6: **Description:**	**System Evaluation** Overall system evaluation for interchangeability, complexity and current limitations	
F16: *Example:*	**Materials availability** Heavy metals used in some components can be hard to obtain and to be used	[5-pt scale]
F26: *Example:*	**Components availability** Some components such as batteries can be expensive to be used in large fleets	[5-pt scale]
F36: *Example:*	**Technology development state** During the transition to hydrogen, breakthroughs are required	[5-pt scale]
F46: **Description:** *Example:*	**Regulations and legal framework** Regulations for fuels and vehicles should be completed Hydrogen regulations? Testing regulations for hybrids?	[5-pt scale]
F56: **Description:** *Example:*	**System complexity** System complexity may cause difficulties during driving and maintenance, etc. Control strategies of the systems, sensors, actuators, etc.	[5-pt scale]
F66: **Description:** *Example:*	**System safety** System safety with respect to onboard components and fuel related actions Safety of fuel or any other storage tanks, fuel safety during filling, etc.	[5-pt scale]
Criterion 7: **Description:**	**Market** Position in market and/or market entrance of the systems	
F17: *Example:*	**Availability of the vehicles** Are the vehicles with the respective technology available today?	[5-pt scale]
F27: *Example:*	**Sales volume** What are the sales volume of the vehicles with the respective technology?	[%]

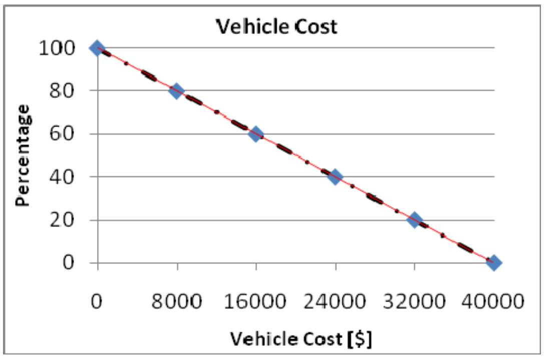
APPENDIX D

Table D.1 : Description of 5 point scales required to assess factors

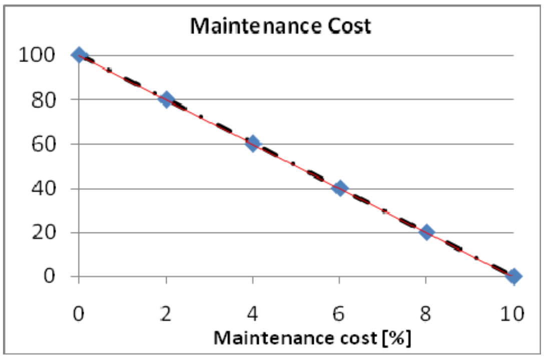
Factors	5-point scale	Description
F32: System control technologies	*Excellent (E)*	System control software and strategies are well defined and not complex.
	Very good (VG)	System control software and strategies are well defined and not complex but requires optimization.
	Good (G)	System control software and strategies need to be defined better and is somewhat complex.
	Acceptable (A)	System control software and strategies are complex.
	Poor (P)	System requires highly complex control software and strategies.
	Unacceptable (UA)	Complexity of the software and strategies cause system failure.
F15: Fuel availability	*Excellent (E)*	Fuel is accessible for each driver all over the country and distribution infrastructure is widely spread.
	Very good (VG)	Fuel is accessible for each driver in most of the cities and distribution infrastructure fairly spread.
	Good (G)	Fuel is accessible for each driver in large cities and distribution infrastructure is fairly spread.
	Acceptable (A)	Fuel is accessible for each driver in large cities and distribution infrastructure requires development.
	Poor (P)	Fuel is accessible for each driver in only a few stations in large cities and distribution infrastructure requires development.
	Unacceptable (UA)	Fuel is not accessible for any drivers and distribution infrastructure requires extensive development.
F16: Materials availability	*Excellent (E)*	Materials required for the system are easily accessible with low cost
	Very good (VG)	Materials required for the system are easily accessible with high cost
	Good (G)	Materials required for the system are somewhat accessible with low cost
	Acceptable (A)	Materials required for the system are somewhat accessible with high cost
	Poor (P)	Materials required for the system are not easily accessible with low cost
	Unacceptable (UA)	Materials required for the system are not easily accessible with high cost
F26: Components availability	*Excellent (E)*	System components are commonly available and are interchangeable with same components made by numerous manufacturers
	Very good (VG)	System components are commonly available and are interchangeable with same components made by few manufacturers
	Good (G)	System components are available only in specialized stores and are interchangeable with same components made by few manufacturers
	Acceptable (A)	System components are available only in specialized stores and are interchangeable with same components made by the original manufacturer.
	Poor (P)	System components are not easily available and are interchangeable with same components made-to-order by the original manufacturer.
	Unacceptable (UA)	System components are not easily available and have to be redesigned specifically when required.
F36: Technology development state	*Excellent (E)*	There is a large gap in the technology and will require further development, therefore is a subject for new R&D projects.
	Very good (VG)	There is a gap in the technology and will require further development, therefore may be a subject for new R&D projects.
	Good (G)	There is a little gap in the technology and will require development, therefore may be a subject for new R&D projects.
	Acceptable (A)	There are no gaps in the technology, however some development is required to become widespread.
	Poor (P)	Technology needs a breakthrough for further development.
	Unacceptable (UA)	System technology has reached its limits and cannot be improved any further.
F46: Regulations and legal framework	*Excellent (E)*	Mandatory regulations of the system and/or fuel are already adopted, harmonization of the regulations is completed, test procedures and requirements are set.
	Very good (VG)	Mandatory regulations of the system and/or fuel and the harmonization of the regulations is currently being proposed, test procedures and requirements are almost set.
	Good (G)	Mandatory regulations of the system and/or fuel, harmonization of the regulations and test procedures and requirements are currently being reviewed.
	Acceptable (A)	Mandatory regulations of the system and/or fuel, harmonization of the regulations and test procedures and requirements are in preparation phase.
	Poor (P)	Test procedures and requirements are currently being reviewed; however, there are no mandatory regulations available.
	Unacceptable (UA)	There are no regulations, test procedures or requirements adopted.

F56: System complexity	*Excellent (E)*	System is not complex, do not cause any trouble during driving and maintenance is easy.
	Very good (VG)	System is not very complex, do not cause any trouble during driving and maintenance is relatively easy.
	Good (G)	System is not very complex, may cause some trouble during driving and maintenance is relatively easy.
	Acceptable (A)	System is somewhat complex, may cause some trouble during driving and maintenance is not very easy.
	Poor (P)	System is complex, may cause trouble during driving and maintenance is not easy.
	Unacceptable (UA)	System is very complex, likely to cause trouble during driving and maintenance is not easy.
F66: System safety	*Excellent (E)*	System and filling components, as well as fuel specifications do not cause any safety hazards.
	Very good (VG)	System and filling components, as well as fuel specifications may require some safety precautions.
	Good (G)	System and filling components, as well as fuel specifications may require several safety precautions.
	Acceptable (A)	System and filling components, as well as fuel specifications are dangerous and require safety precautions.
	Poor (P)	System and filling components, as well as fuel specifications are very dangerous.
	Unacceptable (UA)	System and filling components, as well as fuel specifications are extremely dangerous.
F17: Availability of the vehicles	*Excellent (E)*	Vehicles are commonly available and not any more expensive than a conventional vehicle.
	Very good (VG)	Vehicles are commonly available and more expensive than a conventional vehicle.
	Good (G)	Vehicles are available and more expensive than a conventional vehicle.
	Acceptable (A)	Vehicles are available and far more expensive than a conventional vehicle.
	Poor (P)	Vehicles are not commonly available and far more expensive than a conventional vehicle.
	Unacceptable (UA)	There are only prototypes of the vehicles.

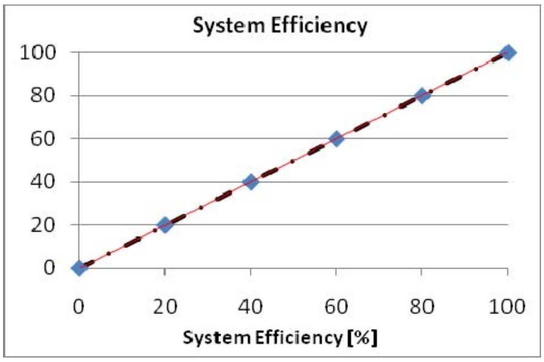
APPENDIX E



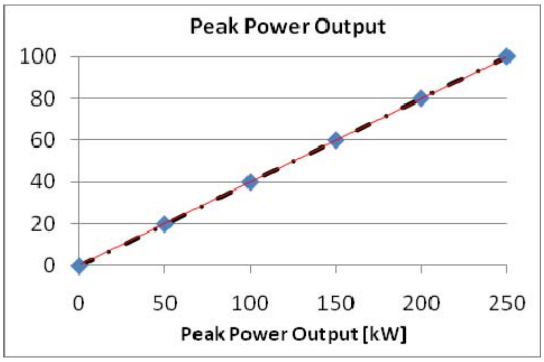
Vehicle Cost
Percentage
100
80
60
40
20
0
0
8000
16000
24000
32000
40000
Vehicle Cost [$]



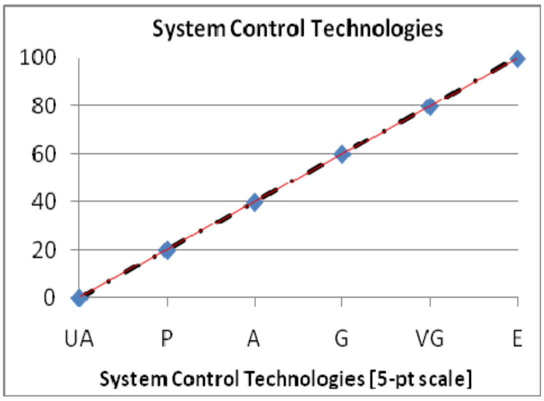
Maintenance Cost
100
80
60
40
20
0
0
2
4
6
8
10
Maintenance cost [%]



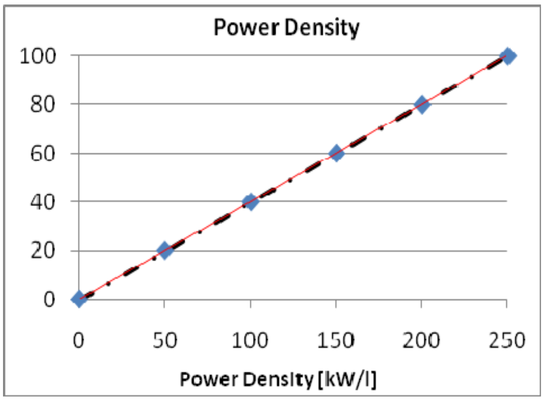
System Efficiency
100
80
60
40
20
0
0
20
40
60
80
100
System Efficiency [%]



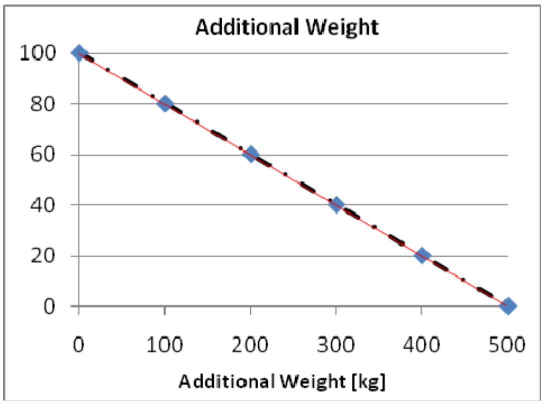
Peak Power Output
100
80
60
40
20
0
0
50
100
150
200
250
Peak Power Output [kW]



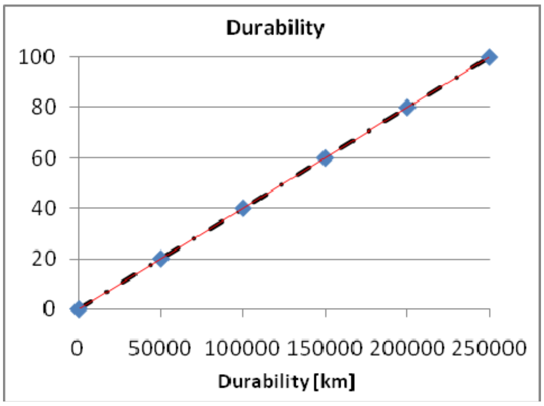
System Control Technologies
100
80
60
40
20
0
UA
P
A
G
VG
E
System Control Technologies [5-pt scale]



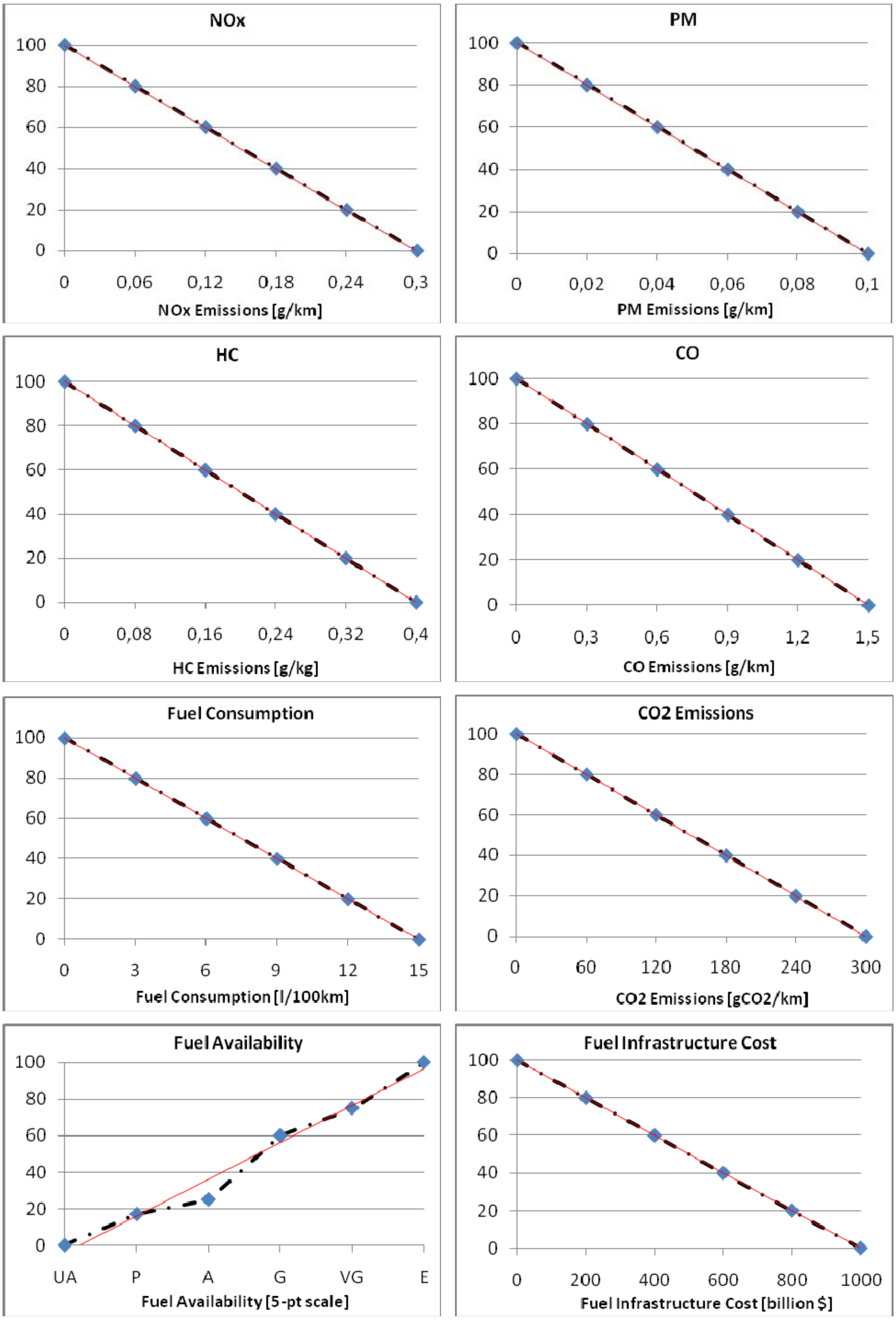
Power Density
100
80
60
40
20
0
0
50
100
150
200
250
Power Density [kW/l]

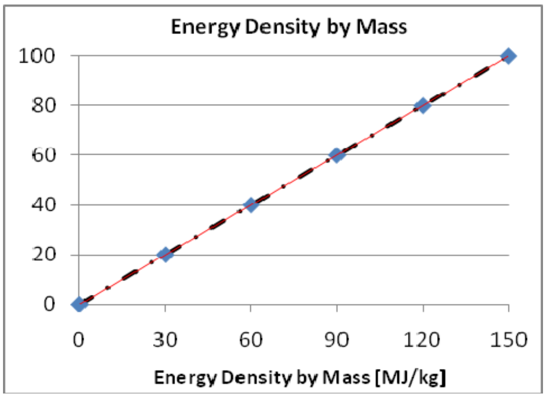


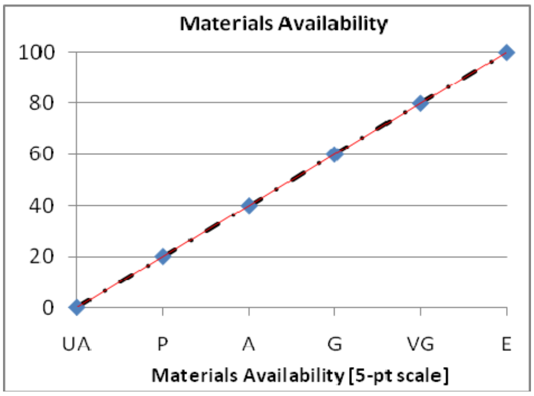
Additional Weight
100
80
60
40
20
0
0
100
200
300
400
500
Additional Weight [kg]

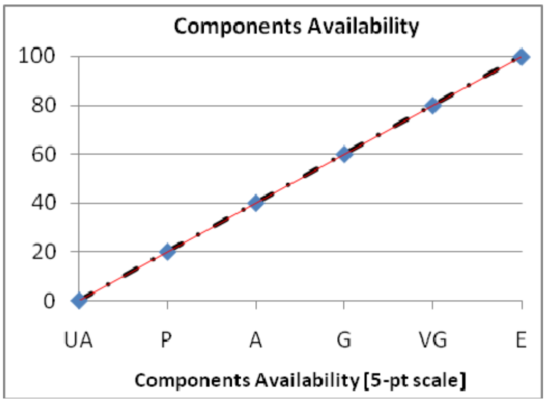


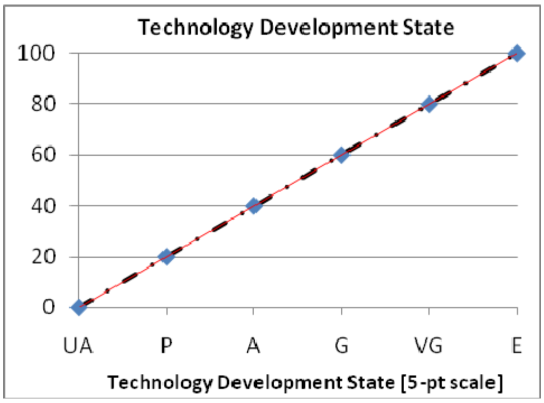
Durability
100
80
60
40
20
0
0
50000
100000
150000
200000
250000
Durability [km]

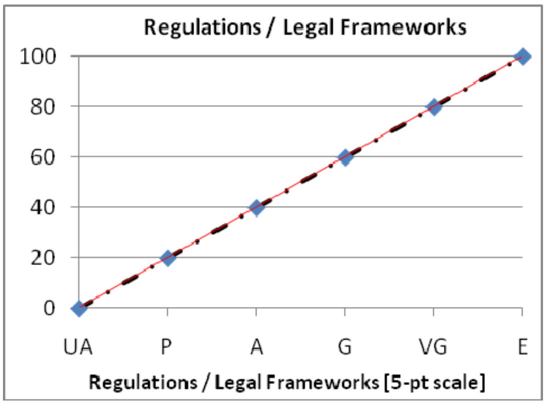

NOx
100
80
60
40
20
0
0
0,06
0,12
0,18
0,24
0,3
NOx Emissions [g/km]
PM
100
80
60
40
20
0
0
0,02
0,04
0,06
0,08
0,1
PM Emissions [g/km]
HC
100
80
60
40
20
0
0
0,08
0,16
0,24
0,32
0,4
HC Emissions [g/kg]
CO
100
80
60
40
20
0
0
0,3
0,6
0,9
1,2
1,5
CO Emissions [g/km]
Fuel Consumption
100
80
60
40
20
0
0
3
6
9
12
15
Fuel Consumption [l/100km]
CO2 Emissions
100
80
60
40
20
0
0
60
120
180
240
300
CO2 Emissions [gCO2/km]
Fuel Availability
100
80
60
40
20
0
UA
P
A
G
VG
E
Fuel Availability [5-pt scale]
Fuel Infrastructure Cost
100
80
60
40
20
0
0
200
400
600
800
1000
Fuel Infrastructure Cost [billion $]

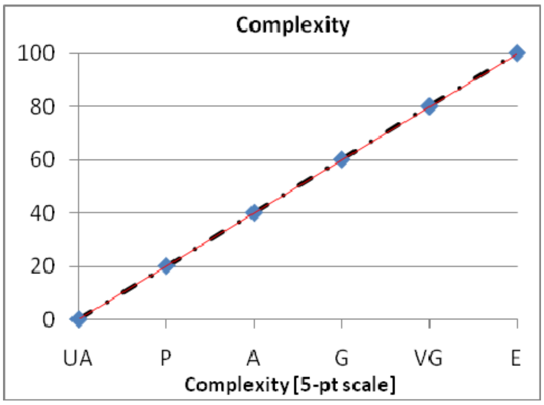

Energy Density by Mass
100
80
60
40
20
0
0
30
60
90
120
150
Energy Density by Mass [MJ/kg]

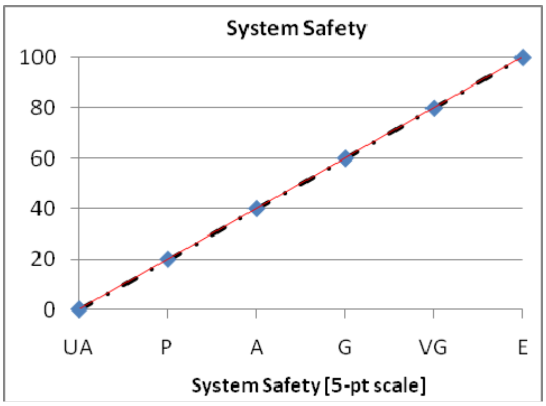

Materials Availability
100
80
60
40
20
0
UA
P
A
G
VG
E
Materials Availability [5-pt scale]

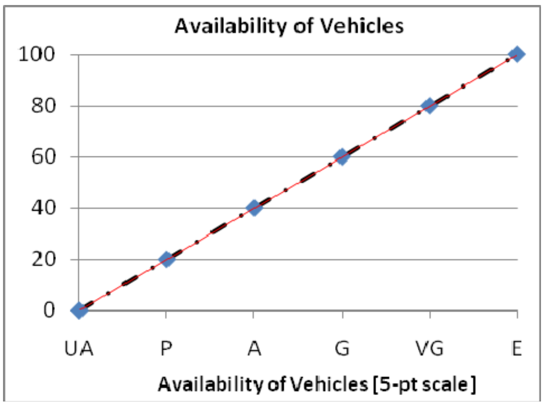

Components Availability
100
80
60
40
20
0
UA
P
A
G
VG
E
Components Availability [5-pt scale]


Technology Development State
100
80
60
40
20
0
UA
P
A
G
VG
E
Technology Development State [5-pt scale]


Regulations / Legal Frameworks
100
80
60
40
20
0
UA
P
A
G
VG
E
Regulations / Legal Frameworks [5-pt scale]


Complexity
100
80
60
40
20
0
UA
P
A
G
VG
E
Complexity [5-pt scale]


System Safety
100
80
60
40
20
0
UA
P
A
G
VG
E
System Safety [5-pt scale]


Availability of Vehicles
100
80
60
40
20
0
UA
P
A
G
VG
E
Availability of Vehicles [5-pt scale]

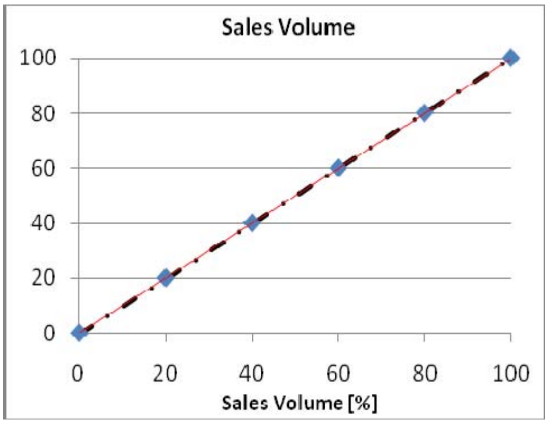


Figure E.1 : Desirability curves of all 21 factors

APPENDIX F:

Table F.1 : Metrics and desirability values estimated for 2015-2025

			Technological Metrics						Desirability Values					
Criteria	**Factors**	**Units**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
C1: Cost Effectiveness	F11: Vehicle cost (additional)	$	4.000	5.000	14.000	8.000	4.500	12.500	90,00	87,50	65,00	80,00	88,75	68,75
	F21: Maintenance cost	%	4	5	7	6	4	4,5	60,00	50,00	30,00	40,00	60,00	55,00
C2: Performance	F12: System efficiency	%	16	16	50	32	25	25	16,00	16,00	50,00	32,00	24,50	25,00
	F22: Peak power output	kW	135	135	105	125	125	81	54,00	54,00	42,00	50,00	50,00	32,20
	F32: System control tech.	5 pt scale	E	VG	G	VG	E	G	100,00	80,00	60,00	80,00	100,00	60,00
	F42: Power density	kW/l	78	84	82	92	118	75	31,20	33,60	32,80	36,80	47,33	30,00
	F52: Additional weight	kg	20	15	100	175	245	20	96,00	97,00	80,00	65,00	51,00	65,00
	F62: Durability	km	160.000	160.000	90.000	90.000	130.000	150.000	64,00	64,00	36,00	36,00	52,00	60,00
C3: Emissions	F13: NOx	g/km	0,150	0,075	0,200	0,100	0,093	0,000	50,00	75,00	33,33	66,67	68,89	100,00
	F23: PM	g/km	0,005	0,005	0,000	0,003	0,005	0,000	95,00	95,00	100,00	97,00	95,00	100,00
	F33: HC	g/km	0,002	0,130	0,350	0,020	0,021	0,000	99,50	67,50	12,50	95,00	94,71	100,00
	F43: CO	g/km	0,550	1,810	1,000	0,001	0,567	0,000	72,50	9,50	50,00	99,98	71,67	100,00
C4: Fuel Consumption	F14: Fuel consumption	l/100 km	8	7	4	10	5	4	50,00	56,67	73,33	33,33	68,33	76,67
	F24: CO2 emissions	gCO2/km	200	172	120	1	125	0	33,33	42,57	60,00	99,83	58,33	100,00
C5: Fuel Specifications	F15: Fuel availability	5 pt scale	E	VG	G	A	E	A	100,00	75,00	60,00	25,00	100,00	25,00
	F25: Fuel infrastructure cost	billion $	0	0	0	500	0	500	100,00	100,00	100,00	50,00	100,00	50,00
	F35: Energy density by mass	MJ/kg	42	42	48	120	42	120	28,00	28,00	32,00	80,00	28,00	80,00
C6: System Availability	F16: Materials availability	5 pt scale	E	VG	VG	VG	VG	A	100,00	80,00	80,00	80,00	80,00	40,00
	F26: Components availability	5 pt scale	E	VG	VG	VG	E	A	100,00	80,00	80,00	80,00	100,00	40,00
	F36: Technology dev. state	5 pt scale	G	A	G	VG	E	E	60,00	40,00	60,00	80,00	100,00	100,00
	F46: Regulations	5 pt scale	G	A	VG	VG	E	E	60,00	40,00	80,00	80,00	100,00	100,00
	F56: Complexity	5 pt scale	VG	G	E	E	G	A	80,00	60,00	100,00	100,00	60,00	40,00
	F66: System safety	5 pt scale	E	E	E	E	E	E	100,00	100,00	100,00	100,00	100,00	100,00
C7: Market	F17: Availability of vehicles	5 pt scale	VG	G	G	A	G	A	80,00	60,00	60,00	40,00	60,00	40,00
	F27: Sales volume	%	18	6	1	8	16	9	18,00	6,00	1,00	8,00	15,67	9,00

Table F.2 : Metrics and desirability values estimated for 2025-2040

Criteria	Factors	Units	Technological Metrics						Desirability Values					
			T1	T2	T3	T4	T5	T6	T1	T2	T3	T4	T5	T6
C1: Cost Effectiveness	F11: Vehicle cost (additional)	$	2.000	4.500	10.000	6.000	750	5.000	95,00	88,75	75,00	85,00	98,13	87,50
	F21: Maintenance cost	%	3	5	5	5	3	2,5	70,00	50,00	50,00	50,00	70,00	75,00
C2: Performance	F12: System efficiency	%	17	17	55	33	29	29	17,00	17,00	55,00	33,00	29,00	29,00
	F22: Peak power output	kW	160	138	110	127	130	84	64,00	55,20	44,00	50,80	52,00	33,60
	F32: System control tech.	5 pt scale	E	VG	G	E	E	E	100,00	80,00	60,00	100,00	100,00	100,00
	F42: Power density	kW/l	80	85	85	93	130	83	32,00	34,00	34,00	37,20	52,00	33,00
	F52: Additional weight	kg	10	10	0	150	170	10	98,00	98,00	100,00	70,00	66,00	92,50
	F62: Durability	km	160.000	160.000	100.000	100.000	160.000	175.000	64,00	64,00	40,00	40,00	64,00	70,00
C3: Emissions	F13: NOx	g/km	0,050	0,050	0,100	0,070	0,060	0,000	83,33	83,33	66,67	76,67	80,00	100,00
	F23: PM	g/km	0,004	0,003	0,000	0,002	0,003	0,000	96,00	97,00	100,00	98,00	97,00	100,00
	F33: HC	g/km	0,001	0,100	0,300	0,010	0,014	0,000	99,75	75,00	25,00	97,50	96,46	100,00
	F43: CO	g/km	0,400	1,500	0,900	0,001	0,467	0,000	80,00	25,00	55,00	99,98	76,67	100,00
C4: Fuel Consumption	F14: Fuel consumption	l/100 km	7	6	4	9	3	3	53,33	60,00	76,67	40,00	80,00	83,33
	F24: CO2 emissions	gCO2/km	170	159	100	0	82	0	43,33	47,00	66,67	99,87	72,67	100,00
C5: Fuel Specifications	F15: Fuel availability	5 pt scale	VG	G	VG	VG	E	E	75,00	60,00	75,00	75,00	100,00	100,00
	F25: Fuel infrastructure cost	billion $	0	0	0	800	0	800	100,00	100,00	100,00	20,00	100,00	20,00
	F35: Energy density by mass	MJ/kg	42	42	50	120	42	120	28,00	28,00	33,33	80,00	28,00	80,00
C6: System Availability	F16: Materials availability	5 pt scale	E	G	E	E	E	VG	100,00	60,00	100,00	100,00	100,00	80,00
	F26: Components availability	5 pt scale	E	G	E	G	E	E	100,00	60,00	100,00	60,00	100,00	100,00
	F36: Technology dev. state	5 pt scale	P	P	A	G	VG	E	20,00	20,00	40,00	60,00	80,00	100,00
	F46: Regulations	5 pt scale	A	P	G	G	VG	E	40,00	20,00	60,00	60,00	80,00	100,00
	F56: Complexity	5 pt scale	E	VG	E	E	VG	VG	100,00	80,00	100,00	100,00	80,00	80,00
	F66: System safety	5 pt scale	E	E	E	E	E	E	100,00	100,00	100,00	100,00	100,00	100,00
C7: Market	F17: Availability of vehicles	5 pt scale	E	G	G	G	VG	VG	100,00	60,00	60,00	60,00	80,00	80,00
	F27: Sales volume	%	22	7	2	9	30	23	22,00	7,00	2,00	9,00	30,00	22,50

APPENDIX G

Table G.1 : Calculation of the technology value of Technology 2 for 2009-2015

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{2,11})$	85,00	13,09
		F21	0,30	$V(t_{2,21})$	30,00	1,98
C2: Performance	0,21	F12	0,21	$V(t_{2,12})$	15,00	0,66
		F22	0,20	$V(t_{2,22})$	48,00	2,02
		F32	0,12	$V(t_{2,32})$	40,00	1,01
		F42	0,16	$V(t_{2,42})$	32,00	1,08
		F52	0,13	$V(t_{2,52})$	90,00	2,46
		F62	0,18	$V(t_{2,62})$	40,00	1,51
C3: Emissions	0,14	F13	0,32	$V(t_{2,13})$	66,67	2,99
		F23	0,32	$V(t_{2,23})$	95,00	4,26
		F33	0,19	$V(t_{2,33})$	67,50	1,80
		F43	0,17	$V(t_{2,43})$	9,50	0,23
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{2,14})$	40,00	4,88
		F24	0,47	$V(t_{2,24})$	20,67	2,23
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{2,15})$	100,00	1,85
		F25	0,45	$V(t_{2,25})$	100,00	2,25
		F35	0,18	$V(t_{2,35})$	28,00	0,26
C6: System Evaluation	0,08	F16	0,09	$V(t_{2,16})$	100,00	0,72
		F26	0,26	$V(t_{2,26})$	80,00	1,66
		F36	0,09	$V(t_{2,36})$	80,00	0,58
		F46	0,09	$V(t_{2,46})$	60,00	0,43
		F56	0,15	$V(t_{2,56})$	40,00	0,48
		F66	0,32	$V(t_{2,66})$	80,00	2,05
C7: Market	0,07	F17	0,59	$V(t_{2,17})$	20,00	0,83
		F27	0,41	$V(t_{2,27})$	3,00	0,09
						51,36

Table G.2 : Calculation of the technology value of Technology 3 for 2009-2015

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{3,11})$	52,50	8,09
		F21	0,30	$V(t_{3,21})$	10,00	0,66
C2: Performance	0,21	F12	0,21	$V(t_{3,12})$	45,00	1,98
		F22	0,20	$V(t_{3,22})$	40,00	1,68
		F32	0,12	$V(t_{3,32})$	40,00	1,01
		F42	0,16	$V(t_{3,42})$	32,00	1,08
		F52	0,13	$V(t_{3,52})$	60,00	1,64
		F62	0,18	$V(t_{3,62})$	32,00	1,21
C3: Emissions	0,14	F13	0,32	$V(t_{3,13})$	3,33	0,15
		F23	0,32	$V(t_{3,23})$	100,00	4,48
		F33	0,19	$V(t_{3,33})$	5,00	0,13
		F43	0,17	$V(t_{3,43})$	45,00	1,07
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{3,14})$	70,00	8,53
		F24	0,47	$V(t_{3,24})$	53,33	5,77
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{3,15})$	25,00	0,46
		F25	0,45	$V(t_{3,25})$	100,00	2,25
		F35	0,18	$V(t_{3,35})$	30,80	0,28
C6: System Evaluation	0,08	F16	0,09	$V(t_{3,16})$	60,00	0,43
		F26	0,26	$V(t_{3,26})$	60,00	1,25
		F36	0,09	$V(t_{3,36})$	80,00	0,58
		F46	0,09	$V(t_{3,46})$	100,00	0,72
		F56	0,15	$V(t_{3,56})$	80,00	0,96
		F66	0,32	$V(t_{3,66})$	80,00	2,05
C7: Market	0,07	F17	0,59	$V(t_{3,17})$	40,00	1,65
		F27	0,41	$V(t_{3,27})$	0,05	0,01
						48,12

Table G.3 : Calculation of the technology value of Technology 4 for 2009-2015

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{4,11})$	57,50	8,86
		F21	0,30	$V(t_{4,21})$	20,00	1,32
C2: Performance	0,21	F12	0,21	$V(t_{4,12})$	30,00	1,32
		F22	0,20	$V(t_{4,22})$	48,00	2,02
		F32	0,12	$V(t_{4,32})$	60,00	1,51
		F42	0,16	$V(t_{4,42})$	36,00	1,21
		F52	0,13	$V(t_{4,52})$	58,00	1,58
		F62	0,18	$V(t_{4,62})$	32,00	1,21
C3: Emissions	0,14	F13	0,32	$V(t_{4,13})$	50,00	2,24
		F23	0,32	$V(t_{4,23})$	95,00	4,26
		F33	0,19	$V(t_{4,33})$	90,00	2,39
		F43	0,17	$V(t_{4,43})$	99,95	2,38
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{4,14})$	26,67	3,25
		F24	0,47	$V(t_{4,24})$	99,71	10,78
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{4,15})$	0,00	0,00
		F25	0,45	$V(t_{4,25})$	90,00	2,03
		F35	0,18	$V(t_{4,35})$	80,00	0,73
C6: System Evaluation	0,08	F16	0,09	$V(t_{4,16})$	80,00	0,58
		F26	0,26	$V(t_{4,26})$	40,00	0,83
		F36	0,09	$V(t_{4,36})$	100,00	0,72
		F46	0,09	$V(t_{4,46})$	100,00	0,72
		F56	0,15	$V(t_{4,56})$	80,00	0,96
		F66	0,32	$V(t_{4,66})$	80,00	2,05
C7: Market	0,07	F17	0,59	$V(t_{4,17})$	20,00	0,83
		F27	0,41	$V(t_{4,27})$	1,00	0,03
						53,80

Table G.4 : Calculation of the technology value of Technology 5 for 2009-2015

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{5,11})$	76,25	11,74
		F21	0,30	$V(t_{5,21})$	46,67	3,08
C2: Performance	0,21	F12	0,21	$V(t_{5,12})$	20,50	0,90
		F22	0,20	$V(t_{5,22})$	47,00	1,97
		F32	0,12	$V(t_{5,32})$	80,00	2,02
		F42	0,16	$V(t_{5,42})$	43,00	1,44
		F52	0,13	$V(t_{5,52})$	45,00	1,23
		F62	0,18	$V(t_{5,62})$	40,00	1,51
C3: Emissions	0,14	F13	0,32	$V(t_{5,13})$	55,56	2,49
		F23	0,32	$V(t_{5,23})$	82,67	3,70
		F33	0,19	$V(t_{5,33})$	91,17	2,43
		F43	0,17	$V(t_{5,43})$	64,50	1,54
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{5,14})$	65,00	7,92
		F24	0,47	$V(t_{5,24})$	52,33	5,66
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{5,15})$	100,00	1,85
		F25	0,45	$V(t_{5,25})$	100,00	2,25
		F35	0,18	$V(t_{5,35})$	28,00	0,26
C6: System Evaluation	0,08	F16	0,09	$V(t_{5,16})$	60,00	0,43
		F26	0,26	$V(t_{5,26})$	40,00	0,83
		F36	0,09	$V(t_{5,36})$	100,00	0,72
		F46	0,09	$V(t_{5,46})$	100,00	0,72
		F56	0,15	$V(t_{5,56})$	60,00	0,72
		F66	0,32	$V(t_{5,66})$	80,00	2,05
C7: Market	0,07	F17	0,59	$V(t_{5,17})$	40,00	1,65
		F27	0,41	$V(t_{5,27})$	4,67	0,13
						59,25

Table G.5 : Calculation of the technology value of Technology 6 for 2009-2015

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{6,11})$	1,25	0,19
		F21	0,30	$V(t_{6,21})$	40,00	2,64
C2: Performance	0,21	F12	0,21	$V(t_{6,12})$	22,00	0,97
		F22	0,20	$V(t_{6,22})$	30,00	1,26
		F32	0,12	$V(t_{6,32})$	40,00	1,01
		F42	0,16	$V(t_{6,42})$	27,60	0,93
		F52	0,13	$V(t_{6,52})$	35,00	0,96
		F62	0,18	$V(t_{6,62})$	50,00	1,89
C3: Emissions	0,14	F13	0,32	$V(t_{6,13})$	100,00	4,48
		F23	0,32	$V(t_{6,23})$	100,00	4,48
		F33	0,19	$V(t_{6,33})$	100,00	2,66
		F43	0,17	$V(t_{6,43})$	100,00	2,38
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{6,14})$	68,33	8,33
		F24	0,47	$V(t_{6,24})$	100,00	10,81
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{6,15})$	0,00	0,00
		F25	0,45	$V(t_{6,25})$	99,00	2,23
		F35	0,18	$V(t_{6,35})$	80,00	0,73
C6: System Evaluation	0,08	F16	0,09	$V(t_{6,16})$	20,00	0,14
		F26	0,26	$V(t_{6,26})$	0,00	0,00
		F36	0,09	$V(t_{6,36})$	100,00	0,72
		F46	0,09	$V(t_{6,46})$	100,00	0,72
		F56	0,15	$V(t_{6,56})$	0,00	0,00
		F66	0,32	$V(t_{6,66})$	40,00	1,02
C7: Market	0,07	F17	0,59	$V(t_{6,17})$	0,00	0,00
		F27	0,41	$V(t_{6,27})$	0,75	0,02
						48,57

Table G.6 : Calculation of the technology value of Technology 1 for 2015-2025

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{1,11})$	90,00	13,86
		F21	0,30	$V(t_{1,21})$	60,00	3,96
C2: Performance	0,21	F12	0,21	$V(t_{1,12})$	16,00	0,71
		F22	0,20	$V(t_{1,22})$	54,00	2,27
		F32	0,12	$V(t_{1,32})$	100,00	2,52
		F42	0,16	$V(t_{1,42})$	31,20	1,05
		F52	0,13	$V(t_{1,52})$	96,00	2,62
		F62	0,18	$V(t_{1,62})$	64,00	2,42
C3: Emissions	0,14	F13	0,32	$V(t_{1,13})$	50,00	2,24
		F23	0,32	$V(t_{1,23})$	95,00	4,26
		F33	0,19	$V(t_{1,33})$	99,50	2,65
		F43	0,17	$V(t_{1,43})$	72,50	1,73
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{1,14})$	50,00	6,10
		F24	0,47	$V(t_{1,24})$	33,33	3,60
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{1,15})$	100,00	1,85
		F25	0,45	$V(t_{1,25})$	100,00	2,25
		F35	0,18	$V(t_{1,35})$	28,00	0,26
C6: System Evaluation	0,08	F16	0,09	$V(t_{1,16})$	100,00	0,72
		F26	0,26	$V(t_{1,26})$	100,00	2,08
		F36	0,09	$V(t_{1,36})$	60,00	0,43
		F46	0,09	$V(t_{1,46})$	60,00	0,43
		F56	0,15	$V(t_{1,56})$	80,00	0,96
		F66	0,32	$V(t_{1,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{1,17})$	80,00	3,30
		F27	0,41	$V(t_{1,27})$	18,00	0,52
						65,33

Table G.7 : Calculation of the technology value of Technology 2 for 2015-2025

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{2,11})$	87,50	13,48
		F21	0,30	$V(t_{2,21})$	50,00	3,30
C2: Performance	0,21	F12	0,21	$V(t_{2,12})$	16,00	0,71
		F22	0,20	$V(t_{2,22})$	54,00	2,27
		F32	0,12	$V(t_{2,32})$	80,00	2,02
		F42	0,16	$V(t_{2,42})$	33,60	1,13
		F52	0,13	$V(t_{2,52})$	97,00	2,65
		F62	0,18	$V(t_{2,62})$	64,00	2,42
C3: Emissions	0,14	F13	0,32	$V(t_{2,13})$	75,00	3,36
		F23	0,32	$V(t_{2,23})$	95,00	4,26
		F33	0,19	$V(t_{2,33})$	67,50	1,80
		F43	0,17	$V(t_{2,43})$	9,50	0,23
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{2,14})$	56,67	6,91
		F24	0,47	$V(t_{2,24})$	42,57	4,60
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{2,15})$	75,00	1,39
		F25	0,45	$V(t_{2,25})$	100,00	2,25
		F35	0,18	$V(t_{2,35})$	28,00	0,26
C6: System Evaluation	0,08	F16	0,09	$V(t_{2,16})$	80,00	0,58
		F26	0,26	$V(t_{2,26})$	80,00	1,66
		F36	0,09	$V(t_{2,36})$	40,00	0,29
		F46	0,09	$V(t_{2,46})$	40,00	0,29
		F56	0,15	$V(t_{2,56})$	60,00	0,72
		F66	0,32	$V(t_{2,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{2,17})$	60,00	2,48
		F27	0,41	$V(t_{2,27})$	6,00	0,17
						61,75

Table G.8 : Calculation of the technology value of Technology 3 for 2015-2025

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{3,11})$	65,00	10,01
		F21	0,30	$V(t_{3,21})$	30,00	1,98
C2: Performance	0,21	F12	0,21	$V(t_{3,12})$	50,00	2,21
		F22	0,20	$V(t_{3,22})$	42,00	1,76
		F32	0,12	$V(t_{3,32})$	60,00	1,51
		F42	0,16	$V(t_{3,42})$	32,80	1,10
		F52	0,13	$V(t_{3,52})$	80,00	2,18
		F62	0,18	$V(t_{3,62})$	36,00	1,36
C3: Emissions	0,14	F13	0,32	$V(t_{3,13})$	33,33	1,49
		F23	0,32	$V(t_{3,23})$	100,00	4,48
		F33	0,19	$V(t_{3,33})$	12,50	0,33
		F43	0,17	$V(t_{3,43})$	50,00	1,19
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{3,14})$	73,33	8,94
		F24	0,47	$V(t_{3,24})$	60,00	6,49
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{3,15})$	60,00	1,11
		F25	0,45	$V(t_{3,25})$	100,00	2,25
		F35	0,18	$V(t_{3,35})$	32,00	0,29
C6: System Evaluation	0,08	F16	0,09	$V(t_{3,16})$	80,00	0,58
		F26	0,26	$V(t_{3,26})$	80,00	1,66
		F36	0,09	$V(t_{3,36})$	60,00	0,43
		F46	0,09	$V(t_{3,46})$	80,00	0,58
		F56	0,15	$V(t_{3,56})$	100,00	1,20
		F66	0,32	$V(t_{3,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{3,17})$	60,00	2,48
		F27	0,41	$V(t_{3,27})$	1,00	0,03
						58,21

Table G.9 : Calculation of the technology value of Technology 4 for 2015-2025

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{4,11})$	80,00	12,32
		F21	0,30	$V(t_{4,21})$	40,00	2,64
C2: Performance	0,21	F12	0,21	$V(t_{4,12})$	32,00	1,41
		F22	0,20	$V(t_{4,22})$	50,00	2,10
		F32	0,12	$V(t_{4,32})$	80,00	2,02
		F42	0,16	$V(t_{4,42})$	36,80	1,24
		F52	0,13	$V(t_{4,52})$	65,00	1,77
		F62	0,18	$V(t_{4,62})$	36,00	1,36
C3: Emissions	0,14	F13	0,32	$V(t_{4,13})$	66,67	2,99
		F23	0,32	$V(t_{4,23})$	97,00	4,35
		F33	0,19	$V(t_{4,33})$	95,00	2,53
		F43	0,17	$V(t_{4,43})$	99,98	2,38
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{4,14})$	33,33	4,06
		F24	0,47	$V(t_{4,24})$	99,83	10,79
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{4,15})$	25,00	0,46
		F25	0,45	$V(t_{4,25})$	50,00	1,13
		F35	0,18	$V(t_{4,35})$	80,00	0,73
C6: System Evaluation	0,08	F16	0,09	$V(t_{4,16})$	80,00	0,58
		F26	0,26	$V(t_{4,26})$	80,00	1,66
		F36	0,09	$V(t_{4,36})$	80,00	0,58
		F46	0,09	$V(t_{4,46})$	80,00	0,58
		F56	0,15	$V(t_{4,56})$	100,00	1,20
		F66	0,32	$V(t_{4,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{4,17})$	40,00	1,65
		F27	0,41	$V(t_{4,27})$	8,00	0,23
						63,31

Table G.10 : Calculation of the technology value of Technology 5 for 2015-2025

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{5,11})$	88,75	13,67
		F21	0,30	$V(t_{5,21})$	60,00	3,96
C2: Performance	0,21	F12	0,21	$V(t_{5,12})$	24,50	1,08
		F22	0,20	$V(t_{5,22})$	50,00	2,10
		F32	0,12	$V(t_{5,32})$	100,00	2,52
		F42	0,16	$V(t_{5,42})$	47,33	1,59
		F52	0,13	$V(t_{5,52})$	51,00	1,39
		F62	0,18	$V(t_{5,62})$	52,00	1,97
C3: Emissions	0,14	F13	0,32	$V(t_{5,13})$	68,89	3,09
		F23	0,32	$V(t_{5,23})$	95,00	4,26
		F33	0,19	$V(t_{5,33})$	94,71	2,52
		F43	0,17	$V(t_{5,43})$	71,67	1,71
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{5,14})$	68,33	8,33
		F24	0,47	$V(t_{5,24})$	58,33	6,31
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{5,15})$	100,00	1,85
		F25	0,45	$V(t_{5,25})$	100,00	2,25
		F35	0,18	$V(t_{5,35})$	28,00	0,26
C6: System Evaluation	0,08	F16	0,09	$V(t_{5,16})$	80,00	0,58
		F26	0,26	$V(t_{5,26})$	100,00	2,08
		F36	0,09	$V(t_{5,36})$	100,00	0,72
		F46	0,09	$V(t_{5,46})$	100,00	0,72
		F56	0,15	$V(t_{5,56})$	60,00	0,72
		F66	0,32	$V(t_{5,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{5,17})$	60,00	2,48
		F27	0,41	$V(t_{5,27})$	15,67	0,45
						69,14

Table G.11 : Calculation of the technology value of Technology 6 for 2015-2025

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{6,11})$	68,75	10,59
		F21	0,30	$V(t_{6,21})$	55,00	3,63
C2: Performance	0,21	F12	0,21	$V(t_{6,12})$	25,00	1,10
		F22	0,20	$V(t_{6,22})$	32,20	1,35
		F32	0,12	$V(t_{6,32})$	60,00	1,51
		F42	0,16	$V(t_{6,42})$	30,00	1,01
		F52	0,13	$V(t_{6,52})$	65,00	1,77
		F62	0,18	$V(t_{6,62})$	60,00	2,27
C3: Emissions	0,14	F13	0,32	$V(t_{6,13})$	100,00	4,48
		F23	0,32	$V(t_{6,23})$	100,00	4,48
		F33	0,19	$V(t_{6,33})$	100,00	2,66
		F43	0,17	$V(t_{6,43})$	100,00	2,38
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{6,14})$	76,67	9,35
		F24	0,47	$V(t_{6,24})$	100,00	10,81
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{6,15})$	25,00	0,46
		F25	0,45	$V(t_{6,25})$	50,00	1,13
		F35	0,18	$V(t_{6,35})$	80,00	0,73
C6: System Evaluation	0,08	F16	0,09	$V(t_{6,16})$	40,00	0,29
		F26	0,26	$V(t_{6,26})$	40,00	0,83
		F36	0,09	$V(t_{6,36})$	100,00	0,72
		F46	0,09	$V(t_{6,46})$	100,00	0,72
		F56	0,15	$V(t_{6,56})$	40,00	0,48
		F66	0,32	$V(t_{6,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{6,17})$	40,00	1,65
		F27	0,41	$V(t_{6,27})$	9,00	0,26
						67,22

Table G.12 : Calculation of the technology value of Technology 1 for 2025-2040

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{1,11})$	95,00	14,63
		F21	0,30	$V(t_{1,21})$	70,00	4,62
C2: Performance	0,21	F12	0,21	$V(t_{1,12})$	17,00	0,75
		F22	0,20	$V(t_{1,22})$	64,00	2,69
		F32	0,12	$V(t_{1,32})$	100,00	2,52
		F42	0,16	$V(t_{1,42})$	32,00	1,08
		F52	0,13	$V(t_{1,52})$	98,00	2,68
		F62	0,18	$V(t_{1,62})$	64,00	2,42
C3: Emissions	0,14	F13	0,32	$V(t_{1,13})$	83,33	3,73
		F23	0,32	$V(t_{1,23})$	96,00	4,30
		F33	0,19	$V(t_{1,33})$	99,75	2,65
		F43	0,17	$V(t_{1,43})$	80,00	1,90
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{1,14})$	53,33	6,50
		F24	0,47	$V(t_{1,24})$	43,33	4,68
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{1,15})$	75,00	1,39
		F25	0,45	$V(t_{1,25})$	100,00	2,25
		F35	0,18	$V(t_{1,35})$	28,00	0,26
C6: System Evaluation	0,08	F16	0,09	$V(t_{1,16})$	100,00	0,72
		F26	0,26	$V(t_{1,26})$	100,00	2,08
		F36	0,09	$V(t_{1,36})$	20,00	0,14
		F46	0,09	$V(t_{1,46})$	40,00	0,29
		F56	0,15	$V(t_{1,56})$	100,00	1,20
		F66	0,32	$V(t_{1,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{1,17})$	100,00	4,13
		F27	0,41	$V(t_{1,27})$	22,00	0,63
						70,80

Table G.13 : Calculation of the technology value of Technology 2 for 2025-2040

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{2,11})$	88,75	13,67
		F21	0,30	$V(t_{2,21})$	50,00	3,30
C2: Performance	0,21	F12	0,21	$V(t_{2,12})$	17,00	0,75
		F22	0,20	$V(t_{2,22})$	55,20	2,32
		F32	0,12	$V(t_{2,32})$	80,00	2,02
		F42	0,16	$V(t_{2,42})$	34,00	1,14
		F52	0,13	$V(t_{2,52})$	98,00	2,68
		F62	0,18	$V(t_{2,62})$	64,00	2,42
C3: Emissions	0,14	F13	0,32	$V(t_{2,13})$	83,33	3,73
		F23	0,32	$V(t_{2,23})$	97,00	4,35
		F33	0,19	$V(t_{2,33})$	75,00	2,00
		F43	0,17	$V(t_{2,43})$	25,00	0,60
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{2,14})$	60,00	7,31
		F24	0,47	$V(t_{2,24})$	47,00	5,08
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{2,15})$	60,00	1,11
		F25	0,45	$V(t_{2,25})$	100,00	2,25
		F35	0,18	$V(t_{2,35})$	28,00	0,26
C6: System Evaluation	0,08	F16	0,09	$V(t_{2,16})$	60,00	0,43
		F26	0,26	$V(t_{2,26})$	60,00	1,25
		F36	0,09	$V(t_{2,36})$	20,00	0,14
		F46	0,09	$V(t_{2,46})$	20,00	0,14
		F56	0,15	$V(t_{2,56})$	80,00	0,96
		F66	0,32	$V(t_{2,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{2,17})$	60,00	2,48
		F27	0,41	$V(t_{2,27})$	7,00	0,20
						63,14

Table G.14 : Calculation of the technology value of Technology 3 for 2025-2040

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{3,11})$	75,00	11,55
		F21	0,30	$V(t_{3,21})$	50,00	3,30
C2: Performance	0,21	F12	0,21	$V(t_{3,12})$	55,00	2,43
		F22	0,20	$V(t_{3,22})$	44,00	1,85
		F32	0,12	$V(t_{3,32})$	60,00	1,51
		F42	0,16	$V(t_{3,42})$	34,00	1,14
		F52	0,13	$V(t_{3,52})$	100,00	2,73
		F62	0,18	$V(t_{3,62})$	40,00	1,51
C3: Emissions	0,14	F13	0,32	$V(t_{3,13})$	66,67	2,99
		F23	0,32	$V(t_{3,23})$	100,00	4,48
		F33	0,19	$V(t_{3,33})$	25,00	0,67
		F43	0,17	$V(t_{3,43})$	55,00	1,31
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{3,14})$	76,67	9,35
		F24	0,47	$V(t_{3,24})$	66,67	7,21
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{3,15})$	75,00	1,39
		F25	0,45	$V(t_{3,25})$	100,00	2,25
		F35	0,18	$V(t_{3,35})$	33,33	0,31
C6: System Evaluation	0,08	F16	0,09	$V(t_{3,16})$	100,00	0,72
		F26	0,26	$V(t_{3,26})$	100,00	2,08
		F36	0,09	$V(t_{3,36})$	40,00	0,29
		F46	0,09	$V(t_{3,46})$	60,00	0,43
		F56	0,15	$V(t_{3,56})$	100,00	1,20
		F66	0,32	$V(t_{3,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{3,17})$	60,00	2,48
		F27	0,41	$V(t_{3,27})$	2,00	0,06
						65,77

Table G.15 : Calculation of the technology value of Technology 4 for 2025-2040

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{4,11})$	85,00	13,09
		F21	0,30	$V(t_{4,21})$	50,00	3,30
C2: Performance	0,21	F12	0,21	$V(t_{4,12})$	33,00	1,46
		F22	0,20	$V(t_{4,22})$	50,80	2,13
		F32	0,12	$V(t_{4,32})$	100,00	2,52
		F42	0,16	$V(t_{4,42})$	37,20	1,25
		F52	0,13	$V(t_{4,52})$	70,00	1,91
		F62	0,18	$V(t_{4,62})$	40,00	1,51
C3: Emissions	0,14	F13	0,32	$V(t_{4,13})$	76,67	3,43
		F23	0,32	$V(t_{4,23})$	98,00	4,39
		F33	0,19	$V(t_{4,33})$	97,50	2,59
		F43	0,17	$V(t_{4,43})$	99,98	2,38
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{4,14})$	40,00	4,88
		F24	0,47	$V(t_{4,24})$	99,87	10,80
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{4,15})$	75,00	1,39
		F25	0,45	$V(t_{4,25})$	20,00	0,45
		F35	0,18	$V(t_{4,35})$	80,00	0,73
C6: System Evaluation	0,08	F16	0,09	$V(t_{4,16})$	100,00	0,72
		F26	0,26	$V(t_{4,26})$	60,00	1,25
		F36	0,09	$V(t_{4,36})$	60,00	0,43
		F46	0,09	$V(t_{4,46})$	60,00	0,43
		F56	0,15	$V(t_{4,56})$	100,00	1,20
		F66	0,32	$V(t_{4,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{4,17})$	60,00	2,48
		F27	0,41	$V(t_{4,27})$	9,00	0,26
						67,54

Table G.16 : Calculation of the technology value of Technology 5 for 2025-2040

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{5,11})$	98,13	15,11
		F21	0,30	$V(t_{5,21})$	70,00	4,62
C2: Performance	0,21	F12	0,21	$V(t_{5,12})$	29,00	1,28
		F22	0,20	$V(t_{5,22})$	52,00	2,18
		F32	0,12	$V(t_{5,32})$	100,00	2,52
		F42	0,16	$V(t_{5,42})$	52,00	1,75
		F52	0,13	$V(t_{5,52})$	66,00	1,80
		F62	0,18	$V(t_{5,62})$	64,00	2,42
C3: Emissions	0,14	F13	0,32	$V(t_{5,13})$	80,00	3,58
		F23	0,32	$V(t_{5,23})$	97,00	4,35
		F33	0,19	$V(t_{5,33})$	96,46	2,57
		F43	0,17	$V(t_{5,43})$	76,67	1,82
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{5,14})$	80,00	9,75
		F24	0,47	$V(t_{5,24})$	72,67	7,86
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{5,15})$	100,00	1,85
		F25	0,45	$V(t_{5,25})$	100,00	2,25
		F35	0,18	$V(t_{5,35})$	28,00	0,26
C6: System Evaluation	0,08	F16	0,09	$V(t_{5,16})$	100,00	0,72
		F26	0,26	$V(t_{5,26})$	100,00	2,08
		F36	0,09	$V(t_{5,36})$	80,00	0,58
		F46	0,09	$V(t_{5,46})$	80,00	0,58
		F56	0,15	$V(t_{5,56})$	80,00	0,96
		F66	0,32	$V(t_{5,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{5,17})$	80,00	3,30
		F27	0,41	$V(t_{5,27})$	30,00	0,86
						77,60

Table G.17 : Calculation of the technology value of Technology 6 for 2025-2040

Criterion		Factors		Desirability Value		Technology Value
C1: Cost effectiveness	0,22	F11	0,70	$V(t_{6,11})$	87,50	13,48
		F21	0,30	$V(t_{6,21})$	75,00	4,95
C2: Performance	0,21	F12	0,21	$V(t_{6,12})$	29,00	1,28
		F22	0,20	$V(t_{6,22})$	33,60	1,41
		F32	0,12	$V(t_{6,32})$	100,00	2,52
		F42	0,16	$V(t_{6,42})$	33,00	1,11
		F52	0,13	$V(t_{6,52})$	92,50	2,53
		F62	0,18	$V(t_{6,62})$	70,00	2,65
C3: Emissions	0,14	F13	0,32	$V(t_{6,13})$	100,00	4,48
		F23	0,32	$V(t_{6,23})$	100,00	4,48
		F33	0,19	$V(t_{6,33})$	100,00	2,66
		F43	0,17	$V(t_{6,43})$	100,00	2,38
C4: Fuel Consumption	0,23	F14	0,53	$V(t_{6,14})$	83,33	10,16
		F24	0,47	$V(t_{6,24})$	100,00	10,81
C5: Fuel Specifications	0,05	F15	0,37	$V(t_{6,15})$	100,00	1,85
		F25	0,45	$V(t_{6,25})$	20,00	0,45
		F35	0,18	$V(t_{6,35})$	80,00	0,73
C6: System Evaluation	0,08	F16	0,09	$V(t_{6,16})$	80,00	0,58
		F26	0,26	$V(t_{6,26})$	100,00	2,08
		F36	0,09	$V(t_{6,36})$	100,00	0,72
		F46	0,09	$V(t_{6,46})$	100,00	0,72
		F56	0,15	$V(t_{6,56})$	80,00	0,96
		F66	0,32	$V(t_{6,66})$	100,00	2,56
C7: Market	0,07	F17	0,59	$V(t_{6,17})$	80,00	3,30
		F27	0,41	$V(t_{6,27})$	22,50	0,65
						79,48

APPENDIX H

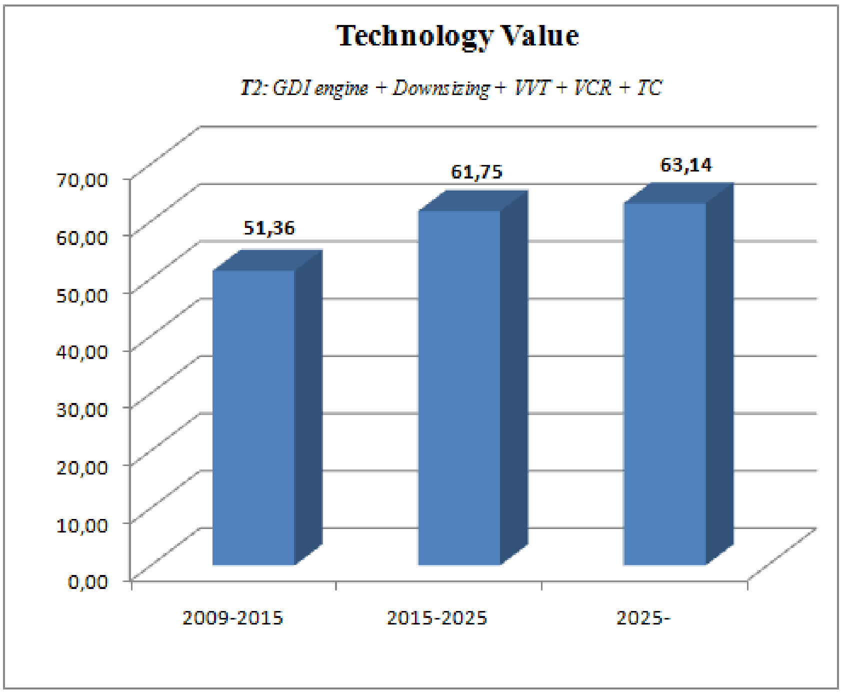


Figure H.1 : Technology values for Technology 2 for each time period

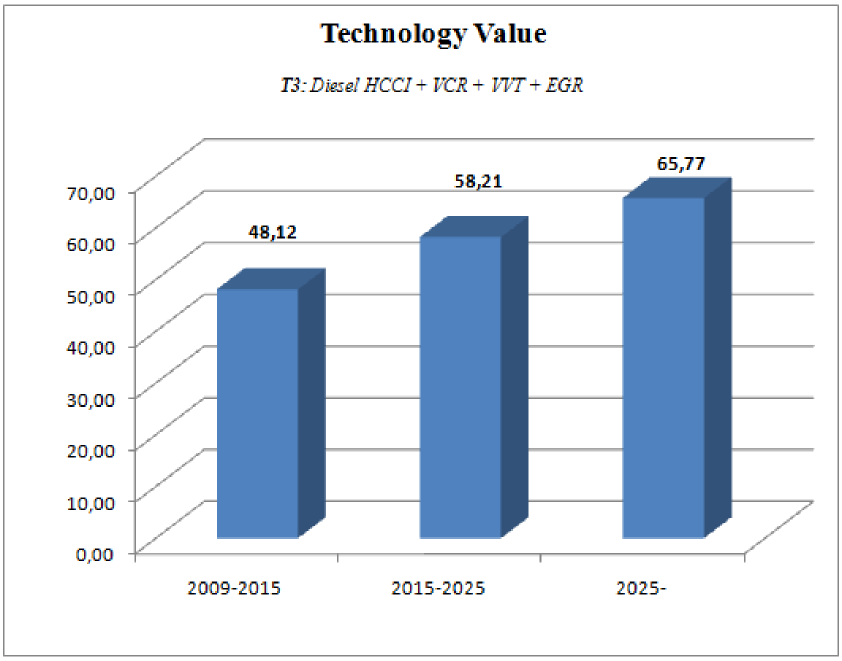


Figure H.2 : Technology values for Technology 3 for each time period

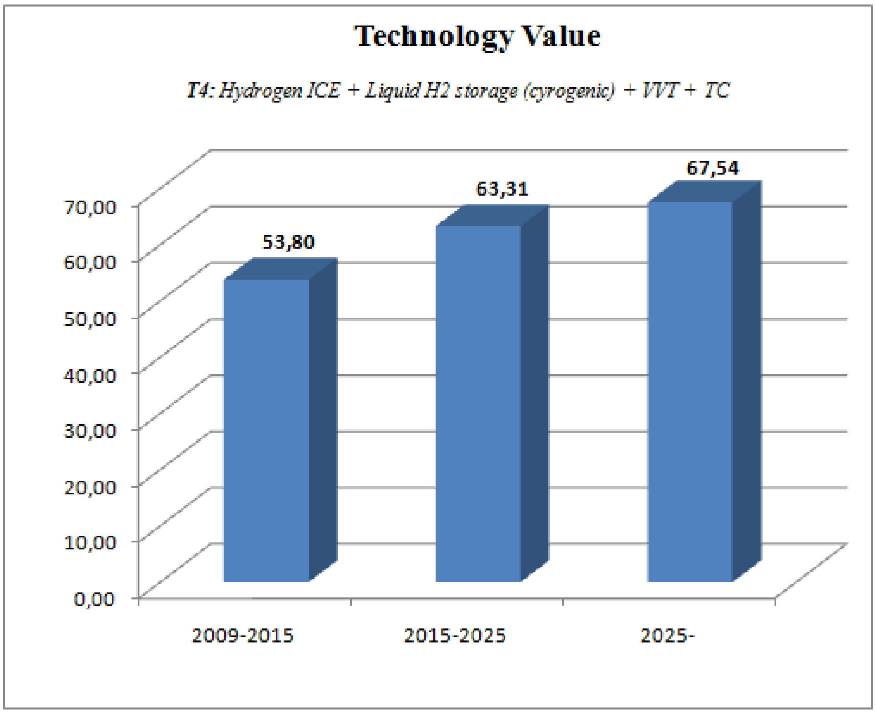


Figure H.3 : Technology values for Technology 4 for each time period

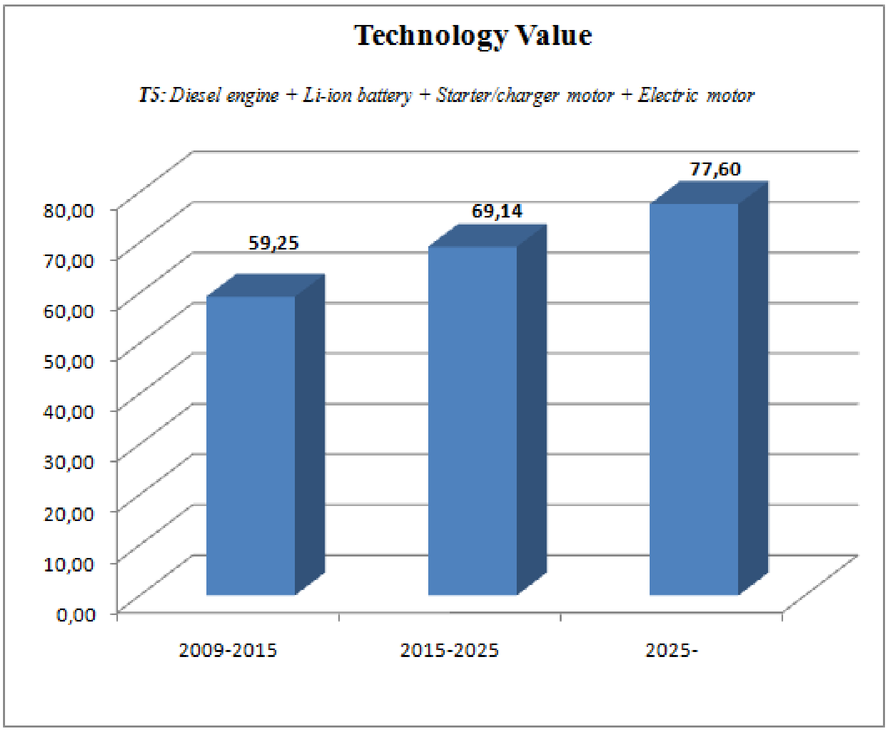


Figure H.4 : Technology values for Technology 5 for each time period

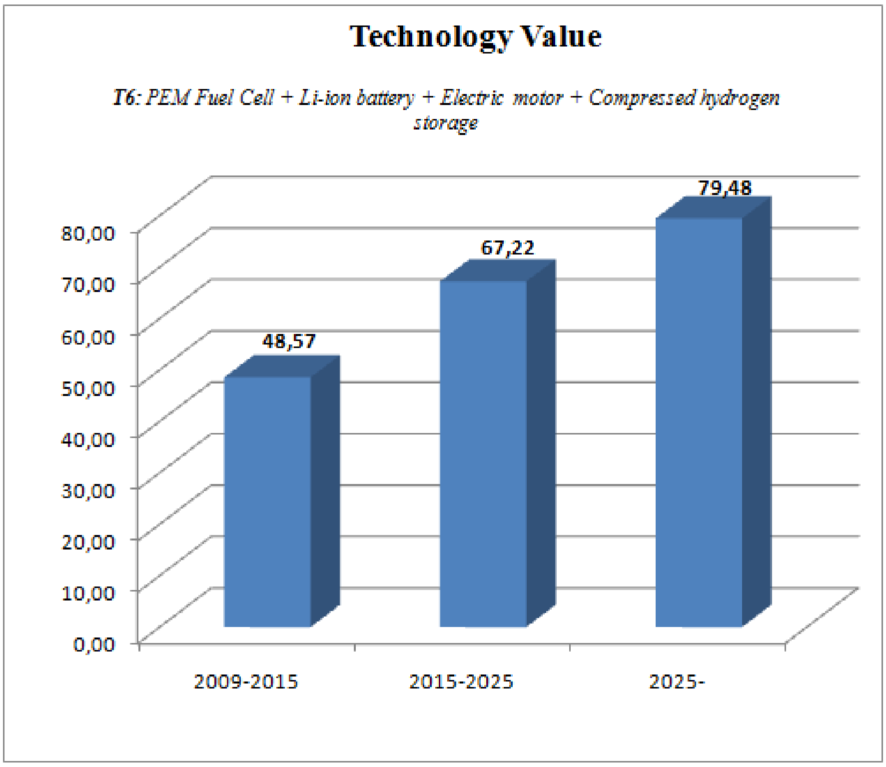


Figure H.5 : Technology values for Technology 6 for each time period

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Publications:

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