Roadmapping future powertrain technologies: a case study of Ford Otosan

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Abstract: This study explores 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 operationalisable is used for a case study of Ford Otosan's technological planning concept. In the first section, technologic roadmapping methodology is explained. As a next step, each powertrain solution is explained. Advantages regarding efficiency, fuel consumption, cost-effectiveness, emissions, infrastructure and performance have been listed. In the next sections, TDE methodology and the application DELPHI method are described in detail. A series of criteria and sub-factors have been generated with the aim to compare the different powertrain systems to identify the best solutions.

Keywords: technology roadmap; technology development envelope; powertrain; automotive; decision making.

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1 Introduction

Automotive industry is going through many challenges and requires accommodating with future technologies in order to make an impact during increasing competition. However, choosing the right technology target is not often an easy decision to make. Therefore, technology roadmapping plays an important role.

This paper focuses on an emerging approach to roadmapping; creation of a technology development envelope (TDE) for future powertrain technologies. This research will identify a series of technologies that will have an impact on Ford Otosan's competitiveness overtime, through technology identification and selection processes. The results will show the way for future investments and can be reviewed and updated for different applications.

2 Challenges affecting the automotive industry

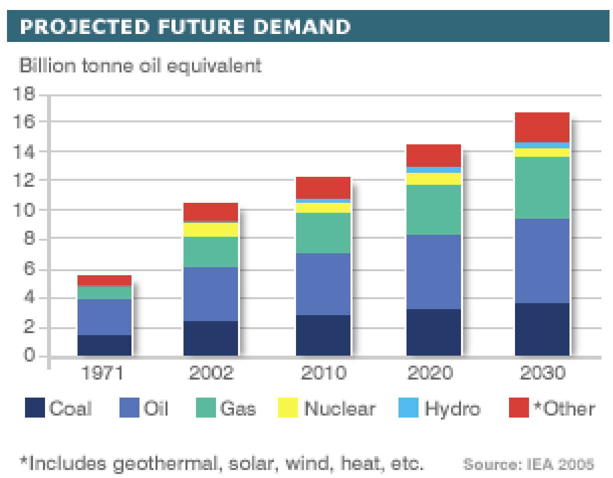
Automotive industry needs a breakthrough in energy systems for the upcoming decades due to unavoidable depletion of world fossil fuel resources. Furthermore, CO_2 and other pollutants are becoming more dangerous for global warming and human health. To reduce these emissions, governments started adopting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

2.1 Energy trends

Worldwide energy demand is increasing exponentially. 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 consumption worldwide. This demand cannot be met with shrinking fossil fuel supplies which emit greenhouse gases, causing the negative impacts of global climate change and air pollution. Figure 1 shows the world future energy demand is projected to increase.

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 (Sato and Kobayashi, 1997).

Figure 1 World's projected future energy demand (see online version for colours)



Source: 'Global energy guide', Available at: http://news.bbc.co.uk/2/shared/spl/hi/sci_nat/06/global_energy/html/introduction.stm, Retrieved on 22 December 2008.

2.2 Exhaust emission reduction requirements

Over decades global pollution concerns have increased and air quality targets have been established in programmes, like the Clean Air Act in the USA or the Clean Air for Europe programme (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 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.

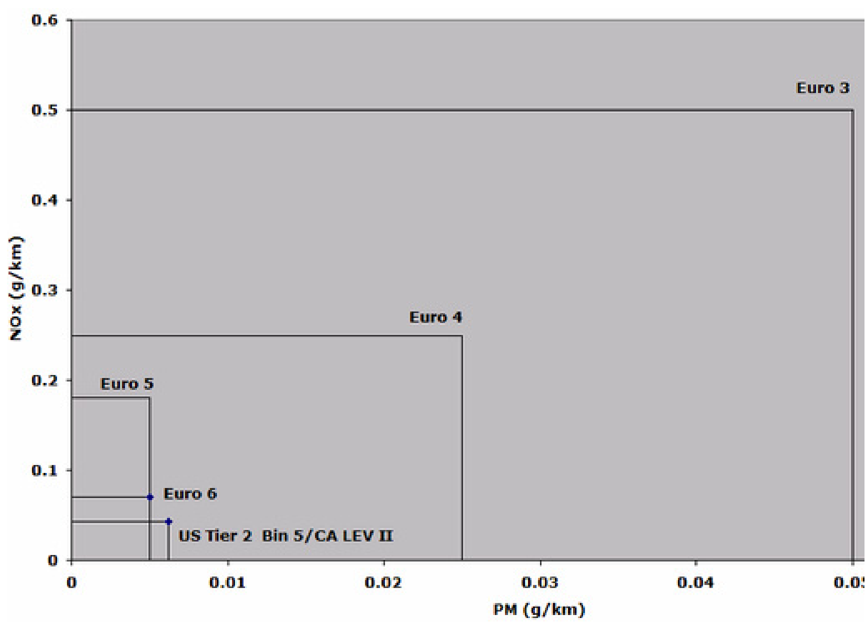
Most of the development of new regulations in 2007 occurred in Europe, with the finalisation of the light-duty Euro 5 and 6 emissions standards, and a proposal from the Commission for Euro VI heavy-duty standards (*Official Journal of the European Union*, 2007).

Figures 2 and 3 compare the European regulations with the US Tier 2 regulations.

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 (Dohle, 2006).

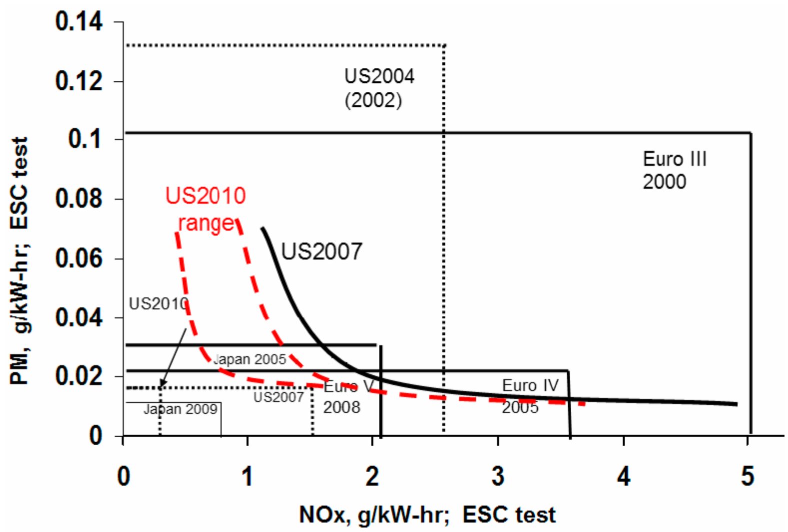
California State emission requirements are usually more stringent than set by EPA, however developed from similar procedures. In 1998, California Air Resources Board (CARB) has adopted Low Emission Vehicle II (LEV II) regulations following a less strict LEV I regulations. These standards set the limit for NOx and PM emissions even lower than European exhaust emission standards. In Figure 4, a comparison of LEV standards with ultra low emission vehicle (ULEV) and super ultra low emission vehicle (SULEV) standards is shown.

Figure 2 PM and NOx-emission limits comparison for diesel cars



Source: 'Emission standards', Available at: http://www.dieselnet.com/standards/, Retrieved on 1 August 2008.

Figure 3 General comparison of on road heavy-duty standards in the USA, Japan and Europe (see online version for colours)



Source: Johnson, T., 'Diesel emission control in review', *SAE Paper 2007-01-0233*.

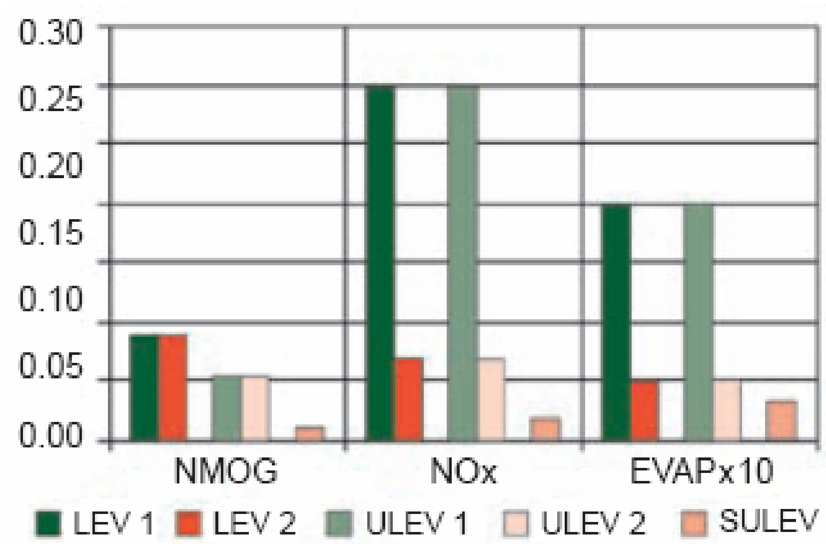
2.3 CO_2 emissions

Due to rapid industrialisation and human activities such as the combustion of fossil fuels and deforestation, and the concentration of atmospheric carbon dioxide has increased by about 35% since preindustrial times (Kotz and Treichel, 1999). The intergovernmental panel on climate change (IPCC) has predicted an average global rise in temperature of 1.4–5.8°C between 1990 and 2100 (Climate Change, 2001).

Figure 5 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 (Available at: http://cdiac.ornl.gov/trends/co2/contents.htm.).

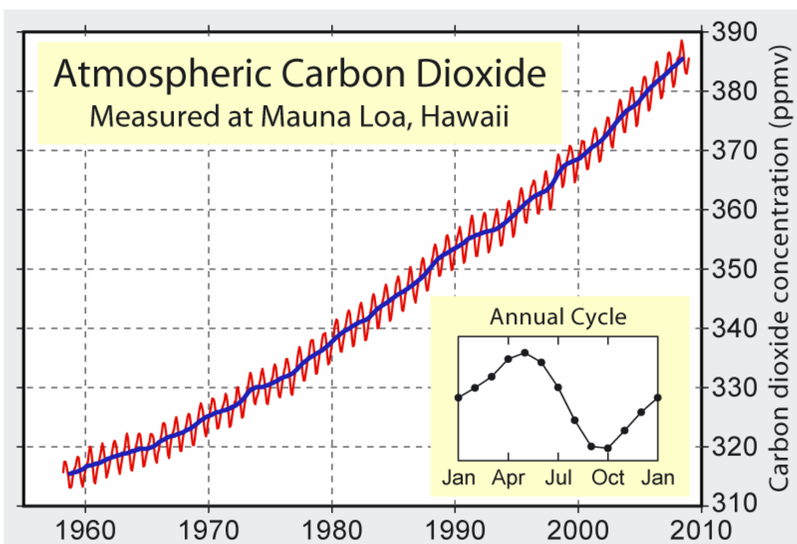
The climate change has gained great momentum due to Kyoto protocol to the United Nations Framework Convention on Climate Change (UNFCCC or FCCC), an international environmental treaty produced at the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro, Brazil, from 3 to 14 June 1992. Under Kyoto, industrialised countries agreed to reduce their collective GHG emissions by 5.2% compared to the year 1990 (United Nations Environment Programme, 1997).

Figure 4 LEV emission standards comparison (see online version for colours)



Source: 'The plain English guide to tailpipe standards', Available at: http://www.ucsusa.org/clean_vehicles/vehicle_impacts/cars_pickups_and_suvs/the-plain-english-guide-to.html, Retrieved on 2 September 2008.

Figure 5 Atmospheric CO_2 emissions (see online version for colours)



Source: Available at: http://cdiac.ornl.gov/trends/co2.htm, Retrieved on 19 March 2009.

Table 1 Transportation GHG emissions by mode

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 1 (Green and Schafer, 2003). 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.

3 TDE methodology

In order for the companies to face fierce competitive problems, it is highly important to depend on technology planning. 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.

Technology roadmapping is a needs driven technology-planning process to help, identify, select and to develop technology alternatives to satisfy a set of product needs. It brings together a team of experts to develop a framework for organising and presenting the critical technology-planning information to make the appropriate technology investment decisions and to leverage those investments.

The main benefit of technology roadmapping is that it provides information that help to make better technology investment decisions. It defines the technical risks associated with the project or programme 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 and provides a framework to plan and coordinate science and technology developments within a project or programme.

3.1 Literature search

There is a wide range of research available on technology forecasting and roadmapping as well as many industrial roadmaps (Bright and Schoeman, 1973; Kostoff and Schaller, 2001; Lizaso and Reger, 2004; Phaal et al., 2000, 2001, 2003; Porter, 1991; US Department of Energy, 2007). Furthermore, most forecasting and assessment methods, such as Delphi are investigated thoroughly (Costa, 2000; Linstone and Turloff, 1975; Skulmoski et al., 2007). 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 (Chen et al., 2005; Laughlin and Roper, 2007; Richey and Grinnell, 2004). 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 (Walsh, 2004). Therefore, another approach is required to conduct a roadmap.

Current roadmaps on automotive industry focus on general aspects of the future technologies and reflect an overall evaluation (Phaal, 2004).

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, it is highly important to form a link between both external and internal technology developers and researchers (Gerdsri, 2005).

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’ (Gerdsri, 2006).

It should also 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 have never been studied before.

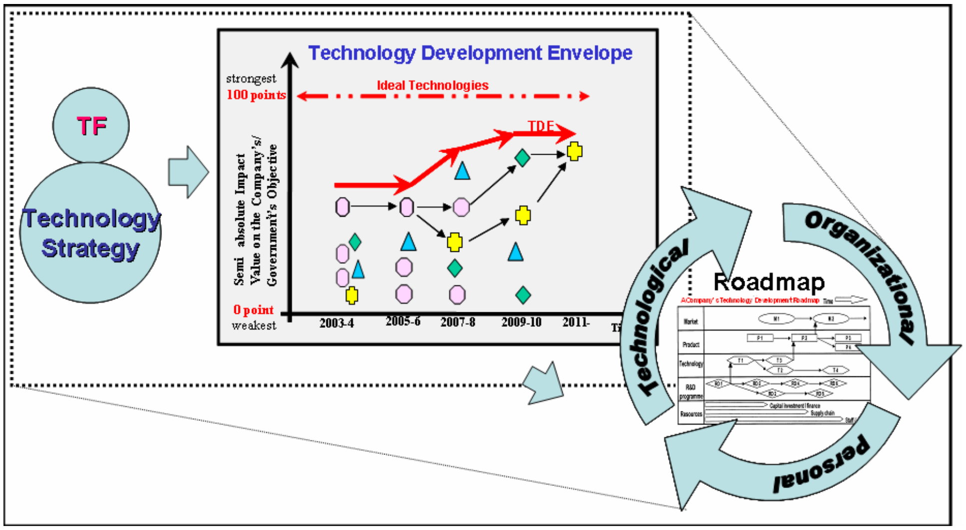
All these roadmapping gaps require a more flexible approach that can evaluate emerging technologies by gathering data from both technology developers and technology implementers.

Therefore, a new methodology called TDE is introduced (Gerdsri, 2005, 2006, 2007).

3.2 Methodology analysis

TDE is a new concept proposed by Gerdsri and Kocaoglu for identifying the optimum path in developing technology strategies and combining them with business strategies and/or policy decisions (Gerdsri, 2005, 2007).

Figure 6 TDE framework (see online version for colours)



Source: Gerdsri (2005).

TDE helps companies to identify emerging technologies, evaluate the value of those technologies with respect to the organisation's objective. 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 (Gerdsri, 2007). Once the best path is identified, it can be used to structure the technology elements in a roadmap, making it more flexible and alive. Figure 6 shows the relationship between TDE and roadmaps.

The development of a TDE is designed to be completed through six model development steps (Figure 7): TECHNOLOGY forecasting, technology characterisation, technology assessment, technology evaluation, hierarchical modelling and formation of TDE (Gerdsri, 2007).

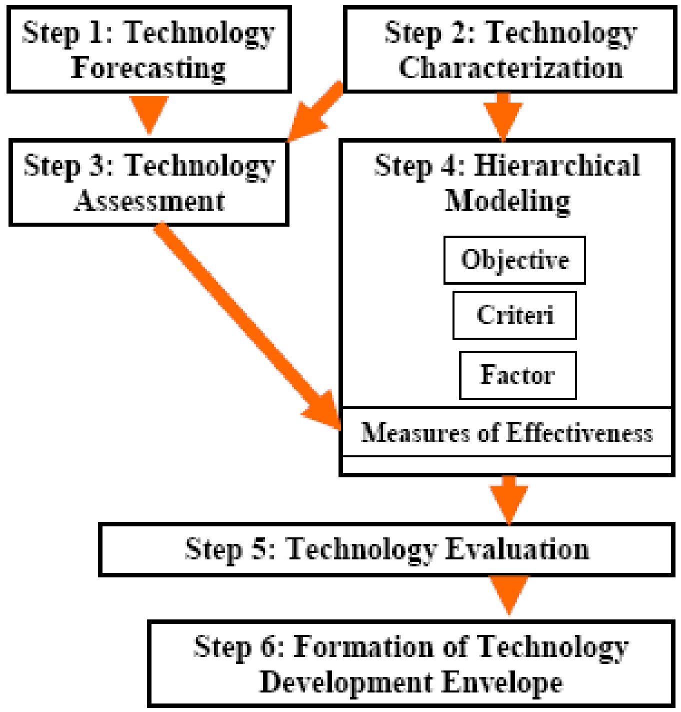
3.2.1 Technology forecasting

The main purpose of this step is to forecast the future trend of emerging technologies and to define the timing of their occurrences. 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 characterised 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 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 (Fowles, 1978).

Figure 7 Flowchart representing the six model development steps (see online version for colours)



Source: Gerdsri (2007).

For the technology forecasting step, two sets of Delphi process are 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.

3.2.2 Technology characterisation

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.

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.

3.2.3 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. An example of the base chart sent to experts for technology assessment is shown in Figure 8.

Figure 8 Evaluation of each technology according to criterion and respective factors (see online version for colours)

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

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.

3.2.4 Hierarchical modelling

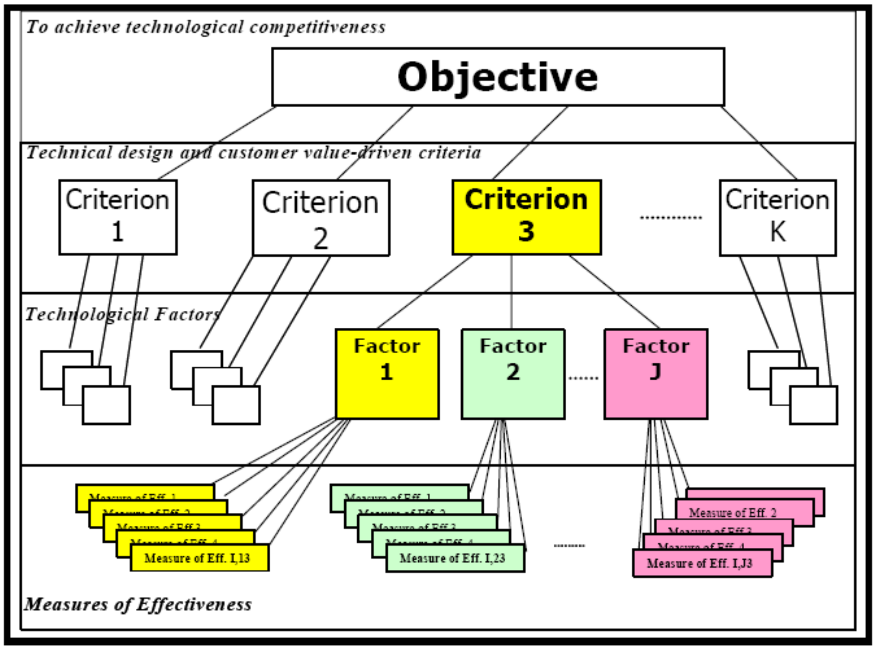
For this step, a hierarchical model is developed to determine the relative impact of measures of effectiveness on a company's objective. A generalised hierarchical model can be constructed with a four-level hierarchy; objective, criteria, factors and technologies.

In this study, analytic hierarchy process (AHP) is used as a hierarchical decision model to rank the contribution of each candidate technology to an organisation's objectives according to some decision criterion.

Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analysed independently. Once the hierarchy is built, the decision makers systematically evaluate its various elements, comparing them to one another in pairs. 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 (Saaty, 2008). 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 (http://en.wikipedia.org/wiki/Analytic_hierarchy_process).

In Figure 9, a hierarchical model for determining the relative impact of measures of effectiveness is shown.

Figure 9 Hierarchical model for determining the relative impact of measures of effectiveness (see online version for colours)



Source: Gerdsri (2005).

3.2.5 Technology evaluation

During the development of the hierarchical model, an index called 'technology value' is defined. For the hierarchical model, in Figure 9, the technology value of an emerging technology (TV*n*) can be calculated with the formula below (Gerdsri and Kocaoglu, 2004, 2007)

$$\mathrm{TV}n = \sum_{k=1}^{K} \sum_{k_k=1}^{J_k} w_k f_{j_k,k} V\left(t_{n,j_k,k}\right) \tag{1}$$

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

The mean values among all experts' judgement for each criterion are calculated to represent the group's judgement.

$$\sum_{k=1}^{K} w_k = 1.0 \quad \text{where, } w_k > 0 > 0 \tag{2}$$

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

$$\sum_{j_k=1}^{J_k} f_{j_k,k} = 1.0 \quad \text{where, } f_{j_k,k} > 0 \tag{3}$$

Next, the calculation of the relative desirability of measures of effectiveness under each combination of factor and criterion is required.

$$0 \le V\left(m_{i_{jk},j_k,k}\right) \le 100 \tag{4}$$

There are two approaches to complete the process:

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 (Gerdsri and Kocaoglu, 2004).

The mean values were calculated among the relative values given by each expert to represent the group decision according to the approaches above. As a result, the 'desirability curves' were developed.

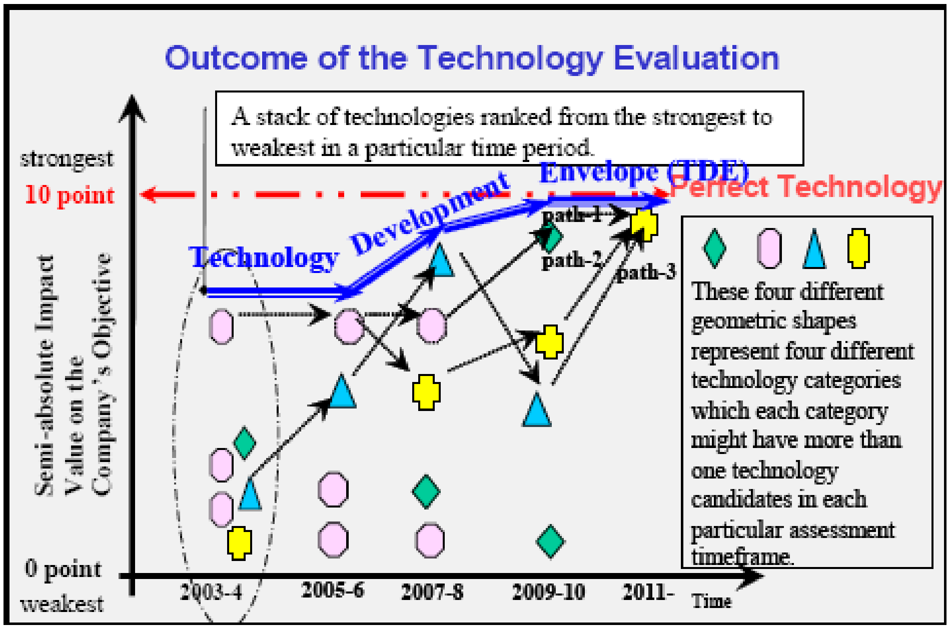
In the next step, the calculation includes the mapping of technological metrics ($t_{n,j_k,k}$) to the desirability values [$V(t_{n,j_k,k})$] using the relative desirability value of measures of effectiveness [$V(m_{j_k,k})$].

Finally, the technology value is calculated for each emerging technology by applying Equation (1). The ideal technology from a company's point of view would represent the technology value of 100.

3.2.6 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 10 (Gerdsri, 2007).

Figure 10 TDE diagram representing various possible paths of technology development (see online version for colours)



Source: Gerdsri (2007).

4 Case study on future powertrain technologies

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 Background

Due to challenges explained in Section 2, future powertrain systems are going though a transition phase and it is important for a vehicle manufacturer to decide the right technology to follow for the upcoming years.

Due to it 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 will be the dominant propulsion system for future generations. However, in the face of increasing requirements for propulsion systems, discussions about replacing the well established ICE by 'unconventional propulsion systems' such as hybrids and fuel cells are on the way (Pischinger et al., 2002).

To fulfil the future gasoline emission limits, there is no need for a totally new technology. The three way catalytic converter technology can realise the lowest known emission limits. However, engine design, exhaust after-treatment systems and engine control must be optimised to the extreme. Gasoline engines produce a negligible amount of NOx and PM emissions, but they are an important source of CO_2 emissions. Therefore, many technological approaches for the reduction of CO_2 are required. With the introduction of technologies and actions such as direct injection, fully variable valve train systems, downsizing with variable compression, homogeneous lean combustion, controlled auto ignition; a reduction of CO_2 emission by up to 25–30% will be possible, reaching fuel economy levels of today's diesel engines (Assanis et al., 2005; Kleeberg et al., 2006; Kurt, 2004; Lang et al., 2004, 2005; Noma et al., 1998; Pischinger et al., 2002; Wallace and Lux, 1964; Yang and Kenney, 2002).

Diesel engines have naturally lower HC, CO and CO_2 than gasoline vehicles, and are more durable; however do emit higher NOx and PM emissions. Therefore, in order to fulfil 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). The literature search shows that SCR and LNT systems are often used as separate aftertreatment systems; but after 2006 adding an SCR after the LNT improves efficiency and decreases cost (Lambert, 2005). Increased boosting levels at part load operation allow a leaner combustion at the same NOx-emission level. The main challenge is to realise higher boosting levels at upper part load operation without generating excessive gas exchange losses. This requires the implementation of improved boosting systems such as two stage boosting systems, parallel-sequential charging systems or improved VNT-turbochargers. It is known that turbocharging provides a cost-effective way of reducing GHG emissions (Arnold et al., 2001, 2005; Cooper, et al., 2006; Jackson, 2006; Johnson, 2004, 2007; Kawatari et al., 2006; Lambert, 2005; Lütkemeyer et al., 1996; Rohr et al., 2006).

Today hybrid electric vehicles (HEV's) are commonly understood as they combine an ICE with an electrical motor system to improve efficiency. If their use becomes more widespread, they could help to improve the overall efficiency of the vehicle fleet and could help to limit oil consumption, without significant changes to existing infrastructure, which has been a key barrier to the expanded use of alternative fuel vehicles. They produce zero emissions due to electric driving; consume less fuel and therefore reduce CO_2 emissions due to brake energy recovery, start–stop operation, operation point shifting and engine downsizing. The combination of a conventional gasoline engine and an electric motor with high torque at low rpm permits exceptional launch and acceleration. With smaller engines and all-electric drive at low speeds, hybrids are likely to be quieter than conventional gasoline vehicles. Batteries have been in use as an energy storage medium for a very long time in many applications, including conventional automobiles. In hybrid vehicles batteries as well as flywheels and supercapacitors can be used as an energy storage medium. Each system has its own characteristics and therefore has its own advantages and disadvantages. To summarise; batteries, which store energy in an electro-chemical process have a limited specific power regarding absorbing and delivering energy compared to flywheels, which store energy mechanically and supercapacitors and which store energy in a physical process (Biscarri et al., 1998; Cuddy and Wipke, 1997; Duleep, 1994; Mason and Kristiansson, 1994; Miller et al., 2007; O'Keefe and Vertin, 2002; Stienecker et al., 2006; Zheng et al., 2008).

However, the incremental price of a hybrid system is undoubtedly the biggest barrier to its success. The weight and price of electric components, such as battery and electric motor; limit the extent of hybridisation to small electric powers. Therefore, weight, cost and battery durability are the main topics that require further development (Friedman, 2003; Harris and Ventimeglia, 2002; Kelly and Rajagopalan, 2001; Markel and Simpson, 2006).

Fuel cells are electrochemical devices that convert the chemical energy of a gaseous fuel directly into electricity. 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 utilised 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 (*Fuel Cell Handbook*, 2004).

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 utilise 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 are 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) (*Fuel Cell Handbook*, 2004).

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 entering to the fuel cell.

Every major auto company in the world is evaluating the use of fuel cells in passenger vehicles, and almost all of them are testing fuel cell concept cars on the road. Current fuel cell demo vehicles are running on hydrogen or methanol, and advances have been recently made in the reforming of gasoline for use in fuel cells. Fuel cell transit bus demonstrations are ongoing in the USA, Canada and Germany. However, fuel cells must overcome a number of challenges to succeed in the commercial marketplace, such as, cost, fuel infrastructure and distribution inadequacy, size and packaging problems, and fuel storage technologies (Cockroft and Owen, 2006; Fuel Cells and Hydrogen..., 2008; Gayer, 2008; OECD/IEA, 2005; Ogden et al., 1998; Takamura and Matsumoto, 2002).

There are several papers on the comparison and efficiency analysis of different powertrain systems (An and Santini, 2003; Atkins and Koch, 2003; Pischinger et al., 2002; Rousseau and Sharer, 2004). However, these researches only focus on the performance, emission and efficiency characteristics of the systems and do not include other important criteria such as cost, safety, infrastructure, etc.

During the course of this research, more powertrain technologies and alternative fuels will be investigated selected by the expert answers to surveys.

4.2 Case study TDE development

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 centre experts, focusing on advanced technologies and control strategies. Third group represents the industry that involves in powertrain development and production. Details of the questionnaire are described in the Appendix A.

Even though the emerging technologies will be finalised according to expert reviews, a list of pre-defined powertrain technologies was selected according to the company objective. The objective is defined as 'to achieve technological competitiveness through future powertrain systems'. The pre-defined technologies were explained in Section 4.1, for example, advanced gasoline and diesel engines, battery hybrid vehicles and fuel cell vehicles. However, according to the first feedbacks of the survey indicate that hydrogen ICE, full electric vehicles and HCCI should also be included in the final technology lists.

In accordance with pre-defined technologies, a table was created to categorise them according to design criteria and technological factors associated with each criterion. All the criteria and the factors are detailed in Appendix B, whereas, the description of all 5-point scales defined for each factor are explained in Appendix C. These tables are very flexible according to the nature of TDE and will be finalised according to the expert feedbacks of the Delphi Questionnaire.

5 Results

This model will be a unique implementation of future powertrain roadmapping approach and can be expanded to other technologies, companies or industries.

The main characteristic of this approach is its flexibility; therefore, the research can be reviewed, updated or even adapted for different technologies after completion.

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Appendix A

Delphi questionnaire

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

	Today	*2010–2015*	*2015–2025*
Gasoline			
Diesel			
CNG			
LPG			
Biodiesel			
Ethanol			
Hydrogen			
Electric			
Synthetic			
Solar			
Biomass			
Ammonia			
Others:			
...			
...			
Spark ignition			
Diesel			
Full electric			
Fuel cell			
Full hybrid			
Mild hybrid			
Plug-in hybrid			
HCCI			
Hydrogen ICE			
Others:			
...			
...			

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

	Today	*2010–2015*	*2015–2025*
Lithium – ion battery			
Lead – acid battery			
Lithium polymer battery			
Nickel-cadmium battery		...	
Nickel-metal hydride battery		...	
Zinc-air battery			
Ultracapacitor			
Flywheel			
Others:			

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	*2010–2015*	*2015–2025*
High pressure injection			
Injection optimisation			
Combustion chamber optimisation			
Aftertreatment systems			
EGR			
SCR			
LNT			
Cooled EGR			
DPF			
Variable valve timing			
LTC strategies (low temp. combustion)			
VCR (variable compression ratio)			
Others:			

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

	Today					*2010-2015*					*2015-2025*				
	1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
Diminishing resources	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environmental issues	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Technological improvement threshold	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Others:															
...	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
...	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
...	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

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: Greatest challenge – 5: Smallest challenge). Please add others if necessary and include your comments below.

	Today					*2010–2015*					*2015–2025*				
	1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
Components															
Batteries	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Power control unit	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Power-split device	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Electric motor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Generators	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other:															
…	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
…	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other challenges															
Cost vs. payback	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Vehicle weight	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Pollution control	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Vehicle control	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

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: Greatest challenge – 5: Smallest challenge). Please add others if necessary and include your comments below.(continued)

	Today					*2010–2015*					*2015–2025*				
	1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
	Today					*2010–2015*					*2015–2025*				
	1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
Complexity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Auxiliary systems	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Engine choice	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other:															
…	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
…	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

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: Greatest challenge – 5: Least important challenge). Please add others if necessary and include your comments below.

	Today					*2010–2015*					*2015–2025*				
	1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
Components															
Fuel cell engine unit	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fuel storage	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Batteries	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Electric motor/generator	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Power control unit	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Power-split device	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other:															
…	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
…	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other challenges															
Hydrogen infrastructure	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Hydrogen source	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Durability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Precious metals	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Other:															
…	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
…	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Appendix B

The description of objective, criteria and technological factors is associated with each criterion (see online version for colours)

Criterion 1: Cost Effectiveness **Description:** Overall expenses of powertrain systems	
Factors associated with Performance Criterion	Measurement Unit
F11: Powertrain cost **Description:** Overall system cost and production expense. *Example:* Total expense of engines, motors, aftertreatment systems, energy storage systems, etc.	[$]
F12: Energy storage systems cost **Description:** *Example:* Total expense of energy storage systems	[$]
F13: Materials cost **Description:** Total expense of materials *Example:* In some cases, precious metals must be used in several components, hence the higher costs	[$]
F14: Maintenance cost **Description:** *Example:* Spare parts of some systems or components may be extremely expensive	[$]

Criterion 2: Performance **Description:** Comparison of system requirements for powertrains	
Factors associated with Performance Criterion	Measurement Unit
F12: Engine brake thermal efficiency / system efficiency **Description:** The measure of the effciency and completeness of combustion of the fuel *Example:* (bhp / heat input of fuel) x 100 -- bhp: useful or shaft work	[%]
F22: Peak power output **Description:** Maximum level of work or energy output that is measured during an observation period *Example:*	[kilowatts]
F32: System control technologies **Description:** *Example:* Some powertrain systems may require advanced control strategies to work in the most efficient area	[5 points scale]
F42: Power density **Description:** Ratio of the power to volume of a device *Example:*	[kilowatts/liters]
F52: Additional weight **Description:** Additional powertrain system weight compared to conventional vehicle *Example:* Weight is a critical factor for vehicles which should be reduced	[kilograms]
F62: Durability **Description:** Ability of something to perform its function repeatedly *Example:*	[hours]
F72: Cold start up to peak power **Description:** *Example:* Some systems may have difficulties during start-up in cold weathers/conditions	[seconds]

Criterion 3: Safety **Description:** Avoidance of automobile accidents as a result of improvements in vehicles & highways	
Factors associated with Performance Criterion	Measurement Unit
F13: Active safety **Description:** Devices and systems are those which the vehicle occupant must act to make functional *Example:* Good visibility, low noise level, handling, good grip, ABS braking, ESP, intelligent speed adaptation etc.	[5 points scale]
F23: Passive safety **Description:** Devices and systems are those which operate without any input or action from the vehicle occupant *Example:* Seat belts, loadspace barrier-nets, air-bags, laminated glass, fuel tanks, fuel pump kill switches, etc.	[5 points scale]

Criterion 4: Emissions **Description:** Emissions standards to be fulfilled before market introduction	
Factors associated with Performance Criterion	Measurement Unit
F14: NOx emissions **Description:** Nitrogen oxides are usually emitted from high temperature combustion *Example:* Can be seen as the brown haze dome above or plume downwind of cities	[grams/kilometers]
F24: PM emissions **Description:** Tiny particles of solid or liquid suspended in a gas *Example:* Averaged over the globe, PM emissions by human activities is account for about 10 percent of the total amount	[grams/kilometers]
F34: HC emissions **Description:** Have high enough vapor pressures under normal conditions to significantly vaporize and enter the atmosphere *Example:* Contributes to enhanced global warming	[grams/kilometers]
F44: CO emissions **Description:** Product by incomplete combustion of fuel such as natural gas, coal or wood *Example:* Colourless, odourless, non-irritating but very poisonous gas	[grams/kilometers]

Criterion 5: Fuel Consumption **Description:** Fuel consumption and respective CO2 emission values	
Factors associated with Performance Criterion	Measurement Unit
F15: Fuel consumption **Description:** Energy efficiency of a vehicle where its total output is given as a ratio of range units per amount of input fuel *Example:* In direct proportion with CO2 emissions	[liters/100 km]
F25: CO2 emissions **Description:** In order to reduce the greenhouse effects on the environment, CO2 emissions from vehicles should be reduced *Example:* To stabilize CO2 concentration below 550ppm, CO2 emissions from all new vehicles must be reduced by 70%	[g CO2/km]

Criterion 6: Fuel Specifications **Description:** Comparison of the systems with respect to their fuels	
Factors associated with Performance Criterion	Measurement Unit
F16: Fuel infrastructure availability **Description:** *Example:* Is the fuel infrastructure available for each driver?	[5 points scale]
F26: Fuel infrastructure cost **Description:** Total cost for fuel distribution & fuelling infrastructure *Example:*	[billion $]
F36: Energy density by mass **Description:** Amount of energy stored in a given system or region of space per unit mass *Example:*	[MJ/kg]

The description of objective, criteria and technological factors is associated with each criterion (see online version for colours) (continued)

Criterion 7: System Evaluation **Description:** Overall system evaluation for interchangeability, complexity, further improvements and current limitations	
Factors associated with Performance Criterion	Measurement Unit
F17: Materials availability **Description:** *Example:* Heavy metals used in some components can be hard to obtain and to be used	[5 points scale]
F27: Components availability **Description:** *Example:* Some components such as batteries can be expensive to be used in large fleets	[5 points scale]
F37: Technology development state **Description:** *Example:* During the transition from fossil fuels to hydrogen, some technologies may need to be improved	[5 points scale]
F47: Regulations and legal framework **Description:** Regulations for fuels and vehicles should be completed *Example:* Hydrogen regulations? Testing regulations for hybrids?	[5 points scale]
F57: System complexity **Description:** System complexity may cause difficulties during driving and maintenance and cost more *Example:* Control strategies of the systems, sensors, actuators, etc.	[5 points scale]
Criterion 8: Market **Description:** Position in market and/or market entrance of the systems	
Factors associated with Performance Criterion	Measurement Unit
F18: Availability of the vehicles **Description:** *Example:* Are the vehicles with the respective technology available today?	[5 points scale]
F28: Sales volume **Description:** *Example:* What are the sales volume of the vehicles with the respective technology?	[number of units]

Appendix C

Description of 5-point scale specifically defined for each qualitative factor

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 optimisation.
	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.
F13: Active safety	*Excellent (E)*	Integrated vehicle safety systems include all of the following technologies or more: ABS, ESC, traction control, brake assist, vehicle stability control, adaptive cruise control, near object detection system, night vision enhancement, anti roll-over, lane departure warning, driver assistance, HMI, etc.
	Very good (VG)	Integrated vehicle safety systems include almost each of the following technologies: ABS, ESC, traction control, brake assist, vehicle stability control, adaptive cruise control, near object detection system, night vision enhancement, anti roll-over, lane departure warning, driver assistance, HMI, etc.
	Good (G)	Integrated vehicle safety systems include most of the following technologies: ABS, ESC, traction control, brake assist, vehicle stability control, adaptive cruise control, near object detection system, night vision enhancement, anti roll-over, lane departure warning, driver assistance, HMI, etc.
	Acceptable (A)	Integrated vehicle safety systems include some of the following technologies: ABS, ESC, traction control, brake assist, vehicle stability control, adaptive cruise control, near object detection system, night vision enhancement, anti roll-over, lane departure warning, driver assistance, HMI, etc.
	Poor (P)	Integrated vehicle safety systems include only a few of the following technologies: ABS, ESC, traction control, brake assist, vehicle stability control, adaptive cruise control, near object detection system, night vision enhancement, anti roll-over, lane departure warning, driver assistance, HMI, etc.
	Unacceptable (UA)	Integrated vehicle safety systems include none of the following technologies: ABS, ESC, traction control, brake assist, vehicle stability control, adaptive cruise control, near object detection system, night vision enhancement, anti roll-over, lane departure warning, driver assistance, HMI, etc.
F23: Passive safety	*Excellent (E)*	Integrated vehicle safety systems include all of the following technologies or more: Smart seatbelts, smart air-bags, occupant detection systems, impact absorption, positioning of passengers etc.
	Very good (VG)	Integrated vehicle safety systems include most of the following technologies: Smart seatbelts, smart air-bags, occupant detection systems, impact absorption, positioning of passengers, etc.
	Good (G)	Integrated vehicle safety systems include only a few of the following technologies: Smart seatbelts, smart air-bags, occupant detection systems, impact absorption, positioning of passengers, etc.
	Acceptable (A)	Integrated vehicle safety systems include some of the following technologies or more: Seatbelts, smart air-bags, impact absorption, etc.
	Poor (P)	Integrated vehicle safety systems include only a few of the following technologies or more: Seatbelts, air-bags, impact absorption, etc.
	Unacceptable (UA)	Integrated vehicle safety systems include only the conventional versions of the following technologies: Seatbelts, air-bags, impact absorption, etc.
F16: Fuel infrastructure availability	*Excellent (E)*	Fuel is accessable for each driver all over the country and distribution infrastructure is widely spread.
	Very good (VG)	Fuel is accessable for each driver in most of the cities and distribution infrastructure fairly spread.
	Good (G)	Fuel is accessable for each driver in large cities and distribution infrastructure is fairly spread.
	Acceptable (A)	Fuel is accessable for each driver in large cities and distribution infrastructure requires development.
	Poor (P)	Fuel is accessable for each driver in only a few stations in large cities and distribution infrastructure requires development.
	Unacceptable (UA)	Fuel is not accessable for any drivers and distribution infrastructure requires extensive development.

F17: Materials availability	*Excellent (E)*	Materials required for the system are easily accessable with low cost
	Very good (VG)	Materials required for the system are easily accessable with high cost
	Good (G)	Materials required for the system are somewhat accessable with low cost
	Acceptable (A)	Materials required for the system are somewhat accessable with high cost
	Poor (P)	Materials required for the system are not easily accessable with low cost
	Unacceptable (UA)	Materials required for the system are not easily accessable with high cost
F27: 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.
F37: 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.

F47: Regulations and legal framework	*Excellent (E)*	Mandatory regulations of the system and/or fuel are already adopted, harmonisation of the regulations is completed, test procedures and requirements are set.
	Very good (VG)	Mandatory regulations of the system and/or fuel and the harmonisation of the regulations is currently being proposed, test procedures and requirements are almost set.
	Good (G)	Mandatory regulations of the system and/or fuel, harmonisation of the regulations and test procedures and requirements are currently being reviewed.
	Acceptable (A)	Mandatory regulations of the system and/or fuel, harmonisation of the regulations and test procedures and requirements are in preperation 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.
F57: 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.
F18: 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.